Quantitative effect indication of a counter action in an abnormal plant situation

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Abstract: In an automated plant, the expected roles of operators are conducting smooth non-stationary operations and taking suitable counter actions in an abnormal situation. In order to generate operator support information for undertaking an appropriate counter action, the authors proposed a technique to generate explanation sentences for the causal relations of influences of an abnormal cause and the effects of an operation by operators based on a model by the Multi-level Flow Modeling (MFM). However, the technique only generates qualitative information pertaining to the effect propagation of a counter action. This study improves the technique in the quest to quantitatively explain the effects of a counter action by introducing the information generated by a numerical simulation. The applicability of the technique is examined by applying it to an oil refinery plant. Considering the results obtained, it is confirmed that this technique can generate explanation sentences including quantitative information of cause-effect correlations of a counter action.

Keyword: operator support information; quantitative effect explanation; multi-level flow modeling; numerical simulation

1 Introduction

In an automated plant, the expected roles of operators are conducting smooth non-stationary operations, monitoring plant condition and executing appropriate counter actions when an abnormal situation happens. To support the activities of operators, a plethora of diagnostic systems[1, 2, 3] have been proposed in order to detect and identify the anomaly occurring by processing plant process signals. Recently, some studies have been devoted in pursuit to develop operator support systems by considering cognitive aspects of operators[4, 5]. In order to share important information among operators, the operation control rooms of newly constructed plants are equipped with a large screen and necessary summary information is generated and displayed by advanced information and interface technologies[6].

With the aim of generating operator support information to take an appropriate counter action, the authors proposed a technique[7] to generate explanation sentences as for the causal relations of influences of an abnormal cause and the effect of an operation by operators based on a model by the Multi-level Flow Modeling[8, 9] (MFM) that is a functional modeling methodology. However, owing to the fact that functional information of a component or a system only involves qualitative information, the acquisition of quantitative information was cumbersome.

In view of such considerations, this study proposes a technique to explain quantitatively the effect of a counter action by complimenting a functional model and a numerical simulation. First, the information regarding the qualitative effect propagation to each part of a plant by a counter action is generated based on a model by the MFM. On the other hand, a static numerical simulation based on a numerical model of the plant provides numerical information about the final condition of the plant when a counter action is executed. Thereafter, by combining this information, explanation sentences pertaining to the propagations of quantitative effects and influences are generated by arranging the quantitative effect / influence information in line with the cause-effect relations of the counter action. The applicability of the proposed technique is examined relative to an oil refinery plant.

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2 Quantitative effect explanation of a counter action

Qualitative reasoning has the following advantageous features for generating operator support information. The reasoning process is principally to trace the influence of a cause along a model and this process is similar to that of human when he / she considers and explains how a cause influences plant future conditions. The qualitative reasoning can generate all possible ways to be influenced by a cause. In particular, a qualitative reasoning based on an MFM model of a plant can generate influence paths from a means-end analysis point of view[10] as well as plausible counter actions[11]. It however does not avail any information pertaining to the severity of an influence. On the contrary, a numerical simulation can predict a future condition of a plant when an anomaly occurs. In spite of this, it does not directly generate the information on how the influence of a cause propagates within a plant. Considering the advantages and disadvantages of both a qualitative reasoning and a numerical simulation, this study combines a qualitative reasoning based on an MFM model and a static numerical simulation in a complementary way.

2.1 Flow of quantitative cause-effect information generation

Figure 1 shows the flow of quantitative explanation information generation of the effects of a counter action by combining a qualitative reasoning based on an MFM model and a numerical simulation. As is apparent in the figure, a numerical simulation and a qualitative reasoning based on an MFM model are conducted in parallel. Such parallelism is indeed beneficial as the information of a counter action by operators is given and then converted to suitable formats for a numerical simulation and a qualitative reasoning. The numerical values predicted by a numerical simulator are thereafter incorporated into linguistic explanation regarding the effect of the counter action that is generated by the influence estimation based on an MFM model.

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. For this purpose, a static numerical simulation to predict a final plant condition after undertaking a counter action is sufficient albeit it does not generate information on how fast the plant condition converges to the final one.

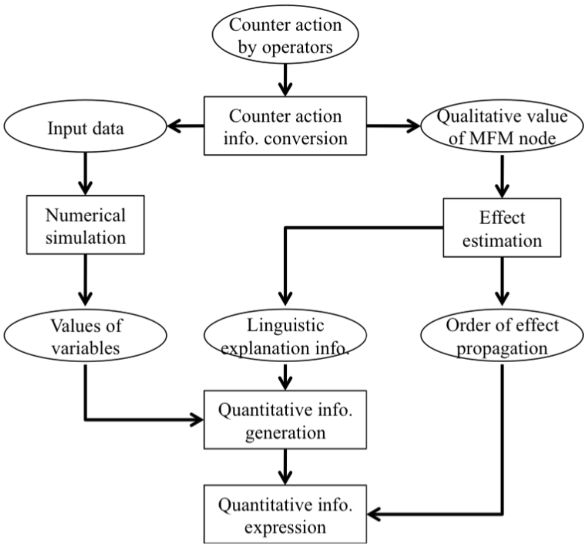

Fig. 1 Flow of quantitative explanation information generation of the effects of a counter action.

Conversely, the qualitative reasoning 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. This study applies the reasoning technique[10] of influence propagation based on an MFM model and extends the linguistic information generation technique[7] of the influence of an anomaly. The linguistic information is given by the following format. The starting node of effect estimation (*i.e.* a counter action) is expressed by:

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

where [Quantity] is a 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 component to conduct a counter action. On the other hand, other nodes are expressed by:

> [Quantity] of [Flow instance] of/to/from

[Structure] increases/decreases to [Value] ([Unit]).

In the formats, [Quantity], [Flow instance], and [Structure] are specified in developing an MFM model. The [Value] is the calculation result of the variable of a static numerical simulator that corresponds to a node of the MFM model. The [Unit] is automatically selected corresponding to [Quantity].

2.2 Effect estimation of a counter action based on an MFM model

The qualitative influence estimation technique[10] based on an MFM model of a plant proposed by the authors is applied for the effect estimation of a counter action. The MFM can qualitatively represent plant behaviors relating to the goals / sub-goals of the plant.

Based on the MFM model, the influences of an operation are estimated in accordance to the following four steps. The outline of the estimation is shown in Fig. 2. First, an operation is mapped to the corresponding function or behavior in the MFM model. Second, the functional influence is propagated in a flow structure using effect propagation rules derived from the causal characteristics of each functional primitive of the MFM. Third, the influences on the goals connected to a function by achievement relations are estimated by the qualitative causality knowledge specified for the relations in developing the MFM model. Finally, the influences on the functions in upper flow structures connected to the goals by condition relations are estimated by the qualitative causality knowledge specified beforehand for the relations. By repeating steps 2 and 4, the influences of an operation on the entire plant behaviors are estimated.

2.3 Quantitative effect prediction of a counter action by numerical simulation

It is desirable for operators to have information about the quantitative effects of a counter action. The information will aid operators to monitor and interpret the plant condition after executing a counter action. The quantitative effects of a counter action are evaluated by a static numerical simulation in this study.

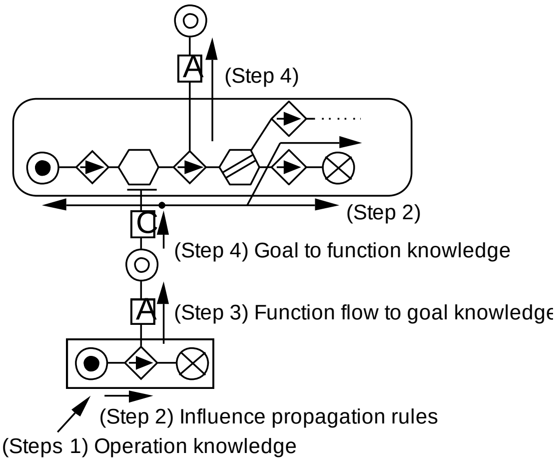

Fig. 2 Estimation of effects of an operation on plant behavior by an MFM model.

A detailed cause analysis may not expected in an emergency situation due to the time limitation for preparing a detailed analysis model and obtaining enough data for the model. Moreover, information regarding the plant condition is obtained from the sensor values of plant instrumentation. This means that some ambiguity is included in the time responses of variables corresponding to the cause and the current plant condition that are necessary for a very concise and detailed numerical simulation. In consideration of the aforementioned restrictions, this study utilizes a static numerical simulation with a simplified plant model. Although static numerical simulation only provides information regarding a final converged plant condition after executing a counter action, it is adequate for the purpose of evaluating the effects of a counter action. This study utilizes a static simulator for an oil refinery plant developed by the authors based on simple mathematical models of components as will be introduced in Section 3.3.

3 Static simulator of an oil refinery plant

3.1 Outline of an oil refinery plant

The target plant in this study is an oil refinery plant. The plant is composed of a crude tank, a de-salter, 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 in the desalter. The desalted crude enters into the pre-flush drum after heating by heat exchangers. The gas is separated and directly enters the main fractionator. The liquid crude flows into the crude heater and is heated. The heated crude then enters the main fractionator. The productive ingredients of kerosene, light gas oil, and heavy gas oil are extracted from the main fractionator based on the differences of boiling temperatures. They are introduced to their corresponding strippers and thereafter, 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.

3.2 Outline of numerical simulation models

A simple static simulator for the oil refinery plant has been developed in order to obtain quantitative effect information of a counter action. Simplified lumped parameter mathematical models considering mass and energy balance equations are developed for main fractionator, stripper, heat exchanger, crude heater, pre-flush drum, reflux drum, cooler, pump and valve. Figure 3 shows the various connections of component models of the simulator. The equations for each component are combined into a simultaneous equation and are solved using the Gaussian elimination method. The mathematical models of main components of the oil refinery plant such as stripper, main fractionator, heat exchanger, crude heater, pump and valve are outlined hereafter.

3.3 Model of stripper

The flows of steam and oil in a stripper are shown in Fig. 4, where w_{draw}, w_{stm}, w_x, w_{rtn}, and w_d are oil flow rate into the stripper, steam flow rate, stripping flow rate, return flow rate to main fractionator, and flow rate of productive ingredient, respectively. We took into consideration the following assumptions during the modeling of the stripper:

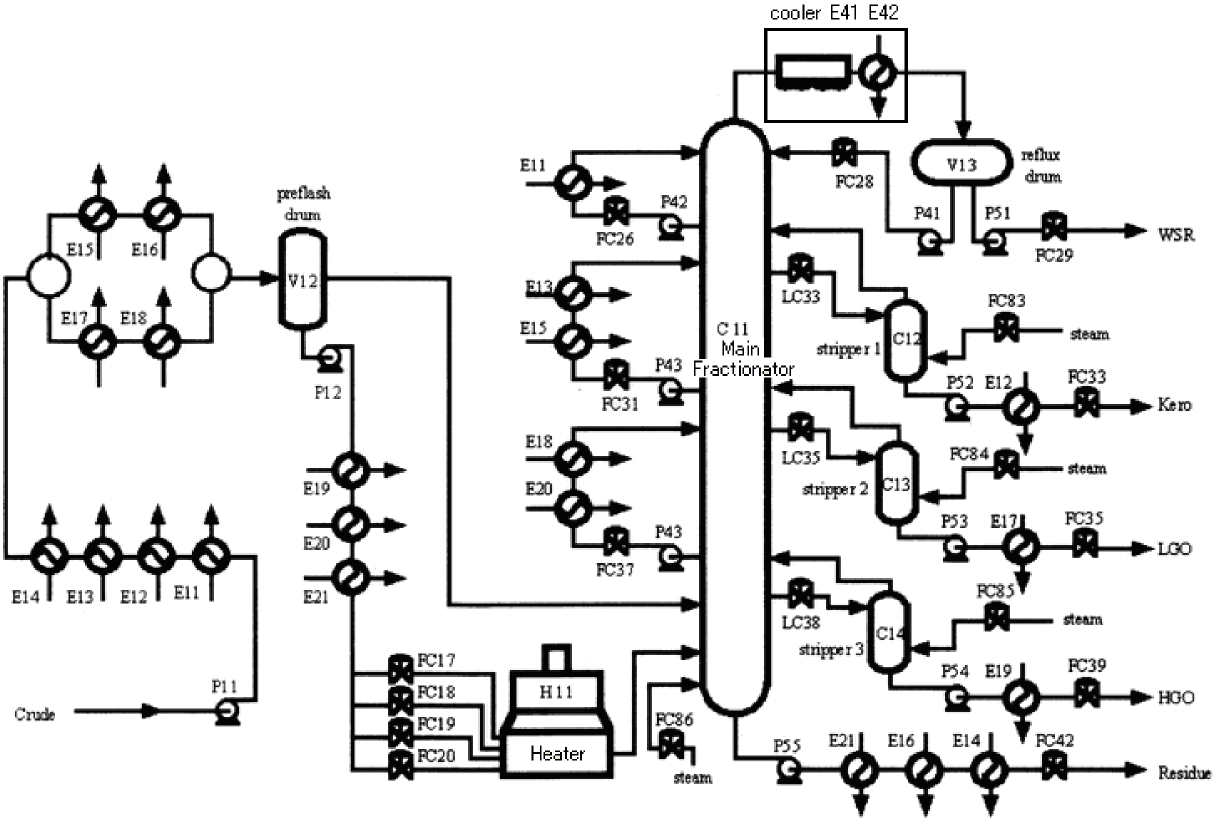

Fig. 3 Diagram representing the connections of component models for an oil refinery plant.

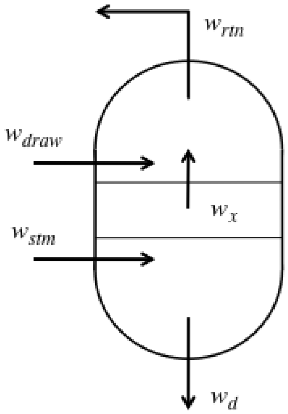

Fig. 4 Model of stripper.

(1) The flow rate of steam is given, and
(2) The stripping flow rate is calculated by multiplying the coefficient given as a function of steam flow rate to the drawing flow rate.

Based on the assumptions mentioned above, mass and energy balance equations as well as the equation to calculate the stripping flow rate from the steam flow rate are formulated.

3.4 Model of main fractionator

Prior to the modeling of the main fractionator, the following assumptions were taken into consideration:

(1) The flow is in a completely mixed condition,
(2) The physical properties such as specific heat at each tray is estimated by the values at the steady state operating condition,
(3) The pressure distribution is akin to that at the steady state operating condition, and
(4) The temperature differences between trays are the same as those at the steady state operating condition.

The flows in the upper section of main fractionator are shown in Fig. 5, where

w: flow rate,
T: temperature,
subscript:
l: liquid,
g: gas,
gl: gas to liquid,
ld: condensation by side reflux,
rd: condensation by reflux,
r: reflux,
sr: side reflux,
1, 3, 10, and 12: tray, side reflux, or stripper number,
$draw$: drawing flow, and
rtn: return flow.

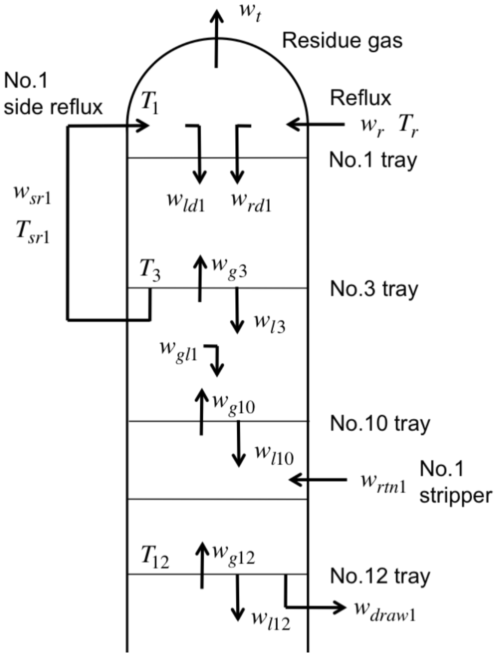

Fig. 5 Model of upper section of main fractionator.

The same modeling is applied to the middle, lower, and bottom sections of main fractionator. Under these models, mass and energy balance equations for each part of main fractionator and the equations to calculate temperature distribution are formulated.

3.5 Model of heat exchanger

There are three models of heat exchangers: (a) model incorporating evaporation of the lower temperature fluid, (b) model devoid of evaporation of the lower temperature fluid, and (c) model combining an air-fin cooler and a cooler. In this subsection, the model type (a) of heat exchanger is outlined.

The flows in a heat exchanger with evaporation of lower temperature oil flow are shown in Fig. 6, where

w: flow rate,
T: temperature,
P: pressure,
cp: specific heat,
H: heat,
subscript:
1: higher temperature side,
2: lower temperature side,

g: gas phase,
l: liquid phase,
s: saturation,
i: inlet, and
o: outlet.

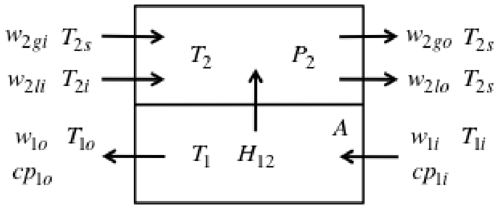

Fig. 6 Model of heat exchanger with evaporation at lower temperature side.

The main assumptions for modeling the heat exchanger are as follows:

(1) The pipes of higher and lower temperature sides are lumped into two pipes, respectively,
(2) The pressures at both sides are constant,
(3) The outlet in the lower temperature side is in a saturated condition,
(4) The total outlet flow rate is equal to the total inlet flow rate in the lower temperature side,
(5) The liquid phase is the non-compressive fluid,
(6) The inlet flow rate and the enthalpy of inlet flow for both sides are given,
(7) The heat transfer coefficient between the both sides is constant, and
(8) The enthalpy of the flow in the lower temperature side is approximated by a first-order function of its temperature.

In order to express mathematically the phenomena in the heat exchanger, mass and energy balance equations are formulated. In the energy balance equation, the heat transfer rate is calculated from the average temperature of the fluids at both sides. The enthalpy at the lower temperature side is calculated by a function of its temperature.

3.6 Model of crude heater

The flows of crude and heat in crude heater is shown in Fig. 7, where

w: flow rate,
h: specific enthalpy,
H: heat from burner,

subscript:
1, 2, 3 and 4: crude heater pipe number,
i: inlet, and
o: outlet.

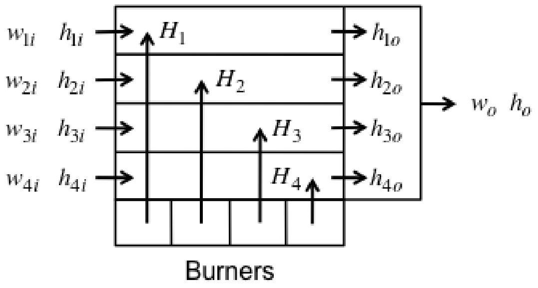

Fig. 7 Model of upper part of crude heater.

The main assumptions for modeling the crude heater are as follows:

(1) The pipes of crude heater are modeled independently,
(2) The four burners are independently controlled and their output heats are given,
(3) The flow rates and specific heats of inlet crude flows are given, and
(4) The crudes flowing from the four pipes are completely mixed at the outlet.

Based on such assumptions, mass and energy balance equations are formulated.

3.7 Model of pump

The main assumptions for the modeling of the pump are:

(1) A valve is connected at the outlet,
(2) The flow through pump is liquid phase,
(3) The maximum flow rate (w_p) through the pump is a function of the pump's rotational speed (ω),
(4) The rotational speed of the pump is given,
(5) The flow rate (w) through the pump and valve system is calculated by multiplying valve opening (a) to the maximum flow rate (w_p),
(6) The valve opening is given, and
(7) The enthalpy of the flow is constant.

Under the above assumptions, the outlet flow of pump with valve is calculated by the following equations:

$$w = a \cdot w_p, \qquad (1)$$

$$w_p = \eta \cdot f_p(\omega), \qquad (2)$$

where η is the pump efficiency.

3.8 Model of valve

The main assumptions taken into account prior to the modeling of the valve that is not connected to a pump at its inlet are:

(1) The flow rate (w) through the valve is calculated by multiplying the valve opening (a) to (a) its maximum flow rate (w_i) if the flow is liquid phase or (b) a function of the square root of pressure difference ($P_1 - P_2$) between its inlet and outlet if the flow is gas phase,
(2) The valve opening is given, and
(3) The enthalpy of the flow is constant.

Under these assumptions, the outlet flow of valve is calculated as follows:

$$w = a \cdot w_i, \qquad (3)$$

or

$$w = a \cdot f_v(\sqrt{P_1 - P_2}). \qquad (4)$$

3.9 Calculation accuracy of static simulator

For the calculations relating to the normal operating condition and several abnormal conditions generated by decreasing crude flow rate, the calculation accuracy of the static simulator is evaluated by a comparison with those of a dynamic simulator[12].

Table 1 shows some examples of the comparisons of the steady state values for the normal and abnormal conditions between the static simulator and the dynamic simulator. In the abnormal case of decreasing crude flow rate to pump P11 (see Fig. 3) by 10%, the extraction flow rates to strippers are also decreased by 10 %. The calculation results show that the static simulator can calculate the steady state conditions with subtle differences from those obtained by the dynamic simulator (except for the residue flow rate).

The relatively big difference of residue flow rate can be ascribed to the fact that the model of the static simulator does not treat the crude as a mixture of productive ingredients since it only considers their latent heats to calculate their flow rates. Thus, based on this modeling, the flow rate of flare increases as the temperature of the crude at the outlet of crude heater monotonously increases.

Table 1 Steady state values
for normal and abnormal conditions

(a) Normal operating condition

Process parameter	Static simulator	Dynamic simulator
Crude flow rate	157.0 [kg/s]	159.1 [kg/s]
Flare flow rate	4.1 [kg/s]	not calculated
Naphtha flow rate	22.5 [kg/s]	24.4 [kg/s]
Kerosene flow rate	23.2 [kg/s]	23.2 [kg/s]
Light gas oil flow rate	22.9 [kg/s]	23.0 [kg/s]
Heavy gas oil flow rate	7.8 [kg/s]	7.8 [kg/s]
Residue flow rate	77.0 [kg/s]	80.2 [kg/s]
Temperature at the outlet of crude heater	340.4 [℃]	342.5 [℃]
Temperature at tray 17	229.3 [℃]	229.4 [℃]

(b) Abnormal condition of 10 % decrease of crude flow rate

Process parameter	Static simulator	Dynamic simulator
Crude flow rate	141.3 [kg/s]	143.4 [kg/s]
Flare flow rate	16.0 [kg/s]	not calculated
Naphtha flow rate	21.2 [kg/s]	21.8 [kg/s]
Kerosene flow rate	20.9 [kg/s]	20.9 [kg/s]
Light gas oil flow rate	20.6 [kg/s]	20.7 [kg/s]
Heavy gas oil flow rate	7.0 [kg/s]	7.0 [kg/s]
Residue flow rate	54.5 [kg/s]	72.6 [kg/s]
Temperature at the outlet of crude heater	359.8 [℃]	362.7 [℃]
Temperature at tray 17	229.9 [℃]	230.6 [℃]

4 Application to an oil refinery plant

4.1 Anomaly and counter actions

In order to evaluate the applicability of the proposed technique, several case studies of explanation generation are conducted for an anomalous condition of an oil refinery plant. This study utilizes the MFM model shown in Fig. 8 and the static numerical simulator described in section 3.

The anomaly considered in the case studies 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 state variable P_51 (see Fig. 3) of the static numerical simulator expresses the performance level of the naphtha extraction pump.

The effect explanation of a counter action for the anomaly is discussed in this paper. The counter action is to decrease the fuel supply rate of the crude heater by 5%. The state variable of ht_tm in the simulator corresponds to the fuel supply rate. This counter action has some effect of mitigating the influence of the anomaly since the decrease of heating rate of the crude will decrease the temperature of the main fractionator resulting to a decrease in the generation of light productive ingredients.

4.2 MFM model

An MFM model of the oil refinery plant has been developed. Figure 8 shows the simplified version by only representing the sub-goals and functions of extracting productive ingredients for only naphtha and kerosene ingredients due to the limited space available for the figure.

The pivotal goal is obtaining productive ingredients. To achieve this 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 in order to separate the productive ingredients. The achievement of each mass transport function from the mass storage St-0 that corresponds to the mass storage function of the main fractionator is influenced by Go-2. Therefore, this 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. Conversely, 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 ingredient 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.

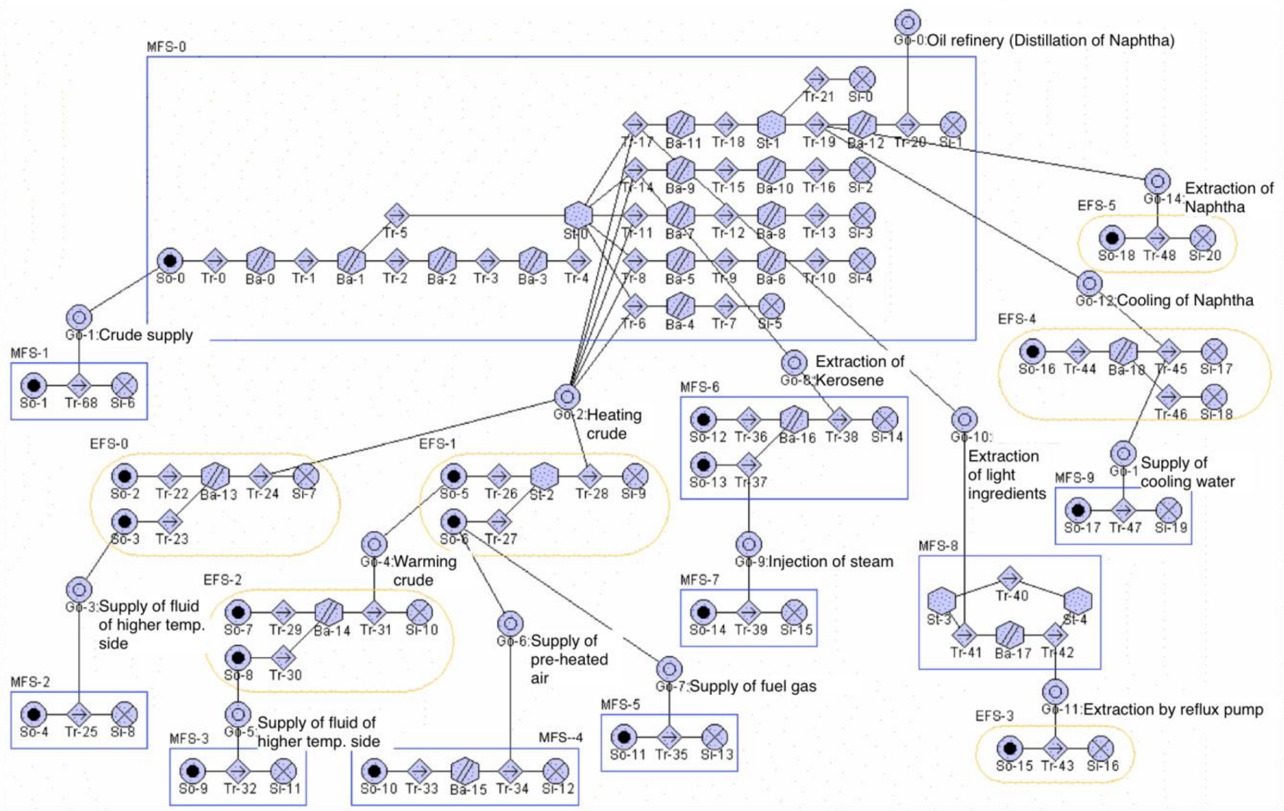

Fig. 8 MFM model of an oil refinery plant.

4.3 Explanation generation example

The calculation results for some important state variables by the static numerical simulator are shown in Table 2. Figure 9 shows the effect propagation path from the counter action to the behavior of the reflux drum in the MFM model. In the figure, the characters that are surrounded by ellipses indicate the state variables of the simulator.

Table 2 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

By using the results of the static numerical simulation and the inference of effect propagation based on the MFM model, explanation generation of the effect of the counter action is obtained as shown in Table 3. As is apparent in the table, almost suitable words are used in the explanation sentences. The explanation sentences with parentheses are the explanations of influences to the downstream of the reflux drum by the counter action. The information will be useful for operators to monitor plant condition after taking the counter action.

Table 3 Generated effect explanation sentences

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].

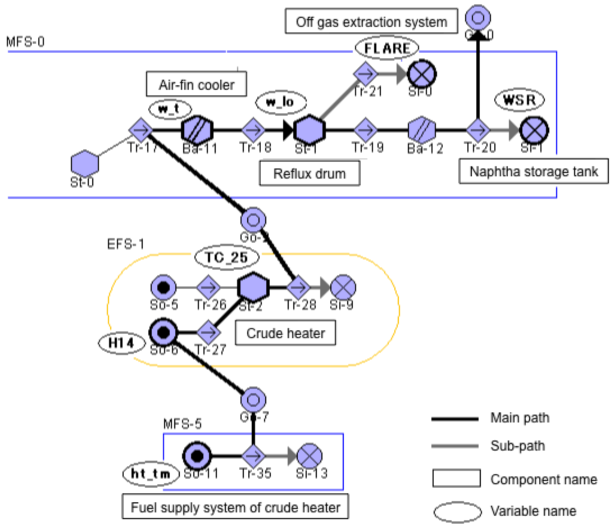

Fig. 9 Effect propagation path.

4.4 Discussions

Operators will understand both the cause-effect relations and quantitative effects of the counter action from the explanation sentences. Moreover, operators can understand the quantitative side effects of the counter action by indicating the explanation sentences of the influences to the other parts of the plant.

Owing to the fact that a human being exhibits good performance to understand causality when the information is presented along the order of cause-effect relations[13], the explanation sentences generated by the proposed technique is considered to be consistent with the human cognitive process. Therefore, operators can easily and accurately grasp the quantitative cause-effect relations in an emergency plant situation.

5 Conclusions

This study proposes a technique to explain quantitatively the effects of a counter action by complimenting a qualitative cause-effect inference technique based on a functional model and a numerical simulation. The information pertaining to the qualitative effect propagation to each part of a plant by a counter action is generated based on a model by the MFM. In parallel, the quantitative information about the final plant condition when a counter action is taken is generated by using a static numerical simulation based on a numerical model of the plant. Then, by combining the two types of information, explanation sentences about propagations of quantitative effects and influences are generated by arranging the quantitative effect information in the order of causality of the effects of the counter action.

The applicability of the technique is examined by applying it to an oil refinery plant. Based on the results, it is confirmed that this technique can generate explanation sentences including quantitative information of causal relations of the effects of a counter action.

The problems that future works should tackle include the development of a technique to display quantitative cause-effect relations including the side effects of a counter action and the relations of all plausible counter actions in a compact format. The applicability of the proposed technique should be examined by its applications to real plants including nuclear power plants.

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