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APPLICATION OF THE MECHATRONIC-SYSTEM-MODEL-APPROACH FOR THE DEVELOPMENT OF AN INDUSTRIAL ANNELING SIMULATOR

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1. Introduction

The development of heating zones for industrial annealing simulators merges solutions from disparate engineering disciplines, such as mechanical engineering, electrical engineering, control engineering as well as thermodynamics. Therefore, heating zones for annealing simulators can be classified as mechatronic products, also known as systems-of-systems, integrated systems or mixed systems (e.g., [De Silva 2005]). 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. The Mechatronic-System-Model-Approach (MSM-Approach) according to [Follmer et al. 2011] can be used to support the development of such a multi-disciplinary system.

This paper shows the application of the MSM-Approach for the development of an industrial annealing simulator, and is structured as follows: The second chapter is dedicated to related works. In the third chapter, the MSM-Approach is introduced and the two distinct cases of “new-design” and “re-design” are discussed. A brief overview of industrial annealing simulator is presented in the fourth and the application of the MSM-Approach is show in the fifth chapter. A conclusion summarizes the main aspects of this article and addresses future activities.

2. Related works

A concept for a software prototype supporting the development of mechatronic systems was presented in [Stark et al. 2010]. 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.

Gausemeier et al. [Gausemeier et al. 2010] present an approach for the holistic description of a multi-disciplinary system with the consideration of the essential operating modes and the desired behaviour. They suggest that aspects such as the environment, application scenarios, requirements, the system of objectives, functions etc. should be considered with a certain specification technique. Furthermore, they introduced a procedure model for the conceptual design phase (which includes four sub phases). The research group also developed the software tool “Mechatronic Modeller” that is based on the specification technique for modelling mechatronic systems.

In [Hellenbrand and Lindemann 2011] the authors present a framework for integrated mechatronic process modelling and planning. To support the systems thinking of the involved engineers the framework allows for different and discipline-independent views on the system under consideration. For this purpose an approach based on a Multiple-Domain-Matrix (MDM) with six domains is used to represent and analyse the interdependencies of the product as well as of the related process. In this framework the following four views are considered: (i) product view for the technical system itself, (ii) process view for the belonging development process, (iii) planning view for e.g., constraints and the level of abstraction as well as (iv) controlling view for describing and monitoring the actual status of the project.

The authors of [Qamar et al. 2011] believe that it is difficult to describe all relevant aspects of a multi-disciplinary system with the help of only one modelling language. Hence they pursue an approach which is based on different modelling languages and the relations between them, utilizing SysML-models. In this concept, called “Model Integration Framework”, a system model consists of the description of the system and the relations between the different modelling languages. The “Model Integration Framework” supports model transformations from the system model to the discipline-specific models and vice versa.

3. MSM-Approach

3.1 Generic approach

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 system-model level of 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. In figure 1 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 circles). The hatched rectangles in figure 1 represent discipline-specific models.

The diamond shaped arrangement of the six design phases in each sub-model of the MSM represents a simulation-oriented design process for mechatronic systems, especially for the early phases of design, according to [Follmer et al. 2011]. This approach consists of six phases based on VDI Guideline 2221 [VDI 2221 1993]. It aims at integrating simulation techniques into the design process from the very beginning in order to evaluate the properties of a system under design within each design stage on the system-level. In the first design phases, 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 when the information about the system containing the necessary level of detail becomes available. The MSM extends the common product development processes by additional investigations regarding simulation-oriented modelling on the system-level. According to figure 1 simulations are possible on each abstraction level of the MSM. 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. 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.

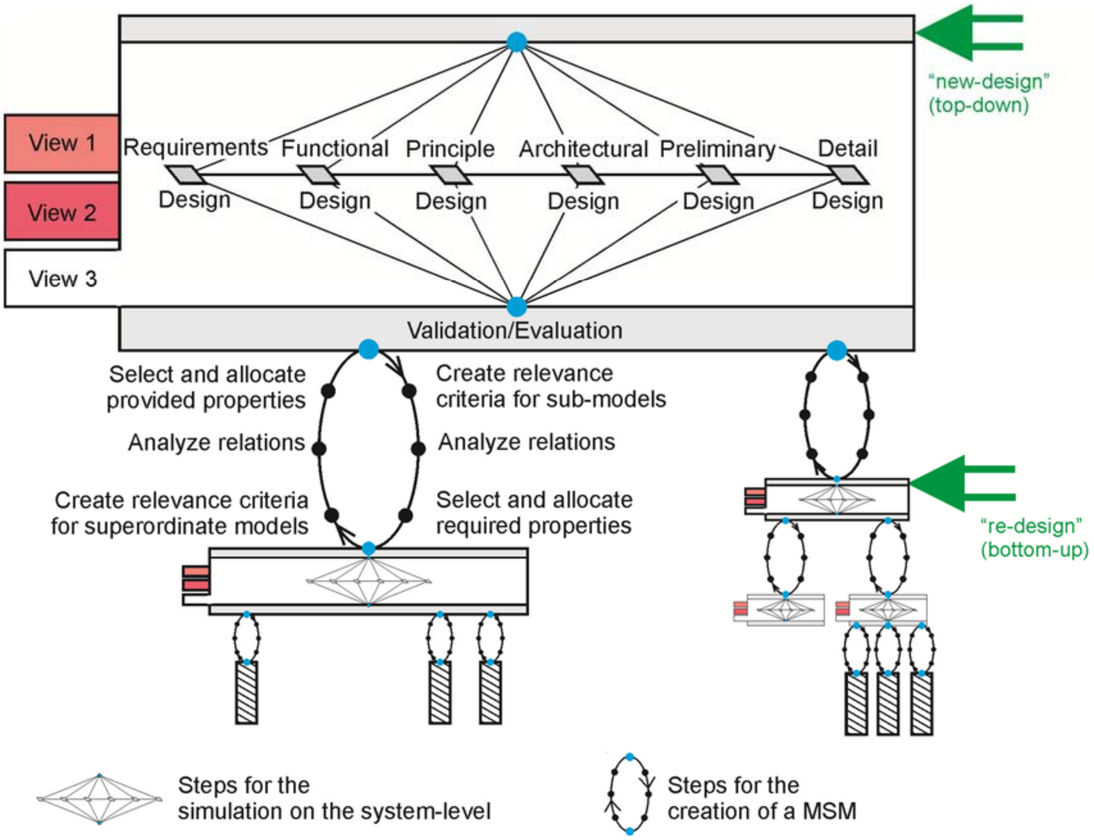

Figure 1. Process model for model based mechatronic design

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

Figure 1 shows the process model for the distinct cases of "new-design" and "re-design" (see the arrows). A very significant difference between these two cases is the amount of available information. Normally, the information base for a new development (new-design) is significantly smaller than that for a further development (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 figure 1 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 a prerequisite for a suitable division into sub-models on a lower level of abstraction. Re-designs of already existing systems are usually induced by modifications of specific sub-systems. According to that a broader information base is available because the system has already been developed. Changes caused by re-designing sub-systems must be transferred 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.

4. Industrial annealing simulator

The MSM-Approach was applied to two already finished industrial projects. These case studies addressed the development of annealing simulators. The first project was a complete new development and the second one a further development. The mentioned case studies were jointly elaborated with the Austrian company "Vatron" within the framework of the "ACCM" (Austrian Center of Competence in Mechatronics). The subsequent sections focus on the second project involving the further development of a specific subsystem (see the arrow "re-design" in figure 1).

4.1 Background

In continuous hot-dip galvanizing lines heat treatment and surface refinement of the strip are carried out in one integrated process step. In order to be able to adjust the optimum thermal treatment for the cold-rolled material to be annealed and galvanized, it is imperative to analyze precisely and in advance the effects of temperature and annealing gas characteristics on the mechanical as well as the surface properties of the annealed material. As such analyses would be very costly and time-consuming in the course of the production process, "voestalpine Stahl" together with "vatron" developed a galvanizing simulator to analyse the dependence of surface and material properties on heat treatment, gas atmosphere and zinc bath characteristics. The galvanizing simulator serves primarily as a device to experimentally simulate heat-treatment cycles in well-defined gas atmospheres.

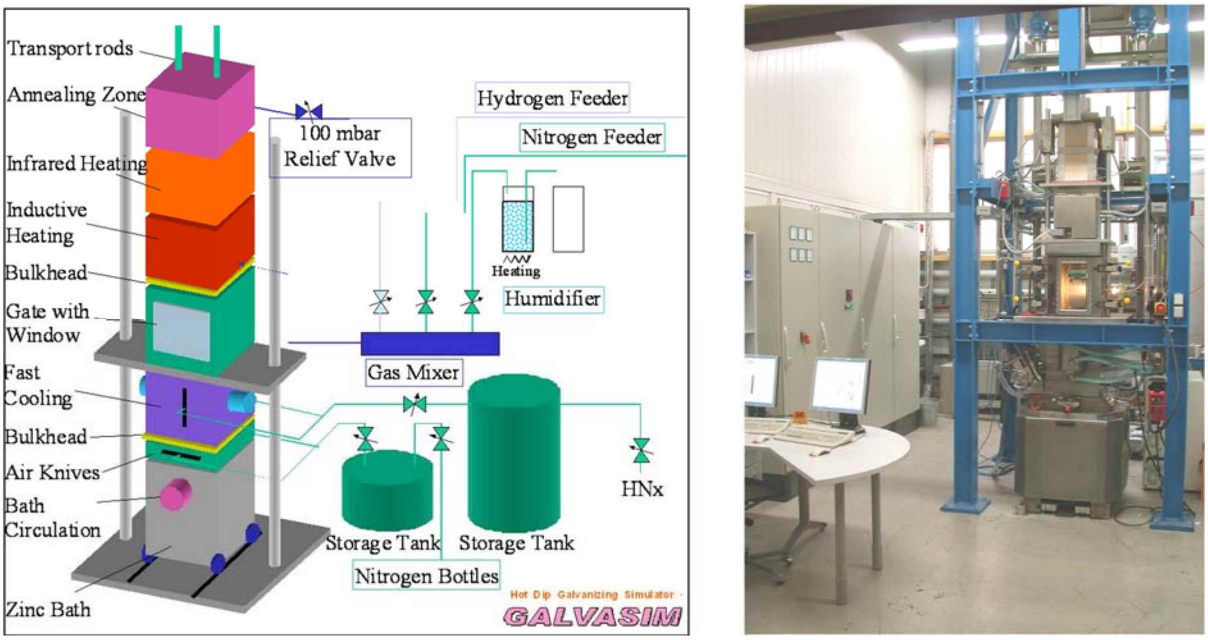

Figure 2. Modular architecture of "Galvasim"

Figure 2 shows the modular configuration of the annealing simulator "Galvasim" according to [Follmer 2010]. The specimen is moved back and forth between the individual zones by means of a driving mechanism that runs according to the specific requirements. The subsequent sections give a closer look on the sub-system "Infrared Heating", in the following referred to as "IR-Zone".

4.2 Structure of the sub-models "IR-Zone" and "Emitter Device"

This application example focuses on the further development of the sub-system "IR-Zone" of the annealing simulator "Galvasim". The "IR-Zone" is therefore part of the overall system "Galvasim" and includes several other sub-systems as shown in figure 4.

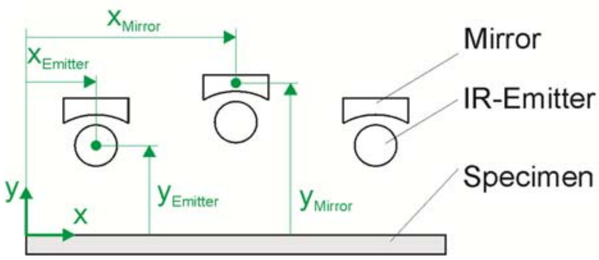

Figure 3. Schematic representation of the architecture of the "IR-Zone" according to [Follmer 2010]

The "IR-Zone" is responsible for the insertion of heat into the specimen using certain IR-Emitters. The goal of the project was to improve the homogeneity of the temperature distribution on the specimen surface. Therefore it was necessary to analyse the existing "IR-Zones" and to identify the main elements, which are shown in figure 3 and their relations. Based on this knowledge and on a literature research, different conceptual considerations were made to improve the homogeneity of the specimen temperature. Some improvements regard the structure of the heating zone (number of IR-Emitters, relay of thyristors etc.), others deal with modifications of the actual geometry (geometrical arrangement of emitters and mirrors etc.). Furthermore, potential improvements may be achieved by variations of the used components such as emitters and mirrors, e.g., in terms of type or shape, as well as by adjustments of the parameters of the control algorithm.

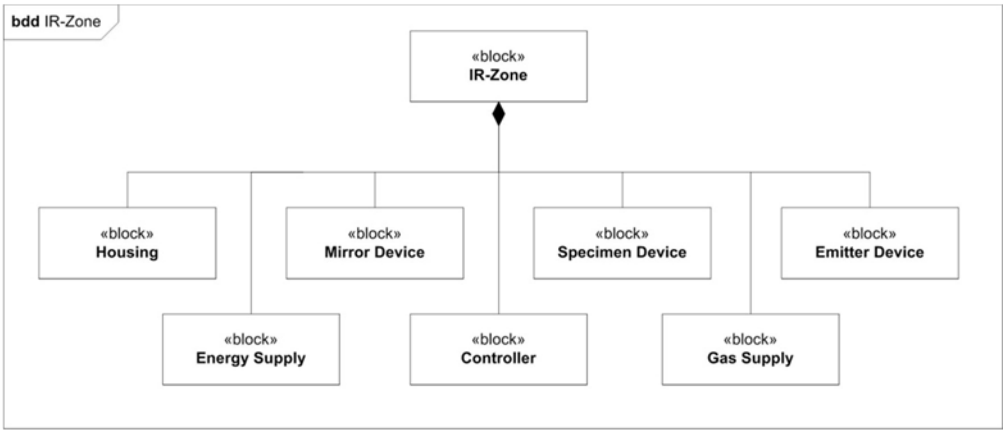

Figure 4. Architecture of the sub-model "IR-Zone"

Figure 4 shows a possible depiction of typical sub-systems of the "IR-Zone" according to [OMG 2010]. In the following only the sub-system "Emitter Device" is considered in more detail, that means all other sub-systems have been neglected for simplification. By way of illustration figure 5 shows the elements of the sub-model "Emitter Device".

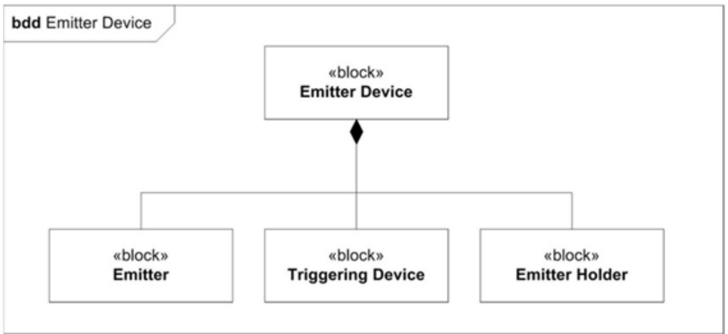

Figure 5. Architecture of the sub-model "Emitter Device"

5. Application of the MSM-Approach

The application of the MSM-Approach for a Bottom-Up- as well as a Top-Down-Modelling and the related MSM-specific working steps are discussed in this section. According to Figure 6 the necessary steps in case of a Bottom-Up-Modelling are:

- Create relevance criteria for superordinate models
- Analyze relations
- Select and allocate provided properties.

Whereas the steps for a Top-Down-Modelling are listed in the following:

- Create relevance criteria for sub-models
- Analyze relations

- Select and allocate required properties.

The MSM-specific working steps are discussed in respect of:

- “Galvasim” as overall-model
- “IR-Zone” as sub-model of “Galvasim” and
- “Emitter Device” as sub-model of “IR-Zone”.

Figure 6 shows a schematic depiction of the relevant sub-models of the MSM, especially the sub-model “IR-Zone” which is the starting point of this development task.

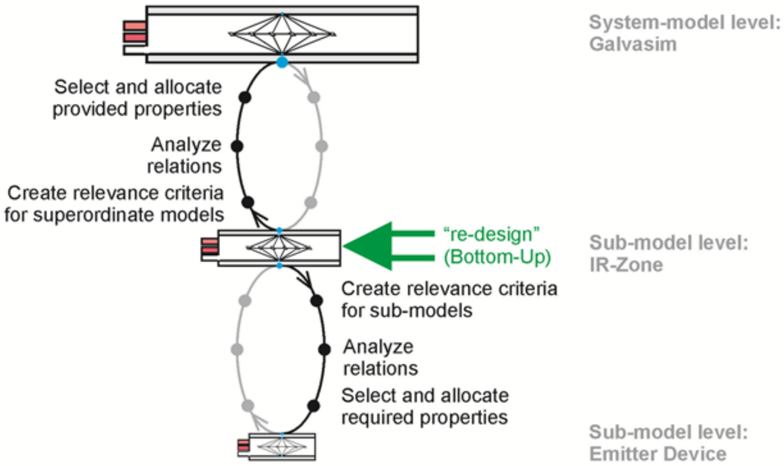

Figure 6. MSM-specific working steps for Bottom-Up- as well as Top-Down-Modelling

5.1 Bottom-Up-Approach

This section discusses the MSM-specific working steps for a Bottom-Up-Modelling-Approach according to figure 6. In this case the focus is on the sub-model “IR-Zone”, as well as on the overall-model “Galvasim” (in that case the superordinate model on the system-model level).

5.1.1 Create relevance criteria for superordinate models

According to [Follmer et al. 2011] relevance criteria have to be defined to determine those model-elements that should be included into the MSM. 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. Not all model-elements are of the same significance to the MSM and an inclusion of each model-element into the MSM would lead to an information overflow. Therefore it is necessary to specify clear criteria for those model-elements and sub-models which should be included into the MSM. As a rule it could be distinguished between general and system-related relevance criteria. In the following only some general relevance criteria are discussed, as shown in Table 1.

Table 1. General relevance criteria

	Models of system-elements which should be considered in the MSM due to their
GP1	relevance for the understanding of the overall system
GP2	relevance for the behavior of the overall system
GP3	relevance for the architecture of the overall system
GP4	interdisciplinary (“global”) relevance

The general relevance criteria are used to identify those model-elements of the “IR-Zone” which are also important for the superordinate model i.e., for the overall-model “Galvasim”. Table 2 shows several system-elements of the “IR-Zone” that have to be considered in the MSM due to valid relevance criteria (shown in the right column). For example the “Housing” of the “IR-Zone” is important for the overall system because of its influences on the structure (architecture) of the overall system “Galvasim”. The chosen system-elements of the “IR-Zone” have to be modelled with appropriate model-elements in the MSM.

Table 2. Relevance criteria for the superordinate model “Galvasim”

System-elements of the “IR-Zone”	relevance criteria
Housing	GP3
Mirror Device	GP1, GP2, GP3
Specimen Device	GP2, GP3, GP4
Emitter Device	GP1, GP2, GP3, GP4
Energy Supply	GP3, GP4
Controller	GP1, GP2, GP3, GP4
Gas Supply	GP3, GP4

5.1.2 Analyze relations

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. Modelling these relations should contribute to a better understanding of the system and should allow for a comprehensive analysis of its internal and external relations. External relations describe the relation between the system and its environment, whereas internal relations characterize system-inherent relations (see also [Follmer et al. 2011]).

Table 3 shows a selection of relations between model-elements of the superordinate model “Galvasim” and the “IR-Zone” which could spread over several views of the MSM.

Table 3. Possible relations between the sub-models “IR-Zone” and “Galvasim”

			”Galvasim”							
			Requirements				Architecture			Functions
			Costs	Space	Temperature homogeneity	Infrastructure for gas	Geometry overall system	Measuring and sensor technology	Gas supply	Control software
Properties provided by ”IR-Zone”	Architecture	Required space		X			X	X		
		Required amount of emitter	X	X	X		X			
		Required amount of mirrors	X	X	X		X			
	Requirements	Required temperature homogeneity			X					
		Required performance	X	X			X			
		Required input signals						X		X
		Required amount of gas				X			X	

According to Table 3 the modelled relations exist between selected model-elements of the views “Requirements” and “Architecture” on the system-model level and the views “Requirements”, “Architecture” and “Functions” on the sub-model level. For example the required space of the “IR-Zone” is related to the views “Requirements” as well as “Architecture” of the overall system “Galvasim” and the required input signals are related to the functions of the control software.

5.1.3 Select and allocate provided properties

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. In accordance to the design process, the allocation process of properties is iterative as well (see also [Follmer et al. 2011]). In general properties have to be classified in the following two groups: (i) provided as well as (ii) required properties. Properties that are offered by a certain model are called provided properties, whereas required properties should be fulfilled by specific models.
In case of the Bottom-Up-Approach the properties provided by the sub-model "IR-Zone" and with relevance for the overall-model "Galvasim" have to be identified. Table 4 shows an excerpt of those properties and the associated model-elements. Thereby, these properties are determined and specified in the sub-model "IR-Zone" and have to be allocated to the overall-model "Galvasim". The required space of the housing is one example for a certain property of the "IR-Zone" that is relevant for the superordinate model "Galvasim".

Table 4. Select and allocate provided properties

Model-elements of the "IR-Zone"	Properties provided by "IR-Zone" that are relevant for "Galvasim"
Housing	Required space
Mirror Device	Required amount of mirrors
Specimen Device	Required temperature homogeneity
Emitter Device	Required amount of emitter
Energy Supply	Required performance
Controller	Required input signals
Gas Supply	Required amount of gas

5.2 Top-Down-Approach

This section discusses the MSM-specific working steps for a Top-Down-Modelling-Approach according to figure 6. Here the focus is on the sub-model "IR-Zone" as well as on the sub-model "Emitter Device".

5.2.1 Create relevance criteria for sub-models

Again in the following only some general relevance criteria, as shown in Table 1, are discussed. The criteria are used to identify those system-elements of the sub-model "IR-Zone" that are important for the sub-model "Emitter Device". Table 5 shows several system-elements and related relevance criteria. For instance the element "Emitter" is one of the system-elements of the "IR-Zone" that is important for the sub-model "Emitter Device" due to its influence on e.g., the structure as well as the behaviour of the sub-model "IR-Zone".

Table 5. Relevance criteria for sub-models

System-elements of the "Emitter Device"	relevance criteria
Emitter	GP1, GP2, GP3, GP4
Triggering Device	GP1, GP2, GP4
Emitter Holder	GP3

5.2.2 Analyze relations

In Table 6 several relations between the sub-model "Emitter Device" and the "IR-Zone" are mentioned. Again these relations could spread over several views of the MSM. In this application example the required type of emitters of the sub-model "IR-Zone" (view: "Architecture") is related to the views "Requirements" and "Architecture" of the sub-model "Emitter Device".

Table 6. Possible relations between the sub-models “IR-Zone” and “Emitter Device”

			“Emitter Device”							
			Requirements				Architecture			Functions
			Costs	Space	Temperature homogeneity	Infrastructure for gas	Geometry overall system	Measuring and sensor technology	Gas supply	Control software
Properties required for the “IR-Zone”	Architecture	Required type of emitter	X	X	X		X			
		Required amount of emitter	X	X	X		X			
		Required type of emitter holder	X	X	X		X			
		Required amount of emitter holder	X	X	X		X			
		Required Triggering								X

5.2.3 Select and allocate required properties

In case of the Top-Down-Approach the properties provided by the sub-model “IR-Zone” and with relevance for the sub-system “Emitter Device” have to be identified. Table 7 shows an excerpt of those properties as well as the associated model-elements and points out that the required type of emitters is one of those properties of the sub-model “Emitter-Device” which is provided by the “IR-Zone” and relevant for the subordinate sub-model “Emitter Device”.

Table 7. Select and allocate required properties

Model-elements of “Emitter Device”	Properties provided by “IR-Zone” that are required for “Emitter Device”
Emitter	Required type of emitters
Triggering Device	Required input signals
Emitter Holder	Required amount of emitter

6. Conclusion

The 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 was already mentioned in [Follmer 2011]. This paper focuses on the application of the MSM-Approach for the development of an industrial annealing simulator (see [Follmer et al. 2010]) and attempted to test its usability.

The MSM-Approach supports the “Systems-View” respectively “Systems-Thinking” of the involved design engineers during the development process. It enables also the identification of the main model-elements and parameters as well as the illustration of the main relations in the system. Different views of the MSM support the modelling of different aspects such as requirements, functions, architecture etc. and allows for a more comprehensive, holistic representation of the system under consideration. Furthermore, the various views should be used to model relations between e.g., functions and architecture (structure of the system). One of the key elements of the MSM-Approach is the support of system-level simulations in the early design phases. These simulations should allow e.g., the simulation of requirements, functions, principle solutions etc. and should also enable the simulation of the relationships among them. For instance the simulation of requirements should provide information regarding their structure and their relations to chosen principle solutions. The MSM-Approach

includes specific working steps for Top-Down- (typically for synthesis tasks) as well as Bottom-Up-Modelling (typically for analysis tasks).
One of the next steps would be the application of the approach during another development project in cooperation with an industrial partner. This will provide the opportunity to gather more practical experience and allows for the improvement of the approach itself. For example the modelling of relations could be extended in order to make concrete statements of the kind of relations. Also further views of the MSM could be created that enable a broader range of system-level simulations. Furthermore, an integrated software support of the MSM-approach is currently not available and the corresponding requirements for such a computer-aided framework has yet to be defined.

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