# Multi-level flow modeling and its applications


## GOFUKU Akio

*Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-Naka, Kita-ku, Okayama, 700-8530 Japan (fukuchan@sys.okayama-u.ac.jp)*



**Abstract:** Because functional information expresses the role of a component in a system and intentions of designers, it is very important in the design, operation, and maintenance of a large-scale engineering plant. The multi-level flow modeling (MFM) is a functional modeling framework that is most widely studied and applied. The MFM models an artifact to express the functional information of an artifact in a graphical format. This article introduces some techniques and systems to support operators of engineering plants and safety engineers based on MFM models of target systems.



**Keyword:** multi-level flow modeling; operator support; dynamic operation permission; safety analysis


## 1 Introduction

Functional information of components and systems is very important in the design, operation, and maintenance of a large-scale engineering plant because a designer designs an artifact under his / her intention. The artifacts that have different structures with the same intention, objective or purpose are sometimes recognized as similar ones. For example, an electric car has a motor and a battery system that are different components from an internal-combustion engine and its related system that are equipped with an ordinal car to generate driving torque. But it is recognized as a car because the purpose of it is the same as that of an ordinal car. Conversely, the artifacts with the same structure may have different purposes.

The intention of a designer is often expressed in terms of goals, purposes, expected behaviors, effects, and so on. Usually, an artifact has a main goal of describing designers' most important intentions, and designers combine hierarchically necessary components and parts to form a structure that realizes the goal. In other words, the components and parts have some roles for realizing the main goal. The roles are often called as functions.

A human tries to understand an artifact or an event that is new for him / her by changing his / her viewpoints and abstraction levels. Thus, dealing with the information from various viewpoints and abstraction level of a complicated system such as a nuclear power plant is crucially important not only for designing a system but also for managing an abnormal situation of it.

There are several advantages of using functional information of a system. First, the role and purpose of a component can be correlated with the system's behavior. Second, causal relations are represented in a functional model owing to the fact that a lower part in a functional hierarchy expresses some conditions to achieve its upper function. Third, a functional modeling framework usually has hierarchical modeling capability to handle a complicated engineering system. Fourth, a functional model involves linguistic representation that can be used to produce understandable explanation of the results of causal inference based on the functional model.

The author has studied function-based inference techniques[1 - 4] and their applications[5 - 13] to operator support systems, safety analyses, and case-based design support systems. In these techniques and systems, the MFM (Multilevel Flow Modeling) [14 - 18] is applied to construct base models.

In this article, a short summary of the MFM with its recent progress will be given in Section 2 first. And then major studies of the author of this paper by applying the MFM will be described in both Sections 3 and 4, although more details of the works were reported in Refs. [5-13].


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## 2 Multi-level flow modeling

The Multilevel Flow Modeling (MFM) [14 - 18] is a framework to express the functional information of an artifact in a graphical format. The MFM models a system in two dimensions, *i.e.*, means-end and whole-part dimensions. In the means-end dimension, it represents the relationships among system goals, sub-goals, and system functions to achieve goals / sub-goals. On the other hand, it represents a system by a multiple of descriptions on different levels of aggregation in the whole-part dimension. The symbols used in MFM have been recently expanded as shown in Fig.1 so as to take into account of semantic meaning of control system, although the studies of this author introduced in this paper use the old MFM symbol set frstly proposed by Lind[14]. See the backgrounds, details, and recent extensions of the MFM in the literatures by Lind[15 - 18].

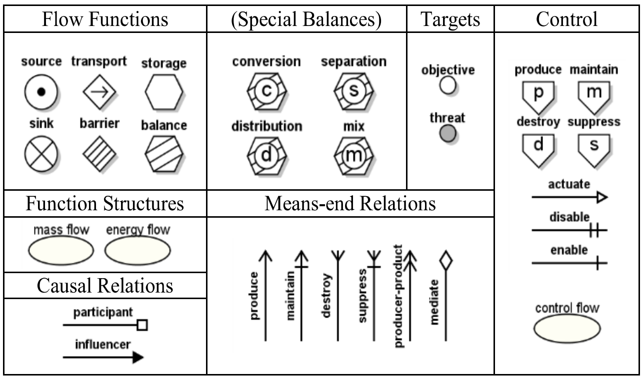



Fig. 1 Symbols used in MFM[5].

As an example, an MFM model of a cooler is shown in Fig. 2. The goal of the cooler is to cool the fluid of the primary side and it is expressed as the top objective. To attain the objective, the heat of the primary side is separated and some part of the heat is transferred to the secondary side. This is expressed in the energy flow structure placed in the lower of the objective. Because the water flows of primary and secondary sides are necessary for the continuous heat removal, the mass flow structures are placed in the bottom of the MFM model.

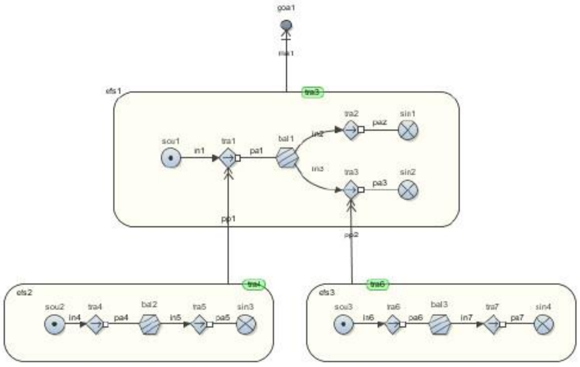


Fig. 2 An MFM model of a cooler.

## 3 Dynamic operation permission

### 3.1 Concept of dynamic operation permission

The main idea of the dynamic operation permission[8, 9] is to prevent obvious commission errors by human operators. A dynamic operation permission system lies as a human-machine interface for plant control. It lets human operators behave as they like so long as they conduct operations following operation manuals and various operation rules. The relation between human operators and a dynamic operation permission system is such that the system assists human operators to carry out suitable operations without eliminating creative ideas of human operators by alerting only their obvious errors and indicating the effects and side effects of the operation that they are going to take.

There are two main subsystems of a dynamic operation permission system. The first one is to decide operation permission according to the evaluation if the operation selected by human operators follows the standard operations described in operation manuals. If operators take an operation that is different from the one described in the operation manual, the operation permission is decided by the second subsystem. It conducts permission decision based on the prediction on what effects and / or influences the operation gives on future plant behavior. The future effects and influences are predicted by the causality estimation technique[1 - 3] based on the MFM model of a target system.

### 3.2 Dynamic operation permission by the prediction of the influence of an operation

There are desirable and undesirable behaviors after taking an operation and they are described in operation manuals as the purposes and notes of the operation. As shown in Fig. 3, the suitability of an operation is evaluated by comparing the predicted influences by applying the causality estimation technique with the desired and undesired behaviors for the next operation(s) to be conducted according to operation manuals.

If an undesired behavior is predicted to appear by carrying out the operation, a strong warning is indicated to human operators. If an undesired behavior is not predicted to occur and the predicted behaviors are consistent to desired behaviors of at least one of operation candidates, the operation is permitted with a comment. If no desired behavior is predicted to appear and no undesired behavior is predicted to appear by carrying out the operation, the operation is permitted with a warning. Note that the levels of warning can be changed depending on the policy of dynamic operation permission.

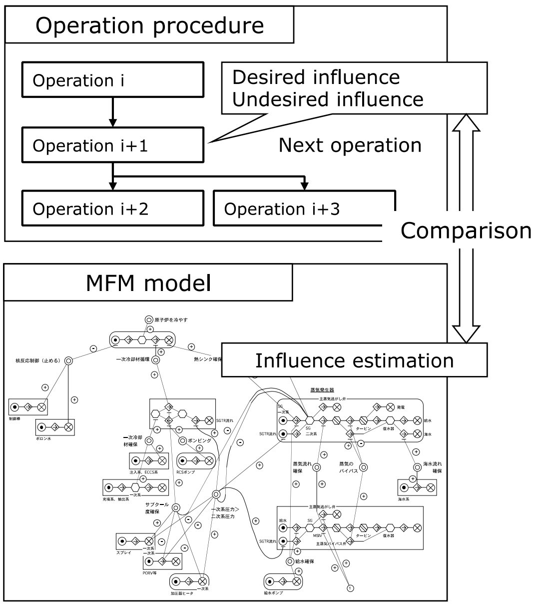
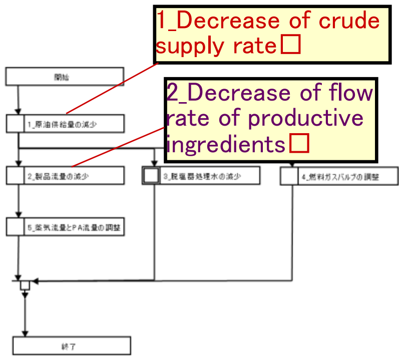


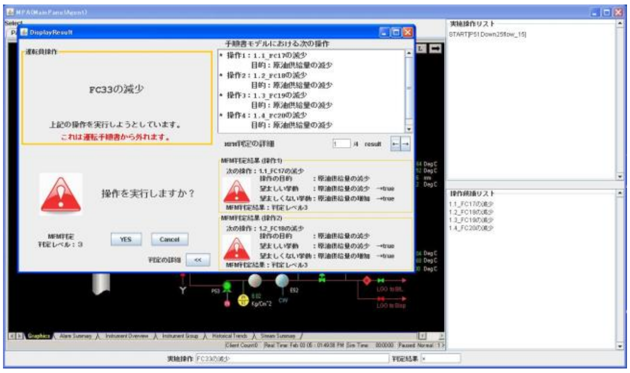

Fig. 3 Suitability evaluation.

### 3.3 Dynamic operation permission system for an oil refinery plant

A dynamic operation permission system for an oil refinery plant was developed on a distributed cooperative environment[6]. Figure 4 shows an example of the graphical expression of the typical operation procedure described in an emergency operation manual and the screen snapshot when an operator tries to take the operation of decreasing the flow rate of productive ingredients before decreasing the crude supply rate that is the next operation described in the operation manual. The applicability of the proto-type system is confirmed by the operation scenarios to decrease the input flow rate of crude by *ca.* 25% of its rated value, and to shutdown the plant.




(a) Typical operation procedure




(b) Screen snapshot

Fig. 4 Example of typical operation procedure and screen snapshot of proto-type system.

## 4 Quantitative causality explanation

### 4.1 Flow of quantitative cause-effect information generation

In the technique of dynamic operation permission, the explanation of the results of causality estimation why the operation is not permitted is important when the technique is applied to real plants. Quantitative causality explanation will be desirable for the purpose because an operator can understand the quantitative effect of a counter action.

Figure 5 shows the flow of quantitative explanation information generation of the effects of a counter action that the authors studied[10]. A numerical simulation and a qualitative reasoning based on an MFM model are conducted in parallel. The numerical simulation is executed in order to predict quantitative effects to recover plant condition or to mitigate the influence of an anomaly when the amount of a counter action is specified. The causality estimation technique[1 - 3] based on an MFM model generates the information on how the counter action contributes to the recovery of plant condition or the mitigation of the influence of an anomaly. The numerical values predicted by the numerical simulation are incorporated into linguistic explanation regarding the effect of the counter action that is generated by the influence estimation based on an MFM model.

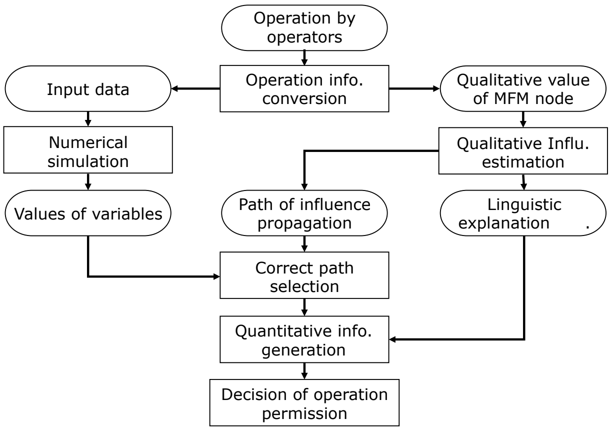



Fig. 5 Flow of explanation information generation.

### 4.2 Example of explanation generation

The technique is applied to an oil refinery plant. A static simulator[10] for the plant is developed to predict plant condition after taking a counter action. A performance degradation of naphtha extraction pump by 10% is considered as an anomaly. This anomaly induces the increase of the liquid level of the reflux drum. The counter action considered to suppress the increase is to decrease the fuel supply rate of the crude heater by 5%. By the effect propagation of the counter action in an MFM model, explanation sentences for the effect are obtained as shown in Table 1. The explanation sentences with parentheses are the ones of the influences to the downstream of the reflux drum.

**Table 1 Explanation sentences of the generated effect**

| |
|---|
| The fuel supply rate to crude heater is set to 0.95 [-]. |
| The heat supply rate of crude heater decreases to 3420 [kcal]. |
| The crude temp. from crude heater decreases to 339 [C]. |
| The gas flow rate from the top of main fractionator to air-fin cooler decreases to 35.9 [kg/s]. |
| The flow rate of Naphtha ingredient to reflux drum decreases to 33.1 [kg/s]. |
| (The off-gas flow rate to off-gas extraction system decreases to 2.75 [kg/s]). |
| (Naphtha flow rate to Naphtha storage tank decreases to 19.3 [kg/s]. |

## 5 Systematic FTA/FMEA

Fault tree analysis (FTA) and failure mode and effects analysis (FMEA) are widely applied in the safety evaluation of systems such as nuclear power plants, chemical plants, and aircrafts. However, education and training are required to learn how to analyze systems by the FTA / FMEA. A human analyzer needs to have expert knowledge of a target domain. In addition, the quality of FTA / FMEA is unreliable and an FTA / FMEA result is difficult to update when a target system is reconstructed because human analyzers conduct the FTA / FMEA.

The principle of FTA / FMEA is to trace comprehensively cause-effect relations among anomaly causes and undesirable effects. It is akin to the causality estimation technique[4] although some additional information and data such as sensors and faults considered are required.

The systematic FTA and FMEA techniques were developed and applied to a simple coolant plant of nitric acid and the design of a fuel supply system of a launcher of medium-sized space rockets[11- 13]. In the application of the systematic FTA technique to the simple coolant plant, the FT generated by the technique is confirmed to be commensurate to the reported FT [19] although the consideration of control systems is a future problem. In the application to the design of a fuel supply system of a launcher of medium-sized space rockets[11, 12], the authors noted that the techniques can be used to review the MFM model constructed and to refine the design of the facility itself as well as to conduct safety evaluation as shown in Fig. 6.

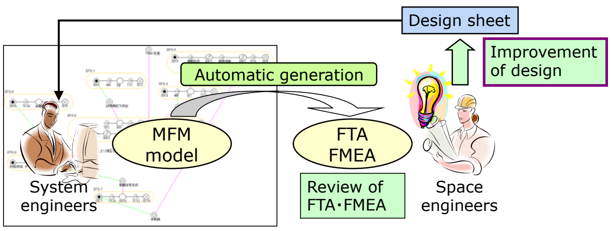



Fig. 6 Applications of systematic FTA/FMEA.

## 6 Concluding remarks

This article introduces some techniques and systems that the authors studied using MFM models as base models. From the applicability evaluation of the techniques and systems, MFM can be said as a strong tool of expressing functional information of an artifact, constructing a base and common model for reasoning, and supporting the activities of plant operators, safety engineers, and designers of engineering systems.

The authors are now developing a technique to derive in real-time a plausible operation procedure when an abnormal situation that its counter operations are not prepared. In the technique, a functional model based on the MFM is the key base data for the derivation because components that have similar functions as those of the components considered in prepared operation procedures should be found.

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