APPROACH FOR THE CREATION OF MECHATRONIC SYSTEM MODELS

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ABSTRACT

One of the major challenges in developing mechatronic products is the increasing complexity of the products themselves. The defining feature of mechatronic products is the interplay between various engineering disciplines such as mechanics, electronics, and software. There is a critical lack of methods and tools supporting the interdisciplinary aspects of the development process of mechatronic products, especially in the conceptual design phase. These deficiencies make it difficult to overview the interdependencies of the involved engineering disciplines. Mechatronic System Models (MSM) can improve this unsatisfactory situation and allow for a holistic view on complex mechatronic systems. This affords a validation of design concepts and a qualified comparison of different concepts in early phases. MSM should at least be able to manage existing data and to illustrate the most important relations. Additionally, they should provide the possibility to execute several simulations of load cases, thus allowing specific "global" system properties to be evaluated. Typically these simulations at the system-level differ from those at the discipline-level.

Keywords: process model, product development process, system-level modelling, system-level models, system models, mechatronics, mechatronic systems, systems-of-systems

1 INTRODUCTION

The defining feature of mechatronic products is the interplay between various engineering disciplines such as mechanics, electronics, and software [1]. Due to that and to the increasing complexity of the products themselves, the need of methods and models supporting the overview of the most relevant system data is present from the very beginning of design processes. However, there is a critical lack of methods and tools supporting these interdisciplinary aspects of the development process of mechatronic products as well as the communication between developers from various disciplines, especially in the conceptual design phase [2]. As quoted in [3] these deficiencies make it difficult to overview the interdependencies of the involved engineering disciplines. The level of abstraction at which the whole product is investigated and discipline-overall models are used is hereafter referred to as "system-level".

Mechatronic System Models (MSM) can improve this unsatisfactory situation and allow for a holistic view on complex mechatronic systems which is generated by various single views such as the consideration of requirements, structure, behaviour, function, parametrics etc. MSM should at least be able to manage existing data and to illustrate both the relationships inside a system (between sub-systems) and between a system and its environment [4]. Additionally, they should provide the possibility to execute several simulations of load cases (test cases), thus allowing specific "global" system properties to be evaluated. Typically these simulations at the system-level differ from those at the discipline-level. Since simulations at the discipline-level are usually conducted by highly skilled and specialized engineers who use specialized, discipline-specific software tools, the simulations at the discipline-level can normally not be replaced by simulations at the system-level. Furthermore, simulations at the discipline-level are used to evaluate "local" properties [5].

The basis for simulations in the various phases of the product development process is a shared database. This database also provides interfaces to discipline-specific software tools and their related models, and must ensure data consistency. Further discussions of the database are beyond the scope of this paper.

This article discusses possible process models for the creation of MSM, and is structured as follows: The subsequent section is dedicated to two process models. The first one shows the working steps necessary for the creation of a MSM whereas the second one discusses the simulation-based design process as shown in [5]. Next, an integrated process model for the creation of a MSM is presented. A conclusion summarizes the main aspects of this article and addresses future activities.

2 RELATED WORKS

VDI Guideline 2206 [6] addresses in particular the design methodology of mechatronic systems and proposes the “V-model” (Figure 1) for the development process. After analyzing all requirements on the total system, the sub-functions and sub-systems are defined (left branch of the V-model). They are to be developed simultaneously by discipline-specific development teams working in collaboration. After verification of the sub-functions and testing the sub-systems, these are integrated stepwise (right branch of the V-model) into the “overall system”. Then the performance of this integrated system is checked by analysis and evaluation in order to assure its properties. If the system must be improved, the initial operation phase is repeated (iterative process).

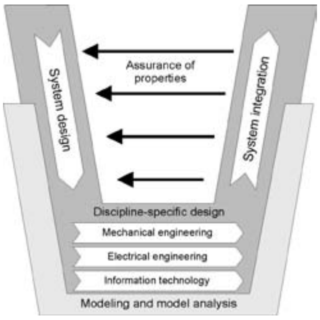

Figure 1. V-model according to VDI 2206 [6]

In [7] and [8] the authors presented an approach for the holistic description of a multidisciplinary system with the consideration of the essential operating modes and the desired behaviour. Therefore aspects such as the environment, application scenarios, requirements, the system of objectives, functions, etc. should be considered in a specific specification technique. Furthermore, a procedure model for the conceptual design phase (which includes four sub phases) was developed. The research group also developed the software tool “Mechatronic Modeller“ that is based on the specification technique for modelling mechatronic systems.

A concept for a software prototype supporting the development of mechatronic systems was presented in [9]. The software prototype called “Connection-Modeller“ should allow various views on the system under design, e.g., requirements, functions, structure. These views are called partial models and can be developed using proprietary software-tools. The Connection-Modeller provides means to define cross-discipline connections between various partial models which e.g. can be used for the propagation of design changes.

A system-level (high-level) model of a multidisciplinary system based on a functional description was introduced in [10]. The architecture of the system is primarily determined by the main functions which are already known in the conceptual phase of design. In later design phases general functions can be decomposed into more concrete ones which lead to a more detailed functional structure of the system under design. The system model should provide a better overview of the system and should also connect abstract with more concrete models. A verification of specific parameters against requirements can also be supported by the functional structure. The same research group presented a function modelling approach in [11] to connect different views on different levels of abstraction to support the designer in the conceptual design phase. The authors discussed the following three industrial problems: (i) design traceability, (ii) design understanding and (iii) system decomposition.

In [12] a communication framework supporting the communication between the model based system engineering efforts and the discipline specific software tools was introduced. In this paper an approach for an integrated design environment is presented in which mappings between SysML and Matlab/Simulink models are built.

In [13] means to use structural, functional or behavioural relations between entities as cues for engineering change prediction were discussed. The authors mentioned a lack of methods for generating plausible estimates of how changes propagate. In [14] the hierarchical structuring as a proper technique for representing complex systems was proposed. The authors also suggested several guidelines which should support designers for attaining a meaningful decomposition.

3 MECHATRONIC SYSTEM MODEL (MSM)

3.1 Process model I: Creation of a MSM

3.1.1 Generic Approach

Mechatronic systems usually consist of several sub-systems and system-elements on different hierarchical levels (also referred to as levels of abstraction). Therein, the terms system, sub-system and system-element have a relative meaning, hence, the allocation of a specific level to the different system-elements depends on the definition and view of the system under consideration and is thus a matter of definition and view.

A Mechatronic System Model (MSM) should represent the overall mechatronic system under consideration (original) and should include all its relevant properties. As the structure of the mechatronic system may be regarded as a significant property, at least this structure has to be mapped to the model, too. Additional, maybe different, structures with various abstraction levels may arise from other views of the system (e.g. requirements, functions, modelling aspects), leading to a multiple-structured model. The MSM covers the highest abstraction level considered, and may include sub-models and model-elements on levels below. The terms model, sub-model and model-element again have a relative meaning and are a matter of definition and view.

Figure 2 shows the generic approach for the creation of a Mechatronic System Model (MSM). This approach describes the necessary steps and their chronological order to create a MSM both for top down and bottom up modelling. In Figure 2, the different levels are depicted as rectangles representing sub-models of the MSM which can be used to structure the MSM with respect to various views. The grey area of each sub-model of the MSM accounts for interfaces and communication between the connected sub- or discipline-specific models by transmitting input and output parameters (depicted as blue circles). Representatively for all levels of the MSM, the granularity of models and respective parameters is depicted only at the system-level of the MSM by circles with different diameters inside the grey areas. The green rectangles in Figure 2 represent discipline-specific models.

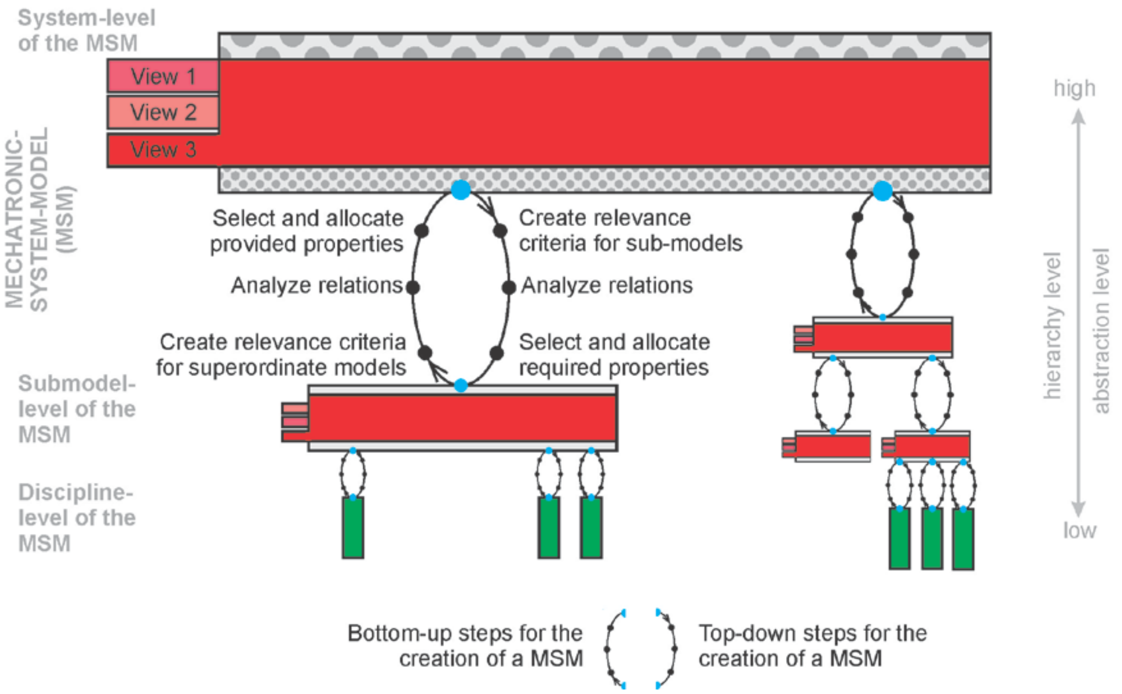

Figure 2. Approach for the creation of a Mechatronic System Model (MSM)

Furthermore, various sub-models of the MSM as well as relations between system- and discipline-level are shown in Figure 2. The interactions between sub-models of different levels as well as between sub-models and discipline-specific models should exhibit the same pattern of steps (depicted as ellipses). To change the level of abstraction, the following steps are required:

- Create relevance criteria (e.g. with respect to the system under consideration, modelling aspects): The relevance criteria are used to determine those model-elements which should be included in the MSM on a specific level of abstraction.
- Analyze relations:
  The relations between model-elements on different levels of abstraction must be established, analyzed and documented. These relations connect models of adjacent hierarchy levels and allow for the propagation of changes across hierarchy levels in the model and therefore in the original as well.
- Select and allocate properties (e.g. of the original, of the model):
  Significant properties have to be chosen and allocated to each sub-model and model-element. To all properties, characteristic parameters have to be assigned which are able to quantify the chosen properties. If a parameter is fixed or changed on a certain level, it has to be transferred to all adjacent hierarchy levels on which possible contradictions are examined.

These steps are important for a top-down as well as a bottom-up approach.

3.1.2 Relevance criteria for the inclusion of model-elements into the MSM

As already mentioned, relevance criteria are used to determine which model-elements should be included into the MSM on a specific hierarchy level (system level of the MSM, sub-model- or discipline-level). These criteria cannot be understood as a rigid set of rules but have to be tailored to the specific design or analysis task and to the corresponding questions to be treated by the MSM. As not all model-elements are of the same significance to the MSM and an inclusion of each and every model-element into the MSM would lead to an information overflow in the MSM, detailed models (e.g., of components that are comparably simple and well-understood such as standard bearings or electrical resistors) should be “condensed” to significant models on a higher level.
Therefore it is necessary to specify clear criteria for those model-elements and sub-models which should be included into the MSM. Table 1 shows various general relevance criteria pro and contra modelling on the system-level.

Table 1. General relevance criteria

	General relevance criteria pro modelling on the system-level
GP1	Models of system-elements which are relevant to the understanding of the overall system
GP2	Models of system-elements which are relevant to the behaviour of the overall system
GP3	Models of system-elements which are relevant to the structure of the overall system
GP4	Models of system-elements with interdisciplinary (“global”) relevance
	General relevance criteria contra modelling on the system-level
GC1	Models of system-elements with intra-disciplinary relevance

GP1 … General Pro 1, resp. GC1 … General Contra 1

Table 2 shows various system-related relevance criteria pro and contra modelling on the system-level.

Table 2. System-related relevance criteria

	System-related relevance criteria pro modelling on the system-level
SP1	Models of system-elements for which GP1 to GP4 are not applicable, but which are relevant due to other criteria (e.g. resulting costs)
	System-related relevance criteria contra modelling on the system-level
SC1	Models of system-elements with interdisciplinary relevance but with low challenge to be mastered (e.g. standard electrical drive for a component with minor importance)

SP1 … System-related Pro 1, resp. SC1 … System-related Contra 1

3.1.3 Analysis of relations

The relations modelled in the MSM comprise not only relations of the system under consideration but also additional relations (e.g. inside and between different views).
A suitable representation of a MSM should include only models of those system-elements and sub-systems which have significant importance to the system-level according to the chosen relevance

criteria. In the course of the assurance of system properties, a further essential task for the MSM is to model the relations of the system under consideration (under design or analysis). Modelling these relations should contribute to a better understanding of the system and should allow a comprehensive analysis of its internal and external relations. Thereby, the representation of relations between all characteristic system parameters enables both a complete overview of the most relevant system data and the identification of the main parameters. Furthermore, the representation of the relations can be used to structure the model of the overall system and to decompose it into sub-models as well as to trace the impact of design changes. The relations may be represented, e.g., by graphs or standardized modeling languages such as SysML, see also [4] and [15]. In general, various kinds of relations between system-elements are possible e.g., physical, geometrical as well as topological relations. In the following, a (certainly incomplete) list of possible relations is mentioned.

Classification of relations

Table 3 shows a classification into external and internal relations as well as corresponding examples. External relations describe the relation between the system and its environment, whereas internal relations characterize system-inherent relations.

Table 3. Classification of relations

External relations
Interfaces to the system environment (energy, material and signal flows)
Stakeholder requirements
Internal relations
Interdisciplinary relations
Intradisciplinary relations
Geometrical relations

Relations between model-elements of the MSM

It is obvious that a lot of relations between MSM-elements belonging to the same view exist (e.g. relations between requirements). Furthermore, various relations may also arise between MSM-elements belonging to different views. Several possible views of a MSM are listed in the following:

- Requirements
- Structure
- Functions
- Behaviour
- Parametrics
- Models (implemented CAx-Models)

One example is the relation between a specific function and the corresponding requirement that should be fulfilled. The correspondence between a 3D CAD model of an assembly and the related bill of material, may serve as an example for relations between models.

Relations due to flows of energy, material and signals

Various system-elements are influenced by the flows of energy, material and signals inside the system as well as to and from the system. As an example, the change of the energy supply of the system (e.g. from hydraulic to electric) has significant influence on the (already existing) relations of the system, as hydraulic devices always need components for pressure generation that are not required when using electrical devices.

Representation of relations

For the representation of relations of the MSM, manifold possibilities are available, for example:

- Text-based
- Matrix-based (e.g. DSM, [16])
- Graphs
- Standardized Modelling Language (see e.g. [15]).

In our investigations a standardized modelling language is preferred.

Description of relations

Various possibilities are available for the description of relations, as well, for example:

- Text-based
- Arithmetic relations
- Geometric relations
- Logical relations.

A text-based documentation of relations is very simple to create but can quickly become too confusing. Several other possibilities, e.g., as usual in CAD-tools are known.

3.1.4 Selection and allocation of properties

As already mentioned, relevance criteria are used to define the level of abstraction for the elements in the MSM. In the next step, significant properties have to be chosen and allocated to each sub-model and model-element. During the design process the granularity of properties is getting finer and finer which corresponds to an increasing level of detail of system-elements as well as their properties. Corresponding to the design process, the allocation process of properties is iterative as well. Here it is essential to distinguish between global and local properties. Global properties are system-specific properties that cannot be evaluated at a discipline-specific level, whereas local properties are to be evaluated at the discipline-level.

3.2 Process model II: Simulation-based design process

A general approach to a simulation-based design process for mechatronic systems, especially for the early phases of design, was presented in [5]. This approach consists of six phases based on VDI Guideline 2221 [17] and aims at integrating simulation techniques into the design process from the very beginning in order to evaluate the properties of a system under design as far, and as early, as possible within each design stage. Thus, the comparison between actual and desired system properties can be drawn faster, better, and easier, thereby improving the design process itself. Figure 3 shows a depiction of the detailed process model on the left side and a simplified (condensed) representation on the right side.

The input to the process model is a specific "development task". The process model consists of six design phases, whereas only phases 1 to 5 are the focus of the present investigation. The design phases (depicted as large rhombuses) include specific working steps (depicted as rectangles) and corresponding working results (depicted as small rhombuses). Each design phase concludes with a query: Are the requirements reachable? If the requirements are attainable, the process continues with the next design phase; otherwise, an "external" iteration is necessary, or the process must be terminated. The step "Validation/Evaluation" represents an "internal" iteration step (inside the actual design phase) at the end of each design phase. Phase 6 and the output ("further realization and documentation") are beyond the scope of this paper.

In the first design steps, requirements and functions can be simulated; in the principle and architectural design, first mathematical models can be executed. System-level simulations are possible in each phase of the design process, whereas discipline-level simulations are feasible only in later phases of the design process (see the markers on the right side in Figure 3) when the information about the system containing the necessary level of detail becomes available.

4 PROCESS MODEL FOR MODEL BASED MECHATRONIC DESIGN

4.1 Integration of the presented process models

Both process models presented extend the common product development processes by additional investigations regarding simulation-based modelling on the system-level. The following step tries to integrate both process models into one holistic approach for the creation of a MSM.

Figure 4 shows the integration of process model II into process model I as well as the specific working steps depicted as ellipses and "diamonds" leading to an integrated process model for model based mechatronic design. Process model I is specifying the steps that are necessary for changing the abstraction level, whereas process model II is representing the steps for the evaluation of global properties by applying system-level simulations at various hierarchy levels. The relevance of the various design steps depends on the phases of the product development process as well as the specific abstraction level of the system under consideration and the corresponding MSM.

According to Figure 4 simulations are possible on each abstraction level of the MSM. As already mentioned, simulations at the system-level differ from those at the discipline-level and should contribute to a better understanding of the overall system by evaluating system-specific (global) properties that cannot be evaluated at a discipline-specific level.

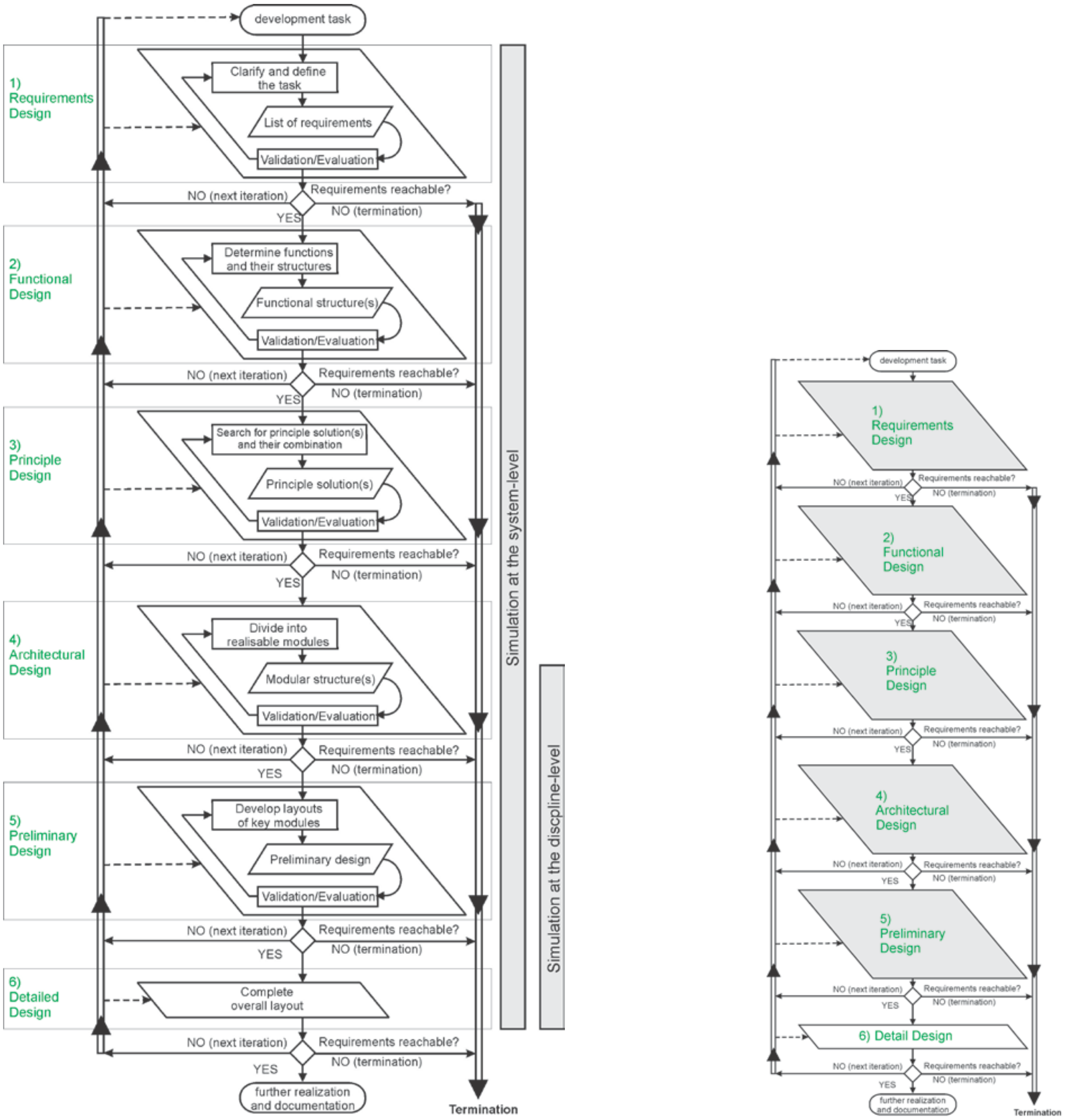

Figure 3. Design process model according to [5]

As explained above, the grey areas in the sub-models are essential for the communication inside the MSM. In the integrated process model according to Figure 4, these areas also include the necessary "Validation/Evaluation" steps for the several system-level simulations depicted in Figure 3.

4.2 MSM for "new-design" and "re-design"

Figure 4 shows the process model for MSM in the distinct cases of "new-design" and "re-design" (see the green arrows). A very significant difference between these two cases is the amount of available information. Normally, the information base for new-design is significantly lower than that for re-design. Depending on the mentioned cases, the design phases from "Requirements Design" to "Preliminary Design" may have different meanings and importance on the distinct levels of the MSM. The diamond shaped arrangement of the design phases in the process model for model based mechatronic design (Figure 4) allows for a free selection of their sequence.

In general, a new-design starts at the highest hierarchy level with a tiny and often uncertain information base. The subsequent phases of the design process contribute to an enlargement of the information base which in turn is requisite for a suitable division into sub-models on a lower level of abstraction.

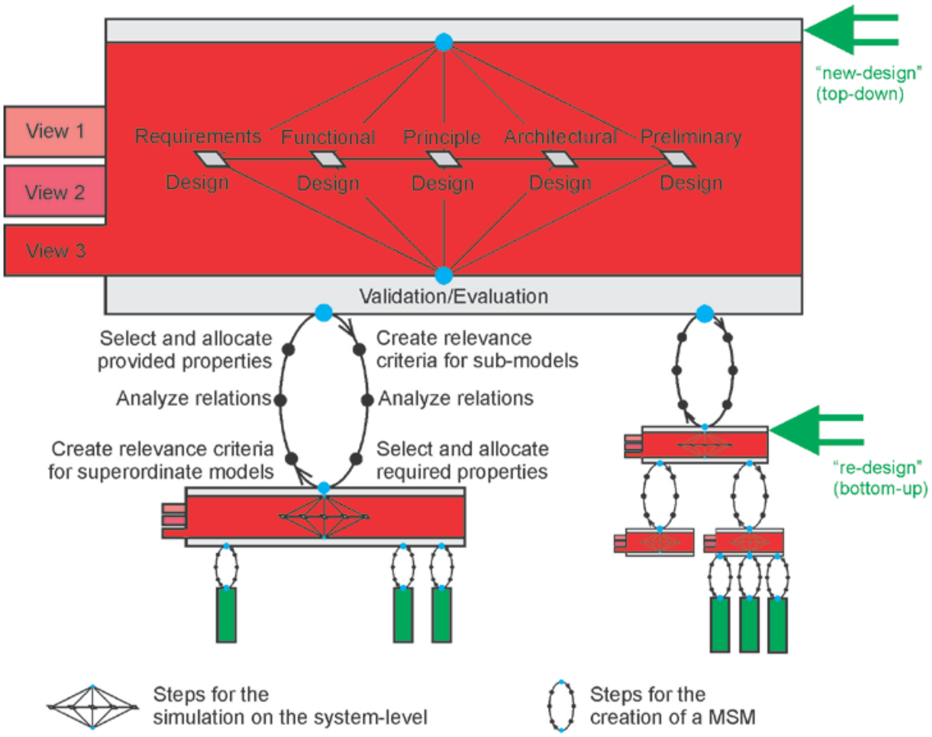

Figure 4. Process model for model based mechatronic design

Re-designs of already existing systems, however, are usually induced by the modification of sub-systems which implies that normally a broader information base is available. Changes caused by re-designing sub-systems must be transmitted to the connected sub-models and discipline-specific models using the MSM-specific working steps such as creation of relevance criteria, analysis of relations and allocation of properties.

5 INTEGRATION INTO COMMON DESIGN MODELS

Figure 1 shows the standard V-model according to VDI 2206 [2]. A complex mechatronic system is, however, usually not developed in the course of a single macrocycle of the V-model. Therefore, it is necessary to iterate through several macrocycles, as shown in Figure 5.

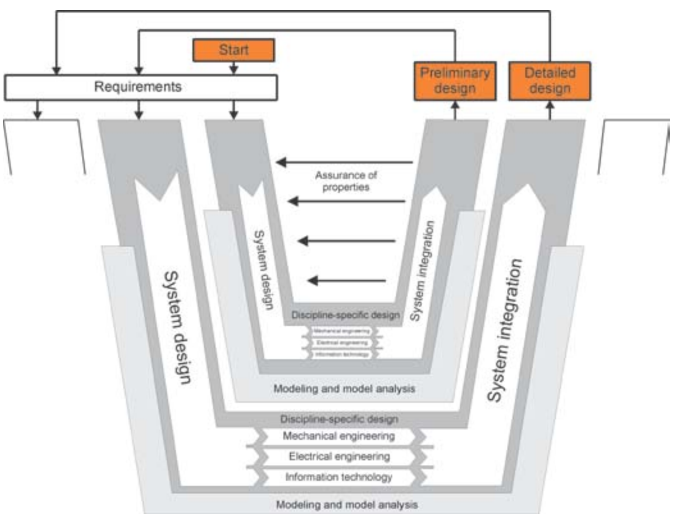

Figure 5. Pass through several macrocycles of the V-model

In addition, the V-model in Figure 5 presents modifications in the phases “System design” and “System integration”, which are depicted in more detail in Figure 6 (the inner V-model of Figure 5). Normally, these two phases (depicted as arrows) do not illustrate the separation (or integration) of system and involved disciplines.

Figure 6 shows the integration of the phases of the design process model (presented in Figure 3) into the V-model. Usually, phases 1 to 3 occur at the system-level. Phases 4 and 5, however, interact with both the discipline- and the system-level. The previously discussed external iteration in the design process model can be done in the course of the “Assurance of properties”.

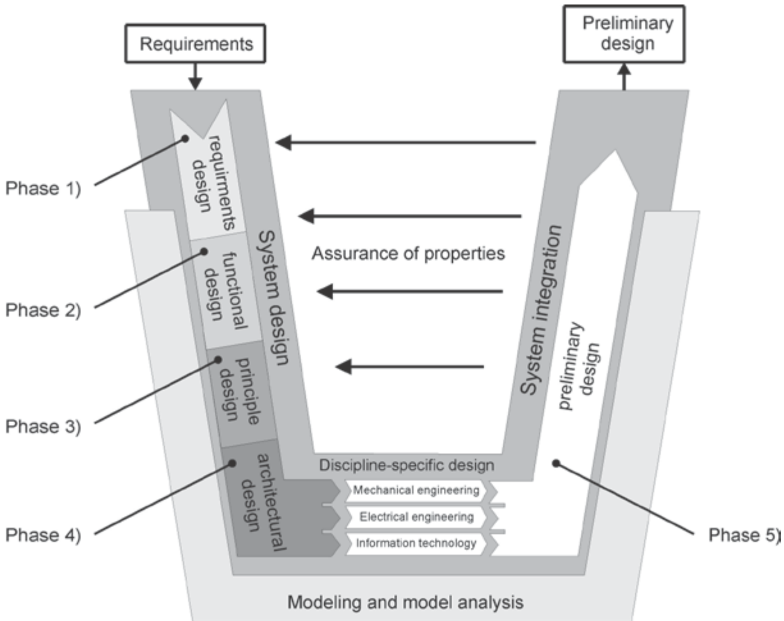

Figure 6. Integration of the different design phases into the V-model

These investigations conclude that even the steps “separation into the disciplines” and “integration of the disciplines“ have particular significance in the product development process. It is essential that the interaction between system-level and discipline-level is managed in these steps.

6 CONCLUSION AND FURTHER ACTIVITIES

It is evident that there still exists a considerable lack of methods as well as software tools that support design engineers in executing simulations in the early phases of the product development process and provide a holistic view of the system under consideration. This paper wants to contribute to the remedy of this deficiency by developing an integrated process model for model based mechatronic design which allows also for the evaluation of global system properties. The next steps of the research work will focus on the creation of further views to be covered by the MSM in order to enable a broader range of system-level simulations.

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