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# A Shared Basis for Functional Modelling

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**Abstract**
The presented research aims at contributing to a better understanding of the diverse functional modelling approaches proposed across disciplines, often involving more than one function model. The paper presents a review of 41 systematic design approaches from different disciplines, analysing what is addressed by functional modelling at which point in the proposed development process, i.e. in which sequence, if any. The analysis aims at deriving potential commonalities across disciplines, which could support the development of an integrative functional modelling approach. Finally, the results of the analysis are discussed, concluding that while there seems to be no shared sequence in functional modelling across disciplines, a common base can be derived, with regard to what is prominently addressed by functional modelling in the different disciplines.

***Keywords: functional modelling, cross-disciplinary, literature study***

## Introduction

Technical system development[1] in industry increasingly requires the integration of different technologies, necessitating a closer collaboration of experts from different disciplines, particularly within early concept development. This requires the establishment of a shared understanding among the involved designers, regarding the design problem to be addressed and the technical system under development, so as to support joint decision-making in early concept development. Integrative functional modelling seems beneficial to foster the establishment of such a shared understanding. Ahmed and Wallace [1] conducted interviews with designers in industry and found that different solution concepts are often transferred between different development projects through expressing them in terms of their function. Erden et al. explicitly argue that "the barriers between […] disciplines can be overcome by using (a) common language of functionality" ([2] p. 147).

Such a common language for describing functions seems widely missing, potentially hindering communication of functions and function models across disciplines [3–5]. Various authors suggest that this is due to the largely diverse ways of understanding and representing function, which are competing when designers of different disciplines collaborate [2, 6, 7]. Different function models can be found across, but also within the different disciplines, and individual systematic design approaches often propose multiple function models, either as alternatives or in sequence [8].

As a first step towards the integration of functional modelling, the presented research aims at deriving a deeper understanding of functional modelling approaches proposed in literature from different disciplines. Using the results of an analysis of function models by Eisenbart et al. [8], the conducted research considers the proposed function models with regard to what is addressed and – if multiple function models are proposed – in which sequence.

[1] The term "technical system" encompasses technical products and Product/Service Systems (PSS) in this paper.

## Diversity related to function

### Ambiguous understanding of function

One solution discussed by researchers to avoid differing understandings of function, is to propose one common understanding. According to Vermaas [3] some researchers aim at deriving this common understanding of function from comparing different functional representations (e.g. [2]), while others seek – respectively impose – one distinct understanding, so as to bridge the existing diversity (e.g. [9, 10]). However, both approaches seem to have various shortcomings [1, 2] and different understandings of functions – at least implicitly – seem to persist [11].

Vermaas [3] and Carrara et al. [5] conclude that ambiguity related to the understanding of function is inherent in design practice and that accepting it enables adapting the understanding of function to a variety of design approaches and contexts. The precise understanding of function thus becomes dependent "on the aim for which it is employed" [11].

### Functional modelling perspectives

The aim-dependent understanding of function discussed by Vermaas [11] seems reflected in the diversity of what different functional modelling approaches address. Eisenbart et al. [8] systematically analysed 70 function models proposed in mechanical engineering, electrical engineering, software development, mechatronic system development, service development and PSS design. The particular content addressed by individual function models is linked to different functional modelling perspectives. Eisenbart et al. identified seven different perspectives, which are described in Table 1 taking the example of a welding robot using welding tongs.

Table 1: Functional modelling perspectives after [8]

| | |
|---|---|
| ***states*** | Representation of the states a system can be in, or of the states of operands before (input) and after (output) a transformation process. Operands are typically specifications of energy, material, and information. |
| | The welding robot changes the state of metal sheets (operands) from "loose" to "welded", while the state of the welding tongs (system) changes from "open" to "closed". |
| | *Typical example*: process structure after [12]. |
| ***effects*** | Representation of the required physiochemical effects, which have to be provided to enable, respectively support, the transformation process(es) changing one state into another state. |
| | Within the welding robot electrical energy needs to be transformed into rotary movement to close the welding tongs. |
| | *Typical example*: function structures after e.g. [13]. |
| ***trans-formation processes*** | Representation of the processes executed by stakeholders or technical systems, which (from the designers' perspective) are part of the technical system under development in order to change the state of the system or of operands. *Technical processes* are transformation processes related to technical systems, while *human processes* are related to stakeholders (thus, including service activities). |
| | The welding robot needs to "move into position" and "close the welding tongs" in order to connect the metal sheets. Transformation processes require various physiochemical effects to be provided by technical systems or stakeholders. |
| | *Typical example*: technical process structure model after [14]. |
| ***interaction processes*** | Representation of interaction processes of users or of other technical systems, which (from the designers' perspective) are not part of the system, with the technical system under development. |
| | If the robot is sold to a customer, without services associated to it, "exchange electrodes", "type in position information", etc. are regarded as interaction processes with the system. |
| | *Typical example*: service process model after [15]. |
| ***use case*** | Representation of different cases of applying the technical system. This is typically associated to the interaction of stakeholders or another technical system with the technical system under development, which triggers, respectively requires subsequent processes to take place. |
| | A potential use case associated to the welding robot is a user requesting the robot to "display the position of the end effector", which includes several sub-processes (e.g. measuring position, processing data, etc.) within the robot. |
| | *Typical example*: use case schematic (see e.g. [16]). |
| ***technical system allocation*** | Representation of the role of a technical system, which is supposed to perform or enable a sub-set of required *effects* or *processes*, either within the technical system under development or by interacting with it. |
| | Changing the electrodes of the welding tongs e.g. may be executed by another robot. |
| | *Typical example*: technical process structure model after [14]. |
| ***stakeholder allocation*** | Representation of the roles of different stakeholders, which may be users benefitting from a system or operators contributing to the system, e.g. through executing required processes or providing resources, etc. |
| | In the PSS context, a service associated to the welding robot, may involve stakeholders like operators to change the electrodes or companies to deliver new electrodes, etc. |
| | *Typical example*: SADT modelling e.g. after [17]. |

Individual function models frequently address multiple functional modelling perspectives and Eisenbart et al. [8] suggest that several functional modelling perspectives are more prominent than others within the different disciplines. Furthermore, they found many of the function models proposed within systematic design approaches to be building upon each other, which implies a stepwise approach i.e. a sequence for modelling and moving from one functional modelling perspective to another.

**Towards an analysis of functional modelling approaches**

In case specific prominent functional modelling perspectives and a shared sequence for addressing individual functional modelling perspectives can be found across the reviewed disciplines, these insights may substantially support the development of an integrative functional modelling approach. Research thus needs to analyse, what is prominently addressed by functional modelling in the different disciplines, i.e. which functional modelling perspectives are inherent in the proposed function models. In addition, if multiple function models are proposed in systematic design approaches, it is necessary to understand how functional modelling is proposed to move from one particular (set of) functional modelling perspective(s) to another. This research is guided by the research questions:

- *Which functional modelling perspectives are addressed within the different disciplines and which are most prominent*?
- *What kind of sequence (if any) is suggested for considering the different functional modelling perspectives in the different disciplines and is there a shared one across*?

## Analysing functional modelling approaches

**Research approach and coding scheme**

The analysis focuses on systematic design approaches that explicitly propose functional modelling. They originate from mechanical engineering design, electrical engineering design, software development, service development, mechatronic system development and PSS design. The proposed function models are classified according to the function modelling perspectives they address. If multiple perspectives are addressed, the most prominent one is indicated. Note is taken if the approach proposes alternative or additional functional modelling perspective(s) or if individual modelling perspectives are implicitly addressed. In total 41 approaches were analysed.

**Functional modelling approaches in different disciplines**

Table 2 shows the function models, their succession and the modelling perspectives they address for a few examples of the reviewed systematic design approaches. The column "proposed models" additionally shows the proposed models directly preceding and succeeding the proposed function model(s), so as to indicate the context in which function modelling is proposed within the respective design approaches. In the following, the findings are presented based on a few examples of design approaches from each reviewed discipline.

*Mechanical engineering design*

In mechanical engineering design, functional modelling proposed by Pahl et al. [13] has been adapted and widely taken up by various authors. Pahl et al. focus on the effects, which are necessary to transform an initial state into a desired state within a technical system. Frequently, a set of individual effects is encompassed as a transformation process.

Approaches which are considerably different from Pahl et al. are proposed e.g. by Hubka [14] and Tjalve [18]. Hubka and Tjalve (and related approaches) – in a slightly different sequence – propose modelling the required transformation processes to change an initial into a final

Table 2: Examples of functional modelling approaches[2]

| | |
|---|---|
| *empty* | does not apply; not included |
| **bold** | driving aspect |
| *brackets* | functional modelling perspective/function model *may* be included |
| "o" | implicitly included in function model |
| * | originates from software development but is used in PSS design |
| ** | discrete, continuous, and signal event flows |
| *** | includes allocation to involved disciplines |

| | Author | Proposed models | | | perspectives: States | Effects | Transformation processes | Interaction processes | Use case | Technical system allocation | Stakeholder allocation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mechanical engineering design | Pahl et al. [13] | preceding | requirements list, overall problem formulation | | **comment:** *Functional decomposition in a tree model is not compulsory* | | | | | | |
| | | function | (function tree) | | x | x | | | | | |
| | | function | function structure | | x | **x** | (x) | | | | |
| | | succeeding | morphological matrix | | | | | | | | |
| | Hubka [14] | preceding | requirements list | | | | | | | | |
| | | function | technical process structure | | x | | **x** | o | | x | x |
| | | function | function structure | | (x) | **x** | x | o | | x | x |
| | | succeeding | Organ structure, morphological matrix | | | | | | | | |
| | Tjalve [18] | preceding | requirements list | | | | | | | | |
| | | function | alternative (manual) process flow models | | x | | **x** | o | | | |
| | | function | man/machine separation list | | | | | (x) | | **(x)** | **(x)** |
| | | function | process/function chart | | x | x | **x** | x | | x | x |
| | | function | function means tree | | | | **x** | | | **x** | |
| | | succeeding | basic structure | | | | | | | | |
| Electrical engineering | Dewey (EDA) [20] | preceding | performance and constraints specification | | **comment:** *Different function models can be used alternatively, no succession proposed* | | | | | | |
| | | function | state diagrams | *in parallel/ alternatively* | **x** | | | | (x) | | |
| | | function | function table | *in parallel/ alternatively* | | **x** | | o | | | |
| | | function | petri nets | *in parallel/ alternatively* | **x** | | | | | | |
| | | function | VHDL description | *in parallel/ alternatively* | x | | **x** | | o | | |
| | | succeeding | circuit diagram | | | | | | | | |
| Software development | Kroll and Kruchten (RUP) [16] | preceding | problem statement | | | | | | | | |
| | | preceding | feature list | | | | **x** | x | o | | |
| | | function | Use case schematics | | | | **x** | x | **x** | x | x |
| | | function | Use case description | | | | x | x | x | | x |
| | | function | Sequence diagram | | | | x | x | | | x |
| | | function | Activity/event diagram | | | | x | x | | | x |
| | | solution | initial system structure/architecture | | | | | | | | |
| Service development | Spath and Demuss [23] | preceding | requirements list, initial system structure | | **comment:** *SADT and FAST used alternatively, in order to develop the complete blueprint* | | | | | | |
| | | function | Function structure | | x | **x** | o | | | | |
| | | function | FAST | *alternatively* | x | | x | | | **x** | |
| | | function | SADT | *alternatively* | x (after each operation) | | **x** | x | | x | (x) |
| | | function | Blueprint | | o | | **x** | (x) | (x) | x | x |
| | | succeeding | module structure | | | | | | | | |
| Mechatronic system development | Buur [6] | preceding | | | **comment:** *State transitions, purpose fcts., transformation fcts. modelled in parallel* | | | | | | |
| | | function | state transition model | *iteratively* | x | | | | **x** | | |
| | | function | (active) purpose fcts. model | *iteratively* | | | **x** | | x | | |
| | | function | transformation fcts. model | *iteratively* | | **x** | | | x | | |
| | | solution | *expanded* function means tree | | | **x** | **x** | | | x | |
| | Salminen and Verho [26] | preceding | requirements list | | **comment:** *Presented succession is not **strictly** proposed in the referenced publications* | | | | | | |
| | | function | function tree | | | | x | | x | | |
| | | function | events list | | | | **x** | x | | x | x |
| | | function | context and flow diagram | | x | | x | x | | **x** | **x** |
| | | function | state transition diagram | | **x** | | x | | (x) | | |
| | | succeeding | principle solution table (after Koller) | | | | | | | | |
| PSS design | Maussang-Detaille [17] | preceding | customer needs | | | | | | | | |
| | | function | inter-actor network | | | | | | | x | x |
| | | function | function list (decomposition) | | | | **x** | | | | |
| | | function | FAST (general) | *alternatively* | | | **x** | (x) | | **x** | |
| | | function | SADT (use activity) | *alternatively* | x (after each operation) | | **x** | x | | x | (x) |
| | | function / succeeding | FAST (function and solution allocation) | | | | **x** | (x) | | **x** | |
| | | function / succeeding | Functional block diagram (FBD) (internal modelling of system with principal elements) | | | | x | x | | x | **x** |
| | | succeeding | SADT - activities within the system | | x (after each operation) | | **x** | x | | x | (x) |
| | | succeeding | FBD (detailed system modelling) | | | | x | x | | x | **x** |
| | Sakao and Shimomura [27] | preceding | initial scenario model and goal setting | | **x** | | | | | | x |
| | | function | flow model | | | | | | | | **x** |
| | | function | scope model | | **x** | | | | | | |
| | | function | scenario model (transition graphs) | | **x** | | | | | | x |
| | | function | chain of actions | | | | **x** | x | | o | o |
| | | function | view model (RSP hierarchy, function tree and realisation structure), modified flow model | | **x** | | **x** | | | | |
| | | succeeding | | | **x** | | **x** | | | x | |

[2] Boxes have been checked, if a specific functional modelling perspective is included in the provided examples of the function models or in the text accompanying them.

state, in order to derive the required effects within the technical systems, enabling these processes. Therein, human operators are also modelled, who either substitute sub-processes (mostly Tjalve) or deal with the system as a whole. Furthermore, additional technical systems, either performing or supporting individual sub-processes, are allocated within functional modelling.

*Electrical engineering design*
In electrical engineering design, functional modelling is prominently process-oriented, addressing the particular switching sequences within different use cases and different system states. While all reviewed systematic electrical engineering design approaches propose a stepwise overall design process, functional modelling involves alternative function models addressing different sets of functional modelling perspectives. A specific succession is rarely proposed (see e.g. [19, 20]). The designers may choose which function models to use and in which particular succession.

*Software development*
In software development, functional modelling strongly focuses on interaction processes with the system as well as transformation processes executed by the system. Kroll and Kruchten [16], for instance, start by listing the processes the system is supposed to enable and to offer the user (see also Scrum [21]), while successive function models focus on the particular use cases and transformation processes, while gradually giving more detail (see also V-Model XT [22]). They include a representation of the interaction processes of a user with the system as well as the triggered transformation processes executed by the system.

*Service development*
Functional modelling in service development prominently seems to focus on modelling human processes, including the allocation of technical systems and stakeholders. Spath and Demuss [23] propose service blueprinting in order to support functional modelling, while other authors frequently propose it for later design stages, in particular concept development, thus addressing the solution rather than the functions the solution has to fulfil (see e.g. [24, 25]).

*Mechatronic system development*
In mechatronic system development, the VDI guideline 2206 [28] proposes a function structure similar to [13]. Buur [6] proposes iterative modelling of the different system states, effects, and transformation processes, associated to different use cases, using multiple function models. Finally, the required effects and processes are allocated to different technologies and solution concepts within a function means tree.
Salminen and Verho [26] propose sequential function models. Most prominently, states, transformation processes, interaction processes with the system as well as stakeholder and technical system allocation are addressed. Several functional modelling perspectives are distributed among two or more function models, which – irrespective of their sequential proposition – implies that the designer will have to move between different function models iteratively. Changes made to one function model, may affect another.

*PSS design*
Except for Sakao and Shimomura [27], none of the reviewed PSS design approaches was found to propose a sequential functional modelling approach and the different approaches differ greatly. The proposed function models prominently address transformation processes, interaction processes with the system, as well as the different states of the user and the system.

Within PSS design, e.g. service blueprinting, SADT[3] and FAST[4] modelling, are often are proposed for different design stages of the system development process. In some approaches, these models are used to independently model the function in one design stage and the concept in another; in other approaches they support the transition from function to concept. Within this transition, the models are refined and gradually stakeholders and technical systems are allocated. Iterative refinement of function models, leading to a spiral design approach, is explicitly proposed by e.g. Brezet et al. [29], and – to a lesser degree – Watanabe et al. [15], Maussang-Detaille [17], and others.

**Comparing functional modelling approaches across disciplines**

The findings suggest that systematic design approaches differ greatly, regarding what is addressed (i.e. which functional modelling perspectives are addressed) within the proposed functional modelling approaches and how the designer is expected to move between individual function models, thus, between the inherent functional modelling perspectives. The results are presented in Table 3.

There seems to be no shared sequence for moving between individual functional modelling perspectives across disciplines. Even within the different disciplines a great diversity can be found. Those reviewed systematic design approaches from mechanical engineering, software, and service development, which propose multiple function models, typically propose a sequential modelling approach. In PSS design and mechatronic system development mostly iterative functional modelling approaches were found or alternative paths are proposed. In PSS design, in addition, spiral approaches can be found. A clear sequence of how to move between the individual function models is rarely proposed.

Table 3: Comparison of functional modelling approaches in different disciplines

| **Discipline** | **Approach** | **Prominent functional modelling perspectives** |
|---|---|---|
| Mechanical engineering | sequentially | States, effects, transformation processes |
| Electrical engineering | *-not clearly specified-* | (Effects), States, transformation processes, (use cases) |
| Software development | sequentially | Transformation processes, interaction processes, use cases, stakeholder allocation |
| Service development | sequentially | Transformation processes, (interaction processes), stakeholder allocation, |
| Mechatronic system development | iteratively, (sequentially) | Effects, transformation processes, interaction processes, use cases, technical system allocation |
| PSS design | as alternative, iteratively, (spiral) | States, transformation processes, interaction processes, technical system allocation, stakeholder allocation |

Most importantly, the findings suggest that the *transformation processes perspective* is a shared prominent functional modelling perspective in all reviewed disciplines (see Table 3). While mechatronic system development and the sub-disciplines mechanical engineering design, electrical engineering design, and software development focus on *technical* processes, service development focuses on *human* processes. Nevertheless, some authors in mechanical engineering particularly stress the inclusion of humans as operators into the system (e.g. as "man-machine systems", see [30]) and thus into functional modelling. As PSS design aims at the inclusion of technical product development and service development, both human and technical processes are addressed by functional modelling.

3 Structured Analysis and Design Technique (SADT)

4 Function Analysis System Technique (FAST)

## Discussion

The presented analysis aims to answer the question, what kind of functional modelling approaches are proposed across disciplines, with regard to the proposed sequence of function models and the functional modelling perspectives these address.

### Hindered communication

The found diversity supports the assumption that ambiguity related to the understanding of function, discussed by Vermaas' [3], is reflected in function modelling proposed in systematic design approaches across disciplines. Designers, who have been introduced to discipline-specific functional modelling approaches, may not be aware of the modelling perspectives relevant to designers from other disciplines or how the respective function models are used. The found differences in the approaches and the different purposes, for which individual models are proposed, support the assumption that communication based on function models is hindered across disciplines. It seems, the particular points in time at which specific information is shared, have to be managed to reduce the risk of miscommunication and ensure information can be adequately shared. In order to support the integration of functional modelling in interdisciplinary system development, an integrative modelling approach needs to cope with the existing diversity.

### A shared basis for integrative functional modelling

The largest diversity in the proposed functional modelling approaches was found in those cases, when particularly many functional modelling perspectives are to be integrated, such as in mechatronic system development and PSS design. No shared sequence for functional modelling within interdisciplinary system development approaches and particularly across disciplines seems to exist. However, the conducted literature study identified transformation processes as a common prominent functional modelling perspective, which is shared across all reviewed disciplines.

Modelling the processes which need to take place may, hence, serve as a common basis for the development of an integrative functional modelling approach. Additional functional modelling perspectives, prominent in the different collaborating disciplines, need to be includable into an integrative modelling approach. That way, the designers can be provided with all the modelling perspectives prominent in their respective discipline. Depending on which disciplines are involved in a particular system development project a different set of additional functional modelling perspectives need to be included (as can be seen in Table 3). Further, it seems beneficial to include modelling both technical and human processes into integrative modelling of transformation processes.

No shared approach for moving between individual functional modelling perspectives exists across disciplines. Hence, an integrative modelling approach not only needs to be able to link all additional functional modelling perspectives to modelling the transformation process perspective, but also needs to support moving between them in alternative successions.

### Limitations

The presented research is based on the assumption that the approaches proposed in design literature are taught or incorporated in design guidelines and – at least subconsciously – influence design practice. The comparison has been based solely on the analysis and interpretation of the function models proposed in systematic design approaches as described and illustrated in literature. In some cases, however, few or no examples and limited descriptions of the proposed models were available.

## Conclusions

As the main design decisions are taken when conceptualising the system, a shared understanding of the system under development is essential for the design of truly integrated technical systems. Integrative functional modelling may serve as a basis for the establishment of a shared understanding across disciplines. The presented literature study suggests that individual modelling approaches are specific in relation to the addressed functional modelling perspectives and the specifics on how to move between different modelling perspectives even within different disciplines. The diversity is particularly large in interdisciplinary system development approaches. However, the perspective of transformation processes is prominently shared in functional modelling across disciplines. Modelling the transformation processes may, hence, serve as a common base for the development of an integrative functional modelling approach. Depending on which particular disciplines need to collaborate in the design process, additional functional modelling perspectives need to be includable and linked to modelling of the transformation process perspective. Such an approach would also enable omitting modelling activities related to perspectives, which are not relevant in a specific system development project.

Providing the designer with a functional modelling approach, which is capable of linking the different functional modelling perspectives to modelling the transformation processes, may improve the designers' understanding of functional modelling and reasoning outside their own expertise. An expansion of the available vocabulary to describe the content of functional modelling and the particular approaches (sequence) associated to it, hence, may positively influence the comprehension of cross-disciplinary functional modelling. However, with respect to the diverse approaches related to moving between different functional modelling perspectives, such an approach explicitly needs to be able to support functional modelling irrespective of the particular direction it is approached.

Future research needs to address the specifics of such an integrative functional modelling approach. Research is also needed to address which function models – and hence, which functional modelling perspectives – are de-facto relevant to designers in industry.

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