ICED13
**INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13**
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

# POTENTIALS FOR REALISING A CONSISTENT TRANSITION BETWEEN FUNCTIONAL MODELLING WITH THE IFM FRAMEWORK AND EARLY SYSTEM SIMULATION

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## ABSTRACT

Conceptual design is considered one of the most demanding design tasks requiring a joint effort of the involved designers, particularly in interdisciplinary design. Sound decision-making across disciplines on alternative solution concepts may be considerably facilitated through early system simulation. A consistent transition of the available information in functional modelling to early system simulation may thus support designers in this task. The IFM framework intends to support cross-disciplinary collaboration of involved designers by providing an integrated functional modelling approach. In the paper it is analysed in how far a consistent transition from the IFM framework to established modelling techniques for simulation may be realised. The paper compares the information required for early system simulation in an interdisciplinary design context to the specific information conveyed in the different views of the IFM framework. The analysis identifies specific potentials and barriers for a consistent transition between them. Finally, the implications of the derived insights are discussed.

*Keywords: function modelling, conceptual design, integrated system development, early system simulation*

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# 1 INTRODUCTION

Conceptual design of technical systems contains the essential transition from a problem to alternative solution concepts. Herein, “technical system” encompasses technical products as well as product/service systems (PSS). Conceptual design is considered to be among the most demanding design tasks and requires a joint effort of involved designers (Blessing, 1997, Chakravarthy et al., 2001). Particularly in an interdisciplinary design context, the success of such collaborative work depends on the ability of designers to share concepts and ideas (Buur and Andreasen, 1989) and to establish a shared understanding of the system under development – including its requirements and expected functionalities – across involved disciplines (Kleinsmann, 2008, Alink et al., 2010).

From a modelling point of view, conceptual design across different disciplines essentially comprises requirements specification, function modelling, and models representing the potential solution concept (Eisenbart et al., 2011). Function modelling is proposed as a means to facilitate conceptual system design. A function model is a first, abstract representation of the system under development and, because of its use in different disciplines, is expected to support the establishment of the required shared understanding (Stone and Wood, 2000; Erden et al., 2008). However, divergent meanings of function and a large variety of alternative function models exist (Vermaas, 2013) and seem competing when designers collaborate (Müller et al., 2007). Recently, a new approach has been proposed to address this issue: the Integrated Function Modelling (IFM) framework (Eisenbart et al. 2013a). The IFM framework is explicitly intended to support designers in determining and specifying solutions to a given problem and results in an initial system structure of a respective solution concept.

A design task is widely regarded to be an “ill-structured problem”, as often neither problem nor desired solution are sufficiently defined at the beginning of a project (Poon and Maher, 1997). Conceptual design thus cannot easily move from a problem to a solution and is typically characterised by *co-evolution*: a stepwise increase of information about the addressed problem parallel to the developed solution. It is an iterative process (Poon and Maher, 1997; Chakravarthy et al., 2001, Braha and Reich, 2003) as in exploring the potential solution(s) to a given problem, certain features or constraints of that potential solution may require redefinition of the problem.

In an interdisciplinary development project, the solution space is particularly large. Early system simulation may support the process of determining and selecting suitable solution concepts, as it offers quick and impartial means for their comparison and validation with respect to function and requirements fulfilment (Paredis et al., 2001). A consistent transition between function modelling and early system simulation could support the iterative synthesis and analysis steps occurring while reasoning towards a potential solution, as mentioned above. That includes verification of consistency across different models regarding the information they address, e.g. as part of change management. It could further reduce time and effort spent for modelling as well as for gathering and managing the required information.

In this particular area first promising attempts have been proposed. Prominent examples are e.g. the “Connection Modeller” (Stark et al., 2010), the “RFLP approach” (Requirements, Functional, Logical and Physical Design) in CATIA Systems or Gausemeier et al.’s approach implemented in the “Mechatronic Modeller” (Gausemeier et al., 2009). Compared to the function models inherent in these approaches, the IFM framework covers a broader amount of function modelling perspectives. These broader capabilities may support a comprehensive analysis of the system under development during interdisciplinary conceptual design using early system simulation.

The presented research aims to answer the question, in how far a consistent transition from function modelling to early system simulation may be realised in an interdisciplinary context, using the IFM framework. The presented research is guided by the question: *What are the specific potentials and barriers for a consistent transition from function modelling using the IFM framework to early system simulation?*

Initially, the IFM framework as well as established tools and modelling techniques for early system simulation are described in the following sections. Then, the specific information required for implementation and execution of the discussed modelling techniques and simulation tools is compared to the particular information conveyed in the IFM framework (see section 4). Finally, the implications of the derived insights are discussed in section 5. The presented research is based on previous work on the IFM framework and research into process support for simulation-based design conducted in the involved research groups.

# 2 THE IFM FRAMEWORK

The IFM framework proposed by Eisenbart et al. (2013a) intends to provide designers with an integrated approach for modelling system functionality. Rather than linking individual existing function models from different disciplines, integration is facilitated through linking the specific contents and information which are prominently addressed within function models from different disciplines (see Erden et al, 2008; Eisenbart et al. 2012, 2013b for a comprehensive review and comparison of function models across disciplines). The framework consists of associated views. A central view (*process flow view*) represents the flow of transformation processes, which is central to function modelling across disciplines (Eisenbart et al., 2013b). The remaining views are linked to this central view and comprise of matrices, which represent information about the different entities (see Table 1) in the framework and/or their interdependencies.

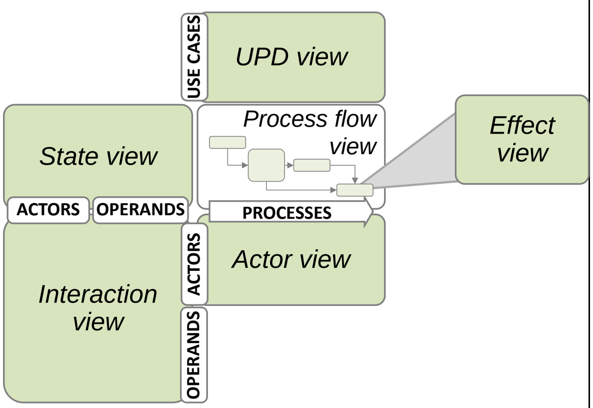
*Table 1: Different entities in the IFM framework*

| Entities | Description |
|---|---|
| Use Case | Different cases of applying the technical system. This is typically associated to the interaction of actors with the technical system under development, which may require subsequent transformation processes to take place. |
| Transfor-mation process | Processes executed by actors, which (from the designers' perspective) are part of the technical system under consideration, in order to change the state of actors or of operands. *Technical* processes are transformation processes related to technical subsystems; human *processes* are related to stakeholders (thus, including service activities). |
| Interaction processes | Representation of interaction processes of actors, which (from the designers' perspective) are *not* part of a system, with actors, which *are* part of the system under consideration. |
| Effects | Representation of the required physiochemical effects, which have to be provided by actors, in order to enable or support transformation process(es) in changing one state into another state. |
| States | Representation of the states of actors or of operands before (input) and after (output) a transformation process. |
| Operands | Operands are typically specifications of energy, material, and information. |
| Technical subsystem | Technical subsystems encompass technical systems (i.e. technical artefacts and associates services), which are part of the technical system under consideration. They can be composed of more technical subsystems. |
| Stakeholder | Stakeholder comprises (groups of) animate beings affected by or affecting the technical system under consideration (including related services). |
| Environment | Environment includes all active and passive parts of nature in general surrounding the system under development. |

## 2.1 Associated views on the functions of a technical system

The views in the IFM framework are modular, as individual views may be added or omitted, depending on the specific needs of the designers. Individual views are briefly described Table 2. The adjacent placement (see illustration in Table 2) supports the parallel development of associated views and allows verification of their consistency.

*Table 2: Associated views in the IFM framework*

| | |
|---|---|
| The *Process flow view* qualitatively visualises the flow of sequential or parallel (interaction and/or transformation) processes related to one specific use case. Processes may be modelled associated to time or – in combination with the *state view* – related to flow of operands. The process blocks are spread horizontally from left to right, so as to enable a direct link to the *actor view*. Quantities may be included in the individual process blocks, in order to specify the processes further. |   |
| The *Effect view* represents the effects, which enable individual transformation processes and are provided by actors. For each process block in the *process flow view*, a separate *effect view* may be created. Individual transformation processes may thus be exchanged with (a set of) general effects. | |
| The *Use case/process dependency (UPD) view* indicates the involvement of individual processes within different use cases. Dependencies between processes, which hinder their parallel or sequential execution, could affect the operability of use cases in which these processes are involved. The *UPD view* is intended to support analysis of this kind of dependencies. | |
| The *Actor view* indicates the involvement of specific actors in the realisation of transformation processes. In the respective matrix, concrete information about the particular involvement (e.g. as either "affecting" or "being affected" by a process) may be specified. | |
| The *States view* represents the specific states of operands and actors as well as their changes within individual processes. It consists of the *actor state matrix* and the *operand state matrix*. | |
| The *interaction view* consists of a Design-Structure Matrix. It depicts the specific bilateral impacts between actors and operands, as well as among each other, in the realisation of processes. Thus, this view essentially results in an initial system structure or interface matrix, respectively. | |

## 2.2 Application

The framework – through its modular character – may be applied in various ways. That includes different entry points and alternative sequences of modelling steps. Eisenbart et al. (2013c) show how the IFM framework can be adapted, in order for it to be used within systematic design approaches from different disciplines. In Table 3 different modelling activities for the application of the IFM framework are presented, which can be iteratively performed.

*Table 3: Potential modelling activities in the application of the IFM framework*

| | |
|---|---|
| ***Use Case definition*** | …includes the consolidation of the different use cases that the system under development is expected to support in the different phases of its life-cycle. The use cases are represented in the respective column in the *UPD view*. |
| ***Process flow modelling*** | …involves modelling separate flows of required processes related to each use case. A multitude of alternative process flows may fulfil a use case. While modelling the process flows, the involvement of individual processes in multiple use cases needs to be considered. |
| ***Operand state modelling*** | …includes modelling the state changes of involved operands in the operand state matrix (as part of the *state view*) related to the chosen process flows. This may be executed in parallel to process flow modelling. |
| ***Effect modelling*** | …involves modelling the required effects related to the specific process blocks or entire flows, respectively. |
| ***Actor allocation*** | …includes allocation of actors involved in individual processes through the delivered effects. |
| ***Actor state modelling*** | …includes modelling the state changes of allocated actors in the actor state matrix (as part of the *state view*) related to the chosen process flows. |
| ***Interaction specification*** | …involves analysing and detailing the specific interactions (i.e. the bilateral impacts) among actors and among operands, and between actors and operands. |

In an original design project, modelling may start on a high level of abstraction: defining use cases, associated processes etc. On the next level of detail, individual process blocks may then be decomposed into sub-processes. These are enabled by function carriers (actors) such as technical subsystems or stakeholders, including any related service operator etc. Actors are iteratively concretised. Therein, *actor allocation* essentially marks the transition from a problem to solution concepts. As discussed above, this process is essentially characterised by co-evolution: as a potential solution evolves, the required sub- and auxiliary functions will change depending on the specific choice of actors and their interactions in function fulfilment. This will in turn affect the generated views in the IFM framework. Establishing consistent links between the IFM framework and methods for early system simulation may support this iterative progression by providing means for comparison of alternative solution concepts, as described above.

# 3 EARLY SYSTEM SIMULATION

Simulation has become an indispensable part in product development today and is more and more substituting physical prototypes (Aberdeen, 2006). The aim of early system simulation is not a detailed and highly accurate analysis of the system but rather an unbiased means for comparison of different concepts (Paredis et al., 2001). The foundation of simulation is a computable model (VDI, 2000), which typically represents both behaviour and structure of the simulated system (INCOSE, 2010). Succeeding function modelling, a system structure or architecture may be generated for a given concept (Eisenbart et al., 2011). These address the respectively involved entities (i.e. modules, components or general function carriers, respectively) and their connections. The application of the IFM framework may result in the generation of such an initial system structure, as described above. However, the available information about the entities of a technical system under development may still be rather abstract (particularly in an original design project). Thus, modelling and simulating behaviour can primarily be performed on system level. Detailed simulation of inherent entities is only feasible in later stages, as more information about the individual design parameters becomes available.

In general, simulation of system behaviour is based on mathematical descriptions. These are capable of describing systems uniformly and independent from engineering disciplines (Kümmel et al., 1998). Besides purely mathematical modelling, further modelling paradigms have been developed for the purpose of (multidisciplinary) system description. They can be classified according to Paredis et al. (2001) into graph-based and language-based, multi-domain and single-domain as well as declarative and procedural. In many cases, the mathematical description is included in those paradigms or can be derived from them. Further descriptions and examples of those paradigms are provided in (Rajarishi et al., 2001).

As described in the previous section, the IFM framework addresses the functions of a technical system related to the specific use cases, their inherent transformation and interaction processes as well as the effects enabling them, which are provided by actors – either a technical system or a human. Early system simulation thus needs to address the particular behaviour of these actors, in order to allow evaluation of function and requirements fulfilment. Therein, technical products may themselves be multi-technology artefacts, such as mechatronic systems. Hence, in the next sections an overview of tools and techniques for modelling and simulation of mechatronic systems, human behaviour and process simulation are described and analysed regarding their usability with the IFM framework.

## 3.1 Mechatronic system behaviour simulation

During recent years, for behavioural system-level modelling of interdisciplinary systems – particularly mechatronic systems – two modelling languages have been established: VHDL-AMS and Modelica. Those can be categorised as language-based, multi-domain and declarative. Furthermore they can model both time-continuous and time-discrete behaviour. In the field of mechatronics both types are relevant, e.g. time-continuous behaviour for the mechanical components and time-discrete for the software control mechanisms, respectively. Therein, system models are typically generated by linking individual module blocks from the libraries provided in the respective software tools. In some of these module blocks specific ports are provided, which allow the inclusion of impacts from or to the environment. Furthermore these tools can also be used for purely mathematical modelling of the system behaviour which also allows the creation of own libraries.

A detailed simulation of the system and its components can often not be performed during conceptual design. Especially geometry-based and thus CAD-based simulation – like finite-element analysis or multi-body simulation – can only be applied to a limited extend in early stages, since geometry has not been determined in full detail, yet. The same limitations apply to simulation of circuit diagrams in electronics – e.g. with PSPICE – or ECAD-systems like EPLAN since those require detailed information about the components of the system. Instead, tools addressing system-level behaviour are more suitable. Examples are Modelica-based tools like Dymola, Matlab/Simulink, 20-sim or CAMeL-View. The last two are based on proprietary object-oriented modelling languages.

Apart from the language-based modelling paradigms, there are several graph-based alternatives. Two very common examples are Bond graphs and block diagrams. Matlab/Simulink and 20-sim for example support both. Furthermore there are possibilities to model the system on a more abstract level only based on its states and their transitions. Typically, for this purpose petri net or finite-state machine modelling can be used which a lot of tools exist for, e.g. SM Cube or Netlab. Furthermore, some of the already mentioned tools for modelling and simulation also integrate those modelling techniques, e.g. the Statechart toolbox for Matlab or the StateGraph Library in Modelica. Using such tools, the reaction of the system related to a specific input can be simulated based on the defined states and transitions. A more comprehensive discussion of further modelling paradigms and simulation tools for early mechatronic system simulation is provided in (Dohr and Vielhaber, 2012; Paredis et al., 2001; Rajarishi et al., 2001).

## 3.2 Human behaviour simulation

Simulation of human behaviour associated to or interacting with technical products can be distinguished between physical behaviour – such as e.g. ergonomics – and cognitive aspects. Most CAD-systems include Manikin extensions, i.e. allow the inclusion of human body models. This enables the integration of humans into ergonomic analyses, which mainly focus on geometrical aspects and thus require detailed CAD-models. In contrast, e.g. Krüger et al. (2012) developed a user-centred approach for the early integration of biomechanical analysis into the design process focussing on the optimisation of the human-product interaction. Nevertheless, even though the full details are not needed, this tool requires a basic degree of knowledge about the geometry as well. Regarding the cognitive aspects of stakeholders within the user-product interaction, there are several attempts to model and simulate human cognition. For example Bernard et al. developed an approach for "the representation of plausible human cognition and behaviours within a dynamic, simulated environment" (Bernard et al., 2007). One application is the generation of suitable concepts of operation of technical systems.

## 3.3 General process simulation

In software development, various simulation tools for use case analysis have been proposed. A relatively new approach has been proposed by Hoffmann and Lichter (2010), which is based on petri net modelling. Therein, the step-by-step transitions of system states are modelled and simulated using a specific use case simulation environment. The tool allows separate modelling of individual use cases based on the required transitions and analysis of consistency between state changes. One example of a commercially available tool for such purposes is Rational Rhapsody.

Modelling and simulating processes and their flows is often used in project management, related to e.g. design or manufacturing processes. A rather comprehensive approach is e.g. the Cambridge Advanced Modeller (CAM) (WWW1). CAM essentially is a discrete-event simulation tool providing toolboxes for modelling processes. For process modelling separate flow diagrams are created; therein, specific inputs are assigned to corresponding tasks, which are expected to create certain outputs (i.e. "deliverables"). Individual tasks may be assigned with certain, mostly mathematically described properties. Simulation is performed using Monte-Carlo process simulation.

Table 4 collocates a selection of established software tools, which are mapped onto the respective inherent modelling techniques.

*Table 4: Modelling techniques used in established simulation tools*

| Simulation tools | Modelling technique | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mathe-matical modelling** | **Modelica** | **VHDL-AMS** | **Further object-oriented paradigms** | **Graph-based modelling** | **Finite-state machine/-Petri net** | **Geometry-based modelling** | **Human behaviour modelling** | **General process modelling** |
| **Matlab/Simulink** | X | | | | X | X | | | |
| **Maple** | X | | | | | | | | |
| **Mathematica** | X | | | | | | | | |
| **Dymola, SimulationX…** | (X) | X | | | | X | | | |
| **ANSYS Simplorer, Mentor…** | (X) | | X | | | | | | |
| **CAMeLView** | (X) | | | X | X | | | | |
| **20-sim** | (X) | | | X | X | | | | |
| **Netlab, SM Cube** | | | | | | X | | | |
| **CATIA Systems** | (X) | X | | | | | X | | |
| **CATIA, Creo, NX …** | | | | | | | X | (X) | |
| **Krüger et al.** | | | | | | | | X | |
| **Bernard et al.** | | | | | | | | X | |
| **Rhapsody** | | | | | | X | | | X |
| **Cambridge Adv. Modeller** | | | | | | X | | | X |

## 4 MAPPING THE IFM FRAMEWORK WITH EARLY SYSTEM SIMULATION

In this paper, the consistent transition of information represented in the IFM framework to established modelling techniques for early behavioural system simulation are analysed. Therefore, it is analysed, which specific information is explicitly needed in modelling when using the different discussed tools and techniques. That involves the specific information about the addressed entities and their interdependencies which are compared to the specific information conveyed in the different views of the IFM framework. The comparison aims to identify the specific barriers and enablers for a consistent transition between them. In the following, the individual views are consecutively discussed.

<u>Actor view</u>

The actor view merely illustrates the involvement of different actors within one or more use cases and related transformation processes but does not reveal information about the specific behaviour of the addressed actors. The respective allocation is implicitly performed while modelling the system for simulation. For instance, use case simulation, Modelica, etc. rely on the allocation of the related entities (actors, modules, function carriers etc.). Hence the actor view is not separately discussed.

<u>UPD view</u>

Use case simulation is particularly prominent in software development. Essentially, use cases may be simulated based on the corresponding (interaction) processes and associated system states. Processes may be both technical and/or human processes. In the following, modelling for simulation, related to the *process flow* and *state view* are discussed in more detail. In the reviewed simulation and modelling approaches, states (that includes e.g. pre- and post- conditioning in software development) have not been separately simulated, but always appear related to corresponding transformation processes.

<u>State view and process flow view</u>

Processes and associated states can be jointly simulated based on petri net or finite state machine modelling. Since the state view describes the system states and the process view the transitions between these states, the IFM framework can directly provide the information needed for petri net or finite state modelling. The corresponding tools for that purpose can be taken from Table 4.

Simulation of general processes uses rather abstract, mostly mathematical descriptions of the properties of respective processes (related simulation tools are e.g. Rhapsody, Cambridge advanced modeller etc.). Compared to the IFM framework, the required information may directly be retrieved from the flow of processes (*process flow view*) and the respectively associated actor states (in the *state view*) related to the individual use cases. Beside those possibilities, processes including humans can be more concretely modelled and simulated on both physical and cognitive level, which build the basis of the interaction of stakeholders and the technical product.

Typically the physical aspects are represented by virtual human bodies in CAD-system which require detailed geometry. Hence the use during conceptual design is limited. In case (some) details about the geometry are already known (e.g. in a redesign project), CAD-based physical analyses may nevertheless be feasible. In contrast, the approach of Krüger et al. (2012) does not rely on detailed geometry. Based on their analysis the motion and forces affecting the human body can be used to determine or to specify the requirements of the technical system.

Simulation of cognitive aspects offers huge potential to improve the interaction of the user and the technical system. Particularly decision making of the user and its reaction to the system can be determined. Nevertheless, this particular type of modelling for simulation is not common in product development and hence not consistently integrated. Furthermore, to determine the reaction of the user on the behaviour of the technical system requires detailed information about the system and the user which is typically not available during conceptual design – at least not in original design projects. Thus, further design activities succeeding function modelling are required to provide the missing information. Hence, in these cases, a consistent transition from the IFM framework towards simulation is limited and requires additional steps.

Effect view

It seems physiochemical effects describe system behaviour on such a specific level of abstraction that the transition to simulation is hindered. In the course of the presented research no separate modelling techniques (except for purely mathematical descriptions) for simulation of basic effects have been found. As described in section 2, individual transformation processes may be replaced by (a set of) basic effects in the course of function modelling. This implies that tools for process simulation could potentially be employed or adapted towards addressing basic physiochemical effects. However, the respective models probably would have to be strongly simplified.

Interaction view

The interactions between actors and operands can be either physical – e.g. a mechanical contact or any kind of exchange of energy or material – or non-physical – e.g. an exchange of information. Hence, depending on the various kinds of interactions, there are scenarios for the use of various modelling techniques (see Table 4). The interaction view results in an initial system structure and can build the basis for the behaviour simulation under consideration of specific solution elements. That includes interaction processes of different actors (stakeholder, technical systems and the environment), as well as mutual input and output relations.

The comparison is collocated in Table 5. Together with Table 4, simulation tools can be matched to the individual views of the IFM framework.

*Table 5: Comparison of the IFM framework and established modelling techniques*

| Views in the IFM framework | Modelling technique | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mathe-matical modelling | Modelica | VHDL-AMS | Further object-oriented paradigms | Graph-based modelling | Finite-state machine/ Petri net | Geometry-based modelling | Human behaviour modelling | General process modelling |
| **UPD view** | X | | | | | X | | | X |
| **State View** | X | | | | | X | | | |
| **Process flow view** | X | | | | | X | (X) | X | X |
| **Effect view** | X | | | | | | | | (X) |
| **Interaction view** | X | X | X | X | X | | | X | X |

Object-oriented modelling techniques like e.g. Modelica, typically, explicitly represent the specific topology of the system under development, i.e. the system structure and connections between individual elements. Modelica-based simulation tools typically allow the predefinition of standard system elements or modules (building up the system structure) which are interlinked by predefined ports. Most Modelica environments provide libraries of such elements or modules. This feature is of particular help for concept generation, since it is possible to directly assign physical elements from the library to the individual function carriers. The ports allow the inclusion of impacts (mechanical, electrical, etc.) from and to actors which are not part of the system, including the environment in general. However, the respective module libraries do not provide blocks for the inclusion of humans. Purely mathematical modelling paradigms (used e.g. in Maple, Mathematica etc.) do not make the system structure explicit and do not allow the inclusion of standard module blocks.

# 5 DISCUSSION

The presented research aims to answer the question: *What are the specific potentials and barriers for a consistent transition from function modelling using the IFM framework to early system simulation?*

## 5.1 Potentials for realising of a consistent transition

Particularly regarding states and their transitions, the information required for simulation may directly be retrieved from the *state view* and associated *process flow view*. These are related to specific use cases, which may be retrieved from the *UPD view*. The consistency between individual state transitions may directly be simulated using use case simulation. On an abstract level, the respective processes themselves may be modelled and simulated using general process modelling and related simulation tools, such as e.g. Rhapsody or the Cambridge Advanced Modeller.

Regarding system level behaviour, including mutual impacts between individual module blocks of a technical product, Modelica-based tools may be used for simulation. The respective information about the individual entities and their links may directly be retrieved from the *interaction view*. It seems the allocation of solution elements and their connection, including their mutual impacts via the respective ports, could enable modelling of the system using the IFM framework and its simulation *in parallel*. The specific ports allow the analysis of model consistency, regarding whether all mutual impacts between actors and/or modules have been established and whether additional actors and/or modules may be required. Module block libraries, which specifically focus on the early stages of system development, may further support object-oriented modelling for simulation during conceptual design. Such “early stages” module blocks would essentially have to be simplified with respect to the specific simulation parameters addressed, in order to facilitate their application during conceptual design.

Modelling techniques for abstract process simulation, state transition consistency simulation and system level behaviour simulation, hence, seem directly applicable succeeding function modelling. They may in fact explicitly support the generation of the IFM framework. However, the inclusion of humans and their specific behaviour into simulation of a system under development seems hampered.

## 5.2 Potential barriers for the transition to early system simulation

Particularly CAD-based simulation tools require specific information about the geometry, which may not be available during conceptual design. Further difficulties originate from parameter uncertainty, as discussed above. The specific amount of design activities required to provide the information seems strongly dependent on the specific type of the design project (original or redesign) and the expected level of accuracy of the performed simulation. Modelling techniques for the simulation of biomechanical and cognitive aspects of human interaction with technical products are promising. They could provide means for the early inclusion of human behaviour simulation. However, these specific modelling techniques have not yet been integrated into technical system development. The joint simulation of human behaviour and technical product behaviour is thus hampered.

Simulation results generated in different tools need to be comprehensively fed back into the different views of the IFM framework, particularly as part of change management. The missing link between the respective simulation tools may thus present an additional barrier for the consistent use of early system simulation associated to function modelling.

Future research needs to address, whether the IFM framework may potentially serve as a means for linking the reviewed modelling techniques and related simulation tools. Based on the IFM framework alternative modelling techniques may be used to feed the addressed information into corresponding simulation tools. Through continuously feeding back generated simulation results into the IFM framework, it thus could potentially serve as a shared source of information for modelling and simulation in subsequent steps.

Another example, where the direct link to simulation is not provided yet, is modelling the required effects enabling individual transformation processes and related state transitions. As discussed in the previous section, it might be possible to expand general process modelling and simulation onto the effects. However, eventual adaption of the respective simulation tools or further modelling and/or design steps may be required, in order to support and enable such a simulation of physiochemical effects. Given that effects, so far, cannot be simulated, the question remains, whether simulation on the level of effects is indeed needed by practical designers during conceptual design. Depending on the specific design context and intended purpose of simulation, it may be more feasible during embodiment design or other design stages. The specific benefit effect simulation could offer to designers needs to be addressed and evaluated in future research.

The benefit and feasibility of early system simulation to individual designers may generally strongly depend on the specific purpose, design context and effort associated to modelling and simulating. Particularly cognitive aspects of human behaviour may only be feasible in specific design contexts. Required time and cost for modelling and simulating need to be evaluated against e.g. the generation of physical prototypes. It is expected to be strongly dependent on the accuracy of simulation results required for sound decision-making.

## 6 CONCLUSION

The presented research shows that the information addressed in the different views of the IFM framework may be fed into established modelling techniques for simulation, thus enabling the consistent transition to early system simulation in principle. Therein, the specific level of integration between the IFM framework and early system simulation strongly depends on the respective modelling technique and simulation tool applied. It seems the required information for some simulation tools may directly be retrieved from the IFM framework, even providing the potential for integrated generation of a function model with the IFM framework and simulation of the respective aspects. For other modelling techniques and related simulation tools, additional design steps are required, before they can be applied.

One particular barrier for a comprehensive simulation of alternative solution concepts is the missing integration of the different modelling techniques and simulation tools, which may further hamper the consistent feedback of simulation results into the IFM framework and, finally, the requirements specification, if required.

Future research needs to address in how far the IFM framework may serve as a shared information basis for early system simulation. That includes the implementation of the transition between the IFM framework and the respective modelling techniques for simulation. Furthermore, the practical application of early system simulation based on the IFM framework needs to be analysed, in order to derive the specific needs of designers in practice. That includes the specific process-related support enabling individual designers to perform eventually required (additional) design and modelling steps. Furthermore, support may be needed to facilitate extraction of required information from the IFM framework and its transition into the respective simulation tools, as well as the transition of simulation results into the IFM framework. This is essential, in order to facilitate mutual consistency between function modelling with the IFM framework and early system simulation.

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