INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

A FRAMEWORK FOR INTEGRATED PROCESS MODELING AND PLANNING OF MECHATRONIC PRODUCTS

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ABSTRACT

Mechatronic systems are characterized by a high level of interdisciplinarity and complexity in the technical system and the belonging development processes. In consequence this leads to novel requirements for process planning and the used methods and tools. The main challenge is to deal with the high complexity and a variety of interdependencies.
Therefore a framework for integrated mechatronic process modeling and planning is presented. The focus is an effective integration of the involved disciplines mechanics, electronics and computer science into the overall development process. This leads to an improved synchronization of the single development processes and a common focus on the mechatronic system. The development of a mechatronic product is seen as a system of interlinked cross domain processes and relations. The framework provides different and discipline independent views on the system in order to improve systems thinking. A Multiple-Domain-Matrix (MDM) approach is used to represent and analyze interdependencies within the product and the process. It allows for detailed analysis and deduction of implicit interconnections which can be regarded in the planning of the development process.

Keywords: mechatronics, process modeling and planning, interdisciplinarity, complexity

1 INTRODUCTION AND MOTIVATION

Mechatronic systems provide additional functionality and increased performance or efficiency by integrating electronic and software elements into a mechanical structure. Due to rising functional requirements and an increasing demand for flexibility and environmental sustainability they are omnipresent in today's products. Simultaneously the synergistic integration of different engineering domains causes significantly higher complexity levels for the complete system [1]. In order to handle the development of complex but still robust mechatronic systems, improved interdisciplinary system understanding is essential [2]. Regarding the steps of function validation there is the necessity of an effective and on schedule integration of the three disciplines' deliverables, even in early stages of product development. Therefore discipline specific development processes will have to be more effectively interlinked and synchronized. Process modeling and planning techniques currently applied in industry do not sufficiently enhance overall system understanding and don not create enough awareness for the importance of discipline-integrating milestones. This is due to a distinct decoupling of the representations of the technical system itself on the one hand and the belonging development processes on the other.
This contribution introduces a framework for function driven process modeling and planning of mechatronic products. It focuses at improved system thinking, communication and understanding across the involved disciplines mechanics, electronics and computer science. Therefore different views and sub-models for different aspects (product, process, planning, controlling) of the system are provided. Basis for the process planning is a Multiple-Domain-Matrix (MDM) [3] of the technical system and the belonging development process which is used to represent and analyze the system. A procedural model for process planning describes and interconnects the single parts of the framework and shows how they work together.

2 BASIS AND RELATED RESEARCH

Due to the high level of multidisciplinarity in the development of mechatronic systems adapted processes and procedure models are required. There are different approaches in this area which are shortly presented and discussed. Commonly known procedural models like Pahl et al. [4] or Ulrich &

Eppinger [5] can be used for any kind of technical system. They are described on a very generic level and do not deal with mechatronic products in detail. Furthermore there are approaches like VDI 2206 [1], Isermann [6] or Lückel [7] which directly refer to the development of mechatronic systems. As [4] and [5] they split up the development process in different phases and provide guidance which tasks have to be performed and which deliverables have to be produced. The major shortcoming of these approaches is that they are also highly generic. The importance of overall systems thinking is emphasized but there is no assistance in dealing with the large number of interdependencies between the single sub processes. They are focused on the system design phase and the integration phase and disregard the relations between the domain-specific design processes. The approach of Redenius [8] provides tasks and process guidelines on a more detailed level but the interdependencies of the tasks are also not handled in an appropriate way.

However there are also approaches like Buur [9], van Brusel [10], Franke [11] or WU et al. [12] that deal with an integrated and domain spanning description or representation of the technical system. These approaches offer procedural models as well but the focus is on the description and optimization of the technical system. Interdependencies between the system structure and the structure of the processes are not regarded.

The presented framework uses a Multiple-Domain-Matrix (MDM) to deal with the high complexity of mechatronic systems. In this approach the elements of a single domain (e.g. activities) and their relations are represented in a Design Structure Matrix (DSM) [13]. To express relations between two different domains a Domain-Mapping-Matrix (DMM) [14] is used. A MDM allows for a representation of different domains in one overall model. Therefore it consists of the regarded DSMs on the diagonal and the according DMMs in the rest of the matrix [3]. A MDM allows for single domain as well as for cross domain analysis and the deduction of implicit interdependencies within the system [3].

3 OBJECTIVES

In order to deal with the growing complexity of mechatronic products and the development processes it is necessary to provide increased system understanding across the involved disciplines mechanics, electronics and computer science. The framework should be able to assist during the creation of the overall system design as well as for detailed planning of tasks and responsible persons in serial development. Therefore the system and its interdependencies have to be modeled in a way which is understandable for all domains. As the presented framework follows the approach of function driven process modeling [15], [16] the original objectives have been extended and adapted:

- Assistance in creating and planning of multidisciplinary development processes
- Integration and synchronization of the discipline specific sub-processes
- Transparent representation of the chronological correlation of multidisciplinary processes
- Structural analysis and optimization of the process structure
- Illustration of the process structure on different hierarchy levels
- Consideration of different views on the milestone system
- Degrees of maturity with regard to functions and system elements
- Traceability of the impact of changes of the product structure on the process structure
- Transparent allocation of responsible persons
- Assistance in setting up communication structures and team structures
- Transparent visualization of technical system, processes and interdependencies

A major difference to the approaches presented in section 2 is that it is not aiming at optimization or unification of present discipline-specific design processes. The focus is on an effective interlinking and synchronization of these sub-processes. Thereby the approach meets well established working routines in companies and the way designers work.

4 FRAMEWORK FOR INTEGRATED PROCESS MODELING AND PLANNING OF MECHATRONIC PRODUCTS

The framework for integrated modeling and planning of mechatronic processes was created to meet the described goals and objectives. It combines different views on the complex systems and provides an overall model to combine and analyze relations within the system. The various elements of the systems are addressed as domains (e.g. functions, persons, milestones) which interact in different ways

and on different levels. In the following the basic ideas and the different parts of the framework are introduced and described.
The main idea of the approach is to use functional validation of high level mechatronic functions during the integration and testing phase as the basis for structuring and planning of the development process. As this approach aims at the support of serial development processes the basic working principle or concept [4], the major functionality and basic system elements ("mechatonic components", see 4.2) of the product are already known. These assumptions are suitable for most companies since the basic prove of concept is typically provided in research or preliminary development projects before they are transferred to serial development. As a result the applicability of the framework on projects with completely new products or research projects is quite limited due to the high level of uncertainty.
As functional integration and testing are the basis for process planning activities the different views and methods of the framework are connected though the functional validation phase. The addressed views on the systems are the technical system itself (product view) to describe relations and interdependencies within the product. The second view is it the belonging development process to describe interconnections in the process (process view) on an organizational level. In the planning view aspects like constrains (technical and organizational), level of abstraction and relevant interdependencies are addressed. The controlling view is used to describe and monitor the actual status of the project. A last aspect is visualization of the different views on the system.
A procedural model is given to describe the use of the framework, its methods and the interconnections of the different views. It also provides guidelines to for creation of the required models, interpretation of analysis results and the planning process. A graphical representation of the framework and its elements is shown in figure 1.

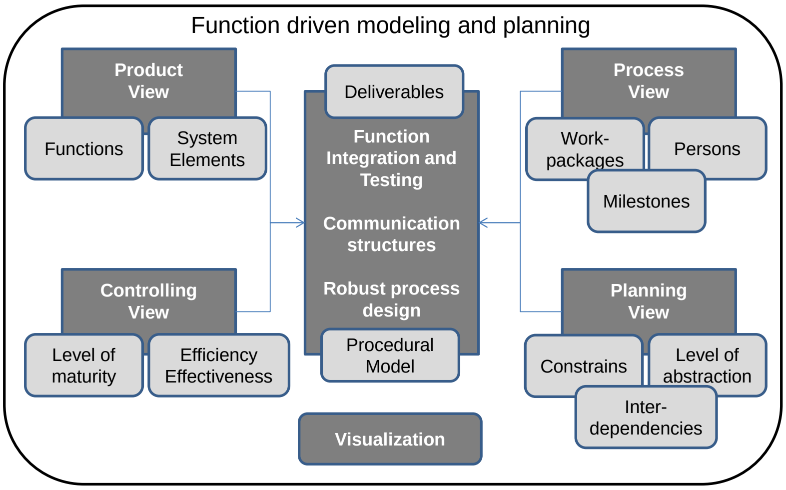

Figure 1. Framework for integrated mechatronic process planning

4.1 Modeling of domains and interdependencies

As introduced in section 3, the main focus of this approach is to provide improved systems thinking and understanding of the technical product and the belonging development process. Following the already presented principles of function driven process design [14], [15] a Multiple-Domain-Matrix (MDM) with six domains is chosen to model and analyze these relations. The domains of the overall system model are (see figure 2):

- Functions
- System elements ("mechatronic components")
- Deliverables
- Work Packages (activities, tasks)
- (Project) Milestones
- (Responsible) Persons

The first two domains (functions, system elements) are part of the product model. The process model is represented by work packages, milestones and persons (developers, engineers). These two partial models are linked through the produced deliverables. In this context deliverables are any kind of

intermediate product representations (requirements list, functional or simulation model, prototype) which are produced during the development process.
There are direct (●) and indirect (○) relations between the different domains. Indirect interdependencies can be deduced out of combinations of different direct relations by using MDM methods [3]. For this application only the upper triangle of the MDM is of interest because the complete matrix is symmetric (DSMs on the diagonal are not).

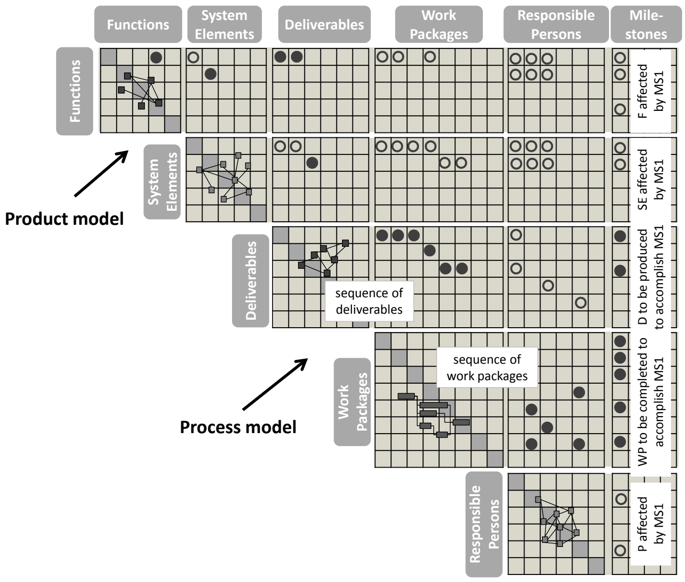

Figure 2. MDM based model for analysis and planning

4.2 Product View

The product model, represented by functions and system elements, is used to describe the technical systems. Within the overall MDM it is allocated in the upper left corner of the matrix (see figure 2). The model provides two different views on the product which are typically not or only basically interlinked. On the one hand there is the function driven view with function hierarchies and functional structure. On the other hand there is the component driven view using working structures and systems hierarchy (modules and assemblies). Using an MDM the intra- and inter-domain dependencies can be modeled and both can be easily transformed into each other.
Thereby the approach meets requirements of the different involved disciplines. Mechanical engineers prefer the system element view (components) while in electronics and computer science the functional view is common.
In this approach the term “system elements” is used for the mechatronic “components”. This is due to the fact that in mechatronics there are not only physical artifacts but also software and control code. In this context these non-physical “components” are important for the functionality of the product and therefore the generic term systems elements is introduced.

4.3 Process View

It was pointed out that functional integration and testing is used as the origin for all process planning and optimization activities. The steps of functional validation require an effective synchronization of the discipline specific development processes and their deliverables to fulfill defined requirements (high level mechatronic functions). Most of the problems within the development process emerge in this phase while typically the reasons for the problems are allocated in earlier phases with too little cooperation of the different disciplines. Therefore the functional testing phase is an appropriate origin for process planning.
The fundamental understanding of the mechatronic process also follows the principles of function driven process design [15], [16] and contains different levels of abstraction (see figure 3). The top level mechatronic functions (large arrows) are realized by various sub-functions and their interaction (midsized arrows). On bottom level the single system elements (components) of the mechatronic system (small arrows) are allocated, which are essential for realizing the sub-functions. Those system elements accomplish one or several bottom level functions (not depicted in chart) each.

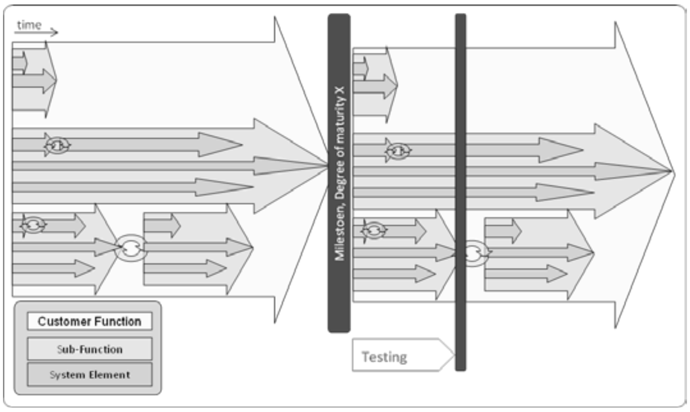

Figure 3. Process model of function driven process design [16]

The single development activities on different abstraction levels are concluded by milestone deadlines. Completion of top level function milestones (large arrows) requires all development efforts on lower hierarchy levels to be available with an according level of maturity. Essential milestones on high level functions are typically defined by integration tests in serial development. Subsequent to those domain integrating testing activities, cross-disciplinary and prompt discussion of obtained results is of fundamental importance (communication structure). Additional to those inter-domain testing activities on functional level, domain specific testing is still existent on lower levels of hierarchy (circle arrows).
In the presented framework three domains are used to describe the process (Process View). Following the described process model the structure of the process is modeled using work packages (activities) and milestones. The third domain contains the responsible persons which are allocated to the design tasks.

4.4 Interconnection and structural interpretation

In order to trace and analyze interdependencies between product and process structure the introduced partial models (product and process model) have to be interlinked into one overall model. This connection is achieved using the deliverables which can be easily related to the system elements and the working packages (see figure 2). The deduction of deliverables is addressed in section 4.5.
A different graphical representation of the integrated overall model is given in figure 4. This symbolic depiction supports the structural interpretation of analysis results and illustrates the content of the different partial matrices. It shows the complete MDM with its six domains where every domain is attributed with as simple graphic figure. With the help of this simple representation it is much easier for engineers who are typically not used to MDM methodology to interpret the results. The dark grey matrices show a possible set of input matrices needed to derive the complete model.

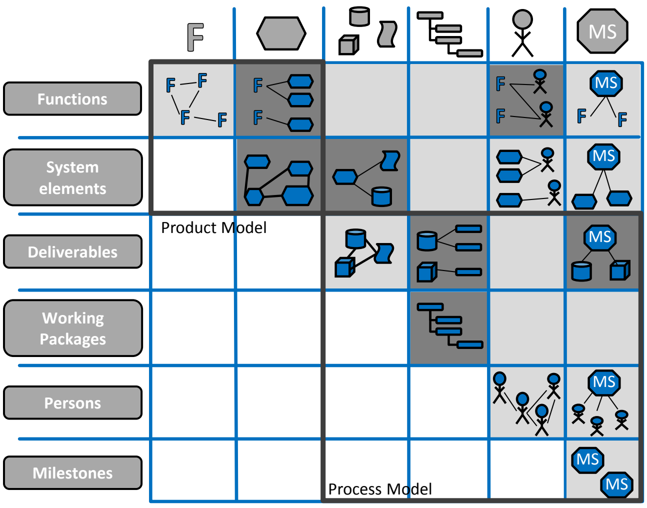

Figure 4. Interpretation and analysis in the Multiple Domain Matrix

4.5 Procedural model for mechatronic process planning

The central goal for planning of mechatronic processes and communication structures is described in the procedural model of the framework. It points out how the overall system model is used for the planning process. The planning process picks up basic principles of function driven process design published in [15], [16], [17] and combines them to an integrated procedural model for mechatronic process planning.

The planning process is based on the presented overall MDM-model (figure 2) and consists of seven major steps. They are performed iteratively until an appropriate result is achieved (see also figure 5):

- Creation of the product model
- Structural analysis of the product model
- Deduction of deliverables
- Structural analysis to derive sequence of deliverables and milestones (integration/testing)
- Deduction of a sequence of work packages according to deliverables and milestones
- Allocation of persons for the design tasks
- Structural analysis of complete model to derive implicit interdependencies
- Deduction of team and communication structures

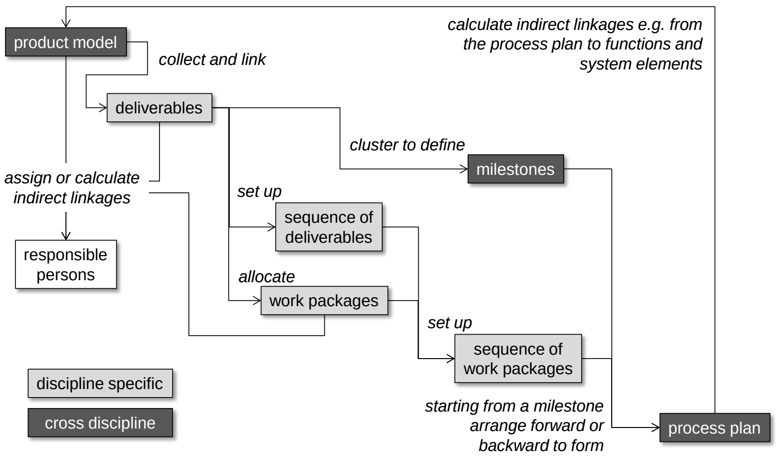

Figure 5. Basic procedural model for process planning [15]

Structural analyses and process synthesis are not described in detail but some basic ideas and examples are presented. Basically function integrating milestones are used for validation and testing of mechatronic functions. Appropriate functions and required deliverables can be derived out of the product model (functions that are effected by system elements of all disciplines). Testing of discipline specific system elements within one domain can be allocated between the milestones. Another way is clustering of the functional structure to identify high level functions which can be validated separately. Afterwards the required deliverables to test these functions can be specified and used for planning of the millstones. In case of a process with a minimum of functional integration milestones (external constraint) it is possible to use the network of the deliverables to identify a minimum set of deliverables that cover all possible functions.

After a first gross network of the complete system has been created (at the end of the first iteration) the relations between product and product model can be taken into account. The network of work packages can be analyzed regarding the network of deliverables and potential conflicts can be identified. Afterwards the structure of the work packages can be optimized e.g. by identification of activities that can be performed simultaneously. A further application is the deduction of optimized team and communication structures by using the interrelations between the functions and the responsible persons.

4.6 Controlling View - Level of maturity

After generating the process plan the ongoing project has to be monitored. Typically the planned and/or the actual level of maturity of the product are taken as an indicator for the progress of the projects. The presented framework offers different ways to address this area and express the level of maturity. The different possibilities are shortly discussed.

A very easy way for defining the level of maturity is using the deliverables directly. The deliverables are closely related to the system elements and can be used to define their (intermediate) status. This way the level of maturity can be expressed in terms like functional model, requirements list, simulation model or physical prototype with a specified functionality. A major disadvantage of this view on the level of maturity is the detailed description of the actual status (quality of documents/simulation model) of the system elements.

Another possibility is to use functions of the overall system to specify the level of maturity. With a functional hierarchy (e.g. support functions, technical functions, basic mechatronic functions and top level functions) the required level of functionality can be specified for all milestones. This view is much more appropriate for mechatronic development since the realization of the functions requires the interaction of system elements from different disciplines. In this case a detailed description of the required characteristics of the system elements is still needed.

The presented system model also offers the possibility to express the level of maturity in terms of numbers (percentage value). Therefore the number of already produced deliverables is compared to the number of planned deliverables. This way of expressing the degree of maturity is very common and meets the requirements of most companies. The disadvantages of this approach are that these values are very abstract and difficult to interpret. Another problem is also the quality of the produced deliverables (Do they meet the specifications?).

This calculation of the level of maturity can also be combined with the two views presented above. So it is possible to calculate percentage values for all kinds of deliverables (e.g. simulation models, prototypes etc.). This can be done for the overall process or relating to the next milestone. In the same way it is possible to calculate values for the fulfilled functions (also with regard to milestone or for the complete process). With a functional hierarchy of the product the level of maturity can be derived separately for every level.

Another option is the expression of the level of maturity in terms of time. Using the DSM of the work packages and analyzing the actual number of fulfilled work packages and the structure of the process it is possible to derive the actual positive or negative delay. For process planning and controlling this number is much more useful than an abstract percentage value. It provides an information how much time is necessary to achieve the desired status and how does this effects the rest of the process. With this information it is possible to adapt the process and find an optimized solution for the new situation. This is also much more accurate since the abstract percentage values are often wrong (intentionally or by accident).

4.7 Visualization

A further issues of the framework deals with the representation and visualization of the MDM model, the interconnections between the disciplines, the derived process plan (sequence of work packages and persons) and the level of maturity. Since process visualization is a very broad field and the research on this aspect of the framework is still ongoing it is not part of this contribution. Therefore this aspect is not presented in detail.

At the moment well introduced visualization methods like process charts, Gantt-Charts or event-driven process charts (EPC) are used to visualize the process. One part of the actual work deals with an integrated view of the process activities and the implicit interconnections which can be derived using the MDM model. The visualization of the overall system model is of special importance because it is the basis for all process planning activities. In general MDM models can be represented as force directed graphs [3]. This representation is very useful for the structural analysis because it is very intuitive and easy to interpret. So it can be used to support e.g. clustering of deliverables for the definition of milestones or the deduction of team structures.

A major disadvantage of force directed graphs is that they are only able to visualize the structure of one single domain. In the planning of mechatronic processes the interconnections between different domains are responsible for most of the difficulties and therefore are of special importance. The process planner has to know these relations to take them into consideration. Consequently a method was needed to visualize the structure of different domains at the same time as well as the inter domain dependencies. In [17] an approach for the visualize Multi-Domain-Matrices is presented which is also based on well-known force directed graphs. The approach uses a 3-dimensional representation of the network. The structures of the single domains are represented by forced directed graphs on the different layers of the model. The interconnections of the different domains are allocated between these layers (see figure 6). The approach also provides different possibilities to navigate through the structure and adjust the presentation of the elements/relations. Therefore this model allows for a domain crossing analysis of the integrated model.

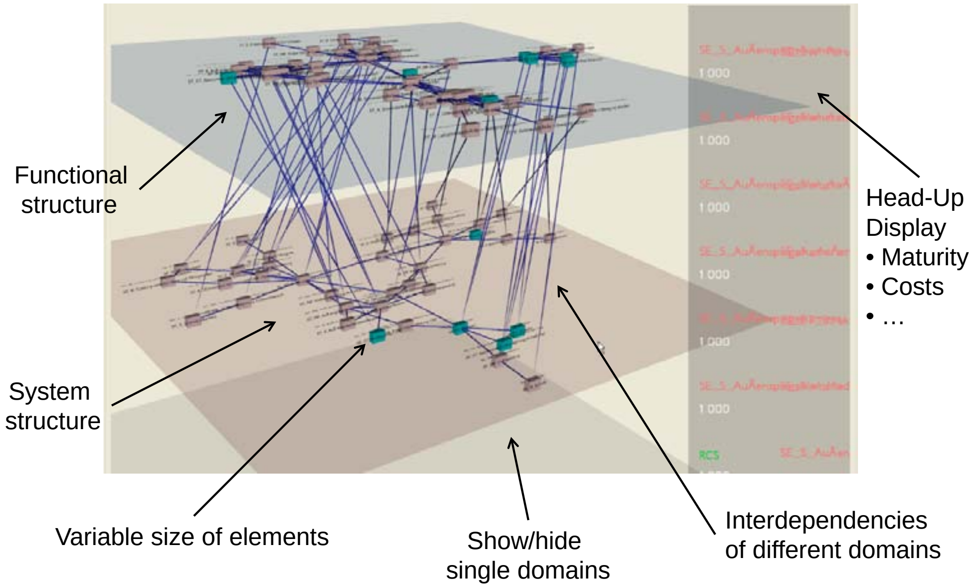

Figure 6. Visualization of the integrated model [17]

5 EVALUATION AND RESULTS

The improvement and evaluation of the framework and its methods was carried out in an ongoing industry project. The approach was applied to the (at this time) actual development process of a car sunroof. Through an analysis of technical descriptions of the sunroof and with documents describing the development process it was possible to get a basic understanding of the product and the associated development process. In parallel there were interviews with engineers of the involved development departments to refine the basic model, capture missing information and recognize problems within the process. In regular meetings the model and first analysis results were presented to the engineers in order to discuss and validate them. The development process of the sunroof offered a high variety of possibilities to analyze and optimize the system. Some example results are discussed in the following.

Within the product model (functions, system elements) it was possible to deduct the functional structure because of (shared) system elements. The graphical representation of this structure enabled the engineers to realize and understand “hidden” interdependencies among the components and the functions even across disciplines and departments. These indirect interdependencies, especially across departments, were often unaware and responsible for unsuccessful functional tests.

In case of changes on the product, the model enabled the developers to notice which functions or other components were affected. This was particularly important because the functional responsibility was often located in a different department. As a result they were able to see who had to be informed of the change and which functions had to be checked (improved communication structure). In addition the linkage of product model and process also offered the possibility to easily trace impacts of changes of the product structure on the process structure.

The combination of the derived functional structure with the DMM mapping functions and responsibilities allowed the deduction of a network of responsibilities based on common functions. The analysis of the matrix showed that there were two kinds of involved responsibilities within the project. On the one hand there is a highly interconnected “inner team” which is responsible for the technical development of the sunroof. On the other hand there are a lot of departments that are only involved in certain aspects like the testing or interior department. This information can be used for the composition of teams or the optimization the companies’ organizational structure.

The created model also allowed associating the project milestones with functions and system elements through the deliverables which meets grown conditions in departments of different disciplines. The engineers were enabled to see immediately which milestone affects which function and system element and could use that information for their personal work planning.

The issue of overall process planning and for this reason the evaluation of the complete framework is still an (partly) open and ongoing topic. Using the framework and the collected information is was possible to plan an optimized development process and derive improved team structures. Due to different reasons it was not possible to implement the new process in the company yet and observe it once more. Still the results were presented to the involved engineers and the common feedback was very positive. Based on their experiences they confirmed that the derived process makes sense and allows for an improved synchronization of the involved disciplines. As a consequence the framework has been applied to another industry project and one student development process. The work on this is still ongoing but first results are very promising.

6 CONCLUSIONS AND FUTURE WORK

The framework for integrated process modeling and planning of mechatronic products presented in this contribution combines a number of different approaches and views to deal with complex mechatronic systems. It focuses on an effective integration and synchronization of the involved disciplines mechanics, electronics and computer science into one interdisciplinary development process. Through an integrated overall model of the technical product and the belonging process implicit interdependencies can be identified and taken into account during the process planning.

The evaluation shows that the framework and its methods are applicable in practical applications and that the results are meaningful and useful for the involved developers. The used MDM approach has been also successfully applied within the area of lean development [18]. It was possible to identify waste in the process and derive an optimized process structure.

Besides the ongoing evaluation of the complete framework there are some parts that have to be improved in the future. This is mainly related to the controlling view (level of maturity) and the (process) visualization part. At the moment there is an ongoing analysis of different approaches that deal with the level of maturity. The aim is to adapt them to mechatronic products and derive a system of hierarchical levels of maturity. Another issue is the process visualization which is also still ongoing. There are some basic ideas to extend common process models to express implicit relations. Finally the complete framework has to be implemented in a software prototype since computational support is essential. With an implemented and integrated prototype all advantages of the framework can be demonstrated.

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