Functional Modeling of Perspectives on the Example of Electric Energy Systems

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Abstract. The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. One of the challenges ahead is the design of control architecture to enable the flexibility and to handle the diversity. This paper presents an approach to model heterogeneous energy systems and their control on the basis of purpose and functions which enables a reflection on system integration requirements independent of particular technologies. The results are illustrated on examples related to electric energy systems.

Introduction

We anticipate that sustainable energy systems are more *intelligent* energy systems. The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. All this results in a demand for ever more advanced control of electric power system to handle the mix of resources with increased flexibility, while the system robustness ought to be maintained.

One approach to improve efficiency of the electricity sector is its integration with the heat sector. As heat can easily be stored, this integration also gives way for a cheaper and more effective type of energy storage: flexible demand. For example, the Danish electricity supply relies mainly on combined-heat-and-power (CHP) plants. All larger CHP plants have been equipped with significant heat storage to offset electricity production from the district heating demand. Studies suggest further an addition of heat pumps to the district heating system to enable the integration of wind power into the electricity supply, e.g. (Lund and Münster, 2006).

In recent years, many visions of future integrated energy systems have been proposed, some are based on a particular technology domain such as Microgrids or Zero-energy Buildings, others are based on an abstract planning and optimization process that does not involve the technical details of an implementation (they often assume some type of global coordination). Such integrated energy systems depend on separate domains of engineering which have their own way of representing design problems and requirements.

Integration of energy systems means the combination of systems that were previously independent and therefore have partly incompatible conceptualizations. Common system analysis is behavioural is therefore dependent on assumptions about the technical realization. The functional modeling approach applied in this paper instead allows the study of interrelations on a more general level by formalizing the semantic relations between different perspectives. The functional models are presented by Multilevel Flow Modeling (MFM). In this paper the method is outlined with a focus on the underlying semantics. The concept of perspectives is introduced and illustrated on an example related to electric energy systems.

Functional Modeling with MFM

Multilevel Flow Modeling (MFM) is an approach to modeling goals and interconnected functions of complex processes involving interactions between flows of mass, energy and information (Lind 2005)[1]. It provides means for a *purpose-centered* (as opposed to *component-centered*) description of a system's functions. MFM enables modeling at different levels of abstraction using well-defined means-ends relations and whole-part compositions (Figure 1b). Process functions are represented by elementary flow functions interconnected to form flow structures which represent a particular goal oriented view of the system (Figure 1a). The views represented by the flow structures, functions, objectives and their interrelations together comprise a comprehensive model of the functional organization of the system represented as a hypergraph. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types.

Models created in MFM are a formalized conceptual representation of the system, which support qualitative reasoning about control situations. MFM is supported by knowledge based tools for model building and reasoning.

MFM models can be and have been employed for the purposes of state identification (and representation) and action generation. State identification applications include: model based situation assessment and decision support for control room operators; hazop analysis; alarm design and alarm filtering. Further possible applications include operator support systems or integrated HMI and process-design.

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[1] Please contact one of the authors for more information on MFM.

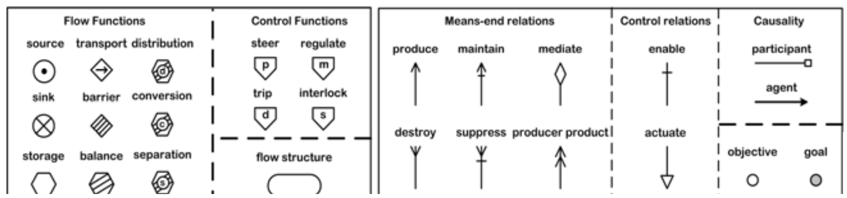


Fig. a) the box on the left lists the MFM-symbols, elementary flow-and contol-functions as well as the flow structure, which combines an interconnection of functions; b) the right box presents all MFM relations and the symbols for objectives and goals..

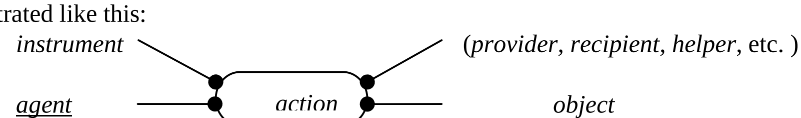
MFM has been used to represent a variety of complex dynamic processes, i.e. in fossil and nuclear power generation and chemical engineering (e.g. oil refineries) and biochemical processes. The method was originally conceived in the context of cognitive systems engineering as an intermediary model for work domain analysis, but has its own path of development now. Its strong semantic concepts and existing software tools make it suitable for integration with modern methods of intelligent control (Saleem et al. 2009). For IT applications it is useful to formalize all aspects of the modeling technique. An outline of this formalization is given below.

Underlying MFM Concepts

In this section we discuss the underlying concepts that establish the functional structures of MFM. The goal is to identify the basic operations on a functional description of a system.

Actions, Roles and Functions

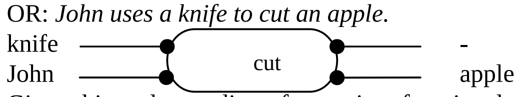
MFM is strongly related to the semantics of action, and it is possible to formalize MFM entities in a framework of actions and action-roles. The “semantic deep structure of an action” (Fillmore 1968) has been analyzed in relation to MFM in (Petersen 2000). What is important for MFM is the concept of semantic roles, which are associated with the semantic deep structure of an action. It can be illustrated like this:



This illustration provides an *action* in the centre with *semantic roles* like “slots” to be filled. The kind and number of slots depend on the specific action, but *agent*, *object* and *instrument* are the most generic:

The apple is cut with a knife by John.

OR: *John uses a knife to cut an apple.*



Given this understanding of an action, functional modeling can be described as a modeling approach that formalizes meaningful combinations of actions and roles in the context of a means-ends framework. MFM provides templates for the interconnection of a number of specific actions. These templates are functions, particularly *flow-functions* and *control functions*.

Definition of *function* (Petersen 2000):

> A function of a concrete entity **E**, which is part of a system **S**, is specified in terms of the role **R** of **E** in relation to an action describing an intended state-change in **S**.

According to von Wright (1963 and 1968), elementary actions can be derived from the concept of elementary change. Given a proposition p about the state of the world the four elementary changes are { "p disappears"= $p\mathrm{T}\neg p$; "p happens" = $\neg p\mathrm{T}p$; $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$ }[2], where "$\neg p$" is "not p" and "T" stands for a transition. An *intentional action* must now be distinguished from a change that does not involve an agent A: Instead of "p happens", we say "A makes p happen, otherwise $\neg p$ happens", in short: $\{\neg p\mathrm{T}[p\mathrm{I}\neg p]\}$[3] . Particularly control functions in MFM are directly derived from elementary actions.

In summary, *propositions* about the state of the system define the effect of a *function* (action), and the *semantic roles* of the action capture the relations between entities in a system. Action *phases* structure temporal information aspects of a function.

Flow structures and Control Structures

There are energy flow structures, mass flow structures and control structures. Most commonly energy- and mass-flow structures are used to represent a particular goal-oriented view of a system.

A *flow* structure allows modeling of a process without direct reference to the agents associated with realizing the process. However, the agent role is associated with each function and can be assumed by an external agent.

A *control* structure is meant to represent the purpose of a control action. Von Wright's theory of intentional action sets a framework for the modeling of control actions. The four elementary interventions define the four possible control functions *steer*, *regulate*, *trip* and *interlock*, respectively (Figure 1a).

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[2] The latter two are non-changes, $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$, which lead to the concept of *elementary omissions*, as discussed in (Lind 2002b).

[3] Please refer to (Lind 2002b, 2004a and 2005b) for a thorough introduction.

A simple control structure is composed of one *process objective*, which is usually an objective associated with another energy or mass flow structure, and a *control function* (steer, regulate, trip or interlock, Figure 1a) (Lind, 2005a and 2005b). A. The control function has an *actuate-relation* to the agent-role of a flow-function in a lower-level means-ends level (example in Figure 8, p. 12). A control-structure has an external *objective* that describes performance requirements of the control.

Perspectives and views

The simplest and elementary form of an MFM model is an energy- or mass-flow structure connected with an objective via an achieve-relation (produce, maintain, destroy or suppress). The objective or goal is an expression of the intention (the "Why") that is associated with the functional structure and the system it represents. A flow structure contains a conceptualization of the functions the system utilizes to achieve its purpose (the "HOW"). MFM provides templates or conceptual schemes for the *representation of functions*, as well as for goals, objectives and means-end relations which form the statement of *intention*. A *perspective*, or elementary functional description, consists therefore of a set of two elements:

1. Intention (Objective+means-end relation)
2. The representation of functions in a functional view.

The suggested definition of a *perspective* is illustrated in Figure 3.

Usually, an MFM-model consists of several such *perspectives* that are connected through a number of possible relations (*mediate*, *producer/product*, *enable*, *actuate* (all in Figure 1b).

MFM model of Energy System Balancing

The concepts introduced above are illustrated in the following on a number of examples from a modeling application to power systems. The examples have been previously published in (Heussen 2009a, Heussen 2009b).

The abstract model in Figure 4 relates the overall goal $\mathbf{g_1}$ to the intended functional organization of the system. The passive role of the generation side reflects system goal, but an analysis of the realization of Generation shows that this role needs to be enabled by the objective $\mathbf{o_1}$. The enabling objective describes a condition to be fulfilled at a lower level of abstraction.

The descriptions followed abstract considerations about the system design, showing a connection between the statement of design intentions ('goals'), functional abstraction and more concrete process objectives.

The objectives are structured into an objective hierarchy, where the original objective is reformulated $\mathbf{o_1}$.= ($\mathbf{o_{1a}}$ *and* $\mathbf{o_{1b}}$) with consideration of the flow-structure of the lower-level functional view, from a (mathematical) decomposition of the original frequency control objective $\mathbf{o_1}$.

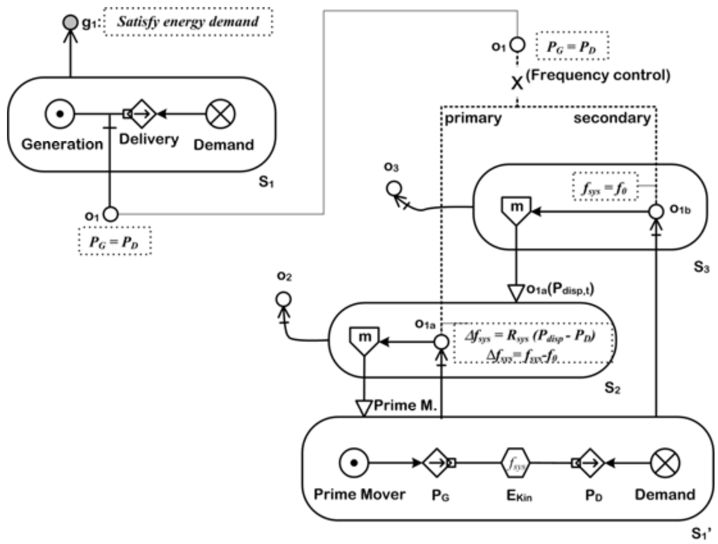

Fig. Abstract (left) and more detailed (right) representations of system balancing functions.

This decomposition is based on AC power systems with synchronous generators. In AC power systems the common frequency reflects the energy stored in the rotating mass of the generators and therefore is a measure of the energy balance. Restoring the frequency therefore is eventually restoring the energy balance.

The objectives of the objective hierarchy are achieved by a combination of a flow structure $\mathbf{S_{1'}}$, representing the energy system, and two control structures representing primary ("droop") and secondary ("integral") frequency control ($\mathbf{S_2}$ and $\mathbf{S_3}$). The objectives are maintained by a cascade of control structures $\mathbf{S_2}$ and $\mathbf{S_3}$, which employ the system frequency measure and actuate the generators to *maintain* their respective control objectives – which means to balance the system. Note that there are three strongly connected perspectives in this MFM-model.

Conclusion

This paper presented an overview of semantic and action theoretical concepts in Multilevel flow Modeling. The concept of *perspective* as a set of *intention* and functional *representation* was introduced. This concept of perspective forms a framework for the formal representation of the role-shifts that occur in MFM-relations – integrating action-roles with the means-ends levels of MFM. An example from the domain of energy systems illustrates how these "shifts in perspective". The work presented here forms a platform for further research. Future work branches out into two directions: A) Computer-implementation of the formalizations and development of new reasoning rules; B) The modeling approach can be applied to analyze possible integrated energy systems or "smart grid" control concepts.

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