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Systematic Partitioning in Mechatronic Product Development by Modeling Structural Dependencies

Nepomuk Chucholowski, Johannes Kriegler, Christoph Hollauer, Niklas Kattner, Lucia Becerril, Dominik Weidmann, Udo Lindemann

Chair of Product Development, Technical University of Munich

Abstract: Mechatronic product development is an interdisciplinary approach that has to deal with the immanent complexity of mechatronic products. While different approaches can be found in literature which aim to support interdisciplinary development, many companies still struggle with a lack of transparency regarding interfaces on product level as well as on an organizational level or process level. This conceptual paper presents an approach towards systematic partitioning that investigates interfaces on all three levels. The approach extends and combines existing approaches by integrating domain allocation and discipline allocation based on structural dependencies. The resulting structural models are used to computationally derive coordination needs. These allow project managers to explicitly plan coordination measures and give an overview for all developers. The paper also discusses further potentials of the analysis and use of the generated structural models.

Keywords: Mechatronic Product Development, Partitioning, Coordination

1 Introduction

Mechatronic product development is an interdisciplinary approach, which combines mechanics, electronics and information technologies (Isermann, 2000). Mechatronic systems feature a high degree of complexity due to a high number of elements from different technical domains and various interdependencies/interrelationships between them (Gausemeier and Moehringer, 2003; Tomiyama et al., 2007). One resulting major challenge regards interdisciplinary collaboration and communication (Isermann, 2000; Hehenberger and Bradley, 2016). This highlights the necessity of analyzing the interfaces between different domains or disciplines in order to plan sufficient coordination.

1.1 Research setting and motivation

This research is embedded in a research project in collaboration with an association of Bavarian companies from the metal and electronical industry which aims at developing support for mechatronic product development. One of the main challenges identified in a qualitative exploratory study with four partner companies (and also often described in literature, e. g. Alvarez Cabrera et al. (2011)) is the fact, that mechatronic product development is strongly dominated by the mechanics domain. The investigated companies further complain about historically grown organizational structures and development processes, and a resulting lack of transparency about cross-domain interfaces for new products. This leads to a lack of necessary coordination throughout the design process, to rework, and thus to increased development effort.

1.2 Research Need

There is a close interplay between the product architecture, the organizational structure of the development team and the design activities (process structure) (Browning et al., 2006; MacCormack et al., 2012). A general underlying question is which of these three systems is dominant for the whole development project system structure. In theory, when changing the product architecture, the organizational system and the process system have to adapt by generating new cross-team interactions and processes (Sinha et al., 2012). However, in practice, it often seems to be the other way around. The products are developed in the context of existing organizational structures and process structures. Still, additional intra- and inter-team coordination is necessary due to the novelty of the system under development (Sinha et al., 2012). New product extents lead to a lack of transparency about who is doing what and who needs to interact with whom (necessary coordination), especially when considering interdisciplinary coordination (Figure 1).

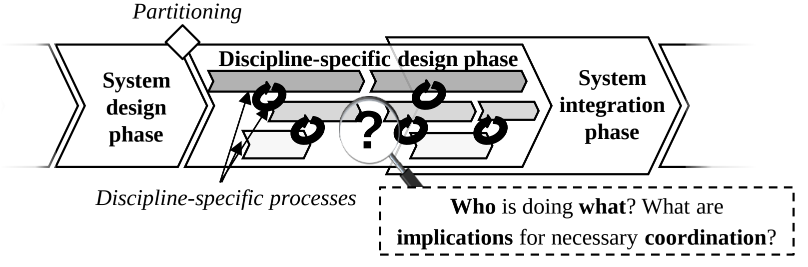

Figure 1. Observable process structure in practice with ambiguity of necessary coordination.

Explicit partitioning (i. e. allocating different technical domains to product elements) is a means that aims to manage the complexity and heterogeneity in a mechatronic product by systematically allocating product elements to different domains (Gausemeier and Moehringer, 2003). According to Jansen (2007) partitioning takes place in the system design phase. We observed in our partner companies that this allocation is often happening only implicitly based on historical structures. Additionally, an explicit domain allocation on a product level does not automatically uncover coordination needs on organization and process level. We found no practical approach addressing this issue in literature and therefor state two guiding research questions for this paper:

- How can discipline-specific design activities (process perspective) and responsibilities (organizational perspective) be systematically allocated based on a product concept at the end of the system design phase?
- How can resulting coordination needs within the discipline-specific design phase be derived systematically?

2 Theoretical Background

2.1 Product perspective

On the one hand, mechatronic products can be described as a combination of a physical basic system (e. g. mechanical, electro-mechanical, hydraulic or pneumatic systems), sensors, actors and an information processing system (VDI, 2004). These elements are interrelated through the kinetic flows *energy flow*, *material flow* and *information/signal flow* (VDI, 2004; Pahl et al., 2007).

On the other hand, standard frameworks describe technical products on three levels of abstraction: functional interrelationships (functions); working interrelationships (working principles); and constructional interrelationships (components) (e. g. Pahl et al., 2007). This step-by-step detailing of a product concept is also the basis for systems engineering approaches (c. f. Walden et al., 2015). In systems engineering, the consideration of interfaces plays an important role. Direct interfaces occur on a functional or geometric level and are summarized in Table 1. Moreover, the product architecture can be defined as the one-to-one, one-to-many or many-to-one mapping of components fulfilling functions (Ulrich, 1995).

Table 1. Overview of functional and geometric interfaces based on Stone and Wood (2000) and Pahl et al. (2007).

Contact	adhesive bond	**Energy**	human	hydraulic	**Material**	human
	form connection		acoustical	magnetic		gas
	friction force connection		biological	mechanical		liquid
	force field connection		chemical	pneumatic		solid
	elastic force connection		electrical	radioactive	**Signal**	status
			electromagnetic	thermal		control

The assignment of abstract product model elements on a functional or component level to the constituting elements of a mechatronic system (cf. Figure 2) is called partitioning or domain allocation (Welp and Jansen, 2004). A detailed approach that supports to model the different levels of abstraction and the allocation of technical domains to functions, components or solution principles is presented by Jansen (2007).

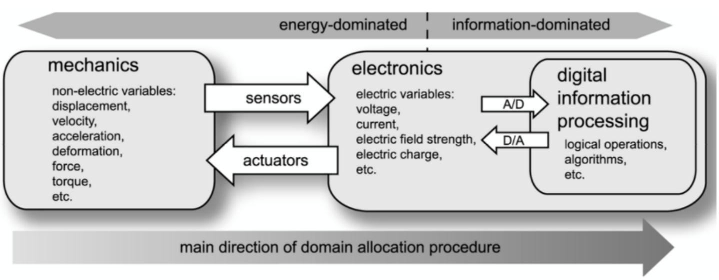

Figure 2. Overview of domains and their interfaces (Welp and Jansen, 2004).

2.2 Process perspective

The general design of a mechatronic system is described in the VDI-guideline 2206 (VDI, 2004) using the V-model and is divided into the phases *system design phase*, *discipline-specific design phase* and *system integration phase*. The discipline-specific process steps are not detailed any further in the guideline, but references to literature from the respective disciplines are given. Interestingly, it is mentioned in the guideline that functional incompatibilities, which could arise from the separation in discipline-specific development activities, are to be resolved in the system integration phase. We think that this kind of rework should be reduced by effective coordination.

Literature suggests to take advantage of synergies by coordinating interdisciplinary interactions with simultaneous engineering approaches (e. g. Isermann, 2000). Then, the adjustment of processes regarding content and timing depend on a high level of interdisciplinary communication and synchronization (Stetter and Pulm, 2009). This requires knowledge about all coordination needs. Hellenbrand and Lindemann (2011) present methodical support towards synchronization planning. Their approach links process steps with product elements (functions or components) via process results (information, documents) on a generic level. Yet, correlations that arise from the novelty of a product under development are not considered. Hence, this approach cannot be used in order to increase the transparency for project-specific coordination needs.

2.3 Organizational perspective

Companies that develop mechatronic products often group their engineering departments in the three disciplines *mechanics*, *electrics/electronics*, and *information technologies*. However, we also found other types of disciplines in our partner companies that can be distinguished:

- Company-wide, functional disciplines such as: management; (research &) development; testing; sales; marketing; purchasing; production; service; etc.
- Project-specific, functional disciplines such as: team leading, project management, testing, engineering; etc.
- Divisional disciplines such as: motor, gear box, body, tool holder, etc.

Regarding the organizational structure, individuals are affiliated with different departments or project-specific teams. Responsibility assignment matrices (PMI, 2013) are often used in order to define who is responsible for what.

3 Approach towards Systematic Partitioning

The approach towards systematic partitioning at the end of the system design phase aims at identifying coordination needs in the subsequent discipline-specific design phase. It extends and combines existing approaches (Jansen, 2007; Hellenbrand and Lindemann, 2011; Chucholowski and Lindemann, 2015) and especially supports to link the (conceptual) product structure to the organization and process structure via allocating domains and disciplines, respectively. For this we make use of dependency structure modeling techniques such as multiple domain mapping (Lindemann et al., 2009) and graph transformation (Heckel, 2006). In summary, the approach contributes to answering the question: Who has to talk to whom about what in discipline-specific design?

Note: We want to use the term *domain* from a product perspective and *discipline* from an organizational or process perspective. Other authors often use the terms interchangeable.

The approach consists of five parts: preparation; discipline allocation (organizational perspective and process perspective); domain allocation (product perspective); integration, and structural analysis and coordination planning.

3.1 Preparation

Existing information about the product system, organizational system and process system is collected as a preparation. Known elements from different types and their interrelations within these three systems are modeled. On the one hand, not a lot of details about the product under development are known in the system design phase. On the other hand, we assume that the products are seldom developed from scratch but are based on existing developments from the past. Consequently, the planned product architecture is already known (product functions and – as far as already defined – components mapped to the functions). Companies have an organizational structure (individuals being part of departments) and have models of their development processes. A predominant part of the necessary data is stored in different IT systems in our partner companies, such as PDM systems, ERP systems, process/project management tools, or even spreadsheets and presentation programs. Missing data has to be modeled manually.

The following steps summarize the preparation phase as illustrated in Figure 3.

- Model the product system with all known functions, components, functional interfaces, geometric interfaces and the product architecture. Within this step, also new potential working principles as solution variants can be identified.
- Model the process system with all predefined process steps and their logical dependencies (sequence).
- Model the organization system with relevant departments or teams, available individuals and their affiliation.

3.2 Discipline allocation

Discipline allocation concerns the organizational system and the process system. In our simplified example we distinguish the three disciplines *mechanics*, *electronics* and *information technologies*. The disciplines have to be allocated to the elements of the organization system and the process system. The discipline allocation for an academic example is shown in Figure 4 (Step 1). It is acknowledged that the discipline allocation always takes place at least implicitly. We allocate the disciplines explicitly in order to facilitate systematic partitioning and to be able to structurally derive resulting coordination needs.

3.3 Domain allocation

Based on the models generated as preparation, the allocation of domains on product level is done by mapping the elements from the product system to domains (cf. Jansen, 2007). Again, the three domains *mechanics*, *electronics* and *information technologies* are differentiated. Step 2 in Figure 4 shows the mapping in an academic example.

3.4 Integration: Connecting product perspective with organizational and process perspective

This step responds to the following question: Who is doing what and when? It aims to support the clarification of which department or team develops which extents of the mechatronic product and what discipline-specific processes are necessary. To do so, elements from the product system that are allocated to more than one domain should be decomposed first.

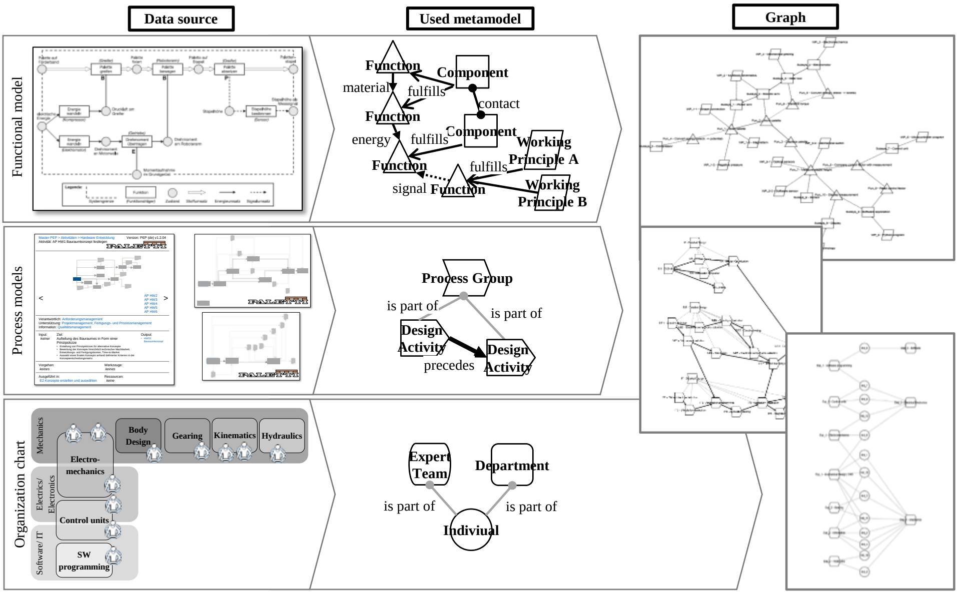

Figure 3. Illustration of the transfer of existing data into a graph using an academic example.

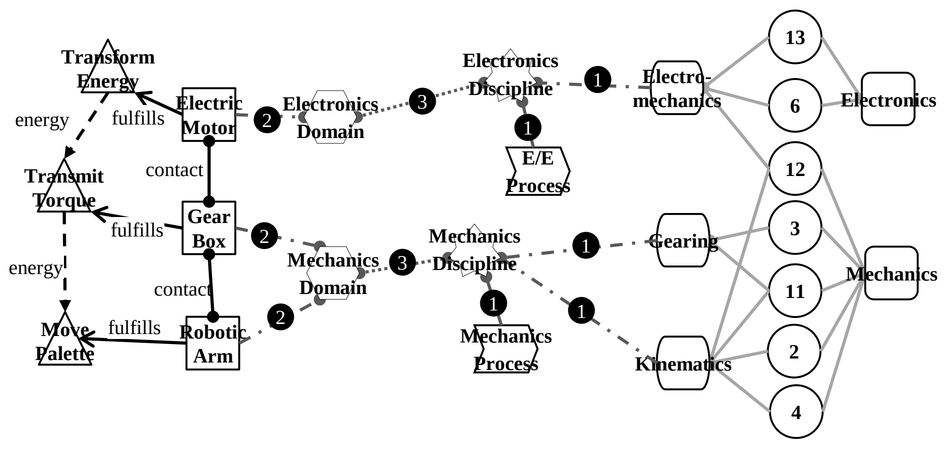

Figure 4. Exemplary discipline allocation for the organization and process system (1), and domain allocation (2). The mapping of domains and disciplines brings all perspectives together (3).

After detailing the modeling basis, the organization and process systems can be correlated indirectly with the product system by matching domains and disciplines (Step 3 in Figure 4). This step is trivial in our example, but is not necessarily trivial in practice (refer to section 2.3) and is therefore made explicit in our approach. Furthermore, discipline-specific processes for each product system element can be instantiated based on the respective generic discipline-specific processes (see different detailed processes in Figure 5).

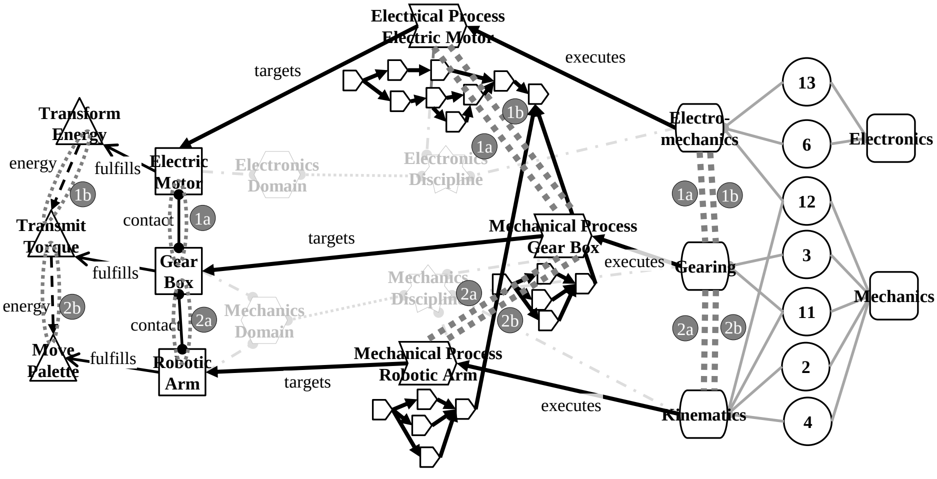

Figure 5. Exemplary instantiation of the discipline-specific processes and structural analysis. Coordination needs between the correlated processes and organizational units are derived for each interface within the product system (1a, 1b, 2a, 2b).

3.5 Structural analysis and coordination planning

Coordination needs between organizational units (departments, individuals) and between processes (instantiated process steps) can now be derived from the modeled structures by looking at interfaces on product level. Since the design process steps have been instantiated for different product system elements (one process stream each), interfaces can be projected on a process level as need for coordination. The coordination has to take place to some extent somewhere in between the two process streams and indicates about what and when interaction is needed. In addition, the interfaces between product system elements can be projected to interfaces between organizational units and give indications who has to interact with whom. The projections can be derived computationally by either using graph transformation with predefined rules or by multiplying the underlying adjacency matrices (=DSMs and MDMs). We considered all direct and first-order indirect relationships in our example. Additional information about each coordination need can be provided by characterizing the product interfaces with the help of Figure 2. For example, issues regarding a geometric interface between two components could be: statics, dynamics, force transmission, etc. If the components share an indirect functional relationship and are allocated to different domains (mechanics, electronics), the indirect relationship implies that a converter could be needed.

The computationally derived coordination needs serve as a basis to systematically plan coordination measures. For this, however, expert judgement about the relevance and about adequate coordination measures is necessary.

4 Discussion and Outlook

This research contributes to the state of the art by presenting an actionable approach towards systematic partitioning that integrates the product perspective, organizational perspective and process perspective. The integration of the three projects systems is done by matching the technical domains allocated to the product with disciplines allocated to discipline-specific processes and the organization. A structural analysis of the product system in terms of interfaces then enables the derivation of needs for coordination on a process and organizational level. The derivation is done computationally by the use of dependency structure modeling techniques such as multiple domain matrices and graph transformation. The generated list of coordination needs not only enables project managers to explicitly plan coordination, but also gives developers an overview of who should talk to whom about what (product interface) and when (related processes).

The presented approach bears potentials when applied consequently. First, the models generated during the application of the approach in previous, similar development projects can be used as input for the preparation phase. This minimizes the modeling effort in this phase. Second, companies can define their own domains and disciplines (and a specific mapping of the two) that are relevant for them. This would also enrich the interpretation of the respective cross-domain and cross-disciplinary interfaces. As an example, considering information technologies it is reasonable to differentiate programming languages such as Python, C++ or Java since they require different software architectures and programming skills. This is why skills/expertise on a certain level of abstraction could also be considered as disciplines for the discussed approach. Third, it is proposed to use the approach to consider coordination needs in the discipline-specific design phase based on data available at the end of the system design phase. But also new upcoming coordination needs, which arise due to a more detailed or changed product structure during discipline-specific design, could be identified. Thus, it could be valuable to keep the structural models updated and repeat the analysis continuously.

So far, the approach is kept as detailed as necessary in order to create new implications but as simple as possible. Still, extensions of the approach could enhance its value:

- Functional and non-functional requirements could be included in the product system model. This would enable the consideration of further relevant indirect relationships via relationships with and in between requirements. Also the modeling of the tool system could be worthwhile. The different tools are strong indicators for relevant domains, disciplines or even required skills/expertise.
- Predefined tailoring criteria that enable to differentiate prescriptive process variants for process instantiation could be used.
- Further analysis could also consider second-level indirect relationships derived from first-level indirect relationships.
- When considering complex systems, a very large number of derived coordination needs is expected. Structural criteria such as the criticality of components (refer to Lindemann et al., 2009) could be helpful indicators for the relevance of a coordination need. This enables computational prioritization.

The approach was developed based on explorative studies on the situations and needs of our industry partners regarding systematic mechatronic product development. As a next step, the approach will be evaluated with our industry partners. For this, we are working on a software prototype, which eases modeling and enables automatic computational analysis and visualization of the results.

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Contact: N. Chucholowski, Chair of Product Development, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany, +49-89-28915138, chucholowski@pe.mw.tum.de

About the Authors:

All authors are involved in a research project in collaboration with an association of Bavarian companies from the metal and electronical industry. The project aims at supporting the top-down development of mechatronic products and integrates issues regarding process management, requirements management and engineering change management.

Dipl.-Ing. Nepomuk Chucholowski, Technical University of Munich (TUM) (chucholowski@pe.mw.tum.de) – Nepomuk is a PhD candidate at the Chair of Product Development. He graduated in Mechanical Engineering at TUM. His research focuses on project engineering for complex product development projects with special regard to managing activity dependencies.

Johannes Kriegler, B.Sc., TUM (johannes.kriegler@tum.de) – Johannes earned his Bachelor's degree in Engineering and Management and is currently master student in Mechanical Engineering at TUM. As student assistant at the Chair of Product Development he supports research related to managing complexity in mechatronic product development projects.

Dipl.-Ing. Christoph Hollauer, TUM (hollauer@pe.mw.tum.de) – Christoph is a PhD candidate at the Chair of Product Development. He graduated in Engineering and Engineering Management at TUM. His current work focuses on the strategic planning of engineering design processes with regard to organizational contexts.

Niklas Kattner, M.Sc., TUM (kattner@pe.mw.tum.de) – Niklas studied Mechanical Engineering at the Karlsruhe Institute of Technology with major field in Product Development. Now he is a PhD candidate at the Chair of Product Development. His research focuses on the management of engineering changes within the development of mechatronic products.

Lucia Becerril Izquierdo, M.Sc., TUM (becerril@pe.mw.tum.de) – Lucia is a PhD candidate at the Chair of Product Development. Her current research focuses on Engineering Change Management and on the implementation of mechatronic product development processes. She graduated with a master's degree in mechanical engineering from TUM.

Dominik Weidmann, M.Sc., TUM (weidmann@pe.mw.tum.de) – Dominik is a PhD candidate at the Chair of Product Development at the Technical University of Munich. He studied mechanical engineering with focus on systematic product development. His current research field is interdisciplinary requirements engineering for mechatronic products.

Prof. Dr.-Ing. Udo Lindemann, TUM (lindemann@pe.mw.tum.de) – Udo Lindemann became full professor at the Chair of Product Development in 1995 after making his doctoral degree in 1979 and working in industry for several years. He is co-editor of several international journals and is founding member and Fellow of the Design Society.