Support systems of plant operators and designers by function-based inference techniques based on MFM models

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Abstract: The usage of functional information is important in plant operation and system design because functional information expresses the role of a component in a system and intentions of designers. The previous article introduced three function-based inference techniques *i.e.*: (1) causality estimation technique based on an MFM model, (2) function flow simplification of an MFM model, and (3) generation of explanation sentences for inference process. This article first discusses the concept of a co-operator as a human-centered operator support system for future plants. It then introduces techniques and systems that apply the function-based inference techniques: a technique to find plausible counter actions for an anomaly, a dynamic operation permission system to reduce commission errors by human operators, a technique to generate quantitative causality explanation sentences, systematic techniques for FTA and FMEA, and a design support technique of functional case-based design.

Keyword: function-based inference; co-operator; multi-level flow modeling; operator support information; safety analysis; system design

1 Introduction

Construction of new nuclear power plants equipped with advanced type of operation control panel[1, 2] that applies the information and interface technologies is progressing rapidly. The characteristic features of the control panel are

(1) a large screen to share important information of plant conditions for the members of an operation crew,
(2) suitable arrangement of CRT-based operation panels to give flexible ways of monitoring plant conditions and taking operational actions, and
(3) digital computer systems to process the data by plant instrumentation and control (I&C) systems.

The introduction of digital computer systems means that the measured data by plant I&C systems can be processed intelligently. In addition to this, the operation actions by human operators can be monitored through the CRT-based operation panels. However, an intelligent automation system may be difficult for a human to comprehend the behavior of the system due to the complex processing of data. In view of this, it is crucially important to design an effective collaborative relation between human operators and intelligent automation systems.

As a feasible solution to realize a human-centered plant operation system, the authors proposed a concept of co-operator[3]. Owing to the fact that functional information is pivotal toward understanding an intricate system, the function-based inference techniques described in the previous article[4] will be potent and viable tools to developing a co-operator.

The authors studied several operator support systems[5 - 9] in conjunction with companies. In the human media project[10], a semantic information presentation agent[5] was developed to computerize a part of the model-based thinking process of human operators and to support their situation awareness. A technique to find plausible counter actions based on a model by MFM (Multilevel Flow Modeling) [11 - 13] for a plant was developed[6, 7]. The authors proposed a framework of dynamic operation permission[8, 9] with the aim to reduce commission errors by human operators in plant operations. In a dynamic operation permission system, it is necessary to estimate the effect of an operation by human operators on a plant's future behavior in order to evaluate the validity of the operation. The estimation is carried out

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based on an MFM model of the plant.

For a co-operator, the explanation capability of the obtained results and the process of its inference is necessary, because the co-operator is regarded as a member of an operation team. From this point of view, an explanation technique of a model-based inference result is studied and a generation technique of essential explanation has been proposed[14]. The technique has been extended to include quantitative information by complimenting a simple numerical simulation for the target plant[15, 16].

The author joined a project aimed at developing a diagnostic system[17] of a fuel supply system for small space rocket launchers, and applied the causality inference technique based on an MFM model to the influence estimation of an anomaly of the system. The authors also proposed systematic techniques[18, 19] for the FTA (Fault Tree Analysis) and FMEA (Failure Mode and Effects Analysis) that are conventional safety evaluation techniques for the design of a complicated engineering system. These techniques are applied in the design of the fuel supply system of the rocket launcher.

In the field of mechanical and system design, the importance of expressing functional information has been recognized from time immemorial. The authors proposed a functional cased-based design[20] that effectively utilizes the functional information of past designs. The function simplification technique[4, 14] introduced in the previous article is applied to the functional case-based design.

The previous article[4] described the importance of the usage of functional information in plant operation and system design and introduced three function-based inference techniques:
(1) CET: causality estimation technique based on an MFM model,
(2) FFS: function flow simplification of an MFM model, and
(3) GES: generation of explanation sentences for inference process.

This article first discusses the concept of co-operator and thereafter introduces several systems and techniques that apply the function-based inference techniques based on MFM models as application exemplars. Table 1 shows the systems and techniques that will be introduced in this article and their applied function-based inference techniques. In the table, the symbol “X” means that the marked function-based inference technique is applied. The symbol “(x)” means that the marked technique can easily be applied in order to improve the systems and techniques albeit the applications by authors do not utilize the technique.

Table 1 Applications of function-based inference techniques

	CET	FFS	GES
Finding plausible counter actions	X	(x)	(x)
Dynamic operation permission	X	(x)	(x)
Quantitative causality explanation	X	(x)	X
Systematic FTA/FMEA	X		(x)
Functional case-based design		X	

2 Co-operator as a human-centered operator support system

2.1 Concept of co-operator

The co-operator[3] is a software agent installed in the control room of each plant. The co-operator will increase the safety and reliability of plants operated by fewer human operators by supporting the situation awareness of human operators, and taking appropriate counter actions at an abnormal situation in cooperation with human operators. The expected roles of co-operator are: (1) a subordinate to execute accurately the tasks requested by human operators, (2) a partner to share operation tasks with human operators, and (3) an adviser to give useful knowledge stored in its reliable and robust memory.

The relationship between a human operator and the co-operator is shown in Fig. 1. The co-operator monitors plant condition through plant instrumentation. It shares plant models, diagnostic knowledge, operation knowledge, *etc* with human operators. It can understand the context of the thinking of human operators based on the history of interaction. Although human operators will make a final decision, the co-operator interacts mutually with them. If an anomaly arises, it aids human operators by diagnosing plant condition, displaying operator support information, and at times executing operations by heeding to the requests of human operators.

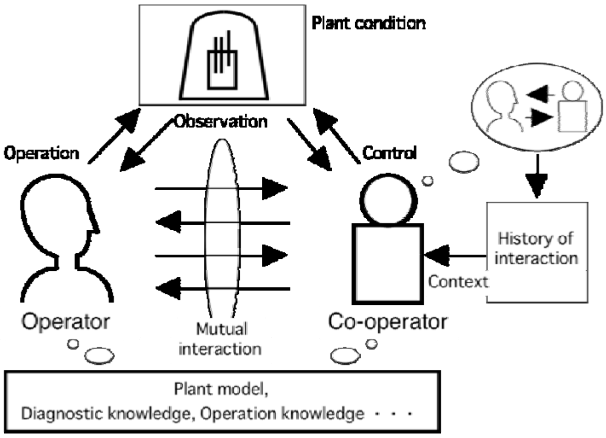

Fig. 1 Relation between a human operator and co-operator.

A summary of the desirable features of a co-operator are furnished in Fig. 2. This figure also shows the tasks of the co-operator indicated in the bold boxes. The arrows connected with the boxes indicate the orders of tasks. One of the prime features is to make human operators have trust on the co-operator. Suitable interaction with human operators as well as generating correct and helpful information is most important to realize this feature. At least, the grounds and processes for an inference made by the co-operator should be clearly indicated to human operators. In the task of information display based on the results of diagnosis of plant condition, it is worthwhile to give different viewpoints from those of human operators in order not to make them fall into the contraction of viewing field that may happen in an emergency situation of plants. Functional viewpoint is exceptional in its own right. The feature of ability of growth is also important because human operators improve their skills through the experiences of plant operation.

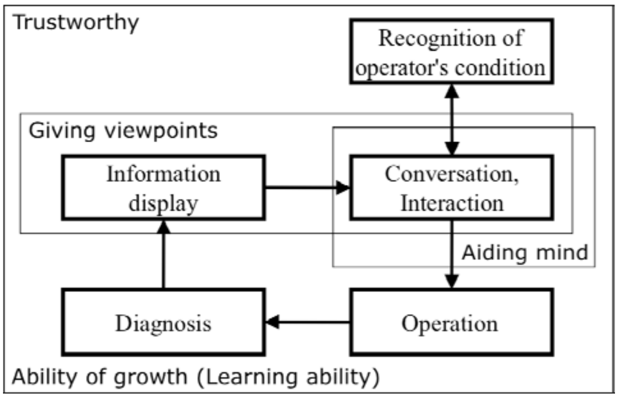

Fig. 2 Desirable features of co-operator.

2.2 Research topics for developing a co-operator

Considering the tasks and desirable features of a co-operator discussed in the previous subsection, a study of the following four topics is necessary in the quest to develop a co-operator. They are:

(1) plant monitoring from different viewpoints beside those of human operators as well as viewpoints akin to those of the human operators,

(2) backing up the errors made by human operators,

(3) comprehensible explanation display of processes and conditions of reasoning, and

(4) understanding of the intentions of human operators.

As for the first topic, the author thinks that the information of plant function is important because a plant has its own goals, and functions are assigned to achieve the goals. The backing up will also contribute in nurturing the skills of younger operators with less experience of plant operation. For the last topic, historical data of actions of human operators and interactions between them and co-operator will be a valuable data source. This highlights the necessity to advance the machine learning techniques with data mining and concept generation methods.

3 Finding plausible counter actions

3.1 Necessity of finding plausible counter actions

Operation manuals are prepared for normal and abnormal situations of a plant. Human operators conduct the operations described in the operation manuals after recognizing a plant condition. Of course, recommended operations are prepared for as many abnormal situations as we can suppose. However, accidents sometimes happen by an unexpected cause or in the case of a failure of the supposed component for recovery action from an abnormal situation.

Usually, there are several operations to recover from an abnormal situation or to mitigate the influence of an anomaly caused. The operation in operation manuals is selected and described as a best option from operation candidates by considering the effect, operating easiness, side effects of operation, and so on. Skilled operators will have the knowledge for operation candidates that have similar effects as those of the operation described in the operation manual. However, it should not be assumed that they would remember the operation candidates in an emergency situation. Instead, an operation support system should have the ability to generate the operation candidates when an unexpected cause happens or when a component for recovery action fails.

Functional information is worthwhile in deriving candidates of counter actions because it expresses the role and desirable effects of a component. For example, consider the case of depressurizing a tank with volatile fluid. An effective counter action may presumably be to increase the flow rate of inlet cooled fluid into the tank. There are many other counter action possibilities: (1) to increase the outlet flow rate of gas from the tank, (2) to spray some cooled fluid into the tank, (3) to purge some gas outside the tank if the gas is not toxic, (4) to cool the wall of the tank by pouring water, and so on. The description of all plausible counter actions in operation manuals is not pragmatic since the effects of a counter action depend on the condition of the tank and there are several restrictions for plant operation. The outflux of toxic gas is not allowed in the case of a subtle increase of tank pressure. However, the counter action may be suitable when the tank pressure rapidly increases. All the counter actions can be categorized in terms of: (1) decreasing the volume of fluid and gas in the tank or (2) decreasing the energy inside the tank. The aforementioned categories are functional descriptions for candidates of counter actions. From such a simplistic consideration, it is indeed worthwhile to make a functional model of a system and utilize it to derive plausible counter actions in an emergency situation.

3.2 Algorithm for finding plausible counter actions

The algorithm for finding plausible counter actions assumes that the anomaly is identified beforehand. The location (component), type, and degree of anomaly are known by identification. The algorithm is comprises the following three steps:

(Step 1) The influence of an anomaly to goal / sub-goals of plant is estimated based on an MFM model for the plant by applying the influence propagation rules of the causality estimation technique[4],

(Step 2) The goal / sub-goal or anomalous behavior to be recovered or mitigated in the highest priority is selected by using the dangerous situation knowledge of the plant.

(Step 3) The demand propagation rules of the causality estimation technique are applied to the MFM model by setting the selected goal / sub-goal or anomalous behavior as a starting point for demand propagation. If an operation is assigned to the function by the operation knowledge for the plant whose flow can be changed to satisfy with the propagated demand, the operation is regarded as a plausible counter action.

3.3 Application to an oil refinery plant

In this subsection, the technique to find plausible counter actions is applied to an oil refinery plant. An MFM model shown in Fig. 4 of the previous article[4] is constructed and additional knowledge and data for causality estimation are prepared. The anomaly that happened is assumed as a performance degradation of naphtha extraction pump. The anomaly induces an increase of the liquid level of reflux drum. Plausible counter actions are derived to decrease the liquid level.

Twelve feasible counter actions are derived by the technique as shown in Table 2. In the table, the counter actions suggested by an expert of the plant are also indicated. Two of the three suggested counter actions are derived. The reason of not deriving the third counter action suggested by the expert is to exclude the control of temperature at the top of main fractionator in the operation knowledge. Instead of the third suggested counter action, the counter action of increasing top reflux flow rate is derived. The counter action can be considered as an equivalent counter action to the third suggested one because increasing top reflux flow rate results in decreasing the temperature of the upper part of the main fractionator.

A number of counter actions that may not be suggested by the expert are derived. This is owing to the fact that the expert probably takes into consideration the standard operations for the anomaly as well as quantitative and side effects of an operation in the derivation. The expert evaluates that the derived counter actions will have some effects of decreasing the liquid level of the reflux drum although the effects will be subtle or the counter actions are not usually taken into consideration in a real operation. The evaluation by the expert can be interpreted that the derivation technique may find a counter action that human operators might not remember, especially in an emergency plant situation.

Table 2 Derived counter actions and suggested ones by an expert of oil refinery plant

Derived counter actions	Counter actions suggested by an expert
1. Increase of the flow rate of naphtha extraction pump	1. Check the operational condition of naphtha extraction pump
2. Decrease of crude supply rate	2. Decrease of crude supply rate
3. Increase of top reflux flow rate	3. Decrease of the set point of top temp. of main fractionator
4. Increase of the temp. of naphtha flowing into reflux drum	
5. Increase of extraction rate of kerosene from main fractionator	
6. Increase of extraction rate of LGO from main fractionator	
7. Increase of extraction rate of HGO from main fractionator	
8. Decrease of heat output rate of crude heater	
9. Decrease of steam supply rate to main fractionator	
10. Increase of steam supply rate to No. 1 stripper	
11. Increase of extraction rate of flare from reflux drum	
12. Increase of side reflux flow rate	

4 Dynamic operation permission

4.1 Concept of dynamic operation permission

The main idea of the dynamic operation permission[8, 9] is to prevent apparent commission errors by human operators. There can be a case that human operators, for instance, want to take in advance an operation that will be necessary later in a plant's operation. In such a case, a dynamic operation permission system evaluates the validity of the operation from the viewpoint of the influence of futures plant behavior.

A dynamic operation permission system lies between human-machine interfaces for plant control and plant control systems. It lets human operators behave as they like so long as they conduct operations following operation manuals and various operation rules, and the action by them does not induce adverse effects on plant condition. 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.

Figure 3 shows the outline of the procedure of the dynamic operation permission. When human operators carry out an operation, the operation is first identified by the screen selected and the console button pushed. There are two main functions of a dynamic operation permission system. One is to decide the permission according to the evaluation if the operation selected by human operators follows the typical operations described in operation manuals. The other is to decide the permission based on the prediction on what influences the operation selected impart on futures plant behavior. The future influences are predicted by the causality estimation technique based on an MFM model.

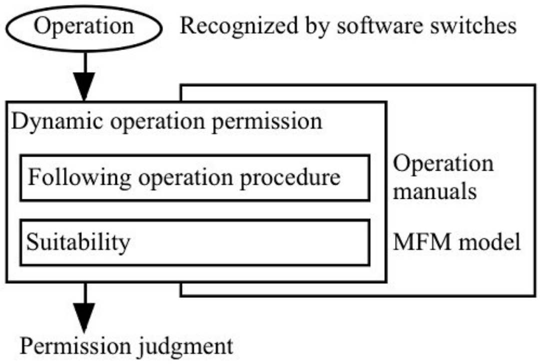

Fig. 3 Outline of the procedure of dynamic operation permission.

4.2 Dynamic operation permission by the prediction of the influence of an operation

Owing to the fact that an operation is conducted in order to recover some functions of a plant under some goals that take into consideration the plant conditions, the usage of the information of plant goal / sub-goals and functions is crucial in the evaluation of an operation. The prediction of effects and influences of an operation on plant behaviors is made by the causality inference technique based on an MFM model. The qualitative prediction is sufficient because the purpose of the dynamic operation permission is to prevent obvious commission errors. In the cases that quantitative information for the support of human operators is necessary, introduction of numerical simulations is a promising idea.

The desirable and undesirable behaviors for the operations in operation manuals are extracted from the description of operation manuals and represented in relation with the operations. As shown in Fig. 4, the suitability of an operation is evaluated by comparing the predicted influences by using the causality estimation technique with the desired and undesired behaviors for the next operation(s) to be conducted according to operation manuals.

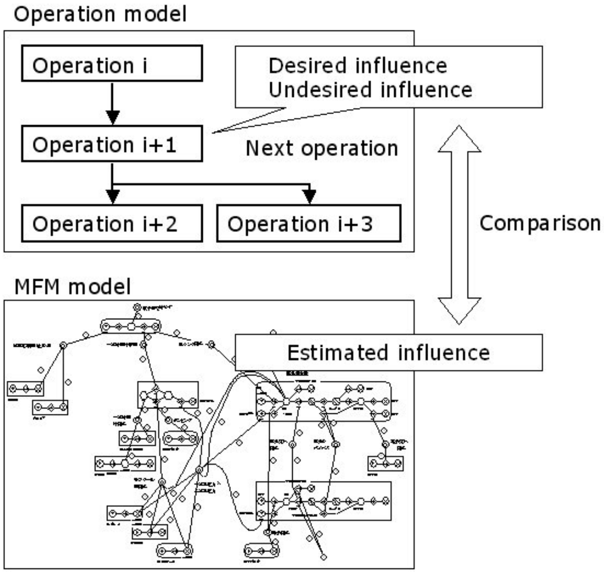

Fig. 4 Suitability evaluation by considering estimated influences on plant behavior.

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. The levels of warning can be changed depending on the policy of dynamic operation permission.

4.3 Example of dynamic operation permission

A dynamic operation permission system for an oil refinery plant was developed on a distributed cooperative environment[9]. The MFM model described in the previous article[4] is employed. The operation scenarios considered in the proto-type system[9] are: to decrease the input flow rate of crude by *ca.* 25% of its rated value, and to shutdown the plant.

Feasible examples of examining the validity of operations by the MFM-based operation permission are shown in Table 3. The operations in the table are supposed to be conducted when the liquid level of reflux drum is increasing due to the degradation of naphtha extraction pump by *ca.* 25%. The next operation described in the operation manual is to decrease crude flow rate. The purpose of this operation is to decrease the liquid level of the reflux drum. The desired behavior is to decrease the flow rate of naphtha flowing into the reflux drum. The undesired behavior is to increase the liquid level of reflux drum. The operation of increasing the flow rate through the valve of FC29 in naphtha extraction line will have positive effect of decreasing the liquid level of reflux drum according to the results of the MFM-based influence estimation. Such an operation does not yield undesired behavior and thus, the operation is permitted with a comment although the operation is not the next one in the operation manual. Conversely, the operation to decrease the flow rate through the valve of FC29 is given a strong warning because the desired behavior will not appear and the undesired behavior of increasing the liquid level of reflux drum will appear.

Table 3 Examples of MFM-based operation permission results

Operation	FC29 +	FC29 -	FC71 +
Desirable behavior	True	False	True
Undesirable behavior	False	True	True
Permission level	With comment	With strong alarm	With alarm

FC29: Flow controller of naphtha flow
FC71: Flow controller of fuel gas for heater

5 Quantitative causality explanation

5.1 Flow of quantitative cause-effect information generation

In the techniques of finding plausible counter actions and dynamic operation permission, the explanation of the results of causality estimation is important when the techniques are applied to real plants. Quantitative causality explanation will be desirable for such purpose, although qualitative causality explanation may be adequate in an emergency plant situation.

Figure 5 shows the flow of quantitative explanation information generation of the effects of a counter action that the authors studied[15, 16]. 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 possible quantitative effects to recover plant condition or to mitigate the influence of an anomaly when the extent of a counter action is specified. The causality estimation technique[4] 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 a numerical simulator are incorporated into linguistic explanation regarding the effect of the counter action that is generated by the influence estimation based on an MFM model.

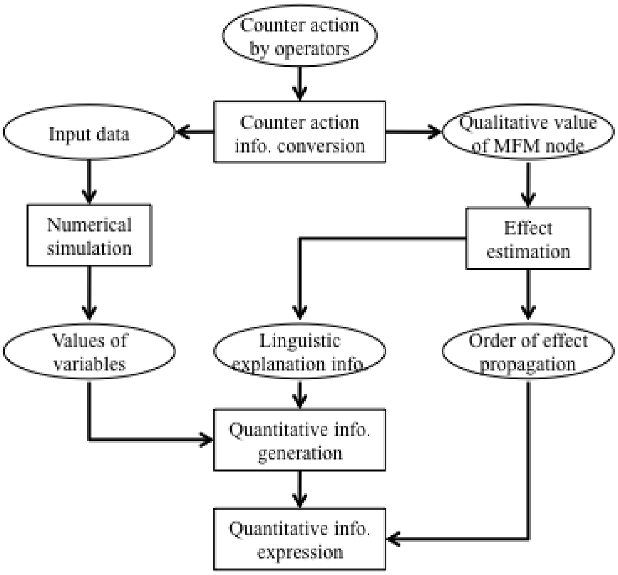

Fig. 5 Flow of quantitative explanation information generation of the effects of a counter action.

5.2 Explanation generation example

The technique is applied to an oil refinery plant. A static simulator[15] for the plant is developed to predict plant condition after executing a counter action. The anomaly considered, in this case, is a performance degradation of naphtha extraction pump by 10%. Due to the anomaly, the liquid level of the reflux drum increases resulting in an undesirable condition of the oil refinery plant. The counter action is to decrease the fuel supply rate of the crude heater by 5%.

The calculation results for some important state variables by the static numerical simulator are shown in Table 4. Figure 6 shows the effect propagation path from the counter action to the behavior of the reflux drum in an MFM model. In the figure, the characters that are surrounded by ellipses indicate the state variables of the simulator.

Table 4 Part of static numerical simulation results

State variable	Meaning [Unit]	Value
fl_tm	Normalized crude supply rate [-]	1.0
ht_tm	Normalized fuel supply rate of crude heater [-]	0.95
P_51	Normalized performance of naphtha extraction pump [-]	0.90
T_i	Inlet temp. of crude heater [C]	234.0
TC_25	Outlet temp. of crude heater [C]	338.8
T_pre	Temp. of No.1 tray of main fractionator [C]	151.7
w_t	Gas flow rate from the top of main fractionator [kg/s]	35.9
w_draw1	Extraction flow rate to No. 1 stripper [kg/s]	25.8
w_rtn1	Return flow rate from No. 1 stripper [kg/s]	2.76
WSR	Naphtha extraction flow rate [kg/s]	19.3
FLARE	Off gas extraction flow rate [kg/s]	2.75

The obtained explanation sentences of the effect of the counter action are furnished in Table 5. Suitable words are almost entirely used in the explanation sentences. The explanation sentences of the influences to the downstream of the reflux drum are also generated as indicated by the explanation sentences with parentheses. The information will be valuable for human operators to monitor plant condition after executing the counter action, and to understand its side effects on a plant's future behavior.

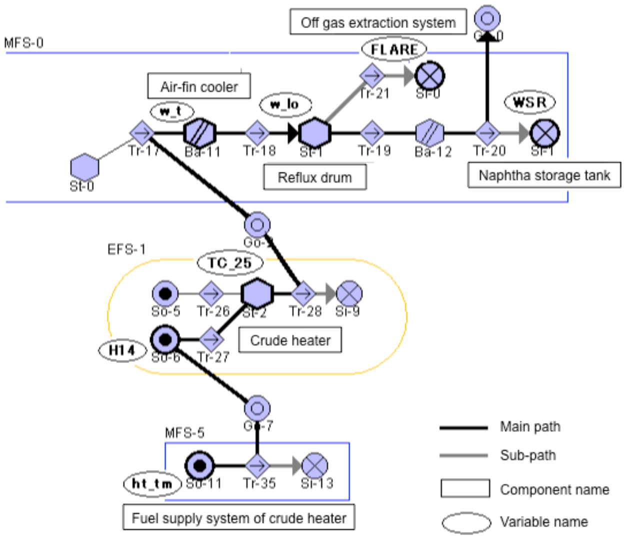

Fig. 6 Effect propagation path.

Table 5 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].

6 Systematic FTA and FMEA

6.1 Problems in executing FTA and FMEA

Fault tree analysis (FTA) and failure mode and effects analysis (FMEA) are widely applied in the safety evaluation of systems, especially in the development of large-scale and mission-critical systems such as nuclear power plants, chemical plants, and aircrafts. FTA is a top-down method to evaluate the risk of a system for the purpose of preventing the occurrence of undesirable events. On the other hand, FMEA is a bottom-up method to predict the consequences on a system by supposed anomalies of its lowest level components.

The following problems in applying FTA / FMEA are (highlighted) pointed out[18].

(1) Education and training are required to learn how to analyze systems by the FTA / FMEA.

(2) The quality is unreliable because human analyzers conduct the FTA / FMEA.

(3) Expertise of a target domain is required for human analyzers.

(4) It is difficult to update FTA / FMEA results when a target system is reconstructed, because the initial rationale of the analysis is susceptible to being lost.

A systematic FTA / FMEA generation technique will be a solution for some of these problems. The principle of FTA / FMEA is to trace comprehensively cause-effect relations among anomaly causes and undesirable effects. This principle is akin to the causality estimation technique[4], although some additional information and data are required.

6.2 Knowledge and data for FTA and FMEA

An MFM model expresses the functional and structural information of a system. The systematic techniques for FTA and FMEA utilize the causality estimation technique[4] based on an MFM. In addition to the MFM model and necessary rules and knowledge for the causality estimation technique, the following knowledge and data are necessary for systematic FTA and FMEA:

(a) *sensor information data* that represent sensor names, locations of sensors, and functional meaning of the measured plant behavior by the sensors, and

(b) *anomaly ontology* of devices that ground the tracing results of cause-effect relation using an MFM model onto the corresponding anomaly instances as well as the information of anomaly causes.

6.3 Algorithms for systematic FTA and FMEA techniques

The construction algorithm of FTs for FTA based on an MFM model of a system is as follows:

(Step 1) The top event of FT is determined by the *dangerous situation knowledge*. The functional effect of the top event is given by the representation of the corresponding goal / sub-goal or function node of the MFM model.

(Step 2) The *demand propagation* is conducted in the MFM model.

(Step 3) All the paths in *demand propagation* are traced from the MFM node corresponding to the top event to leaf nodes. In the trace, (1) a sub-goal is captured as an intermediate event in the FT and (2) a component behavior is regarded as a parent node of end events in the FT if a possible change of the component behavior is found by using the *component behavior knowledge* and *operation knowledge*. The end events are derived from the *anomaly ontology* related to the component of the parent FT node.

On the other hand, the generation algorithm of the FMEA table sheets based on an MFM model is outlined as follows:

(Step 1) By referring the *component behavior knowledge*, all plausible abnormal components are identified.

(Step 2) Using the *anomaly ontology*, the failure modes and anomaly causes are derived for each abnormal component.

(Step 3) For each anomaly, the influences of the anomaly on plant behaviors are estimated using *influence propagation*.

(Step 4) By referring the *dangerous situation knowledge*, the priority of an influence is determined and the number of anomaly causes to induce the influence is obtained.

(Step 5) By using the *sensor information data* and the influence estimation results of an anomaly, the change patterns of sensors are considered as a detecting method of the anomaly.

(Step 6) The results of the above steps are summarized in an FMEA sheet.

6.4 Applications of systematic FTA and FMEA techniques

The systematic FTA and FMEA techniques were 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[18, 19].

In the application of the systematic FTA technique to the simple coolant plant, the authors constructed an MFM model for the plant excluding its control systems[18]. By comparing the FT reported in the literature[21], the FT generated by the technique is confirmed to be commensurate to the reported FT albeit the modeling 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[19], the authors noted that the engineers who are acquainted with FTA / FMEA effectively performed the validation process using the generated FTA / FMEA results, and sometimes gave in short time useful comments for the revision of MFM model. Furthermore, the work in the validation process lets the engineers notice several points to be improved in the facility *per se*, although the design review process was already completed. This means that the systematic FTA / FMEA techniques aided to refine the design itself as well as to conduct safety evaluation of the facility.

7 Case-based design support

7.1 Functional case-based design

As described in the previous article[4], an artifact is designed based on the intention of designers. The intention is expressed in terms of functions. An artifact has its own structure in order to realize the functions. From such a viewpoint, then, a system design can be deemed a mapping of functional space to structural space.

In the conceptual design phase in design activities, designers are required to determine roughly a novel structure that satisfies all design requirements described as specifications. A designer first converts the design requirements to functions that are abstract and qualitative expressions of design requirements in order to have creative ideas. In general, there are a variety of components to realize a function. He / she selects a suitable component from a set of components by considering performance, cost, size, and so on.

Due to the fact that most designs belong to improvement designs, past designs are good references for a new design. The case-based reasoning[22] that is a problem-solving technique by using past cases is a potent and viable tool to support an improvement design. In order to support designers in the conceptual design phase to determine structure from design requirements through functions, the authors studied a support system[20] of functional case-based design that applies the case-based reasoning in dealing with functional information of designs.

In the functional case-based design, the functional information of a design as well as its structural information is stored in a case base. A similar design case is retrieved from the case base by comparing the functional information of a new design and those of the case bases. After selecting a past design by using functional information, the structure of a design is determined by referring the structure of the selected past design. In the studies[20] by the authors, the MFM was applied to express the functional information of a design. The authors developed the technique of function flow simplification that has been introduced in the previous article[4], to flexibly retrieve a past case by changing the aggregation level of the MFM model of a past design.

7.2 Application of functional case-based design

The authors developed a support system[20] for the conceptual design phase of refuse incineration plants in order to demonstrate the applicability of the functional case-based design. A design case is modeled by the MFM as shown in Fig. 7. The function-goal model expresses the relations among goal / sub-goals and functions of a plant. The function-structure model expresses the relations among functions and components of the plant to realize the functions. MFM models of 53 plants are stored in the case base.

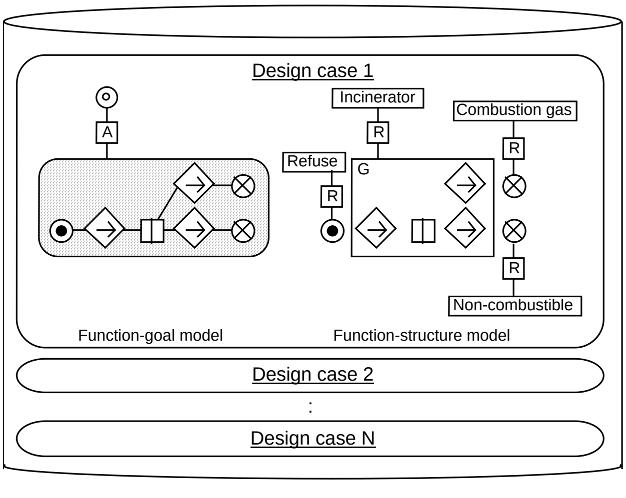

Fig. 7 Case data in case base.

Figure 8 shows an MFM model drawn by a designer to express his / her initial idea of design. Cases 1 and 5 shown in Fig. 9 are examples of retrieved cases. Case 1 is retrieved after function flow simplification of its function-goal model by one step. On the other hand, case 5 is retrieved after simplification by two-steps. In this way, the functional case-based design can strongly help designers in remembering past design cases.

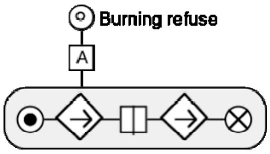

Fig. 8 An MFM model expressing designer’s initial intentions.

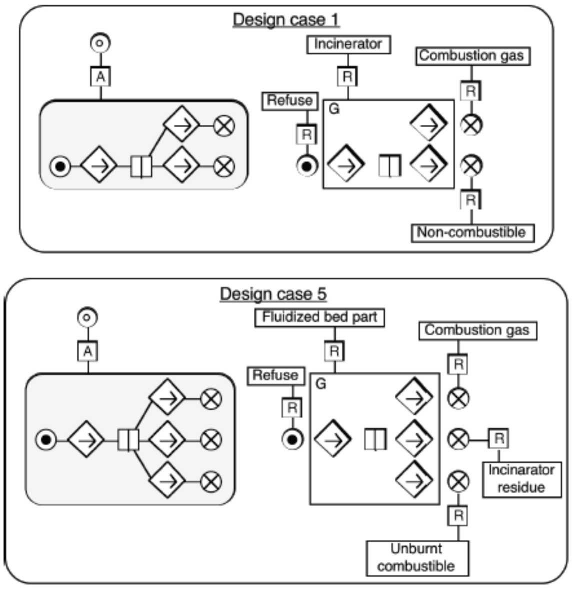

Fig. 9 Examples of retrieved cases.

8 Concluding remarks

This article first discusses the concept of co-operator as a human-centered operator support system for future plants by applying advancing computer and interface technologies. Techniques and systems the authors studied by applying the function-based inference techniques introduced in the previous article[4] are then presented. They are: (1) a technique to find plausible counter actions for an anomaly, (2) a dynamic operation permission system to reduce commission errors by human operators, (3) a technique to generate quantitative causality explanation sentences, (4) systematic techniques for FTA and FMEA, and (5) a design support technique of functional case-based design.

As is apparent in the techniques and systems presented in this article, the functional information is very useful in plant operation and system design and the MFM is a potent tool to expressing functional information of an artifact with structural information. However, several future problems are still pending as regard to the modeling and expressing of functional information of a system. First, modeling and representing control systems is cumbersome owing to the fact that there are different features in control systems from those of physical components, and deep insights are necessary to trace the causality of control loops. Recently, Lind discussed the modeling of control systems[23]. The function flow simplification only treats the function primitives of a flow structure. In view of such consideration, it is necessary to develop a technique for simplifying a part of an MFM model including some sub-goals and flow structures. Since quantitative information is vital in an optimization problem, a technique to include and use systematically quantitative information of system behavior in a functional model is indispensable toward diversifying the applicability of the function-based inference techniques based on an MFM model.

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