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CROSS-DISCIPLINARY APPLICATION OF SYSTEM ENGINEERING APPROACHES IN MULTI-DISCIPLINARY EDUCATION PROJECTS

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ABSTRACT
Aiming at handling today's challenges as rising product complexity and shorter development cycles, industrial product development projects have established multi-disciplinary teamwork of both technical and non-technical disciplines. In order to prepare students to this multi-disciplinary team work, the university collaboration project "Smart TripElec" was processed. The project aims at applying industrial relevant Systems Engineering methods and tools for multi-disciplinary project teamwork of engineers and product designers. This paper's objective is to design and evaluate this cross-disciplinary approach.

Keywords: Design in engineering, Cross-disciplinarity, immersive technologies.

1 INTRODUCTION

Rising complexity of products and systems combined with shorter development life cycles determine today's markets and industries [1]. The product development process is highly affected by this competitive environment. A shorter time to market and increasing product functionalities on a high quality level are the requirements a development process has to meet [2].
To handle this complexity, specialized experts of technical and non-technical disciplines have to collaborate as early as possible in and during the whole product development process in order to reduce time consuming changes and finish development with holistically optimized products [3]. These kinds of multi-disciplinary development processes necessitate the application of new methods, work procedures and new development tools to ensure a flexible and objective-oriented development process in industrial practice, but also modifications in education of the future process participants.
The approach of System Engineering (SE) addresses these challenges by offering an interdisciplinary approach to establish a base for the realization of complex mechatronic systems [4]. SE thereby integrates all the system-related disciplines and specialist groups into an interdisciplinary-oriented, structured development process that proceeds from the conceptual phase to the operating stage.
Studies of SE [5] show SE already to be firmly established in the aerospace industry and to be promoted as an "enabler" by Original Equipment Manufacturers (OEMs) in vehicle manufacturers industry. Several approaches of SE in the field of education show well-established multi-disciplinarity teaching concepts by integrating technical development tasks in the fields of mechanic, E/E (electrical/electronic) and software development in continuous and applicable formats. Focused on the technical disciplines, effects, as they occur in industrial, multi-disciplinary development teams containing of technical, but also non-technical participants, are neglected by these approaches. Aiming at closing this gap, the TU Berlin and the Berlin University of Arts started a collaboration project that aimed to apply SE methods and development tools for multi-disciplinary project teams containing of two parties of technical and non-technical students. This paper's objective is to design and evaluate this cross-disciplinary approach. The following sub-objectives were identified to be achieved:

1. The applicability of the SE methods and technologies as a cross-disciplinary approach for multi-disciplinary education projects with non-engineers have to be shown.
2. A didactic format for application of SE methods and technologies in multi-disciplinary education projects have to be defined.
3. The application of the approach has to be validated using an industrial relevant use case.

2 SYSTEMS ENGINEERING IN INDUSTRY

On the one hand, traditional SE approaches offer a consistent, interdisciplinary paper or document-based opportunity in developing multi-disciplinary systems. On the other hand, today's product development is based on various digital models whose development is described by Model Based Engineering (MBE) processes. The models in the product development process can be described as a simplified or abstracted version of a development concept, structure or system and can have different formats such as 3D CAD, class diagram or flow chart [6].
The Model Based System Engineering (MBSE) approach closes this gap by connecting SE with MBE approaches. Figure 1 shows the MBSE process by Fraunhofer IPK [7].

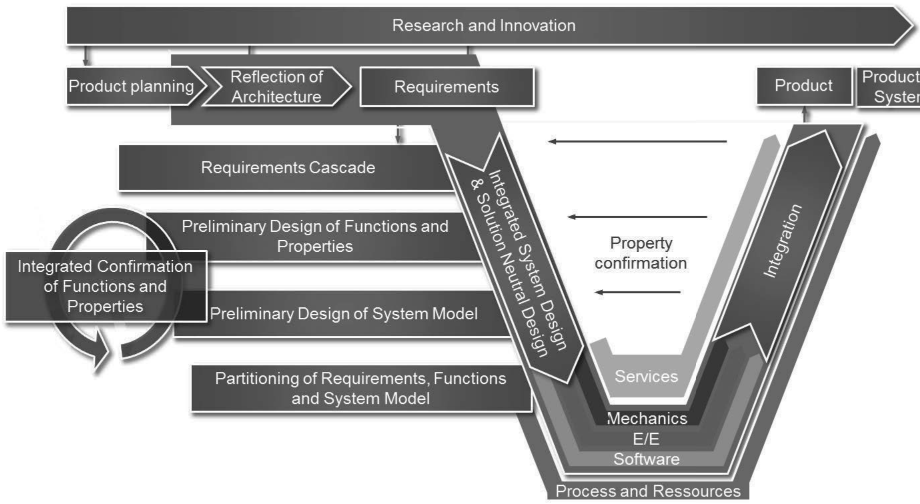

Figure 1. MBSE Development Process (based on [7])

This V-model based approach starts with the product development upstream tasks of strategic planning, analysation of the existing product architecture and market and competition analysis and requirements gathering from both internal and external sources. The product development process, starts with the V-models left, descending branch that includes the solution neutral, development domain-spreading tasks. They are followed by the domain specific development activities and models in the fields of mechanic, electrical/electronic and software on the V's bottom and the integration task uniting these domain specific models to the product on the right, ascending branch of V. The integration task uses the domain-spreading models for validation of properties. The MBSE process offers a – formalized – application of modelling to support system requirements over design, analysis, verification and validation activities.
The integrated V6 PLM Environment developed by Dassault Systèmes aims at supporting the left branch of the MBSE process by supporting at software for the steps Requirements Analysis, Function Architecture, System Architecture, Concept of System & Logic and Dynamic Behaviour Simulation and Physical Model [8]. Being used by several industrial users since its first release in 2008, the V6 PLM Environment is an appropriate software environment for educational usage in the field of MBSE.

3 DIDACTIC CONCEPT AND STRUCTURE

3.1 Overall structure

To fulfil the objectives set, a didactic concept for cross-disciplinary MBSE education needs to be defined. Following Brewer [9], experiential learning, as it presents a problem-based learning approach that confronts students with real-life problems and provides them with the opportunity to apply their concept, is an appropriate didactic format to be used in cross-disciplinarity. Based on Kolb's experiential learning cycle [10], three phases for the experiential learning project were defined starting with the abstraction/conceptualization phase. In this phase, the students get the theoretic knowledge required for the understanding of the specific processes, tools and methods required in processing the tasks. This first phase is followed by the second phase of active experimentation/concrete experience, where students actively work on the specific task. The cycle is closed by the reflection phase, where students reflect the positive and negative aspects of their experience within task processing.

3.2 Industrial relevant SE application

Aiming at using the industrial relevant SE technologies, as it is done by V6 PLM Environment usage, but also industrial relevant SE methods within the project, the second phase of active experimentation/concrete experience has to be in focus as it contains the industrial relevant work. Industrial product development processes, as they summarize all activities for design and testing of the product [11], require instruments to deal with their complexity. The automotive industry, as a representative industrial user of SE methods, separates the product development process into different phases by setting milestones and describes process chains as well as the process participating players and their specific roles [11]. Different types of design reviews, which are meetings during which a system, hardware, or software design is presented to project personnel, managers, users, customers, or other interested parties for comment or approval [12], are used to verify the deliverables and the specific results of the milestones.

Transferring this automotive industry approaches to the education project, leads to the three sub phases:

1. Conception. Here the product development upstream tasks and the tasks of requirements, requirements cascade and functional modelling take place.
2. System design with its tasks of preliminary system design and partitioning of requirements, functions and system model including system models extension with logic and dynamic behaviour models enabling the opportunity to simulate the system behaviour.
3. Detail design and validation: This sub phase includes the tasks of domain specific development and their integration and property confirmation to the final virtual product.

Each of these three sub phases is connected with specific milestones at their respective end and milestone-specific deliverables. A design review between all project participants is used to review the results and the deliverables achieved after each sub phase.

3.3 The product designer in MBSE process

As the MBSE process is designed to address the engineering product development, the applicability of MBSE to the – creative – product design process has to be investigated. Following the considerations of Howard [13], product design processes necessitate a creative output. With four possible creativity outputs that range from most to least original, Howard identifies the outputs of original design, adaptive design and variant design to be creative and thus part of the creative product design process. The engineering task of function design thereby is connected to adaptive design output, which adapts a known solution to satisfy a new or changed task. Behaviour modelling, which is a sub-task of system modelling, is connected to the original design output, as it describes an original solution principle for a system with a new or changed task. Variant design, a variation of certain aspects of the system leaving the function and solution principle unchanged, as the least original step in creative product design process, is connected to the tasks of embodiment design, which takes place in the mechanic (design) task. The last of the initially described four outputs, the least original output of detail design, is described to be not connected to the creative design process. Thus, detail design activities, as they take place in mechanic and integration task of MBSE process, are not part of the product designer’s task.

4 CASE STUDY: PROJECT “SMART TRIPELEC”

4.1 Use Case Design

Aiming at designing an industrial relevant education project, the project task was chosen to address the current trend of bicycles electrification. Composed out of a pedal driven mechanic bicycle with electric drivetrain, electric bicycles have the potential to replace partly the use of passenger cars in urban mobility as the range of the bicycle is extended. The use case of electric bicycle in urban mobility have a sufficient, but not too high complexity as it is still comprehensible without specific bicycle expert knowledge. Aiming at overcoming ingrained habits and ways of thinking, further specifications were taken as the electrified bicycle was defined to have three wheels. This specification aimed to drive the field of solution away from conventional, two wheel bicycle-designs onto innovative solutions to support the finding process between engineering and product design disciplines.

4.2 Project Results, Didactic Experience and Shortfalls

Figure 2 shows the conduction of the “Smart TripElec” project in the three phases overall structure showing the proceeded work parts of product designers in upper, red coloured half and those of the engineers in lower, green coloured half. The MBSE process, taking place in phase of experimentation/ concrete experience is broken down to a (simplified) sequential task order with iteration loops (red circles) in between and the three sub phases which are each finished by a design review.

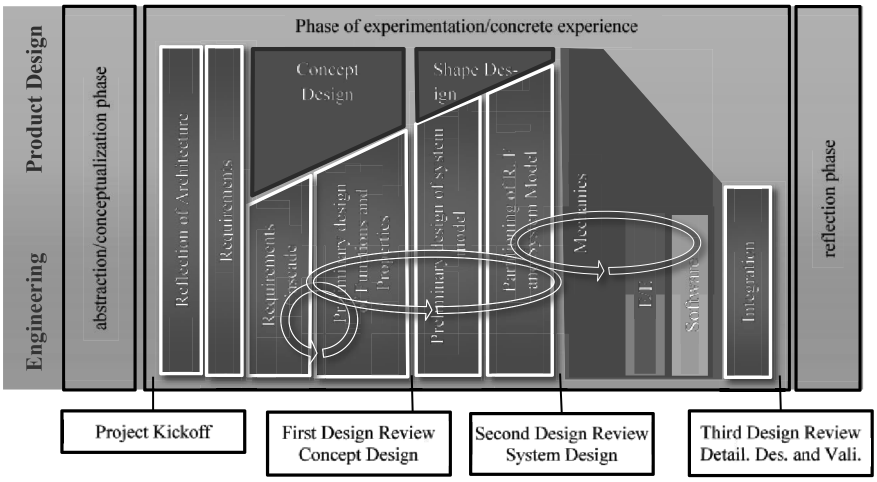

Figure 2. Conduction of Case Study “Smart TripElec”

4.2.1 Abstraction/Conceptualization phase

The project started with the abstraction/conceptualization phase. In this phase, the methods and process of MBSE were introduced and the Software usage of V6 PLM Environment programs ENOVIA V6, CATIA V6 Flow Modelling, Dymola and CATIA V6 CAD was taught in classroom courses to the engineers. The product designers had no education of methods or technologies as self-learning is more usual in their education, but they were enabled to attend the courses. With just two out of nine product designers using this opportunity, one could observe that they had more problems to understand the contents taught than engineers with more prior knowledge in the various aspects.

4.2.2 Phase of experimentation/concrete experience

The second phase of experimentation/concrete experience started with the project kick-off including team formation and clarification of project tasks. Different to the first phase, not only qualitative observation but also quantitative validation of the intermediate results achieved and products designed were used to evaluate the work of the project teams.

The first sub phase conception started with the MBSE tasks of reflection of architecture, were the teams performed a competitor analysis. Based on the results of this analysis, an analysis of the project task and a research in the field of legal framework took place for the requirements gathering. After processing these first tasks as a team, it was observed that the following task of requirements cascade was processed almost exclusively by the engineers while the product designer started to design concepts by 2D sketching of their ideas. Also the next task of preliminary design of functions and properties was mainly processed by the engineers by modelling flow diagrams in CATIA V6. It was nevertheless observed, that the product designers, by detailing their concepts, influenced the functional modelling as they created an adaptive output and discussed it in their teams. In the first design review, the models and results achieved confirmed the observations as the teams appear separately in solution neutral engineering and the solution based product design sub-teams with yet just a few mutual connection factors. Figure 2 shows the observed split of engineers and product designers after requirements task by implementing the new task of concept design processed by the product designers parallel to the MBSE tasks. The rising interdependencies are shown by shifting the tasks surface proportions towards upper, “product designer” half over the process.

This shifting proceeded in the following sub-phase of system design with the task of preliminary system model design, as function carriers were defined by modelling of flow diagrams in CATIA V6. In parallel, the product designers started to transfer their concepts into 3D models. Extending the system model with logic and dynamic behaviour models in the next task of partitioning of R, F and system model forced both parts of the team to work together to achieve a consistency between the 3D Data and the system model until the second design review. The models, that were presented there showed a well-connected overall product concept with inconsistencies in detail.

The sub-phase of detail design and validation continued with a fully integrated work as both parts of the team switches to 3D CAD modelling activities processed in CATIA V6 in the first task of mechanics. As the product designers were working only on geometric design activities, nevertheless the E/E and software tasks were processed only by the engineers by continuous use of Dymola modelling environment. As figure 2 shows, it was observed that the workload was shifted more and more to the engineers from the point on that activities were shifted from "whole product" design, such as shape design of the bicycle frame or the wheel layout, to detail design activities such as manufacturability of the seat fixing or design of fasteners. As described in chapter 3.3 this was expected as detail design activities does not belong to the creative process. Finishing with integration activities including property validation by using virtual simulations of the integrated product models consisting of E/E and Software parts modelled in Dymola and 3D CAD Models modelled in CATIA V6, the results shown in third design review proved to be fully integrated "Smart TripElecs".

4.2.3 Reflection phase

In the final phase of reflection both the collaboration between the two team parties and the contents and structure of the project were analysed by an online questionnaire and a written self-assessment of each project participant. The project participants concluded that the soft skills in this multi-disciplinary teamwork are more important than in other university projects. This conclusion was based on the experiences of more difficult collaboration with team members from the respective other discipline as decision making and mutual understanding was more difficult. The participants named reasons such as the different education background, which resulted in more creative approaches of the product designers versus the more methodical approach of the engineers, but also in barriers of comprehension especially in cases of technical interdependencies such as those occurring in the tasks of E/E and software and different design focuses as form/shape versus functionality. Different understanding of team structures – on the one hand engineers who are used to work in hierarchic structures with clear and specific task descriptions, on the other hand the product designers who are used to work in equal groups working on wide, unspecific tasks – lead to the conclusion, that this kind of collaboration work necessitates an open-minded attitude from all participants in order to work successfully together as a team.

The participants gave differentiated assessments of the project structure and contents: The overall project structure was graded well like a red thread throughout the tasks and activities processed in development projects especially with the usage of the MBSE process. Identifying a high relevancy of both collaboration and didactic content for later working life, the level of difficulty was assessed to be too high and as too much previous knowledge was needed especially for the aspects of the respective other discipline. The used V6 PLM Environment was assessed to be problematic and to have a prototypic appearance due to its several bugs and non-intuitive handling, the use of different CAD Software by using Rhino 3D for early 3D concepts created further difficulties due to data import problems. The technical task electrified bicycle "TripElec" creation was assessed to be too complex for a one term project resulting especially in the very demanding requirement of "charging while standing". The review format "design review" was unusual to both team parties and was identified to be a source of additional pressure and challenges especially in multi-disciplinary collaboration.

Overall the project was assessed to be a challenging, but very positive and instructive time for all participants.

5 SUMMARY AND OUTLOOK

5.1 Summary

A summary can be made by evaluating whether the objectives and sub-objectives set in chapter one were achieved or not:

First the applicability of the SE methods and technologies as a cross-disciplinary approach for multi-disciplinary education projects with non-engineers had to be shown. In the use case, the multi-disciplinary teams successfully designed different integrated virtual models of the "Smart TripElec" composed of sub-models of mechanic, E/E and software domain. Each team consisted of engineers

and product designers and worked within the context of the MBSE process model and uses MBSE technology. The cross-disciplinary approach of MBSE showed its general applicability for the multi-disciplinary project work. It had lower applicability in the MBSE process left branches solution neutral tasks and missed to provide tasks that addressed the creative design activities of concept design and shape design. Furthermore, the integration of designer in late MBSE tasks with rising detail design activities was missed. The first sub-objective thus could be summarized as partially achieved.
Secondly, a didactic format for application of SE methods and technologies in multi-disciplinary education projects had to be defined. This sub-objective was fully achieved by the definition of the three-phasic overall structure, the application of SE technologies in second phase and the application of this education project design in the use case "Smart TripElec".
Finally, the application of the approach had to be validated using an industrial relevant use case**.** Within the limitations described in achievement of the first sub-objective, the approach was validated by its successful application of the industry relevant use case "Smart TripElec". This third sub-objective thus could be described as fully achieved.
Thus, the cross-disciplinary approach of SE application in multi-disciplinary education projects with engineers and product designers is evaluated to **be generally applicable** but **has to be extended** in order to meet specific partial requirements of product design discipline.

5.2 Outlook

The MBSE process has to be extended to better integrate the product designer tasks in early tasks of solution neutral activities. Furthermore, the creative activities of concept design and shape design have to be integrated. As the detail design rises in later development tasks, either the MBSE process have to be modified to keep the product designers integrated although the drop of their creative activities or the task respectively project extend have to be modified to finish with less detailed product concepts rather than detailed products. The mutual comprehensibility of engineers and product designers have to be increased by improving the pre-education of the project participants and by an improved use case design that takes the different views and previous knowledge better into account.

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