Applications of MFM to intelligent systems for supporting plant operators and designers: function-based inference techniques

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: An artifact is designed based on the intention of designers. The functional information is a description of an artifact in a high level of abstraction. It represents the designers' intention by explaining why a component exists in a system. A human tries to understand an artifact or an event that is new for him / her by changing his / her viewpoints and abstraction levels. Representing functional information is important in understanding an anomalous situation of a system, finding a plausible way to solve a problem when the counter actions prepared are not successfully used in some reason, and designing an artifact. This article first introduces the conception of function, the outline of the MFM that is a functional modeling framework, and an MFM model the authors developed. Thereafter, three function-based inference techniques based on a model by the MFM are presented. The applications of the three techniques and the findings obtained from the studies by authors will be presented in another article.

Keyword: function; multi-level flow modeling; function-based inference; causality estimation; function flow simplification; explanation generation

1 Introduction

A designer designs an artifact under his / her intention. Under the intention, he / she determines the parts and structure of an artifact. The artifacts that have similar structures are sometimes recognized as different tools. For example, a pencil and a stick have similar shape. Usually, a pencil is recognized as a writing tool. However, a musician may consider it to be a baton or a drumstick. An oriental person may view it to be a part of chopstick. A stick may be used to draw something on the ground. Conversely, artifacts that satisfy the same user requirement sometimes have different structures. An airplane and a helicopter are good examples. These few examples make us realize the first feature of multiplicity that a function has. That is, the artifacts with the same structure may have different purposes and the artifacts having the same purposes of usage may have different structures.

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 necessary components and parts to make a structure realize the goal. The components and parts have some roles for realizing the main goal. The roles are often called as functions.

The components and parts of an artifact are combined hierarchically and form a specific structure each having its own function. From these structural features, the second feature of a function that functions have hierarchical correlations with each other is understood. Therefore, functions can be modeled in a hierarchical way and connected to the main goal of an artifact. In a large-scaled engineering system, goal *per se* is expressed by the combination of some sub-goals resulting in the expression of the intention of designers by a hierarchical combination of goals and functions relating with the structure of an artifact.

A human tries to understand an artifact or an event that is new for him / her by changing his / her viewpoints and abstraction levels. When an abnormal situation happens, he / she first tries to find its cause by gathering the information directly related with the cause. However, if he / she does not find symptoms directly related with the cause, he / she then tries to gather the information that exhibits normal and deletes the parts or events considered to be normal

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from a list of candidates of the cause. A human also tries to understand a complicated artifact or event from a macroscopic viewpoint at first. Thereafter, he / she proceeds to its understanding from a microscopic viewpoint. Thus, dealing with the information from various viewpoints and abstraction level of a complicated artifact such as a nuclear power plant is crucially important not only for designing an artifact but also for managing an abnormal situation of a plant.

The author has studied several operator support systems[1-4] based on models by the MFM (Multilevel Flow Modeling) [5 - 8] in cooperation with companies. In the human media project[9], a semantic information presentation agent[1] was developed to computerize a part of model-based thinking process of human operators and to support their situation awareness. An MFM model of an oil refinery plant was used as a base model and a technique to find plausible counter actions was developed[10, 11]. The authors proposed a framework of dynamic operation permission[2, 3] to reduce the commission errors in nuclear power plant operations by leaving human operators behave as they desire so long as they follow operation manuals and various operation rules. In a dynamic operation permission system, it is necessary to estimate the effect of an action by human operators on plant future behavior to evaluate the validity of the action and the estimation is carried out based on an MFM model of the plant. The author joined a project to develop a diagnostic system[4] of a launcher of small space rockets and applied the effect estimation technique to the influence estimation of an anomaly of the launcher. The authors also proposed systematic techniques[12, 13] of the FTA (Fault Tree Analysis) and FMEA (Failure Mode and Effect Analysis) that are popular safety evaluation techniques for the design of a complicated engineering system and applied the technique to a design of the fuel supply system for the launcher.

Although a complicated inference can be executed in a computer system by the advancement of computer technologies, it becomes more difficult for human operators to understand the results of the inference especially during a time-restricted anomalous plant situation. The authors proposed a conception of co-operator[14] for a key conception of human-centered operator support systems. An important role of a co-operator is to communicate with human operators in a natural way. From this viewpoint, an explanation technique of a model-based inference result is studied and a generation technique of essential explanation has been proposed[15]. For generating essential explanation, a technique called function flow simplification[16] is applied to obtain a macroscopic functional model from a microscopic one. The function flow simplification technique was originally developed for a case-based design of a plant[16] that effectively utilizes past designs. The essential explanation generation technique is improved through complimenting quantitative information obtained by a numerical simulator with qualitative cause-consequence information based on an MFM model[17].

The proposed techniques based on MFM models and their applications in the engineering field, particularly to operator support systems will be presented in two articles. This article first introduces the conception of function, the outline of the MFM, and an MFM model the authors developed. Thereafter, three techniques based on a model by the MFM are presented. The applications of the three techniques and the findings obtained from the studies by the authors are described in the next article.

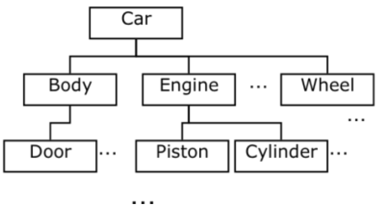
2 Importance of usage of functional information in engineering systems

2.1 Conception of function

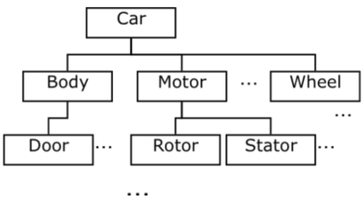
The conception of function is generally difficult to comprehend due to the fact that it is an abstract conception and various definitions may arise depending on researchers. In this subsection, the meaning and significance of the function is explained by using a simple (but convenient) example of cars. The definition of function in this article is thereafter represented.

Let us consider what a car is and how it is represented. Some people may be reminded of a classic car that the driving force is obtained from a gasoline engine. Also, some people may be reminded of a new electric vehicle that does not emit CO_2

during driving albeit the electric power may be generated by a fossil thermal power plant. A gasoline engine car can, in principle, be represented by the hierarchical diagram shown in Fig. 1 (a) by focusing on its structure. In a similar way, an electric car can be represented as shown in Fig. 1 (b). Although these types of cars have many similar elements in structural hierarchy, there is a significant difference when you consider how they generate their driving force. A classic car has a gasoline engine, *vide infra*, an electric vehicle has a motor. The structure and principle between a gasoline engine and a motor are entirely different. Based on the difference of the main component for obtaining the driving force, subcomponents of the cars are naturally different. However, we can consider a classic car and an electric vehicle as cars since we know that they serve the same purpose or function, that is, they are used as means to travel or to carry baggage. From the viewpoint of purpose, the same hierarchical model can be drawn for a classic car and an electric vehicle as shown in Fig. 2. In the figure, a gasoline engine and a motor are represented as means to obtaining driving force.



(a) Gasoline engine car



(b) Electric vehicle

Fig. 1 Structure models of a car and an electric vehicle.

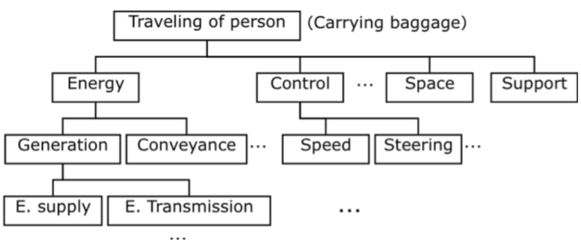


Fig. 2 A functional model of a car.

Based on the simple example, it is clear that we naturally recognize an artifact from a functional viewpoint although the importance of the conception of function is not emphasized except in the field of system design. In the field of plant operation, the activity of "thinking why" to ask why-questions for several times is recommended in order to manage an abnormal situation. The author considers that the essence of "thinking why" is to understand an artifact from a functional point of view.

As described earlier in the Introduction, an artifact is designed under the intention of designers. Therefore, the structure of an artifact reflects the intention and the design considerations of designers. The functional information is a description of an artifact in a high level of abstraction. It explains why a component exists in a system[18]. In other words, the functional information can be a language to bridge a human and a machine as it corresponds with the goal-oriented thinking and the understanding process of a human.

The necessity of representing a system from a functional level was pointed out by Aristotle in the ancient Greek times[19]. A function is given dependent on a context and is represented by a verbal expression. A function is recognized in relation with a system boundary. That is, a weak connection part in a functional hierarchy is a system boundary[19]. In the simple functional model of a car, structural boundaries of a car are naturally understood among the functions such as energy generation, energy conveyance, steering, and so on.

Although a function is defined in different ways depending on researchers, the author defines a function as the behavior selected and modified by an interpreter by extending its definition by Lind as the useful behavior[5]. In this definition, the term "modified" means the modification of representation. Lind also discusses the concept of function and points out that the functional concept is useful as it gives focus on selected aspects of problem-solving situations[20]. In view of this, a function has inter-subjective aspects and a functional model is a sub-set of a behavioral model.

2.2 Multilevel flow modeling

The Multilevel Flow Modeling (MFM) [5-8] is a framework to express the intention of an artifact that designers give from the viewpoint of goals and functions. The MFM represents system functions in a graphical format. Due to the fact that the backgrounds, details, and recent extensions of the MFM are presented in the literatures by Lind[5-8], this subsection outlines the basic MFM[5, 6].

The MFM represents the intentional aspects of a system from the standpoint that a system is an artifact, that is, a man-made purposeful system. The MFM models a system in two dimensions, *i.e.*, means-end and whole-part dimensions. It also represents the relationships among system goals, sub-goals, and system functions to achieve goals / sub-goals by the means-end dimension. Conversely, it represents a system by a multiple of descriptions on different levels of aggregation according to the whole-part dimension.

System functions are represented by a set of mass, energy, activity, and control flow sub-structures on several levels of abstraction. Mass and energy flow sub-structures model functions of systems. On the other hand, activity and control flow sub-structures model operator actions and control system functions. The MFM represents goals / sub-goals, functions, and their correlations by using a set of symbols based on a primitive function concept. Figure 3 shows the flow function concepts (excluding control functions) and their associated symbols in mass and energy flow sub-structures. In the figure, a symbol of conversion is included by the author in order to represent a change of energy form, for instance, from thermal energy to electric energy[21]. Recent extension of the MFM by Lind also includes the conversion function in different symbols[7].

The MFM also represents the relations among functions and the components that realize the functions by realization relations although an MFM model will become an intricate diagram and will be incomprehensible to a human. The author proposed to represent the information of goals, functions, and components separately in goal, function-goal, and function-structure layers[21].

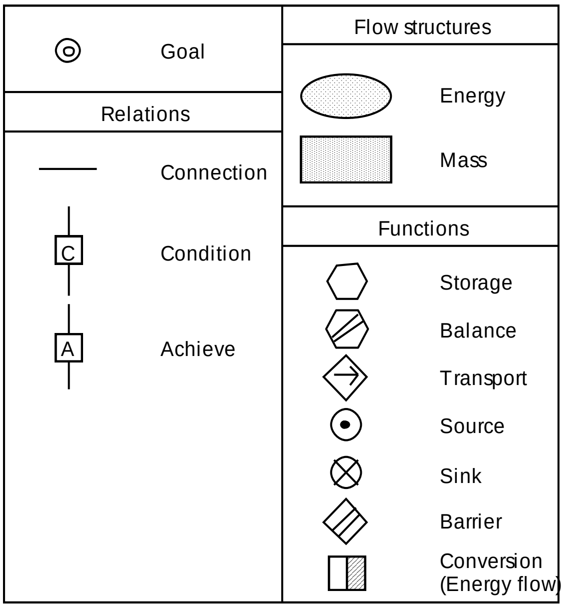


Fig. 3 Symbols used to construct an MFM model.

2.3 Importance of using functional information in engineering plants

There are several advantages of using functional information of a system. First, the role and purpose of each component can be correlated with the system's behavior. This means that functional information that is necessary to control a system particularly in an abnormal condition can be displayed to human operators. The functional information is also important in a design activity. Therefore, an explicit representation of the relations among functions and components and parts of an artifact is indeed useful. 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 in a functional model. By this characteristic feature, it can be possible to estimate qualitatively the effect and influence of an operation or a system failure by using a functional model of the system. Third, a functional modeling framework usually has hierarchical modeling capability to handle a complicated engineering system. The feature will aid to understand a system's behavior and to examine the similarity of two systems in various levels of aggregation. Fourth, a functional model involves linguistic representation that can reduce semantic gap in communicating the results of causal inference based on the functional model by a computer to human operators or designers.

However, a functional model does not directly include quantitative information that is pivotal in understanding the detailed behavior of an artifact. The authors proposed a combination of a qualitative inference based on an MFM model and a numerical simulation to handle the disadvantage[17]. Moreover, it has a difficulty of dynamically changing its model when the function of a system or component changes.

2.4 MFM model of an oil refinery plant

As an example of MFM models the authors developed, an MFM model[1, 3, 17] of an oil refinery plant is introduced in this subsection. The oil refinery plant is composed of a crude tank, a desalter, heat exchangers, a pre-flush drum, a crude heater, a main fractionator, three strippers, a reflux drum, an air-fin cooler, coolers, pumps, and valves.

The crude is continuously supplied to the plant. After increasing the temperature of the crude by heat exchangers, the salt ingredient is removed from the desalter. The desalted crude enters the pre-flush drum after heating by heat exchangers. The gas is separated and directly enters the main fractionator. The liquid crude enters the crude heater and is heated. Thereafter, the heated crude enters the main fractionator. The productive ingredients of kerosene, light gas oil, and heavy gas oil are extracted from the main fractionator on basis of the differences of their boiling temperatures. They are then introduced to their corresponding strippers after which, the mixed lighter productive ingredients are extracted and returned to the main fractionator. The lightest productive ingredients are extracted from the top of the main fractionator and are separated into off gas and naphtha in the reflux drum.

A simplified version of MFM models of the oil refinery plant is shown in Fig. 4. In the figure, the sub-goals and functions of extracting productive ingredients are expressed for only naphtha and kerosene ingredients for brevity reasons. A brief explanation of the main part of the model is as follows:

The prime goal is the obtenance of productive ingredients. To achieve the goal, the mass flow sub-structure MFS-0 is constructed by expressing the flow of crude through the plant. The sub-goal Go-2 is to heat the crude to separate the productive

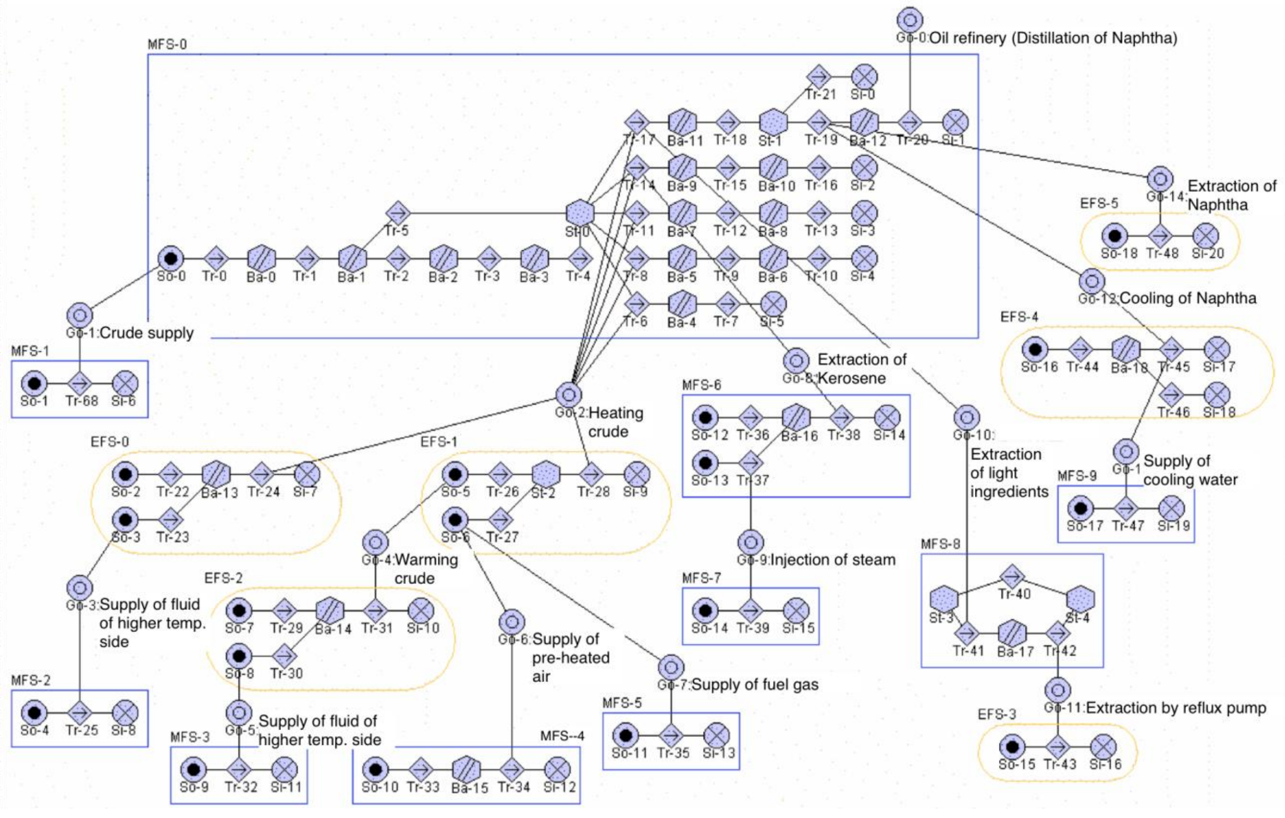


Fig. 4 MFM model of an oil refinery plant.

ingredients. The achievement of each mass transport function from the mass storage St-0 which corresponds to the mass storage function of the main fractionator is influenced by Go-2. This therefore means that the mass transport functions from St-0 are conditioned by Go-2. The sub-goal Go-2 is achieved by the energy flow sub-structure EFS-1 that expresses crude heating function of the crude heater. The energy source function So-5 in EFS-1 corresponds to the energy involved in the crude at the inlet of the crude heater. On the contrary, the energy source function So-6 corresponds to the heat generated in the crude heater. The heat is generated by supplying both the air (Go-6) and fuel gas (Go-7). The extraction of gas ingredient from the main fractionator and the return of some part of it by the reflux pump is expressed by the sub-goals Go-10 and Go-11 and the flow sub-structures MFS-8 and EFS-3. The cooling of the gas from the top of the main fractionator to obtain naphtha is expressed by the sub-goals Go-12 and Go-13 and the flow sub-structures EFS-4 and MFS-9. The energy required to extract naphtha by the naphtha extraction pump is expressed by the sub-goal Go-14 and the energy flow sub-structure EFS-5.

3Function-based inference techniques

3.1 Causality estimation based on an MFM model

Owing to the characteristic feature that a functional model expresses causal correlations, a qualitative influence estimation technique[10, 11] based on an MFM model of a plant was proposed. The technique was applied to find plausible counter actions[10, 11] to estimate the effect of a counter action and the influence of an anomaly[10, 11, 14], and to execute an FTA[12, 13] and an FMEA[13].

An MFM model qualitatively represents plant behaviors relating them with goals / sub-goals of the plant and causal relations among goals / sub-goals and functions. The represented causal relations depend on the function primitives of the MFM. For example, a transport function represents the capacity of physical system to transport mass, energy, or information. By the definition of the transport function in the MFM, the amount of input flow is the same as that of the output flow. There are three possibilities of the trigger inducing a change of achievement for the function. Such possibilities are (1) a change of the function achievement, (2) a change of input flow, and (3) a change of output flow. For instance, the possibilities correspond to a pump anomaly, a change of upstream flow rate, and a change of downstream flow rate when a pump realizes a transport function, respectively. An increase of function achievement means that the flow through the transport function increases. An increase of the flow induces an increase of output flow and inevitably induces an increase of the input flow. When the input flow increases, the output flow increases and the situation can be interpreted as an increase of the function achievement. On the other hand, an increase of output flow can be interpreted as an increase of function achievement which likewise induces an increase of the input flow. A similar trend can be considered in the case of decreasing functional achievement, input flow, and output flow. In consideration of the causal relations for all function primitives of the MFM, the influence propagation rules are derived as shown in Table 1 (a). Basically, the direction of influence propagation is the direction of flow. The propagation rules of reverse direction are derived as the inevitable changes caused by the propagated influence. Conversely, the demand propagation rules shown in Table 1 (b) are applied when possible changes of function achievements and flows are estimated, for instance, in finding plausible counter actions[10, 11] to mitigate the influence of an anomaly. The rules are derived in the same way employed in deriving the influence propagation rules by only considering possible changes.

In addition to the MFM model of a system and the causality propagation rules, the causality estimation based on an MFM model may need the following types of knowledge (shown in Table 2) depending on the application.

The function-goal knowledge (F-G-knowledge) and the goal-function knowledge (G-F-knowledge) are crucial in propagating the influence or demand to other flow sub-structures through sub-goals. F-G-knowledge is a piece of information that represents a change of the achievement of the goal achieved by a function in a qualitative or quantitative expression. On the other hand, G-F-knowledge is a piece of information that represents a change of function achievement of the function conditioned by a goal in a qualitative or quantitative expression.

Table 1 Causality propagation rules

(a) Influence propagation rules

Function	Change		Influence	
Source	Function +	-	Output +	-
	Output +	-	Function +	-
Sink	Function +	-	Input +	-
	Input +	-	Function +	-
Transport	Function +	-	(Output & input) +	-
	Input +	-	(Output & function) +	-
	Output +	-	(Input & function) +	-
Storage	Function +	-	An output -	+
	An input +	-	Function +	-
			An output +	-
			One of other inputs -	+
	An output +	-	Function -	+
			One of other outputs -	+
			An input +	-
Balance Conversion	Function -		An output changes	
			An input changes	
	An input +	-	An output +	-
			One of other inputs -	+
	An output +	-	One of other outputs -	+
			An input +	-
Barrier	Function -		Flow appears	
	A change of input or output		No affection	

(b) Demand propagation rules

Function	Change		Influence	
Source	Output +	-	Function +	-
Sink	Function +	-	Input +	-
Transport	Output +	-	(Input & function) +	-
Storage	Function +	-	An output -	+
			An input +	-
	An output +	-	Function -	+
			One of other output -	+
			An input +	-
Balance Conversion	An output +	-	An output -	+
			An input +	-
Barrier	Function -		Flow appears	

Behavior knowledge (B-knowledge) is a piece of information of behavior that is not recognized as a function in a normal operational condition. The knowledge is used in the technique of finding plausible counter actions[10, 11]. For instance, devices for constructing a plant include functions for avoiding failed conditions, and some of such functions may hardly influence achievement of the main goal. Therefore, such functions are not represented in an MFM model. However, devices whose functions are not represented could be operated in order to deal with a failure. In such a case, information concerning the function of such device is treated as a B-knowledge.

Table 2 Types of additional knowledge

Additional knowledge	Description
Function-goal knowledge (F-G-knowledge)	Qualitative achievement rate of goal by the related function in an achievement relation
Goal-function knowledge (G-F-knowledge)	Qualitative achievement rate of function by the related goal in a condition relation
Behavior knowledge (B-knowledge)	Behavior not being recognized as function in normal operational condition
Operation knowledge (O-knowledge)	Knowledge of possible operation and how a component behaves upon being operated
Component behavior knowledge (CB-knowledge)	Knowledge of the relation between anomaly and behavior of component when an anomaly happens in the component
Dangerous situation knowledge (DS-knowledge)	Situation of system presumed to be dangerous

Operation knowledge (O-knowledge) is a piece of information that represents how the function of a component qualitatively or quantitatively varies when the component is operated. The knowledge is utilized in the techniques of finding plausible counter actions[10, 11], and evaluation of the effect of an operation[14]. Component behavior knowledge (CB-knowledge) is a piece of information that represents the relation between a failure and behavior of a component when the failure occurs in the component. This knowledge is used to evaluate the influence of an anomaly in the techniques of finding plausible counter actions[10, 11], dynamic operation permission[2, 3], systematic FTA[12, 13] and systematic FMEA[13]. Dangerous situation knowledge (DS-knowledge) is a piece of information that represents information of systems presumed to be dangerous together with their orders of priority. This knowledge is used to determine the anomaly or abnormal situation to be considered in the techniques of finding plausible counter actions[10, 11], systematic FTA[12, 13] and systematic FMEA[13].

An outline of causality estimation based on an MFM model is explained for a case of evaluating the effect of an operation. Figure 5 below shows the steps of causality estimation. First, the direct effect of an operation is given to the function that corresponds to the component to be controlled by the O-knowledge. Second, the functional effect is propagated in a flow sub-structure using the influence propagation rules. Third, the effect on the goal connected to a function by an achievement relation is estimated by the FG-knowledge. Thereafter, the effect is propagated to the function in the upper flow sub-structure connected to the goal by a condition relation using the GF-knowledge. By repeating steps 2 to 4, the effects of an operation on the entire plant behaviors are estimated.

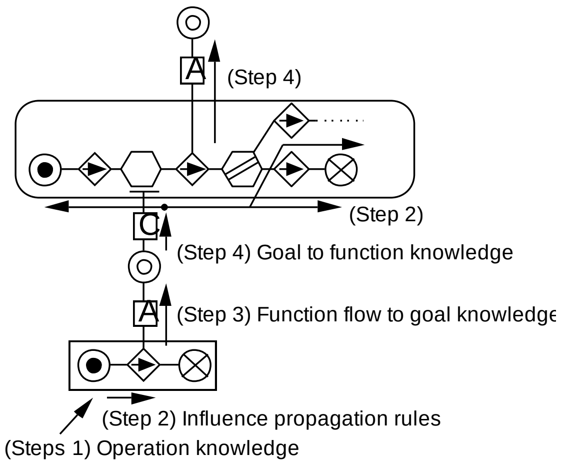


Fig. 5 Estimation of effects of an operation.

3.2 Simplification of an MFM model

In the model-based reasoning, the accuracy of inference results will increase by using a detailed model. However, the results will be difficult to comprehend by a human owing to the long and complicated inference steps. The understandability of the inference results is important in supporting human operators of plants especially at the occurrence of an anomaly. In view of the fact that human operators have deep knowledge of plants, some inference steps can be omitted for their understanding of inference results. This subsection describes a systematic technique termed as function flow simplification[16] to change the aggregation level of an MFM model.

Through the function flow simplification, a complicated function flow is simplified to an equivalent simple function flow. There are six patterns of the function flow simplification as shown in Fig. 6. They are:

(a) Simplification to a transport function,
(b) Simplification of parallel transport function,
(c) Simplification of a function flow loop,
(d) Simplification to a storage function type 1,
(e) Simplification to a storage function type 2, and
(f) Simplification of parallel function flows.

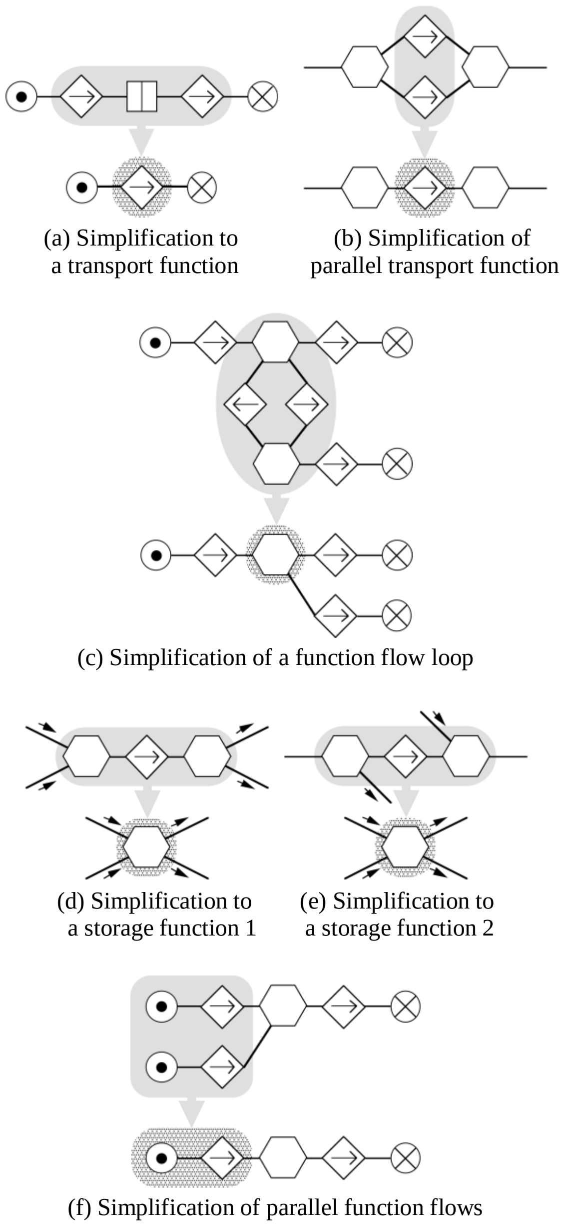
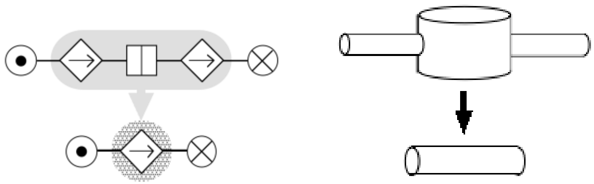


Fig. 6 Patterns of function flow simplification.

As an example, Figure 7 shows the simplification to a transport function. Between two transport functions, if any of the storage, balance or conversion function exists, the three functions (transport function, a function of storage, balance or conversion, and transport function) can be simplified into a transport function. This function flow simplification corresponds to a macroscopic view such that a system composed of a tank and two pipes connected to the entrance and exit of the tank can be considered as a pipe. As is apparent from the example, each type of function flow simplification is composed of two rules: (1) adaptation rule(s) and (2) simplification operation rule(s).



(a) Function flow simplification (b) a tank with two pipes

Fig. 7 Simple example of simplification to a transport function.

By the function flow simplification, the level of aggregation of the corresponding structure model changes from microscopic to macroscopic levels. When we make a structure model of a system, the structure is hierarchically modeled and each element of the model is related to a function or a set of function. The name of an upper element is sometimes not defined (except lowest nodes). It should be obtained by combining the names of the lower nodes.

The technique of function flow simplification is applied to change the aggregation level of function flows in an MFM model. However, the simplification of a part of an MFM model including goals and multiple function flow structures is considered a future problem.

3.3 Generation of explanation sentences of inference process

Owing to the fact that a goal in an MFM model is given a linguistic label and each function primitive has its own abstract name, it is not so difficult to generate the explanation sentences of the process of causality estimation. The explanation of the estimation process is generated by ordering the statements of the change of each function and goal along the process of the causality estimation.

The explanation sentence is generated based on the following format. If the starting node of causality estimation is a counter action and the causality estimation is qualitative, the explanation sentence is expressed by:

[Quantity] of [Flow instance] of/to/from
[Structure] is [Change],

where [Quantity] is the variable that expresses the quantity of [Flow instance] such as flow rate, temperature, supply rate, *etc*. and [Flow instance] is the name of flowing instance such as crude, feed water, and so on. The [Structure] is the name of the component undertaking the counter action. The [Change] is “increased” or “decreased” depending on the qualitative result of the operation. If the causality estimation is quantitative, then the explanation sentence is expressed by:

[Quantity] of [Flow instance] of/to/from
[Structure] is set to [Value] ([Unit]),

where [Value] is a quantitative value of the counter action. The [Unit] is automatically selected corresponding to [Quantity].

On the other hand, the explanation sentences for other function nodes are expressed by

(a) qualitative case:
[Quantity] of [Flow instance] of/to/from
[Structure] [Change],

where [Change] is “increases” or “decreases” depending on the causality estimation result.

(b) quantitative case:
[Quantity] of [Flow instance] of/to/from
[Structure] increases / decreases to
[Value] ([Unit]).

For a goal node, the explanation sentence is generated in the form of :

[Goal content] increases / decreases

where [Goal content] is the linguistic label of the goal.

4 Concluding remarks

An artifact is designed under the intention of designers. The structure of an artifact reflects the intention and the design considerations of designers. The functional information is a description of an artifact in a high level of abstraction. It represents the designers' intention by explaining why a component exists in a system. The conception of function has two characteristic features: multiplicity and hierarchy. A human tries to understand an artifact or an event that is new for him / her by changing his / her viewpoints and abstraction levels. Representing functional information is crucially important in the quest to understand an anomalous situation of a system, finding a plausible way to tackle a problem when the counter actions prepared are not successfully used for some reasons, and designing an artifact.

This article first introduces the conception of function, the outline of the MFM that is a functional modeling framework, and an MFM model the authors developed. Thereafter, three function-based inference techniques based on a model by the MFM are presented. The authors applied the techniques to diagnostic systems of plants, operator support systems, systematic safety analyses, and case-based engineering designs.

We will present in another article some applications of the three techniques and the findings obtained from the studies by the authors.

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