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Apply Functional Modelling to Consequence Analysis in Supervision Systems

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Abstract

This paper will first present the purpose and goals of applying functional modelling approach to consequence analysis by adopting Multilevel Flow Modelling (MFM). MFM Models describe a complex system in multiple abstraction levels in both means-end dimension and whole-part dimension. It contains causal relations between functions and goals. A rule base system can be developed to trace the causal relations and perform consequence propagations. This paper will illustrate how to use MFM for consequence reasoning by using rule base technology and describe the challenges for integrating functional consequence analysis to practical or online applications in supervision systems. It will also suggest a multiagent solution as the integration architecture for developing tools to facilitate the utilization results of functional consequence analysis. Finally a prototype of the multiagent reasoning system will be introduced.

1. Introduction

Prognostics are essential to industry for evaluation of system conditions during operation. It focuses on predicting future events when, for example, an anomaly happens in the system and it will no longer perform its intended function. In the context of supervision and operation support of engineering systems, consequence analysis could be essential both to estimate the potential threats and also for evaluating actions that are performed upon the system. The result of consequence analysis must be meaningful and reliable to make sense to the operators. The information provided need to include actionable suggestions for the operator. With nuclear power plants, complex automation systems are adopted, and quantitative dynamic models are explored to describe system behaviour. However, to make sense of the vast data that generated by the quantitative methods, analysis the functional task. Analyse the consequence propagation on the goal-function level is therefore a useful approach to help the operator interpret the system performance. An on-line consequence analysis tool based on functional models of the plant can facilitate the operation supervision system and risk monitoring, and provides meaningful prediction of the system behaviour.

The goal of this paper is to present the purpose and method of applying functional modelling approach to consequence analysis in supervision systems by using Multilevel Flow Modelling (MFM). This paper also explains how rule-based software tools can be developed to trace the causality in goal-function relations represent in functional models of the system and perform consequence propagation. It also illustrates how to use MFM for consequence reasoning by using rule-based system technology and describe the challenges in integrating functional consequence analysis into online applications in supervision systems. This paper also serves as a guideline for the first author's PhD project founded by Technical University of Denmark and Institute for Energy Technology, Halden, Norway.

The paper is organized as follows. The purposes of applying functional modelling in prognostic problems are introduced in Section 2. The featured modelling methodology MFM is briefly introduced in Section 3. In Section 4, general principles for developing rule-based system for consequence analysis by using MFM are demonstrated. In Section 5, several challenges are addressed concerning how to integrate the analytic tool in a real-time application and a multiagent solution is suggested as the integration architecture. The paper is concluded in the last Section.

2. Why to Use Functional Modelling

2.1 The scope of consequence in the paper

When talking about consequences in the safety and reliability engineering, the term often refers to the result of a realized hazard or critical event [1]. However consequence is also a relative term between two events that has causal relation in between. The realization of a critical event often trace back to anomalies in the system during operation as it causes, that means critical events shall be considered consequences to failures of system components. The consequence propagation that is discussed in this paper starts with one or multiple function anomalies during the system operation and ends at critical events such as system breakdown (goal failure). This is corresponding to the boundary of the system that functional model captures. The grey block in Figure 1 shows the scope of consequence analysis that is discussed in this paper.

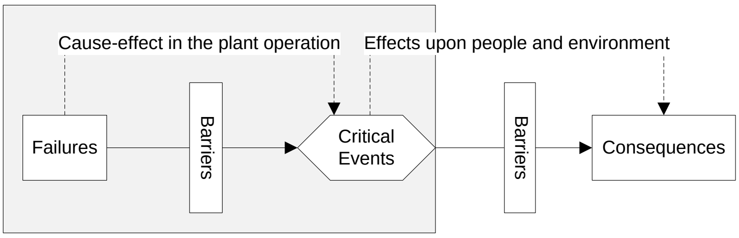

Figure 1. The scope of consequence analysis in the paper

This scope should be clarified so that the readers shouldn't confuse the topic in this paper with methods that used in the other part of consequence propagation, such as consequence modelling.

2.2 Functional modelling approach

System level analysis for an engineering system is becoming more essential as the level of complexity of the system grows. The correlation and interaction between system components has to be studied in order to design and operate a complex system. However, traditional analysis and methods for plant design and operation focus on structure layer's study rather than functional layer, which do not facilitate system level analysis. Traditional modelling approach representing complex system like nuclear power plant have problem to capture the causality between system functions and its operational goals. The study of cause-effect in the system is often based on temporal data and experiential knowledge with traditional methods. Functional modelling is a formalized method to represent purposes and cause-effect in a complex system. The means-end concept encrypted with functional modelling suggest that it can also indicate the temporal order of events propagation, because as commonly understood, means must be realized prior to the ends. A functional representation of the plant is a very good supplement to perceive goal function causality and therefore, provide means to analyse failures and evaluate plant conditions.

Functional modelling comprises concepts, methods and tools for representing the purposes and functional organization of complex dynamic systems. [2] Concepts of functional modelling are relevant to system design and operation because they provide systematic ways to common sense knowledge of the system, which is often hidden behind other model representations and much relies on individual operator's understanding of the operation purposes. Functional models have the capability to capture different perspectives and abstraction levels based on operation purposes.

The adoption of functional approaches to system design in industry has been slow despite its close relevancy. It is much due to the reason that there's lack of conceptual and methodological foundations. With the recent development within the field, some methodology such as Multilevel Flow Modelling (MFM) has been becoming mature. Besides modelling NPP by using MFM [3-6], several application oriented research based on MFM has been conducted including alarm design and risk monitoring. [7-12]

2.3 Consequence analysis in supervision systems

Supervision system performs online condition monitoring (OLM) of plant equipment, systems and processes include the detection and diagnosis of abnormalities in operation. [13] Many studies [14-16] have been devoted to sensor development and sensor data processing. However, synthesis and abstracting meaningful information from sensor data requires support of other technology. Since the 1990s, OLM techniques have been explored by the nuclear industry for equipment condition monitoring beyond sensors. [13] And besides the diagnostic indicators, prognostic indicators are also used to assess the plant condition. Qualitative models are considered and Human Machine Interface (HMI) becomes a major topic. A qualitative method such as fault tree analysis is adopted for diagnostic and prognostic purposes while the event trees are for prognostics in the nuclear industry. However these methods suffer from draw backs such as time consuming and very high requirement of operation knowledge. A systematic method need to be introduced to support the evaluation of operation condition based on the vast quantity of sensor data available.

Therefore, functional level of consequence analysis should be part of the tool repository for system evaluation and operation support. Report [13] suggests that MFM can be used with specially developed algorithms for a number of supervision tasks. With this modelling technique, both root cause analysis and consequence analysis can be performed due to the means-end concept of MFM. The MFM methodology is emphasize in the next section.

3. MFM and Reasoning in MFM

3.1 The MFM principles

Multilevel Flow Modelling (MFM) is a modelling method representing an industrial plant as a system which provides the means required to serve purposes in its environment. [17] MFMs incorporate goals and objectives of the system, functions and structures that describe the physical components, and relations between functions and structures. It also adopts a predefined graphical modelling language, with symbolic representation for objectives, functions and relations. A list of the common symbols for MFM objectives and functions/relations with an example of complete MFM model are showed in Figure 2. Notice that flow structures are represented by individual round corner rectangular in the model, which is not listed in the table as a symbol. They can be either an energy flow, mass flow, or control structure. The whole model example in the Figure 2 is an extended MFM model of watermill [17], which is a commonly used example for beginners of the MFM modelling. [18-20] provides more background for understanding MFM concepts.

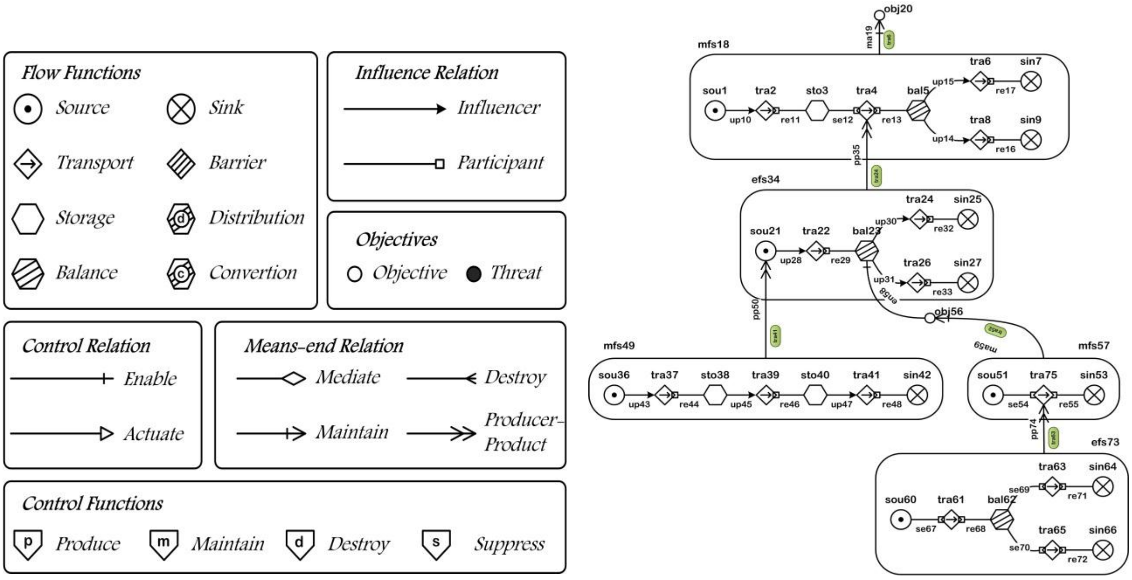

Figure 2. MFM Symbols and Model Example

3.2 MFM Reasoning

As exemplified in Figure 2, MFM constructs the model by using building blocks that correspond to functions and goals. It describes energy and mass flows in a physical system with different level of decomposition, and the representation is in an abstracted way which is independent of individual components that compose the physical system. MFM modelling is not only a way of representation, but also a convenient tool to analyse and reason about the system performance. Reasoning in MFM models is based on dependency relations between states of objectives and functions. The possible states of each MFM entity are listed in Table 1.

Function	Possible States
Source:	normal, abnormal
Sink:	normal, abnormal
Transport:	no flow, low flow, normal, high flow
Storage:	high volume, normal, high volume
Barrier:	leak, normal
Balance:	leak, normal, fill
Objective:	fulfilled, failed

Table 1. Possible state for MFM entities

The dependency relations defined in MFM are independent of the particular modelling object, and only based on predefined patterns [21]. The patterns are created by different combinations of MFM entities, states and the influence relations or means-end relations in between them. They are defined as cause-effect relations. Root cause reasoning and consequences reasoning for MFM are explained in [21]. The basic idea of consequence propagation is that an abnormal state of one function or objective influences another function or objective’s state in a MFM model along the MFM relations so that an effect path can be generated by continuing inferences until the path end at a defined critical failure in operation purposes. Note that MFM reasoning is based on patterns matching and proposition propagation. Therefore a rule-based system can be developed for MFM reasoning.

4. Rule-based System for Consequence Analysis

In computer science, rule-based systems are used as a way to store and manipulate knowledge to interpret information in a useful way. A typical rule based system has four basic components:

- A user interface or other connection to the outside world through which the knowledge of the system is collected and the input and output signal can be sent.
- A knowledge base that stores the system information and conditions.
- A rule base contains a set of rules, which is a specific type of knowledge base.
- An inference engine or semantic reasoner, which infers information or takes action based on the interaction of knowledge base and the rule base.

The overall architecture of MFM reasoning is illustrated in Figure 3. The reasoning system described here is used for consequence analysis. Similar tools can be developed by change the database and reasoning rules.

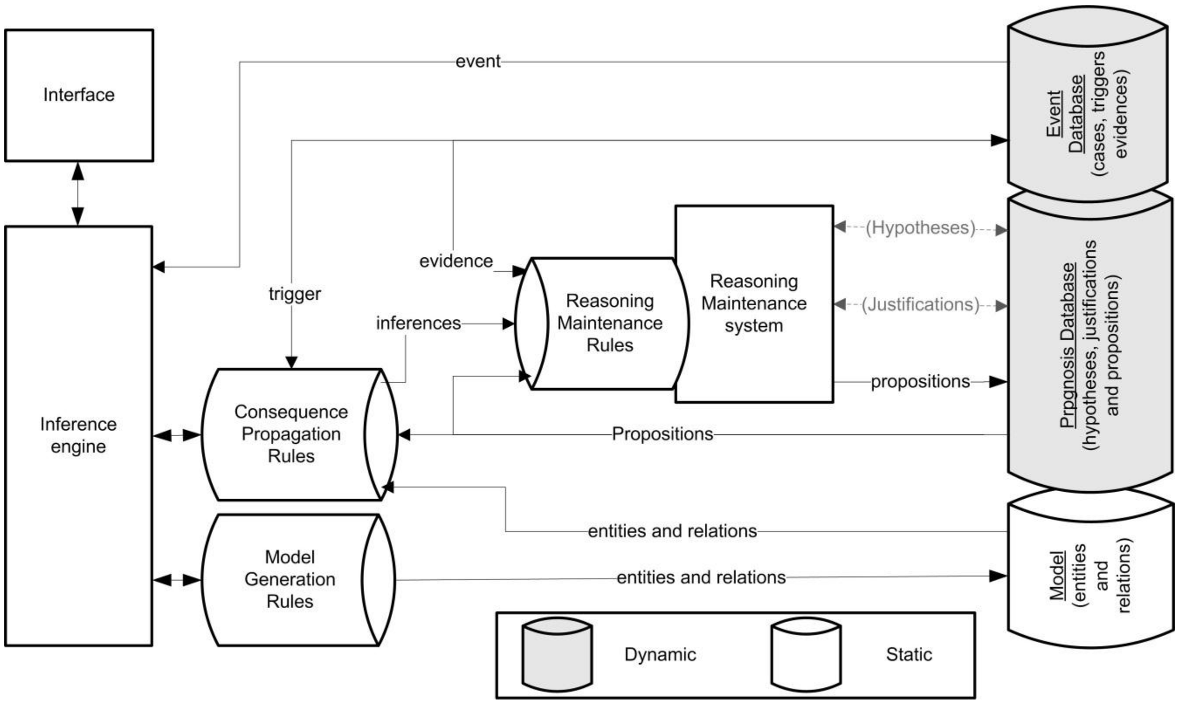

Figure 3. Reasoning System Architecture

As a FM model reasoning tool, the knowledge base of the system is separated into sub-databases, which can be classified as static databases and dynamic databases. The static represent all the plant knowledge that scripted into the plant model. The dynamic database stores event based knowledge sets either the plant condition observation or the deductive results. The rule base is also separated into subsets. This rule sets can be considered as executing modules with each used for a specific reasoning purposes. A combination of different rule bases can perform on one reasoning task. The reasoning maintenance system (RMS) in Figure 3 is a specialized function set which manages the interdependencies of the inferences. This means that when a new proposition is suggested by the inference engine, the RMS with its rules will check the truthfulness of the new proposition. Only if the new proposition is valid and consistent with the existing database, it can be accepted; and otherwise RMS will try to resolve the conflict before make change to the database. RMS is drawn in a separated block to emphasize its critical role in the inference engine. It is a generic module for rule-based system to maintain the access to the database. Other sub-function sets including model generation functions, event generation functions are not specified in the figure. An interface can be built to create static databases or give interactive input.

In general, the architecture described in Figure 3 can be applied to any given FM methodologies such as MFM. This architecture can be extended easily by define a new set of knowledge base, rule base, and also a new interface if necessary. A new knowledge base can be generated through either input interface or existing knowledge bases.

For MFM, root-cause analysis rule-based software (MFM Workbench) has been developed using the same architecture in Figure 3 by Morten Lind and a separate model drawing tool (MFMEditor) for MFM is developed by Harald P-J Thunem of IFE Halden.[22] The first version of integration of software had been done in December 2012 by using intermediate files for interaction between the Reasoner and the Editor. Documentation will be available soon. More sophisticate interaction strategy is under exploring.

5. Integration Challenges

5.1 Real-time reasoning challenges

The first challenge for real-time reasoning of consequence propagation in the system is to identify and handle the propagation loops. MFM models are constructed based on means-end concept. The temporal aspect is represented in MFM models because of its roots in means-end concept. Each set of measurements from a certain time frame reflect to a set of states in the functional model, and this set of function states will be considered as the cause of the states change in all future time. However, the future function state changes may give further influence on the functions that was the cause of this state changes. There are three kinds of consequence propagations.

5.1.1 Loop free propagation

The change of state in Function A influence the state in Function B and Function B have no further influence upon Function A or any of Function A’s upstream functions. This inference can be expressed in a simple IF-THEN sentence:

IF R(A(?),B(?)) and A(X), THEN B(Y).

R is the relation between function A and B. See Figure.4.

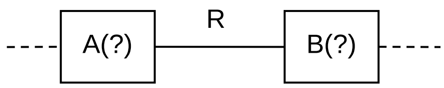

Figure 4. Function A and B with relation R1

5.1.2 Acceleration loop

The state X in Function A will result in state Y in Function B. The state Y in Function B will influence Function A or Function A's upstream functions and result in a more severe level of state X in Function A. That is to say both of the following IF-THEN statements are true:

IF R(A(?),B(?)) and A(X), THEN B(Y).

IF R(A(?),B(?))and B(Y), THEN A(X).

The cause and consequence in this kind of loops must be identified through the temporal information documented in the database. However the propagation loop is equally important because of its exacerbation nature.

5.1.3 Counteraction loop

The state X in Function A will result in state Y in Function B. The state Y in Function B will give a negative influence to state X of Function A and tend to cancel out the effect of the state deviation in Function A. That is to say both of the following IF-THEN statements are true:

IF R(A(?),B(?)) and A(X), THEN B(Y).

IF R(A(?),B(?)) and B(Y), THEN not A(X).

This situation may indicate a self-healing behaviour. However it may also suggest that the system is trying to cover up a physical failure and the problem might be temporarily balanced but will result in increasing stress of component or even more sever failure.

The above three propagation patterns should be properly identified by the reasoning tool. The challenge is not only a software develop problem but a theoretical problem for functional consequence reasoning. Resolve these propagation loops simply as reasoning conflicts may result in untruthful evaluation of the system. Note that the propagation loop cannot be complete in the same cause-effect time frame, but will only happen when the time proceeds. In the MFM Workbench, similar reasoning conflicts have been identified. The reasoning engine can solve conflicts in a single time frame (when propagation loop is considered invalid). How the reasoning should be continued with change of time frame is still open.

The second challenge in consequence reasoning for real time applications is to identify the primary consequence so that it can help the operator to evaluate the situation and make proactive actions to prevent the major failures. As discussed in section 2.1, the consequence propagation should end at a possible critical event in system operation. Without severity study and probability associated with the possible consequences propagation to identify the critical events, the analysis will be over scattered and meaningless for real-time operation.

Associating extra time prediction to functional models is the third challenge for real-time applications. MFM models can indicate the event sequences because it based on means-end concept that can indicate the event sequence. But time prediction is also important in a real-time environment. One solution is to associate historical data with the consequence propagation so that the operator can get a rough prediction of how long time will it take for the failure to propagate to a primary consequence (critical event).

The plant situation will be updated as the time proceeds. Hypothetical consequences may be proved untrue to the system so that the consequence path should be suppressed. Therefore, one may want to reason about the consequences according to the completeness of the plant information. However this problem is more important for online diagnosis to find the real root causes than for prognosis. However, as discussed in section 2.2, functional models also represent shift of operation purposes during different plant conditions. Therefore, another challenge in consequence analysis is to shift the focus and continue the analysis under plant representation changes.

5.2 Integration challenge

The consequence analysis can only provide certain information needed for plant operation. How to integrate the consequence analysis tool with other online support tool is also a challenging problem. Other tools such as root-cause analysis system are closely related to the consequence analysis and the result from the two sorts can be combined for action suggestion, condition monitoring or maintenance management. Higher level reasoning procedures may be required for further development. Therefore a standard architecture for integration is very important.

5.3 Multiagent architecture

To solve the integration problem, multiagent system is proposed to solve the task organization problem. A multi-agent system (MAS) is a system composed of multiple interacting intelligent agents within an operating environment. Multi-agent systems can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve. Supervision System is a very complex system that requires multiple independent functionalities sharing common knowledge of the plant. By packing each function unit into a software agent can provide a standard schema for information exchange and communication.

The multiagent architecture is also a good facility to solve the reasoning challenges by introducing more independent inference engines that can conduct reasoning tasks in parallel with each other. So each agent can handle a certain aspect of the reasoning task and focusing on its own assignment. The distribution of the reasoning task will introduce new challenge of multiagent planning. Reference [23] suggests using blackboard system concept to solve the task organization problem.

6. Conclusions

This paper explains the purposes of applying functional modelling to consequence analysis that to support the plant operation. It introduce a particular functional modelling methodology namely Multilevel Flow Modelling and the basic principles for applying MFM to consequence reasoning and how rule-based system can be developed to facilitate the reasoning. Challenges that will probably be encountered during the theory and tool development have been explained. Multi-agent solution has been suggested as integration framework for NPP online supervision system. Provide theoretical support and practical solutions for these challenges will be the main subject of the first author’s on-going PhD project. .

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