Knowledge Acquisition and Strategies for Multilevel Flow Modelling

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Abstract: The paper presents three different strategies for building Multilevel Flow Models (MFM). The first two strategies are formulated on the basis of the end-means and whole part abstractions which are foundations for MFM. These strategies are generally applicable but it is concluded that they both are inefficient and error prone. A third strategy is investigated which try to overcome these deficiencies and at the same time meet the needs of industry. The aim of the strategy is to use information from plant engineering documents to facilitate the building of MFM models. The main challenge is to acquire knowledge about design and operational intentions which often are not accessible in explicit form. The solutions proposed is to use domain dependent libraries of MFM models to represent goals and functions of process units. The possibility of extracting the knowledge required for library building from engineering documents is investigated.

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Keyword: Functional Modeling, Multilevel Flow Modeling, Causal Reasoning.

1 Introduction

Multilevel Flow Modeling (MFM) has been developed in recent years to become applicable for supervisory control in complex industrial systems [1]. Research by the author and others has shown that MFM is a viable concept for advanced decision support having the potential to increase situation awareness of operators in supervisory control of complex plants[2]. Other potential uses of MFM include process and automation design.

A prerequisite for using MFM for decision support is the availability of a valid model of the plant to be supervised, and algorithms, and tools for cause-consequence reasoning. Tools for MFM reasoning has been developed by DTU and integrated with a model editor developed by IFE Halden in Norway [3]. This modeling and reasoning tool, called the MFMSuite, is used for MFM research and development. Currently commercial products called eGolf and AlarmTracker are under development by Eldor Technology, Norway. The MFMSuite and eGolf includes a graphical editor which interact with a MFM based inference system for root cause and consequence analysis. AlarmTracker is an MFM based online system for operator decision support.

Recent and ongoing research and development projects at DTU develop MFM modeling and reasoning applications for operator decision support in supervisory control in Nuclear Power Plants [4] and risk analysis (Hazop) in Oil and Gas production [5]. The main focus of this research is on improving MFM modeling and validation methods [6,7], modeling and reasoning about control functions [8] and safety barriers [9], and online reasoning [10].

The aim of the present paper is to discuss strategies for building MFM models and the associated needs for acquisition of plant knowledge. MFM concepts and syntax has been developed to a high level of sophistication including rule bases and algorithms for causal reasoning. However, the process of model building has not been developed to a similar level of sophistication. The MFM language gives through its foundational concepts of end-means and whole-part abstraction overall guidance in how to approach the model building. Two basic modelling strategies have been proposed on this basis. They are described in more detail below (see also [11]).

The basic strategies suffer from two deficiencies:

- the basic strategies are not efficient and the model building process is time consuming and error prone, especially for complex plants
- it is not clear how to acquire the plant knowledge required for model building.

The inefficiency of the two basic strategies can make the development of an MFM based application risky and costly. The deficiency of the basic strategies is a problem, in particular for industrial applications of MFM and need consideration.

A third approach to modelling has also been proposed [12] which is based on the decomposition of plant functions performed during the design. This approach to MFM modelling is more relevant for industrial application since it is using information provided by design documents. The aim of this paper is to develop the systematic foundations for such an approach, which eventually may enable automated generation of MFM models from engineering drawings and other documents.

The systematic foundation includes both an identification of plant design knowledge required for model building (the knowledge acquisition problem) and strategies for translation, formalization and representation of the knowledge into MFM models.

Before going deeper into an analysis of the knowledge acquisition problem it is important to distinguish between three varieties of problems.

1.1 Three Knowledge Acquisition problems

In the first variety, which is analyzed in detail below, the knowledge acquisition problem is how to extract information from plant engineering documents and use it to build an MFM model. It is here assumed that the plant has been designed, and that plant information is given through standard forms of engineering documentation such as P&I diagrams, operating procedures, and control logic. This corresponds to the situation where an MFM model is needed for building an MFM application for an existing plant.

In the second variety, knowledge acquisition is seen in the context of on-line applications of MFM models. Here sensor data may be used to adapt an MFM model to plant behavior. The learning algorithms required for the adaptation would specify how sensor data and knowledge of process behavior is used to adjust the MFM model. Such learning approach to building MFM models is currently under consideration and will not be discussed further here.

In the third variety, MFM is used as a tool for process and automation design. The knowledge acquisition problem takes here another form where the means-end concepts of MFM becomes a framework for identification of design alternatives and objectives. Building the MFM model representing these decisions as part of the design process become accordingly a tool for acquisition and formalization of design knowledge. The application of MFM for barrier identification [9] and Hazop [13] are examples illustrating how MFM may be used in the plant design phase.

2 Purposes and Principles of MFM

Before discussing knowledge acquisition and strategies for model building we will present the overall purposes and principles of MFM. Detailed accounts on MFM has been given elsewhere [1,11] and will therefore not be presented here. The interested reader can consult these sources for more information.

2.1 Coping with Complexity

The main purposes of MFM models is to provide an efficient means for reducing complexity in the modelling of large scale processes like oil & gas plants, nuclear power systems and other energy or chemical engineering systems. The formalization provided by the MFM modeling framework facilitate the handling of complex systems by offering a small but generic set of concepts which can be applied on several levels of means-end and part whole abstraction.

2.2 Communication of Plant Design Intentions

Another related purpose is to provide a formalized modeling framework for efficient communication of plant design knowledge and operational intentions between decision makers. Information about design and operational intentions are usually not available in explicit form and therefore difficult to share between decision makers.

2.3 Causal Reasoning

Another purpose of MFM is to support formalized causal reasoning. The concepts of goals and functions used in MFM are derived from the general concept of action and the associated distinction between ends and means. Plant functions are derived from goals and objectives of design and operation, but they are at the same time also representing the intended causal effects of the interactions between plant equipment, subsystems and the materials and energy processed. This coupling of intentions and causes provided by the plant designer are represented by MFM models, and makes them suitable for reasoning about means and ends when solving operational problems like fault diagnosis and counteraction planning. The means of the process are the plant equipment and the materials or energy processed, and they are in MFM represented by the intended effect (function) they have on the process and its objectives. An important aspect of MFM is also the representation of cause-effect relations between functions.

This means that MFM models in addition to their use in communication also has an analytical power. Both of which together make MFM suitable for supporting operators in making decisions in complex situations.

2.4 Principles of Decomposition

MFM apply two principles of decomposition. According to the first principle the system as a whole is decomposed into its parts e.g. its subsystems, equipment, components, and the materials processed. This is the principle of whole-part decomposition. The second principle is the end-means decomposition which decomposes design or operational goals and intentions into the means used for its realization. Note that the decomposition of means-end relations includes both intentional as well as causal aspects (an item is only a means for an end if it can cause the end).

The whole-part and end-means decomposition principles are fundamentally independent but are in practice combined in the modelling. They are combined to satisfy the two main requirements to the model:

- to reflect the structure of intentions
- to reflect the cause-effect structure

The two principles of decomposition should be combined because decomposition of intentions alone will not reflect the causal interactions between parts of the system. And conversely, decomposition of the whole into parts will not necessarily represent the intentional structure.

3 Basic Strategies for building MFM models

There are two basic strategies for building MFM models as described below: 1) bottom up from means to ends, and 2) top down from the ends to the means. Building MFM models using these two basic principles have been, and still are, useful for research and development of MFM and its reasoning capabilities. However, as we will discuss below, they are not by themselves suitable for industrial applications because of problems in acquiring the plant knowledge required for the modeling.

3.1 Bottom-up: from Means to Ends

The aim of this strategy is to build the MFM model from knowledge of plant equipment and the materials/energy processed using basic principles of mass and energy balances for representation of design and operational intentions. The model is built bottom-up from the means towards the ends or purposes. This strategy is accordingly only applicable when the physical implementation of the plant is known. A disadvantage of this strategy is that the model building is time consuming and error prone.

When applying the bottom-up strategy the main challenge is to determine levels of abstraction representing plant purposes and functions. This is a challenge because there are no principles, like natural laws governing plant behavior, for deriving information about plant purposes or operational objectives from information about the means i.e. plant structure and behavior.

Let us make this point clear. Formulation of goals and objectives must necessarily refer directly or indirectly to physical quantities. They can accordingly be *expressed* by concepts of physics and chemistry. The problem is that they cannot be *derived* from laws of nature. Plant goals and objectives are dependent on with what aim the plant is to be used for. This type of contextual information cannot be derived from principles of physics and chemistry alone, but can be derived from the engineering principles used in plant design and operation. These so-called design and operational principles show how knowledge about physical and chemical phenomena are applied in the design, implementation and use of purposeful devices or artifacts. Assignment of purposes and functions to plant parts or subsystems require therefore information about the context of plant design and operation.

Information about plant functions and objectives is included in engineering documents and operational procedures, but it is given in a form which hinders a direct translation into MFM concepts. The logic principles for plant decomposition and functional representation defined by MFM do not match directly the way the industrial standards for system decomposition which are used in plant documentation like P&I diagrams and operational procedures.

If the bottom up strategy is used there is therefore a need for methods for extraction of the plant knowledge from engineering documents and for subsequent translation into MFM models.

3.2 Top-down: from Ends to Means

The aim of this strategy is to build the MFM model from goals/objectives of plant design and operation. The model is accordingly built top down starting with the ends and working towards the means. An advantage of the top down strategy is that it is possible to build MFM models without detailed knowledge of the means used for implementation of the ends. This is possible because the decomposition of ends into means is governed by general principles of operation defined by generic concepts of action. However, as above, the disadvantage of the top down strategy is that the model building is time consuming and error prone.

The main challenge for the top down strategy is to decide where to start the modelling because explicit knowledge of design intent is often lacking, vaguely defined, or difficult to formulate directly using the abstract concepts provided by MFM. Knowledge of system purposes and functions is known by designers and operators but not expressed in an explicit form in textual form or diagrams.

4 Building MFM from Engineering documents

The growing interest for industrial applications of MFM require further development and enhancement of modelling methods and tools to:

- reduce the work effort involved in MFM model building
- ensure validity and correctness of MFM models
- integrate MFM model building in the general workflow of plant and automation design and operation used by industry.

The first two objectives can be met by supporting of reuse of models across applications and domains. Reuse of models can be achieved by the development of modelling libraries representing MFM models for selected plant subsystems or functions. Library elements can then be instantiated and composed to produce an MFM model of the entire plant. Such library facilities can also be used to increase the automation of the model building process. However, it should be noted that model building cannot be completely automated. Although this would be highly desirable by reasons of economy, it is not possible due to both theoretical and practical challenges. A significant challenge is here to cope with the large variety of design solutions. Another challenge is to be able to define library modules which are generic enough to be generally applicable for many modelling purposes.

The third objective can be met by defining library elements matching the way functional decomposition of the plant as designed by the engineers to meet specific design and operational goals. The information required to build MFM models can in this way be generated from engineering documents.

Current research projects at DTU are developing MFM modeling libraries and associated modelling strategies for the Oil and Gas domain: These libraries are expected to be usable for modeling problems in other process domains.

In the following we will discuss in more detail how information in engineering documents can be used together with modelling libraries for building MFM models.

4.1 Information in Engineering Documents

Information about plant purposes and functions is often not documented to the level of details required for MFM because it is not required in the existing automation workflow and therefore not available in the documents produced during plant and automation design such as process flow diagrams (PFD), piping and instrumentation diagrams (P&I), standard operational procedures, control logic and layouts of information display pages. PFD's document process streams and equipment including plant mass and energy balance information. P&I diagrams present plant components, their interconnections and associated instrumentation and control systems. Standard operational procedures specify the overall requirements to plant operation. Documentation of results from HAZOP studies are also available in industries dealing with risky operations like in the Nuclear, Oil and Gas, and Chemical industries.

It is also a practical problem that knowledge of design assumptions and goals are not always made available by subsystem vendors who want to disclose information considered critical for their business. This put limits to how detailed models can be build and influences the definition of library modules.

4.1.1 The challenges

The key challenges in acquisition of knowledge from engineering documents relevant for building MFM models are to extract information about:

- end-means decomposition of plant operating objectives.
- plant functions
- causal relations

The end-means decomposition of plant operating objectives is required to identify the overall multilevel end-means structure of MFM models. This information can be extracted from documentations of plant operation and procedures. This subject will not be discussed further here. Interested readers can consult the example presented by Wu et. al. [9].

Information about plant functions is needed for matching the elementary function types (flow function and control function) used in MFM to the level of functional abstraction used by the industry, which is often defined by standards. However, there is no direct match between the elementary functions of MFM and industrial standards because the criteria for functional decomposition are different. The functional decomposition used by the industry express the decomposition of the overall plant production goals into chains of processing units connected by streams of material and energy. These processing units have functional connotations.

Standards used by industry to name plant subsystems and equipment contain accordingly information about plant purposes and function. The terms used represent principles of plant decomposition which have been agreed among industry sectors or used by a single company. Such standards exist accordingly for oil and gas plants, for power plants, cement industry etc. The purpose of the standards is to provide a common terminology and codes to label plant equipment and subsystems and is used in engineering documents and for information presentation in operator displays.

Note that MFM emphasize a strict separation of function and structure which is in conflict with the standards used by industry where there plant components or subsystems (i.e. structural elements) often are named according to their function. Using the function of a subsystem to name it (e.g. heat exchanger) is convenient when equipment always is used for the same "standard" purpose (i.e. having the same function). But as stressed in MFM, functions are representing what the components do in a context of use. Equipment designed for a purpose may for example be used by an operator for another purpose i.e. have another function than intended by the designer. The design function can accordingly be different from the use function [14] and the design or use function can depend on the mode of operation of the plant. See also [15] for an illustrating example of the mode dependency of functions.

The industrial standards do not directly express causal relations to the level required for MFM reasoning. However, as will be demonstrated below, some causal relations relevant for MFM can be extracted from engineering documents. They relate to the interactions between streams and the processing units. Other causal relations are implicit in the plant design and needs to be identified when building library modules.

The extraction of knowledge from engineering documents needed for MFM modeling is accordingly possible but not straightforward. In the following we will discuss a plant example and its engineering documentation to explain the details of the knowledge extraction required.

4.2 A Plant Example

The example depicted in Figure 1 is a subsection of gas treatment process used in oil and gas industry. The process is simplified but is considered acceptable for the present purpose which is to discuss the problems of knowledge extraction from engineering documents.

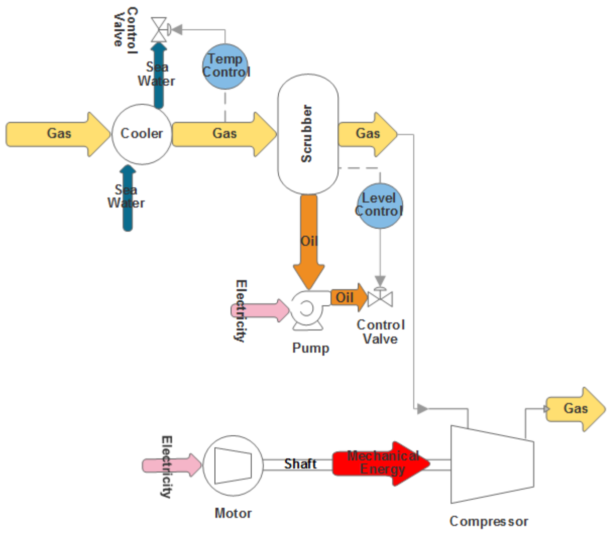

Figure 1. A gas treatment plant depicted as a chain of processing units and associated subsystems connected by material and energy streams.

The plant in figure 1 is depicted as a system composed of process units or functions connected by material and energy streams. Very similar representations are used by industry for plant documentation (e.g. process flow diagrams (PFD) or process and instrumentation diagrams (P&ID). This type of representations are effective for communication among design teams and the operators by explaining the functions of the system.

Note that the representation in Figure 1., does not include equipment like piping necessary for support of the streams. Piping is obviously a necessary means for the plant to work but is not strictly necessary for understanding to overall purpose and functions of the system. Information about piping would obviously be necessary to understand how the power plant is constructed.

Process flow diagrams (PFD) represent plant subsystems and their interconnections by material and energy streams. The streams are tightly connected with the overall plant purpose. The plants we consider are material and energy processing systems i.e. the primary goals and objectives of plant operation can be expressed by the streams and their properties. The subsystems connecting the streams can accordingly be seen as the means provided by the plant designer for the realization of the stream interactions required for achieving the plant purpose. The functions of these subsystems can accordingly be expressed by their intended effect on the streams.

Consider for example the scrubber in figure 1. Its function is to separate the oil and gas contained in the input gas stream. The causal interactions between the input and output streams and the scrubber is related to their spatial connections. We can accordingly read causal information from topological information in the PFD diagram. However, we cannot see how the causal interactions are related to the internals of the scrubber i.e. we are lacking information of the design principles used. Causal relations can in some cases be derived directly from the PFD. But in most cases the information is not there and need to be added to produce an MFM model which can be used to reason about causality.

4.3 Using Libraries for building MFM models

We propose to add the additional information about intentions and causality by using library modules to build the MFM models. The purpose of the library modules is to provide a mapping from the functions of process units (cooler, scrubber, pump, motor in fig 1) and streams in the PFD into an MFM representation for each unit including the causal relations and possible end-means decompositions into sub-functions.

The example in figure 1 illustrates that the identification of causal interactions (and related subsystem functions) may involve a whole-part decomposition of plant physical structure. Note also that the modeling also must take into account the whole-part decomposition of streams into sub-streams and phases in order to represent the functions and causal relations. Streams may be mixtures of several interacting material components and the material components may coexist in several phases (liquid, gas etc.). The functional aspects of interactions between components streams related to chemical reactions and thermodynamic equilibria needs accordingly also to be identified. This is a subject of ongoing research a DTU.

Functions in PFD's are accordingly defined in relation to the material and energy streams and their interactions. In this way the functions are different from functions in MFM. The functions in MFM called flow-functions are representations of basic transformations of mass and energy in time and space. Plant subsystems may realize a multiple of these basic transformations and the streams may include a multiple of components which interact (e.g. reactions). MFM represent accordingly functions on a higher level of detail than the functions represented in PFD's. The main advantage of the higher level of resolution using the basic transformations, is the ability to reason about cause-effect relations on a generic level. In comparison, reasoning using PFD's would require cause-effect information which would be specific for each process unit.

Note that functions of the process units and the streams are reciprocal and represent intentional structures related to the semantics of actions. Take the cooler in figure 1 as an example to understand what this means. A cooler whose function is to cool clearly has an implicit reference to an object or stream cooled and a stream which is doing the cooling i.e. the coolant. This example show that proper representation of plant design intentions require concepts by which these semantic aspects of actions can be clearly distinguished. The action theoretical basis of MFM (including roles) combined with the elementary functions provides such a semantics.

The development of library modules for the functions in figure 1 will accordingly require an interpretation of the information shown by which the causal and intentional relations between streams and process units including their parts and wholes are clarified and expressed in the action theoretical terms supported by MFM.

6 Conclusions

Above we discussed three different strategies for building MFM models. The first two strategies has been formulated on the basis of the foundation concepts of MFM in end-means and whole part abstractions. These strategies are generally applicable but it is concluded that they both are inefficient and error prone.

A third strategy is investigated which try to overcome these deficiencies and at the same time meet the needs of industry. The aim of the strategy is to use information from plant engineering documents to facilitate the building of MFM models. The main challenge is to acquire information about design and operational intentions which often are not accessible in explicit form. The solutions proposed is to use domain dependent libraries of MFM models to represent goals and functions of process units. The possibility of extracting the knowledge required for library building from engineering documents has been investigated. It is concluded that essential information about causal relations can be derived. It is also concluded that the principles of plant design and operation not available in the documents need to be included. An important purpose of the library is accordingly to combine explicit design knowledge from documents with implicit knowledge about implicit principles of design and operation.

Acknowledgement

The work presented here has been supported by Danish Hydrocarbon Research and Technology Centre. The

process example presented in figure 1 is kindly provided by Mr. P. Karnati, Eldor Technologies, Norway.

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