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SYSTEMS THINKING: SENSITIZING FOR SYSTEMS ENGINEERING - EXPERIENCES FROM ACADEMIC TEACHING AND INDUSTRY WORKSHOPS

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ABSTRACT
Today's products are based on the close interaction of mechanics, electronics and software engineering. This is aptly expressed by the term mechatronics. The conceivable development of information and communication technology will enable advanced mechatronic systems that react autonomously and flexibly on changing environmental conditions. The design of such systems is a challenge – established design methodologies are not adequate to this task as they restrain systems thinking. Systems thinking is essential for the successful systems development. We developed a specification technique for the engineering of these systems in the conceptual design phase and tested its performance supporting systems thinking as well as its acceptance within several workshops for students and practitioners.

Keywords: Systems thinking, systems engineering, model-based systems engineering, academic teaching, industry workshops

1 INTRODUCTION

The products of mechanical engineering and related industrial sectors, such as the automobile industry, are based on the close interaction of mechanics, electronics and software engineering. This is aptly expressed by the term mechatronics. The conceivable development of information and communication technology will enable advanced mechatronic systems that react autonomously and flexibly on changing environmental conditions. Their manifold system functions, the cross-linking of elements within systems and their hardly manageable interactions induce a high complexity in the development process and make it challenging. Established design methodologies of conventional mechanical engineering and even newer methodologies of mechatronics are not adequate to this task. Moreover, due to the different discipline-specific development approaches of the involved domains, engineers are not aware of the impact that is caused by their changes on the system. In other words: Current development approaches restrain comprehensive systems thinking. Many engineering projects run into deep trouble, e.g. resulting in long time-to-market or even in product recalls. Obviously there is a great demand for new development approaches to support systems thinking. Especially within the last two years, systems thinking and the related systems engineering are supposed to be the central approach for the development of any kind of technical system. Nevertheless, systems thinking is not new, it only fell into oblivion. Already in the 1930s, BERTALANFFY postulated a general *theory of systems* for overcoming the isolated views of classical natural sciences. This theory of systems analyzes complex interactions among system elements and takes the interaction of the environment and adjacent systems into account [1]. During the Second World War, these ideas and approaches of operations research were adapted for the planning of bombing campaigns, later for the planning of telecommunication networks in the US Bell Laboratories – the begin of transferring the idea of systems theory to the development of technical systems: Systems Engineering [2]. Up to now, systems engineering is well established in UK and US military industry, as well as aerospace and space travel – but never developed a sound methodology [3]. Inspired by the research on systems theory and practice-driven systems engineering, there had been approaches for a scientific fundament for systems engineering in the 1970s in Germany, now often called *Systemtechnik* [4], [5]. *Systemtechnik* should provide new holistic, integrated and applicable procedures, methods and tools for engineering practice, improving process and product as well as innovation competence. Unfortunately, with the shift towards mechatronics in the end of the 1970s, these approaches were forgotten and never refined until now. Nowadays *Systemtechnik* experience a kind of renaissance in Systems Engineering. Current work focuses on model-based systems engineering (MBSE). MBSE is the formalized modelling to support systems, requirements, design, analyses, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phase [6]. Within these efforts we developed an easy understandable model-based specification technique for the engineering of complex systems already in 2005: CONSENS (Conceptual Specification Technique for the Engineering of Complex Technical Systems) [7]. This approach forms the basis for the communication and cooperation of the developers from different domains in the course of the development process and supports systems thinking as well as innovative development. To transfer this approach into widespread application in industry, we developed a workshop concept to train practitioners as well as graduate students in systems thinking using CONSENS. Despite these efforts, we gained experience that approaches, such as CONSENS and SysML [8] that support systems thinking are rarely used and accepted in industry [6]. This raises the question about the courses of these acceptance problems. We are sure: MBSE approaches are crucial for the successful development of tomorrow's systems. For this reason we conducted a covered observation of the workshop participants to identify the reasons for the acceptance problems and to develop the specification technique further.

In this contribution, we present our findings from the covered observation. In section 2 we introduce the specification technique CONSENS. In section 3 we describe our research approach to identify acceptance problems and evaluate the performance of the specification technique. The findings of our observation will be presented and discussed in section 4. Finally we will give a short conclusion.

2 CONSENS: A MODEL-BASED SYSTEMS ENGINEERING APPROACH

The specification technique CONSENS (Conceptual Specification Technique for the Engineering of Complex Technical Systems) provides an interdisciplinary approach for the description of the principle solution of mechatronic systems. The principle solution defines the basic structure and the operation modes within the conceptual design. It describes not only the physical, but also the logical operating characteristics. CONSENS was developed within the CRC 614 to reduce the complexity of the development of complex mechatronic systems [7]. Already at the beginning of the work, it became clear that a comprehensive description of the principle solution of a highly complex system needs to be divided into aspects. These aspects are, according to figure 1 requirements, environment, system of objectives, application scenarios, functions, active structure, shape and behaviour. The mentioned aspects are mapped in the computer by partial models. The relations are modelled between the various constructs of the relating partial models and amount to a coherent system. In order to be able to secure the overall consistency of the principle solution, software support is necessary. We developed the software tool Mechatronic Modeller (MM) to describe mechatronic systems using the specification technique CONSENS [9]. It offers a separate editor for each partial model. Mechatronic Modeller is based upon a metamodel. The principle solution is computer-internally represented as a data model, which is the instance of this metamodel. Since the Mechatronic Modeller is based on a metamodel, the overall consistency of the principle solution model can be ensured easily. Furthermore, cross-references between elements of different partial models are stored in the data model. Thus, Mechatronic Modeller is capable of handling complex dependencies within the principle solution. By using this specification technique and the related software tool, the system is getting modelled in a holistic and domain-spanning way. It is necessary to work alternately on the aspects and the according partial models although there is a certain order. The specification of the principle solution forms the basis for the communication and cooperation of the developers from different disciplines during the complete development process and allows first analyses, e.g. on reliability or development cost.

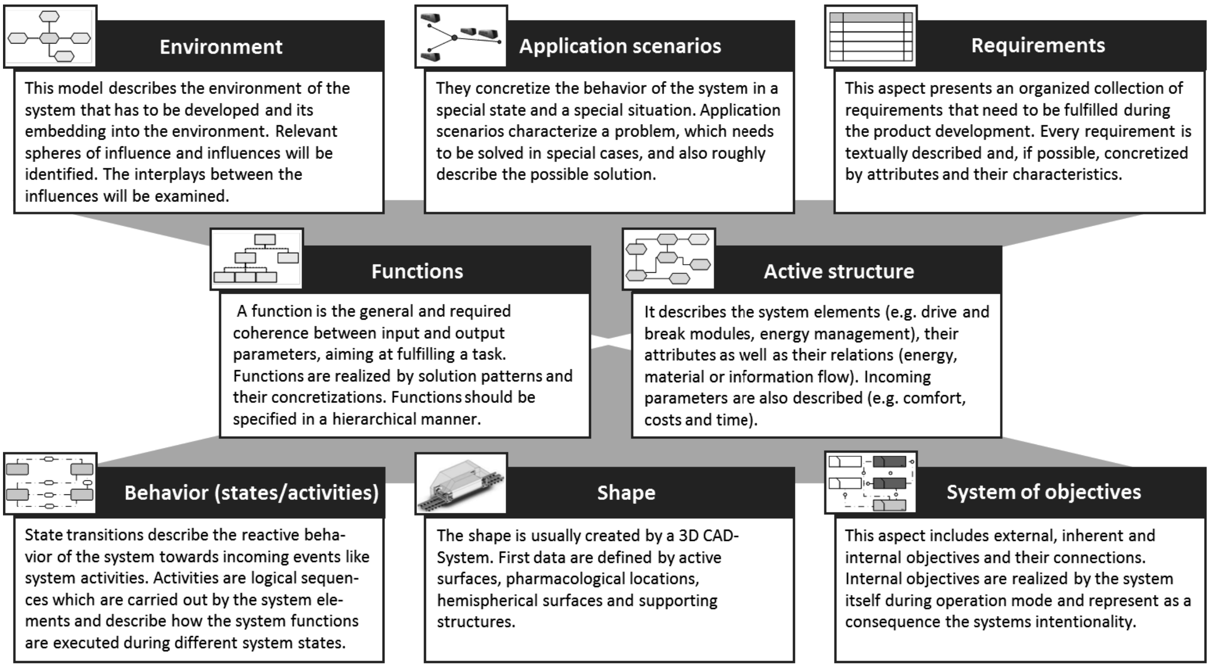

Figure 1. Short description of the used specification technique [7]

3 RESEARCH APPROACH

To improve systems thinking and innovation competence for practitioners as well as students, we developed a workshop concept based on the specification technique CONSENS and the Mechatronic Modeller. The aspects of the principle solution are modelled by using a set of cards for the different elements of the partial models and a metaplan board. Usually we start modelling the environment, application scenarios and the requirements, followed by functions, active structure and behaviour. The course of the workshop is presented in figure 2. A workshop moderator coordinates the system modelling and is responsible for the content consistency and supports the workshop teams. After modelling with the set of cards, the aspects are implemented in the Mechatronic Modeller.

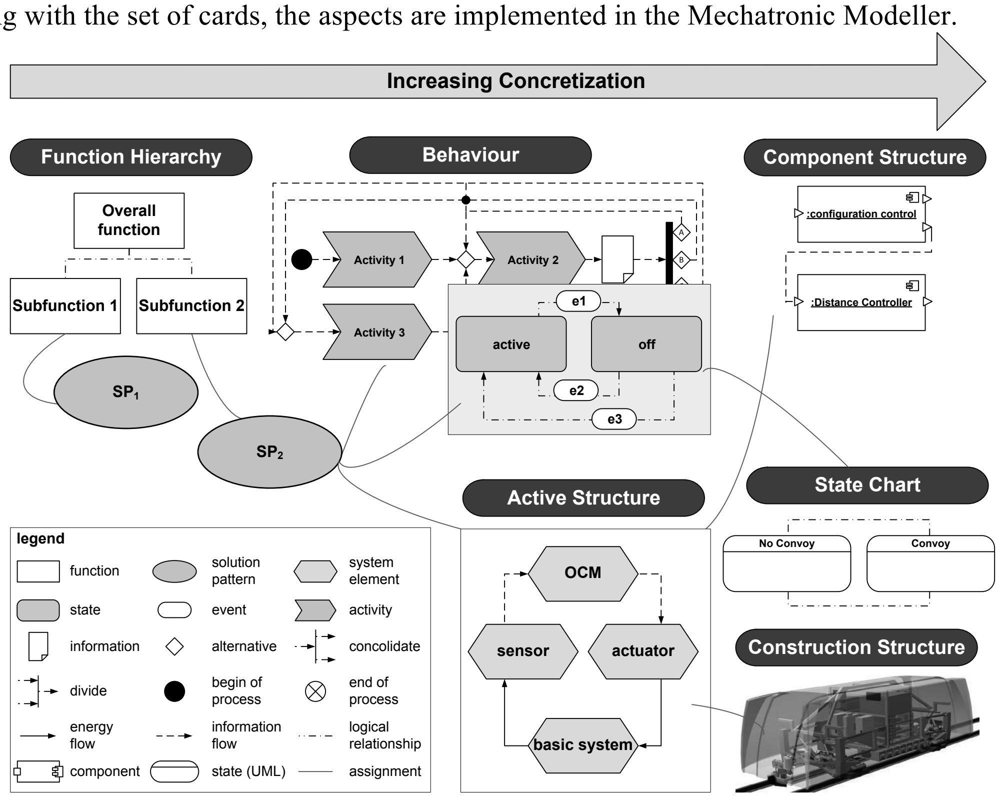

Figure 2. Course of the Workshop [10]

During the survey we observed how students and practitioners handle CONSENS and its systemic tools to identify acceptance problems with new tools and to evaluate the performance of the specification technique CONSENS. For this purpose we used a repeated observation [11]. We observed 15 groups à 5 graduate students in our seminar "Innovation and Development Management". Furthermore, were observed 5 groups à 4 practitioners in workshops on behalf of the BMBF funded transfer project mechatronics. All participants developed simple well known technical systems such as coffee-machines or lawn mowers. The example should be chosen from everyday life to ensure that every workshop participant is familiar with it. The moderator functioned as a participating and covert observer and therefore interacted with the objects of observation [12]. By this the problems of the subjects with the specification technique as well as acceptance problems were easy to identify. Therefore we were able to observe the natural behaviour of the subjects, without disturbance and pressure as a result of the observer's expectations [13]. The handling of CONSENS was evaluated using broad observation criteria (unstructured observation [14]) based on three categories according to BADKE-SCHAUB ET AL. allowing conclusions concerning deficits of a methodology [15]. These categories are **performance** of the method, its **presentation** and its integration in design **process.** We broke down these categories for getting detailed information for the further development of CONSENS.

Performance

1. **Holistic Description of the Principle Solution**: CONSENS has to enable the specification of any mechatronic system.
2. **Encouragement of the Conceptual Design**: CONSENS has to encourage the particularities of the conceptual design of the described systems.
3. **Mastering Complexity**: Approved concepts for structuring like hierarchies and modularization have to be encouraged.
4. **Consistency**: The results of the development phases have to be continuously described by the specification technique.
5. **System Comprehension**: CONSENS has to create system comprehension without describing the system too detailed.
6. **Innovation Competence**: The abstraction of proven solutions has to be enabled, to ensure new innovative solutions.
7. **Vocational Adjustment**: The period of vocational adjustment to work with the specification technique has to be short.

Presentation

8. **Equality of the Domains**: The specification technique has to treat the involved domains equal.
9. **Intuitive Graphical Modelling**: CONSENS has to encourage an intuitive work of domain-spanning teams.
10. **Intuitive Usage of Software**: Mechatronic Modeller can be used without any problems.

Process

11. **Traceability**: The results of the workshop have to be retraceable.
12. **Time Consumption**: Time consumption for the modelling of aspects has to be small.
13. **Management Support**: Management has to support the introduction of new methods.
14. **Process Integration**: The Mechatronic Modeller has to fit the enterprise's processes.
15. **Connectivity**: Intermediate results of CONSENS can be processed in development.

4 EXPERIENCES FROM ACADEMIC TEACHING AND INDUSTRY WORKSHOPS

In this section we present the results of our observations. Within the survey 95 participants were observed while working with CONSENS. The evaluation is presented in figure 3 as a qualitative strengths and weaknesses-profile. The evaluation comes to different results for students and practitioners regarding their ability to work with CONSENS and to think systemic. These differences result from the thought pattern of both groups. While students are still open minded for new approaches, practitioners have entrenched thought pattern, which hinders the application of systems thinking.

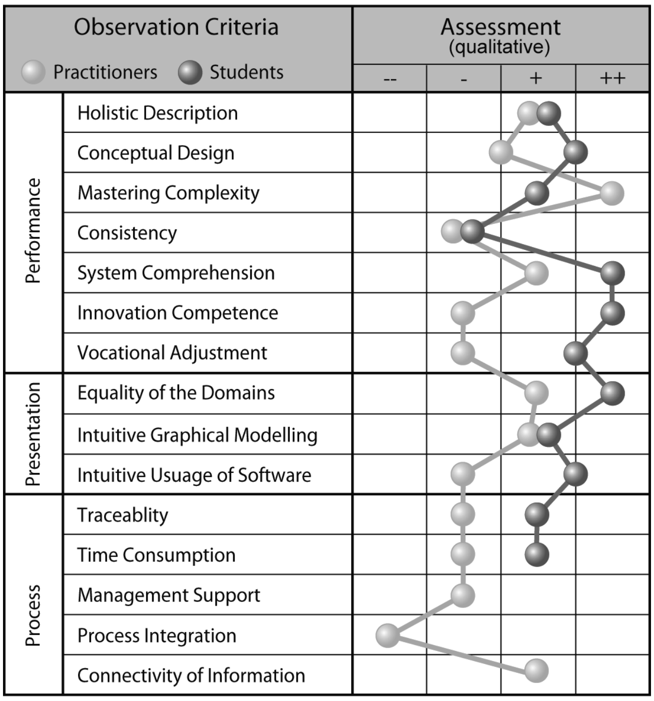

Figure 3. Evaluation of CONSENS

4.1 Academic Teaching

Students of mechanical engineering and related disciplines do not hesitate to get in touch with new methods to improve systems thinking. They understand the importance of a holistic system description and especially the necessity of conceptual design very fast. Through modelling of the system with CONSENS the students got a comprehensive understanding of the system in an acceptable vocational adjustment without paying too much attention for its details. The students used the graphical modelling elements and the software tool for CONSENS naturally and created rather consistent descriptions of the system in an intuitive manner. Nevertheless, at the beginning it took the students some time to describe the system functions solution independent. For example they modelled a function "cutting grass" for a lawn mower instead of "paring grass down", which would enable new solutions replacing the established blades. The survey clarifies that it is important to train articled engineers in systems thinking for future development. We are sure, that especially due to the absence of practical experiences, students are open minded and therefore more able to work in a systemic manner.

4.2 Industry Workshops

In our survey we realized the entrenched thought pattern of the practitioners of small and medium sized companies immediately. They had difficulties with the structured approach of the workshop. From their daily business they are accustomed to ad hoc manners. In industry the development is based on the predecessor system. Therefore practitioners do not need to abstract from the system, but rather design a new system by combining proven components. This approach neglects systems thinking. As they have to develop more and more complex mechatronic systems, they feel the necessity for new approaches, but do not feel familiar with it from the beginning. This leads to long vocational adjustment in the workshop as they are very strong focused on analyzing details or weaknesses of the applied method. During the workshop they overcome these initial acceptability problems. But it is yet more difficult for them to create general system comprehension and new innovative solutions, because many ideas are discarded too quickly. At the end of each workshop the practitioners came to a similar conclusion: The approach CONSENS can provide systems thinking, but for daily business it is too time consuming. This left us to dig deeper on. We added the criteria "Management Support", "Process Integration" and "Connectivity of Information" to our survey for the practitioner workshops. The concluding discussions with the practitioners revealed, that new methods especially for the conceptual design are not supported by the management, because they only take into account the time consumption and implementation cost for the method rather than the long-term benefit. Additionally the internal processes of the companies are very rigid and provide little scope for action. However, it appeared that partial results of the method can be used as input for process steps of the company's processes.

5 CONCLUSION

Systems thinking is essential for the successful development of complex technical systems. MBSE approaches such as CONSENS form the basis for communication and cooperation of the developers from different disciplines during the complete development process. Time-consuming and costly iterations due to heterogeneous understanding of the development task and the technical system can be avoided by paying more attention to the early design phase. Within our workshops we achieved great results in providing a common system understanding with CONSENS. Nevertheless our survey showed that especially practitioners hesitate to apply new methods: They do not see its long-term benefit, but only the current effort to adapt methods into their processes. It is therefore necessary to train articled engineers in systems thinking for future development in time. Especially due to the absence of practical experiences they are open minded for new methods and therefore more able to work in a systemic manner. Thus on the long-term systems thinking can be established into the development processes of the companies. However this will not go far enough: In general we have to pave the way for the establishment of systems thinking in companies by overcoming especially the barrier of process integration. For this purpose we have to analyze these barriers and have to adapt our specification technique as well as systems engineering as a discipline. Thus it can be easily and individually integrated into the development process of any industry – in contrast to classical systems engineering, that focuses on military and aerospace applications and lost the link to its scientific roots.

REFERENCES

[1] von Bertalanffy, L. General System Theory: A new Approach to Unity of Science, 1951 (John Hopkins Press).
[2] INCOSE Handbook on Systems Engineering, 2010.
[3] Hitchins, D. K. System Engineering – A 21st Century Systems Methodology, 2007 (John Wiley & Sons Ltd., Chichester, England).
[4] Ropohl, G. Einleitung in die Systemtechnik. In: Ropohl (Ed.) Systemtechnik – Grundlagen und Antworten, 1975 (Carl Hanser Verlag, Munich).
[5] Daenzer, W.F. and Huber, F. Systems Engineering – Methodik und Praxis, Volume 11, 2002 (Verlag, Industrielle Organisation, Zürich).
[6] INCOSE Systems Engineering Vision 2020, 2007.
[7] Gausemeier, J., Frank, U., Donoth, J. and Kahl, S.: Specification Technique for the Description of Self-Optimizing Mechatronic Systems. Research in Engineering Design, Vol. 20, No. 4, 2009 (Springer, London).
[8] Friedenthal, S., Moore, A., Steiner, R.: A Practical Guide to SysML – The Systems Modelling Language, 2008 (Morgan Kaufmann Publishers, Burlington, MA).
[9] Gausemeier, J., Dorociak, R., Pook, S. and Nyßen, A.: Computer-Aided Cross-Domain Modelling of Mechatronic System. In: *Proceedings of the Design 2010*, *11th International Design Conference*, Dubrovnik, Croatia, May 2010.
[10] Dumitrescu, R., Anacker, H. and Gausemeier, J. Specification of Solution Patterns for the Conceptual Design of Advanced Mechatronic Systems. In: Proceedings of the 2010 International Conference on Advances in Mechanical Engineering (ICAME2010), December 2-5, Shah Alam, Malaysia, 2010.
[11] Weis, H.C. Marketing. 15th edition, 2009 (kiehl).
[12] Mayntz, R., Holm, K. and Hübner P. Einführung in die Methoden der empirischen Soziologie, 5th edition, 1978 (Westdeutscher Verlag).
[13] Kaupp, M.: Digital Signage: Technologie, Anwendungen, Chancen & Risiken, 2010 (Hamburg, Diplomica Verlag).
[14] Atteslander, P. Methoden der empirischen Sozialforschung. 13th edition, 2010 (Erich Schmidt Verlag).
[15] Badke-Schaub, P., Daalhuizen, J. and Roozenburg, N. Towards a Designer-Centred Methodology – Descriptive Considerations and Prescriptive Reflections. In: The Future of Design Methodology, 2011 (Springer, London).