Artificial Intelligence for Engineering Design, Analysis and Manufacturing (2013), *27*, 281–289.

doi:10.1017/S0890060413000280

RESPONSE PAPER

An analysis of functional modeling approaches across disciplines

BORIS EISENBART, KILIAN GERICKE, AND LUCIËNNE BLESSING
Engineering Design and Methodology Group, Université du Luxembourg, Luxembourg
(RECEIVED March 1, 2012; ACCEPTED March 1, 2013)

Abstract

Authors across disciplines propose functional modeling as part of systematic design approaches, in order to support and guide designers during conceptual design. The presented research aims at contributing to a better understanding of the diverse functional modeling approaches proposed across disciplines. The article presents a literature review of 41 modeling approaches from a variety of disciplines. The analysis focuses on what is addressed by functional modeling at which point in the proposed conceptual design process (i.e., in which sequence). The gained insights lead to the identification of specific needs and opportunities, which could support the development of an integrated functional modeling approach. The findings suggest that there is no such shared sequence for functional modeling across disciplines. However, a shared functional modeling perspective has been identified across all reviewed disciplines, which could serve as a common basis for the development of an integrated functional modeling approach.

Keywords: Cross-Disciplinary; Functional Modeling; Functional Modeling Approaches; Literature Study

1. INTRODUCTION

The functions of a technical system allow users to draw value from the system by using it for a certain purpose (Tan et al., 2007). Design strives to generate descriptions of technical systems, which are capable of fulfilling required functions related to ever-growing customer expectations, in sufficient detail for their implementation (Blessing, 1994; Chakrabarti & Bligh, 2001; Eder, 2008). Technical system development increasingly requires the integration of different technologies, necessitating a closer collaboration of experts from different disciplines. The term *technical system* used in this article encompasses both technical products and product/service systems (PSS). Particularly, the conceptual design stage (i.e., the transition from a design problem to an early solution concept) is considered to be among the most demanding design tasks (Blessing, 1997). It requires a joint effort and the establishment of a shared understanding of the technical system under development, including the design problem and expected functional capacities, among the involved designers (Valkenburg, 2000; Kleinsmann, 2008).

Reprint requests to: Boris Eisenbart, Engineering Design and Methodology Group, Université du Luxembourg, 6 rue Richard Coudenhove Kalergi, L-1359, Luxembourg. E-mail: Boris.Eisenbart@uni.lu

Across disciplines, systematic design approaches propose functional modeling in order to support and guide designers during conceptual design (Blessing, 1997; Eisenbart et al., 2011). Integrated functional modeling may thus considerably support the establishment of the required shared understanding and facilitate cross-disciplinary collaboration during conceptual design. However, such a generally accepted approach for integrated functional modeling has not been established. Consequently, the exchange of expertise is hindered, because different understandings and different ways of representing function are competing when designers (of different disciplines) collaborate (Buur, 1990; Müller et al., 2007). The specific way functions are represented is bound to the particular understanding of function applied, as Eckert (2013) and Goel (2013) highlight. Diverse understandings of function (Crilly, 2010; Carrara et al., 2011; Vermaas, 2013) and a large variety of functional models (Erden et al., 2008; Eisenbart et al., 2012) can be found across, but also within, different disciplines.

This article presents the results of an extensive literature study on proposed functional modeling approaches from a variety of disciplines and discusses needs and opportunities for an integrated functional modeling approach. The presented research aims at contributing to a better understanding of functional modeling approaches proposed in different disciplines.

The following section discusses the ambiguity related to the understanding of function and the way functions are represented in research and related to its practical application. Section 3 presents a review of functional modeling approaches proposed in literature from a variety of disciplines. Focus is put on the addressed content (*functional modeling perspectives*) and the proposed sequence for functional modeling, if multiple functional models are proposed. The results of the analysis are discussed in Section 4. Finally, the implications of the derived needs and opportunities are discussed in Section 5.

2. AMBIGUITY RELATED TO FUNCTION

Despite the centrality of function to technical system development "function lacks a single precise meaning. It is a term that has a number of coexisting meanings, which are used side-by-side in engineering" (Vermaas, 2011). Various definitions of function exist (see, e.g., Crilly, 2010; Carrara et al., 2011), and a shared understanding of function has not been established among researchers (see, e.g., Ullman et al., 1992; Umeda & Tomiyama, 1997; Chandrasekaran & Josephson, 2000; Far & Elamy, 2005) or even among practitioners from the same discipline (Alink, 2010; Eckert, 2013). The different authors agree that this ambiguity is problematic in the collaboration of different designers because it may considerably hinder communication about individual functions and expected system functionality.

2.1. Coexistence of different perspectives on function

The divergent understanding of function in research has resulted in a large variety of functional models proposed in literature across disciplines (Eisenbart et al., 2012). In an exhaustive literature study Eisenbart et al. (2012) analyzed a total of 70 functional models (54 original models plus variants proposed by different authors). The considered models originate from mechanical engineering (24 models), electrical engineering (8 models), software development (12 models), mechatronic system development (10 models), as well as service and PSS design (16 models). The analysis led to the identification of different *functional modeling perspectives*, which are described in Table 1, taking the example of a welding robot using welding tongs. Functional modeling perspectives relate to the particular content addressed by individual functional models (i.e., they relate to what is explicitly modeled in a specific functional model), in order to represent individual functions and overall system functionality.

Individual functional models frequently address multiple functional modeling perspectives, and Eisenbart et al. (2012) suggest that several functional modeling perspectives are more prominent than others within the different disciplines. For instance, the proposed functional models in mechanical engineering seem particularly concerned with technical processes and effects. These are typically structured hierarchically and/or related to flows of operands (typically specifications of material, energy, or information), which are to be changed in their state. In contrast, software and PSS development seem to focus on transformation and interaction processes performed by different stakeholders in relation to different use cases. As part of the presented research in this article, it will be analyzed more thoroughly, which specific functional modeling perspectives are particularly prominent within individual disciplines.

2.2. Studies on functional modeling in practice

Ambiguity in the use of function seems to persist not only in research but particularly in how designers approach functional modeling in practice. Eckert (2013) presents the results of an interview study and experiments, which suggest that practical designers do not employ a clearly defined understanding of function. As a consequence, different understandings of function get mixed and are employed inconsistently during functional modeling (see also Alink, 2010; Alink et al., 2010). In the presented experiments, designers essentially switched between understandings of function as related to the purpose of technical systems, flows of operands, or transformation of states. They typically did not differentiate between function and intended behavior. In addition, the inclusion of unintended behavior seems dependent on the individual designer.

Designers tend to make assumptions about the potential solution to a design problem and model the functions of the system accordingly (see, e.g., Blessing, 1997; Eckert et al., 2010). Thus, within the developed functional models, rather than strictly applying suggested functional taxonomies,[1] individual functions have been formulated on an inconsistent level of abstraction and related to different understandings of function (Alink, 2010). Difficulties with the application of functional taxonomies in practice are also discussed by Ahmed and Wallace (2003) and van Eck (2010). Alink (2010) emphasizes that although they are moving toward a potential solution concept, designers *need* to be able to describe functions on different levels of abstraction or concreteness. The functions of a potential solution concept need to be modeled as concretely as possible in order to determine required auxiliary functions (Albers et al., 2010).

Essentially, designers often seem to feel restricted in modeling and reasoning about functions when strictly applying functional modeling as proposed in systematic design approaches (Alink, 2010; Blessing, 1997). Rather, they preferred modeling functions in a way fitting to their particular needs (with a particular potential solution in mind).

2.3. Implications

Although many researchers have strived to determine one generally accepted understanding of function (Vermaas,

[1] Functional taxonomies are specific methods for formulating functions related to a given level of abstraction and understanding of function. Typically, these use verb and noun combinations.

https://doi.org/10.1017/S0890060413000280 Published online by Cambridge University Press

Table 1. *Functional modeling perspectives*

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," and the state of the welding tongs (system) changes from "open" to "closed." Typical example: process structure (Blessing & Upton, 1997)
Effects	Representation of the required physiochemical effects, which have to be provided to enable, 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 (see, e.g., Pahl et al., 2008)
Transformation 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 operands. *Technical processes* are transformation processes related to technical systems, and *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 (Hubka & Eder, 1988)
Interaction processes	Representation of interaction processes of stakeholders or of other technical systems, which (from the designers' perspective) are *not* part of a system, with stakeholders or technical systems, which *are* part of the system under consideration. If the robot is sold to a customer without services associated with it, "exchange electrodes," "type in position information," etc., are regarded as interaction processes with the system. Typical example: service process model (Watanabe et al., 2011)
Use case	Representation of different cases of applying the technical system is typically associated with the interaction of stakeholders or another technical system with the technical system under development, which requires subsequent processes to take place. A potential use case associated with the welding robot is a user requesting the robot to "display the position of the end effector," which includes several subprocesses (e.g., measuring position, processing data) within the robot. Typical example: use case schematic (see, e.g., Kroll & Kruchten, 2003)
Technical system allocation	Representation of the role of a technical system is supposed to perform or enable a (sub)set of required *effects* or *processes*, either as part of the technical system under consideration or by interacting with it. Changing the electrodes of the welding tongs may be executed by another robot. Typical example: technical process structure model (Hubka & Eder, 1988)
Stakeholder allocation	Representation of the roles of different stakeholders, who may be users benefit from a system or operators contributing to the system through executing required processes or providing resources, etc. In the PSS context, a service associated with the welding robot may involve stakeholders like operators to change the electrodes or companies to deliver new electrodes, etc. Typical example: SADT modeling (see, e.g., Maussang-Detaille, 2008)

Note: PSS, product/service systems; SADT, structured analysis and design technique.

2013), designers in practice seem to switch flexibly between alternative understandings and ways of representing functions. Allowing ambiguity is thus seen as a desirable advantage for individual designers to perform functional modeling fitting to their specific needs (Alink, 2010; Carrara et al., 2010; Eckert, 2013; Vermaas, 2013), that is, fitting to their current strain of reasoning: "We see different meanings of function not as an obstacle to functional modeling but as a critical source of the power of functional reasoning" (Goel, 2013).[2]

This suggests that an integrated functional modeling approach needs to link what individual designers represent in their models (i.e., the addressed functional modeling perspectives) regardless of the ambiguous understandings of function these are based on. Such an integrated approach could facilitate joint functional modeling and support the establishment of a shared understanding in interdisciplinary design projects, while at the same time provide designers with the flexibility they require.

3. ANALYZING FUNCTIONAL MODELING APPROACHES

"Functional models of complex systems and functional reasoning about the systems are closely intertwined," and functional modeling is proposed to support functional reasoning of designers (Goel, 2013). Eisenbart et al. (2012) found many of the functional models proposed within systematic design approaches to be building up on each other. A proposed sequence of functional models is intended to guide designers in their reasoning toward a potential solution concept (Chakrabarti, 1992; Eder, 2008), whereas individual synthesis and analysis steps related to individual modeling activities

[2] "Functional reasoning" relates to the analysis and synthesis activities of designers in the gradual determination of a potential solution to a given design problem, supported through functional modeling (Chakrabarti, 1992; Chakrabarti & Bligh 2001; Far & Elamy, 2005; Goel, 2013).

https://doi.org/10.1017/S0890060413000280 Published online by Cambridge University Press

are typically highly iterative. Such a sequence of functional models further implies moving between the respectively addressed functional modeling perspectives. The term *functional modeling approach* is used henceforth, in order to encompass the proposed functional models (with the inherent modeling perspectives these address) and the proposed sequence for modeling (i.e., the sequence in which the respective models are proposed).

The research presented here aims at contributing to a deeper insight into functional modeling approaches proposed across disciplines. Functional modeling perspectives or proposed modeling sequences, which are common across disciplines, may provide a suitable starting point for the development of an integrated modeling approach. The presented research strives to determine the typical (or most prominent) modeling perspectives and proposed modeling sequences in the different disciplines. The research is guided by the following questions:

- *Which functional modeling 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 modeling perspectives in the different disciplines, and is there a shared one across*?

3.1. Research approach: Coding scheme

The analysis focuses on systematic design approaches that explicitly propose functional modeling. In total, 41 functional modeling approaches are analyzed, each proposing between 1 and 5 different functional models. The approaches originate from mechanical engineering, electrical engineering, software development, service development, mechatronic system development, and PSS design.

The individual functional models proposed in the different modeling approaches are coded based on the modeling perspectives identified by Eisenbart et al. (2012; see their table 1). In other words, it is analyzed which functional modeling perspective is represented in the respective models. If multiple perspectives are addressed in a model, the perspective(s) are highlighted (black filling in cell), which drive the associated modeling activities (if applicable). Further, implicitly addressed perspectives are marked with an "o," as described in Figure 1.

3.2. Functional modeling approaches in different disciplines

Figure 1 shows the functional models, their succession, and the modeling perspectives they address for a few examples of the reviewed systematic design approaches. Their succession of the models in the respective rows corresponds to the proposed sequence in the individual modeling approaches. The column labeled "proposed models" includes the particular models the individual functional modeling approaches are based on and result in, respectively. Not all of these are functional models themselves. For instance, the functional modeling proposed by Pahl et al. (2008) is based on a requirements list and results in a working structure, which is represented in a morphological matrix (see Figure 1). The inclusion of these models indicates the individual context for which functional modeling is related to the different approaches. In the following, the findings are presented based on examples from each reviewed discipline.

3.2.1. Mechanical engineering

In mechanical engineering, functional modeling proposed by Pahl et al. (2008; and related approaches) has been adapted and taken up by various authors from mechanical engineering (see, e.g., Roozenburg & Eekels, 1995; Stone & Wood, 2000; Ulrich & Eppinger, 2008) and interdisciplinary system development (e.g., Verein Deutscher Ingenieure, 1993, 2004; Spath & Demuss, 2006; Cross, 2008). Pahl et al. (2008) focus on the effects that 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 that are considerably different from Pahl et al. (2008) are proposed by Hubka and Eder (1988) and Tjalve (1978). These approaches (and related ones) propose modeling the required transformation processes (totally external to the technical product under development) to change operands from an initial into a final state. Subsequently, the required technical processes and effects within the technical product are derived, which enable the external transformation processes. Therein, human operators are also modeled, who either substitute transformation processes or deal with the system as a whole. Furthermore, additional technical systems, either performing or supporting individual transformation processes, are allocated within functional modeling. The proposed sequence for modeling differs slightly between the two authors.

3.2.2. Electrical engineering

In electrical engineering, functional modeling is prominently process oriented, addressing the particular switching sequences (e.g., in relation to the signal flows) within different use cases and different system states. Although all reviewed systematic electrical engineering approaches propose a stepwise overall design process, functional modeling involves alternative functional models addressing different sets of functional modeling perspectives. A specific succession is not clearly proposed (see, e.g., Bleck et al., 1996; Dewey, 2000; Scheffer et al., 2006). The designers may choose which functional models to use and in which particular succession.

3.2.3. Software development

In software development, functional modeling strongly focuses on interaction processes with the system as well as transformation processes executed by the system. Kroll and Kruchten (2003), for instance, start by listing the processes

empty	does not apply; not included
black cell	driving aspect
grey cell	functional modelling perspective is explicitly addressed
x	functional modelling perspective is explicitly addressed in the model
(x)	functional modelling perspective *may* be included
o	implicitly addressed in functional model
x*	changed states included after each operation

Domain	Authors		Proposed models		States	Effects	Transformation processes	Interaction processes	Use case	Technical system allocation	Stakeholder allocation
Mechanical engineering	Pahl et al. (2008)	based on	requirements list, overall problem formulation		**comment:** *Functional decomposition in a tree model is not compulsory*						
			(function tree)		x	x	(x)				
			function structure		x	**x**	(x)				
		results in	morphological matrix								
	Hubka and Eder (1988)	based on	requirements list								
			technical process structure		x		**x**	o		x	x
			function structure		(x)	**x**	x	o		x	x
		results in	Organ structure, morphological matrix								
	Tjalve (1978)	based on	requirements list								
			alternative (manual) process flow models		x		**x**	o			
			man/machine separation list					(x)		**x**	**x**
			process/function chart		x	x	**x**	x		x	x
		results in	function means tree				**x**			**x**	
Electrical engineering	Dewey (2000) - EDA	based on	performance and constraints specification		**comment:** *Different functional models can be used alternatively*						
			state diagrams	*in parallel/ alternatively*	**x**				(x)		
			function table			**x**		o			
			petri nets		**x**						
			VHDL description		x		**x**		o		
		results in	circuit diagram								
Software development	Kroll and Kruchten (2003)	based on	problem statement								
			feature list				**x**	x	o		
			Use case schematics				**x**	x	**x**	x	x
			Use case description				x	x	x		x
			Sequence diagram				**x**	x			x
			Activity/event diagram				**x**	**x**			x
		results in	initial system structure/architecture								
Service development	Spath and Demuss (2006)	based on	requirements list, initial system structure		**comment:** *SADT and FAST used alternatively, resulting in blueprint*						
			Function structure		x	**x**	o				
			FAST	*alternatively*	x		x			**x**	
			SADT		x*		**x**	x		x	(x)
			Service blueprint		o		**x**	o		x	x
		results in	module structure								
Mechatronic system development	Buur (1990)	based on	requirements list								
			state transition model	*iteratively*	x				**x**		
			(active) purpose fcts. model				**x**		x		
			transformation fcts. model			**x**			x		
		solution	*expanded* function means tree			**x**	**x**			x	
	Salminen and Verho (1989)	based on	requirements list		**comment:** *Presented succession is not **strictly** proposed*						
			function tree				**x**		x		
			events list				**x**	x		x	x
			context and flow diagram		x		x	x		**x**	**x**
			state transition diagram		**x**		x		(x)		
		results in	principle solution table (after Koller)								
PSS design	Maussang-Detaille (2008)	based on	customer needs								
			inter-actor network							**x**	x
			function list (decomposition)				**x**				
			FAST (general)	*alternatively*			**x**	(x)		**x**	
			SADT (use activity)		x*		**x**	x		x	(x)
			FAST (function and solution allocation)				**x**	(x)		**x**	
			Functional block diagram (FBD) (internal modelling of system with principal elements)				x	x		x	**x**
		results in	SADT - activities within the system		x*		**x**	x		x	(x)
			FBD (detailed system modelling)				x	x		x	**x**
	Sakao and Shimomura (2007)	based on	initial scenario model		**x**						x
			flow model								[illegible]
			scope model		**x**						
			scenario model (transition graphs)		**x**						x
			chain of actions				**x**	x		o	o
		results in	view model (function tree and realisation structure)		**x**		**x**			x	

Fig. 1. Examples of functional modeling approaches.

https://doi.org/10.1017/S0890060413000280 Published online by Cambridge University Press

the system is supposed to enable and to offer the user (see also Schwaber, 2007), whereas successive functional models focus on the particular use cases and transformation processes, gradually giving more detail (see also V-Model XT in IABG, 2006). 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.

3.2.4. Service development

Functional modeling in service development prominently seems to focus on modeling transformation processes executed by humans (often in conjunction with the use of technical products), as well as the allocation of technical systems and stakeholders. Spath and Demuss (2006) propose service blueprinting in order to support functional modeling, whereas 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 fulfill (see, e.g., Bullinger et al., 2003; Fähnrich & Meiren, 2007).

3.2.5 Mechatronic system development

In mechatronic system development, Verein Deutscher Ingenieure guideline 2206 (Verein Deutscher Ingenieure, 2004) proposes a function structure similar to Pahl et al. (2008). Buur (1990) proposes iterative modeling of the different system states, effects, and transformation processes, associated to different use cases, using multiple functional models. Finally, the required effects and processes are allocated to different technologies and solution concepts within a function means tree.

Salminen and Verho (1989) propose sequential functional models. In particular, system states, transformation processes, interaction processes with the system, as well as stakeholder and technical system allocation are addressed. Several functional modeling perspectives are distributed among two or more functional models, which, irrespective of their sequential proposition, implies that the designer will have to move between different functional models iteratively. Changes made to one functional model may affect another model.

3.2.6. PSS design

Except for Sakao and Shimomura (2007), none of the reviewed PSS design approaches was found to propose a sequential functional modeling approach, and the different approaches differ greatly. The proposed functional 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) structured analysis and design technique modeling and function analysis system technique modeling 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 functional models, leading to a spiral design approach, is explicitly proposed by, for example, Brezet et al. (2001) and, to a lesser degree, Watanabe et al. (2011) and Maussang-Detaille (2008).

3.3. Comparing functional modeling approaches across disciplines

The findings suggest that the functional modeling approaches proposed in design literature form different disciplines differ greatly. That includes the considered functional modeling perspectives (addressed in the respective functional models) and how designers are supposed to move between individual functional models (i.e., between the inherent functional modeling perspectives). The results are summarized in Table 2.

There seems to be no shared sequence for moving between individual functional modeling perspectives across disciplines, and the individual modeling approaches use alternative starting points. Even within the different disciplines a great diversity can be found. The reviewed systematic design approaches from mechanical engineering, software, and service development, which propose multiple functional mod-

Table 2. *Comparison of functional modeling approaches from the different disciplines*

			Functional Modeling Perspectives						
Discipline	Σ Consulted Approaches	Typical Proposition of Funct. Models	States	Effects	Transform. Processes	Interaction Processes	Use Case	Tech. Syst. Allocat.	Stakehold. Allocat.
Mechanical engineering	13	Sequentially	10	11	**13**	4	1	4	2
Electrical engineering	4	As alternative, parallel	**4**	2	**4**	0	1	0	1
Software development	7	Sequentially	2	0	**6**	5	3	4	4
Service development	6	Sequentially	1	1	**6**	1	0	**6**	**6**
Mechatronic system development	6	Iteratively, (sequentially)	4	1	**6**	4	0	5	5
PSS design	5	As alternative, iteratively, (spiral)	**5**	4	**5**	1	2	2	1

Note: The number entries are the amount of functional modellng approaches that were found to explicitly address the respective functional modeling perspective. The bold values are the most prominent functional modeling perspective(s) in the individual disciplines.

els, typically propose a sequential modeling approach. In PSS design and mechatronic system development, mostly iterative functional modeling approaches were found or alternative paths are proposed. In PSS design, in addition, spiral approaches can be found.

The findings suggest that the *transformation processes perspective* is always one of the most prominent, or even the single most prominent, modeling perspective within all reviewed disciplines. Thus, it is prominent across all the disciplines.

Although mechatronic system development and the subdisciplines mechanical engineering, electrical engineering, and software development focus on *technical* processes, service development focuses on *human* processes. In PSS design, both types are prominent. Nevertheless, even in mechanical engineering, some authors particularly stress the inclusion of humans as operators into the system (e.g., as "man–machine systems"; see Andreasen; 1992) and thus into functional modeling.

4. DISCUSSION

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

4.1. Hindered communication

The identified diversity in functional modeling approaches proposed across disciplines supports the general picture of diversity and ambiguity associated with the concept of function. The presented literature study further suggests that, depending on the respective author, the same model may serve entirely different purposes in technical product development; for instance, as is the case with service blueprinting. Designers, who have been introduced to discipline-specific functional modeling approaches, may not be aware of the modeling perspectives relevant to designers from other disciplines or how the respective functional models are used.

All these different issues support the assumption that communication between individual designers is hindered, particularly 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 modeling in interdisciplinary system development, an integrated modeling approach needs to cope with the existing diversity.

4.2. Needs and opportunities for integrated functional modeling

The largest diversity in the proposed functional modeling approaches was found in those cases when many functional modeling perspectives are to be integrated, such as in mechatronic system development and PSS design. Looking across different proposed functional modeling approaches, no shared sequence for moving between the different modeling perspectives seems to exist. Furthermore, individual designers in practice tend to change between specific perspectives taken, as highlighted in Section 2. An integrated functional modeling approach thus needs to enable switching between taken modeling perspectives flexibly, allowing different entry points and moving between individual modeling perspectives in alternative successions.

The conducted literature study further suggests different sets of functional modeling perspectives, which are particularly prominent within the different disciplines (see Table 2). The transformation process perspective has been identified to be prominently addressed across all reviewed disciplines. Modeling the required transformation processes (both human and technical) may, hence, serve as a common basis in an integrated functional modeling approach. Linking the remaining modeling perspectives through the shared transformation process perspective may enable interlinking and translating between the different modeling perspectives taken by designers at a specific point in the development process.

The analyzed functional modeling approaches, from the point of view of the representation, did not differentiate between intended or unintended functionality of a technical system, which resembles design practice (see Alink, 2010).

Finally, embedding different ways of formulating functions needs to be enabled in an integrated functional modeling approach, in order to make it adaptable to a variety of applications, as discussed above (see, e.g., Alink, 2010). A modeling approach that intends to implement the presented insights is the *integrated functional modeling framework* proposed in Eisenbart et al. (2013).

4.3. Limitations

The presented research is based on the assumption that the approaches proposed in design literature are taught to designers 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 functional 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.

5. CONCLUSIONS

As the main design decisions are taken when conceptualizing a technical system, a shared understanding among the involved designers of the system under development is essential. Integrated functional modeling may serve as a basis for the establishment of such a shared understanding across disciplines. It is shown that such an integrated modeling approach needs to link the different functional modeling perspectives relevant to the different disciplines, while at the same time provide designers with the flexibility they require. The article presents the results of an extensive literature study on functional modeling approaches proposed across disciplines. The conducted study led to the identification of specific needs and opportunities for the development of an integrated modeling approach.

The derived insights suggest that individual modeling approaches are specific in relation to the addressed functional modeling perspectives and related to how to move between them. The diversity is particularly large in interdisciplinary system development approaches. However, the transformation process perspective is most prominently addressed in functional modeling approaches across all reviewed disciplines. Modeling the transformation processes may, hence, serve as a common basis for the development of an integrated functional modeling approach. Depending on which additional modeling perspectives are needed in a specific design project, these need to be included and linked to the transformation process perspective. Thus, such an approach could potentially enable addition or omission of modeling perspectives depending on whether these are needed in a specific system development project.

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

Future research needs to address the specifics of such an integrated functional modeling approach. Research is also needed to address which functional models and, hence, which functional modeling perspectives are de facto relevant to designers from different disciplines in practice.

ACKNOWLEDGEMENTS

The authors thank the Fonds Nationale de la Recherche Luxembourg for funding this research as well as Prof. Mogens Myrup Andreasen for valuable discussions preceding the creation of this article. Furthermore, the authors thank the editors and the reviewers for useful comments on the earlier version of this article.

REFERENCES

Ahmed, S., & Wallace, K. (2003). Evaluating a functional basis. *Proc. ASME Design Engineering Technical Conf. Computers and Information in Engineering Conf.*, Chicago, September 2–6.

Albers, A., Sadowski, E., & Braun, A. (2010). Funktionsorientierte Produktentwicklung in frühen Phasen von Entwicklungsprozessen. *Proc. KT 2010, 8. Gemeinsames Kolloquium Konstruktionstechnik*, Magdeburg, Germany.

Alink, T. (2010). *Bedeutung, Darstellung und Formulierung von Funktionen für das Lösen von Gestaltungsproblemen mit dem C&C-Ansatz*. PhD Thesis. Karlsruhe Institute of Technology, Institut für Produktentwicklung.

Alink, T., Eckert, C., Ruckpaul, A., & Albers, A. (2010). Different function breakdowns for one existing product: experimental results. *Proc. Design Computing and Cognition, DCC*, pp. 405–424, Stuttgart, Germany, July 12–14.

Andreasen, M.M. (1992). The theory of domains. In *Understanding Function and Function-to-Form Evolution* (Ullman, D.G., Blessing, L., & Wallace, K., Eds.). Cambridge: Cambridge University Press.

Bleck, A., Goedecke, M., Huss, A., & Waldschmidt, K. (1996). *Praktikum des Modernen VLSI-Entwurfs*. Stuttgart: B.G. Teubner Verlag.

Blessing, L. (1994). *A process-based approach to computer-supported engineering design*. PhD Thesis. University of Twente.

Blessing, L. (1997). *Applying Systematic Design*. The Flight Refuelling Probe Project, CUED/C-EDC/TR 48. Cambridge: University of Cambridge, Engineering Design Centre.

Blessing, L., & Upton, N. (1997). A methodology for preliminary design of mechanical aircraft systems. *Proc. AIAA/SAE World Aviation Congr.*, Paper No. 975537, Anaheim, CA, October 13.

Brezet, H., Diehl, J.C., & Silvester, S. (2001). From eco-design of products to sustainable systems design: Delft's experiences. *Proc. EcoDesign 2001: 2nd Int. Symp. Environmentally Conscious Design and Inverse Manufacturing*, pp. 605–612, December 11–15.

Bullinger, H.-J., Fähnrich, K.-P., & Meiren, T. (2003). Service engineering: methodical development of new service products. *International Journal of Production Economics 85*, 275–287.

Buur, J. (1990). *A theoretical approach to mechatronics design*. PhD Thesis. Technical University of Denmark, Lyngby, Institute for Engineering Design.

Carrara, M., Garbacz, P., & Vermaas, P. (2011). If engineering function is a family resemblance concept: assessing three formalization strategies. *Applied Ontology 6(2)*, 141–163.

Chakrabarti, A. (1992). Functional reasoning in design: function as a common representation for design problem solving. In *Understanding Function and Function-to-Form Evolution* (Ullman, D.G., Blessing, L., & Wallace, K., Eds.). Cambridge: Cambridge University Press.

Chakrabarti, A., & Bligh, T. P. (2001). A scheme for functional reasoning in conceptual design. *Design Studies 22(6)*, 493–517.

Chandrasekaran, B., & Josephson, J.R. (2000). Function in device representation. *Engineering With Computers 16*, 162–177.

Crilly, N. (2010). The role that artefacts play: technical, social and aesthetical functions. *Design Studies 31*, 311–344.

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design*. Chichester: Wiley.

Dewey, A. (2000). Digital and analogue electronic design automation. In *The Electrical Engineering Handbook* (Dorf, R.C., Ed.). Boca Raton, FL: CRC Press.

Eckert, C. (2013). That which is not form: the practical challenges in using functional concepts in design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 217–232 [this issue].

Eckert, C., Alink, T., & Albers, A. (2010). Issue-driven analysis of an existing product at different levels of abstraction. *Proc. 11th Int. Design Conf.* Dubrovnik, Croatia: Design Society.

Eder, W.E. (2008). Aspects of analysis and synthesis in design engineering. *Proc. Canadian Design Engineering Conf., CDEN*, Halifax, July 27–29.

Eisenbart, B., Blessing, L., & Gericke, K. (2012). Functional modeling Perspectives Across Disciplines. A Literature Review. *Proc. 12th Int. Design Conf.* Dubrovnik, Croatia: Design Society.

Eisenbart, B., Gericke, K., & Blessing, L. (2011). A framework for comparing design modeling approaches across disciplines. *Proc. 18th Int. Conf. Engineering Design (ICED'11)*. Lyngby/Copenhagen: Design Society.

Eisenbart, B., Qureshi, A.J., Gericke, K., & Blessing, L. (2013). Integrating different functional modeling perspectives. *Proc. ICoRD'13: Lecture Notes in Mechanical Engineering*, pp. 85–97. New Delhi: Springer.

Erden, M.S., Komoto, H., van Beek, T.J., D'Amelio, V., Echavarria, E., & Tomiyama, T. (2008). A review of function modeling: approaches and applications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 22*, 147–169.

Fähnrich, K.-P., & Meiren, T. (2007). Service engineering: state of the art and future trends. *Advances in Service Innovations 1*, 3–16.

Far, B.H., & Elamy, H. (2005). Functional reasoning theories: problems and perspectives. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 19*, 75–88.

Goel, A.K. (2013). One 30-year case study and 15 principles: implications of an artificial intelligence methodology for functional modeling. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 203–215 [this issue].

Hubka, V., & Eder, W. (1988). *Theory of Technical Systems: A Total Concept Theory for Engineering Design*. Berlin: Springer–Verlag.

IABG. (2006). *V-Model XT.* Accessed at http://www.v-modell.iabg.de/

Kleinsmann, M. (2008). Barriers and enablers for creating shared understanding in co-design projects. *Design Studies 29(4)*, 369–386.

Kroll, P., & Kruchten, P. (2003). *The Rational Unified Process Made Easy: A Practitioner's Guide to the RUP*. Boston: Addison–Wesley.

Maussang-Detaille, N. (2008). *Méthologie de Conception pour les Systèmes Produits-Services*. PhD Thesis. Université de Grenoble.

Müller, P., Schmidt-Kretschmer, M., & Blessing, L. (2007). Function allocation in product-service-systems: are there analogies between PSS and mechatronics? *Proc. Applied Engineering Design Science—AEDS Workshop* (Vanek, V., & Hosnedl, S., Eds.), pp. 47–56. Pilsen, Czech Republic: Design Society.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2008). *Engineering Design: A Systematic Approach*. Berlin: Springer–Verlag.

Roozenburg, N. F. M., & Eekels, J. (1995). *Product Design: Fundamentals and Methods*. Chichester: Wiley.

Sakao, T., & Shimomura, Y. (2007). Service engineering: a novel engineering discipline for producers to increase value combining service and product. *Journal of Cleaner Production 15*, 590–604.

Salminen, V., & Verho, A. J. (1989). Multi-disciplinary design problem in mechatronics and some suggestions to its methodical solution in conceptual design phase. *Proc. 6th Int. Conf. Engineering Design–ICED*.

Scheffer, L., Lavagno, L., & Martin, G. (2006). *EDA for Implementation, Circuit Design, and Process Technology*. Boca Raton, FL: CRC Press.

Schwaber, K. (2007). *Agile Project Management With Scrum*. Microsoft Press.

Spath, D., & Demuss, L. (2006). Entwicklung Hybrider Produkte: Gestaltung Materieller und Immaterieller Leistungsbündel. In *Service Engineering—Entwicklung und Gestaltung Innovativer Dienstleistungen* (Bullinger, H.-J., & Scheer, W.-A., Eds.), pp. 463–502. Berlin: Springer.

Stone, R.B., & Wood, K. (2000). Development of a functional basis for design. *Journal of Mechanical Design 122*, 359–370.

Tan, A.R., McAloone, T.C., & Gall, C. (2007). Product/service-system development: an explorative case study in a manufacturing company. *Proc.16th Int. Conf. Engineering Design–ICED*, Paris, August 28–31.

Tjalve, E. (1978). *Systematic Design of Industrial Products*. Technical University of Denmark, Lyngby, Institute for Product Development.

Ullman, D.G., Blessing, L., & Wallace, K. (Eds) (1992). *Understanding Function and Function-to-Form Evolution*, Workshop Report CUED/C-EDC/TR 12. Cambridge: Cambridge University Press.

Ulrich, K., & Eppinger, S.D. (2008). *Product Design and Development*. Boston: McGraw–Hill.

Umeda, Y., & Tomiyama, T. (1997). Functional reasoning in design. *IEEE Expert 12(2)*, 42–48.

Valkenburg, R.C. (2000). *The reflective practice in product design teams*. PhD Thesis. Delft University of Technology.

van Eck, D. (2010). On the conversion of functional models: bridging differences between functional taxonomies in the modeling of user actions. *Research in Engineering Design 21*, 99–111.

Verein Deutscher Ingenieure. (1993). *Systematic Approach for the Design of Technical Systems and Products*. VDI 2221. Düsseldorf: Verein Deutscher Ingenieure.

Verein Deutscher Ingenieure. (2004). *Design Methodology for Mechatronic Systems*. VDI 2206. Düsseldorf: Verein Deutscher Ingenieure.

Vermaas, P. (2011). Accepting ambiguity of engineering functional descriptions. *Proc. 18th Int. Conf. Engineering Design*, pp. 98–107. Lyngby/Copenhagen: Design Society.

Vermaas, P. (2013). The coexistence of engineering meanings of function: four responses and their methodological implications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 191–202 [this issue].

Watanabe, K., Mikoshiba, S., Tateyama, T., Shimomura, Y., & Kimita, K. (2011). Service design methodology for cooperative services. *Proc. ASME 2011 Int. Design Engineering Technical Conf. Computer and Information in Engineering Conf. IDETC/CIE 2011*, Washington, DC, August 28–31.

Boris Eisenbart is a Research Assistant in the Research Unit in Engineering Sciences at the University of Luxembourg. He obtained his diploma in mechatronics at Saarbrücken University. His research interests include function modeling, modeling approaches, and design methodology for transdisciplinary conceptual design.

Kilian Gericke is a Research Associate at the University of Luxembourg. He attained his PhD in design management in 2011 at Technische Universität Berlin. Dr. Gericke's research interests are in product development processes, design methodology, design thinking and design management.

Luciënne Blessing is a Professor of engineering design and methodology at the University of Luxembourg. She obtained her PhD at the University of Twente in the area of knowledge management in design. Dr. Blessing's research interests include the product development process, diversity (culture, age, and gender), user–technology interaction, design methodology, and design research methodology.