# A Qualitative Reasoning based on an Ontology of Fluid Systems and Its Evaluation

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**Abstract.** This research is concerned with causal understanding and qualitative reasoning of behavior of physical systems, which are crucial issues of model-based problem solving. In this paper, a new method of qualitative reasoning and causal ordering is proposed and its application to a power plant is presented. The method is based on our kernel ontologies of causality and time-resolution and a domain ontology of fluid systems. These ontologies help make the design rationales of our method explicit and facilitate reusability of our models. The whole of the target system is represented by combining a set of local component models and global constraints. The component models include local and causal characteristics of each component which are independent of context for their reuse on the basis of the ontology of causality. Global constraints with time-scales are derived according to the general properties of the physical entity which are prepared beforehand as a part of the domain ontology. They contribute to providing intuitive causal ordering of complex behavior originated in various configurations of components, including inter-component negative feedback. Furthermore, the method has been successfully applied to a power plant. All the reasoning results matched those obtained by a domain expert including their ambiguities.

## 1 Introduction

Causal understanding and qualitative reasoning of behavior of physical systems are crucial issues of model-based problem solving. In this article, a new method of qualitative reasoning and causal ordering is proposed and its application to a power plant is presented. The main issue we discuss is to identify constituents of models and causality suitable to reasoning about behavior of a target system satisfying composability and reusability of the models. *Ontologies* are explicit descriptions of *design rationales* of model-based systems and help to exhibit necessity and sufficiency of the constituents of models for the necessary performance[8]. The method is based on our kernel ontologies of causality and time-resolution and a domain ontology of fluid systems. In section 2, we describe our design rationales referring to these ontologies. Firstly, the performance necessary for reasoning methods with respect to causal time-resolution is discussed. Next, we show conventional methods cannot satisfy the requirements. Lastly, our approach satisfying the required performance is outlined. In section 3, we describe the model representation and discuss categories of causal relations to capture context-independent causal properties of components. In section 4, the details of the reasoning method is described. Moreover, an application of the method to a power plant is presented in section 5. Related work is discussed in section 6.

**Table 1.** Units of time resolution for causal ordering

**T1: Intra-Component Time Unit:** Time intervals between two changes of parameters within *a component*.

**T2: Inter-(Neighboring)Components Time Unit:** Time intervals between two changes of parameters in *neighboring components*.

**T3: Global Time Unit:** Time intervals between two (not simultaneous) changes of parameters in *non-neighboring* components.

**T4: Globally Simultaneous Time Unit:** Time intervals between two *simultaneous* changes of parameters in non-neighboring components.

**T5: Completely-Satisfied-State Time Unit:** Time intervals between two consecutive completely-satisfied-states in which every parameter has a unique value which satisfies all constraints in the system. If not, states are called as partially-satisfied-states.

**T6: Partial-Equilibrium-State Time Unit:** Time intervals between two consecutive partial-equilibrium-states in which a part of the system reaches equilibrium states.

**T7: Complete-Equilibrium-State Time Unit:** Time intervals until the whole of the system reaches equilibrium states.

## 2 The Design Rationales

Among a number of requirements for qualitative reasoning methods we concentrated on the following three: (1)capability in causal explanations in terms of components, (2)reusability of component models and (3)disambiguation of reasoning results, adopting the device ontology[1]. The reasoning engine is designed to reason qualitative behavior of target systems subjected to a perturbation caused by factors external to the system. Such reasoning is a part of diagnostic task, i.e., fault-hypotheses verification, which reasons abnormal behavior of the system with a fault and generates symptoms caused by it. Given an initial (anomalous) value of a parameter, the reasoning engine generates changes of values of parameters over time together with causal relations among the changes for explanations.

### 2.1 Causal Time-Resolution

Since human recognition of causal relations is based on recognition of time delay(i.e. time interval) between the cause and the effect, the performance of a reasoning engine with respect to causal ordering depends on *time-resolution* of the engine. In order to realize such an inference engine that can recognize a fine-grained causality, we have identified the seven units of time-resolution shown in Table 1. Time intervals between two causal changes of parameters are categorized. They represent the performance necessary for reasoning systems with respect to causal ordering.

The necessity to distinguish among these time units is justified by human recognition of causality. Firstly, in order to recognize the behavior in terms of components on the basis of the device ontology, humans assume time delay for interactions between neighboring components due to cognitive distance between them. Thus, humans distinguish time intervals of interactions between components from those of intra-component phenomena, i.e. distinguish T2 from T1. Next, since there are global phenomena such as changes in temperatures caused by global heat balances, discrimination of global phenomena(T3) from neighboring propagations(T2) is necessary. The length of the time interval of T3 is longer than that of T2 because of the structural distance between the cause and the effect. There are, however, cases where changes in non-neighboring components are simultaneous, called *globally simultaneous phenomena*. For example, on the assumption that fluid is incompressible, flow rate of such fluid at each component changes at the same time. Thus, T4 is needed. The length of the time interval of T4 is longer than that of T1 because of the concept of components and shorter than that of T2 because of its simultaneity. T5 represents the time intervals between two consecutive *completely-satisfied-states* in which every parameter value satisfies all constraints in the system. T1-T4 represent, on the other hand, the time intervals between *partially-satisfied-states* in which values of parameters satisfy only a set of constraints. (In the case of T2, for example, the values satisfy a set of constraints in a component.) Such causal orders in T1-T4 are cognitive in a sense that they are not justified by mathematical representations of the models. Therefore, the following inequalities concerning relative lengths of time intervals represented by the units hold.

$$T1 < T4 < T2 < T3 < T5 < T6 < T7$$

### 2.2 Conventional Methods

A main issue to discuss is what contents of domain models we have to represent for distinguishing these time intervals from one another. QSIM[6] uses only qualitative differential equations and adopts a generate-and-test method for constraint satisfaction. Thus, no causal relation among partially-satisfied-states in T1-T4 is identified. The time of QSIM corresponds to T5, and thus QSIM can distinguish only among T5-T7. Although Iwasaki's causal ordering theory[4] can derive a part of causal relations in T1-T4, the theory does not try to derive causal relations among changes caused by *inherently simultaneous equations*[1]. Moreover, it cannot distinguish among T1-T4 due to the lack of the concept of components. The most influential reasoning method based on components has been proposed by de Kleer and Brown in [1]. Our method inherits the device ontology from it. Their reasoning method can generate causal relations in terms of components in *mythical time* corresponding to our T2 according to their general heuristics. Causal relations generated by them, however, are ambiguous due to the arbitrariness of heuristics application. Moreover, since there are no concept of global phenomena, the method cannot distinguish among T2-T4 and may generate ambiguous results for the case of complex topology or feedbacks as mentioned in [10]. The performance of other conventional methods will be mentioned in section 6. In summary, there are no methods of adequate performance.

### 2.3 Our Approach

Our approach to satisfy the necessary causal time-resolution is to take a positive attitude towards incorporating such knowledge that cannot be represented in terms of mathematical equations, satisfying context-independence of the models. Causal characteristics of

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[1] This term represents such simultaneous equations which cannot be solved by substitution alone, borrowed from [1]. In terms of [4], minimal complete subsets.

components are explicitly described, called *causal specifications*. The classification of causal relations shown in the next section helps capture causal properties independent of context. Moreover, we employ *global constraints* derived from general properties of the physical entity such as heat and fluid. Time-scales of phenomena are also described. According to such models, our reasoning engine can distinguish among all the units of the causal time-resolution and derive appropriate causal relations without ambiguity.

The following assumptions contribute to efficiency of the reasoning process. Firstly, we assume that the target system has a normal equilibrium state without any perturbation. This assumption is based on the fact that the intended continuous behavior of mechanical artifacts can be represented by the equilibrium state model by selecting appropriate parameters[2]. Next, we assume that effects of inter-component negative feedbacks do not override instantaneously the original values. The heuristics on this assumption allow the reasoner to determine the values in a feedback loop, as we will see in section 4. Next, although the reasoner copes with mainly transitional behavior from a normal complete-equilibrium state to a final abnormal one, the reasoner generates values only in equilibrium states of T6 and/or T7 for disambiguation of reasoning result in the case of specific parameters. Lastly, we assume that all constraints are continuous, and thus the reasoner cannot treat discrete changes.

## 3 The Model Representation

The overall structure of the system is represented by a combination of component models and connections on the basis of the device ontology[1]. A component model consists of (1)a set of parameters, (2)constraints over parameters, (3)ports for connections, (4)*causal specifications* representing causal properties of the component, and (5)*time scale* of phenomena.

### 3.1 Parameters, Constraints, and Ports

A parameter takes one of the three qualitative values related to the deviation from a normal value. `[+]`(`[-]`) represents a quantity greater(less) than the normal value, i.e. abnormal values. `[0]` represents a quantity equal to the normal value. The normal value of a parameter is defined as a permitted range of the parameter when the overall system is in a normal equilibrium state without any perturbation. In the normal equilibrium state, all derivatives of parameters with respect to time equal to zero.

Constraints are described in terms of qualitative operators and parameters. $D(p)$ represents a derivative of a parameter $p$ with respect to time. It takes one of the three qualitative values `[+]`,`[-]`,`[0]` which correspond to the sign of derivatives. The integral equation: $p_{(t+1)} = p_{(t)} + D(p)_{(t)}$ holds. Constraints "$\exists t,\ D(p)_{(t)} = $ `[0]`" mean that the parameter converges to the equilibrium state.

A parameter can belong to some ports for connections among components. The connection information is represented by relations between the ports. There are global constraints which have connections to local components, as we will see in section 3.3.

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[2] For example, stable oscillation is represented by the equilibrium state modeled in terms of the frequency and amplitude parameters.

**Table 2.** Categories of causal relations

| | Focused scope | Causal chains |
|---|---|---|
| Isolated internal causality | inside of the component | within the component |
| External causality | between components | other components |
| Combined internal causality | inside of the component | other components |

### 3.2 Causal Specifications

The causal specifications represent causal characteristics of the components in order for the reasoner to enable to identify complex causal relations. Such properties prone to dependent on context as discussed in [1][3] and [11]. It motivated us to classify causality of components. We have identified three categories of causal relations shown in Table 2. Causal relations between two changes of values of parameters within a component are categorized with respect to structural scopes focused and locations of parameters of causal chains between the cause and the effect. The classification provides viewpoints for capturing causal properties of components. Causal properties captured from the viewpoint of *the isolated internal causality* are local and independent of the context specified by the whole of the target system. A *causal specification* is an attribute of a parameter, which is denoted by the following two flags representing causal conditions captured from the viewpoint of the isolated internal causality.

**Cause,C:** Changes of the value of the parameter can cause those of values of other parameters in the component through events within the component.

**Effect,E:** Changes of the value of the parameter can be caused by those of values of other parameters in the component through evetns within the component.

A causal specification takes one of the three values, $C\tilde{E}$, $\tilde{C}E$ and $CE$, where ”˜ ” is a negation symbol. If there can be a parameter whose change affects the value of the parameter under consideration, then the flag E is associated with the parameter under consideration. And, if there can be a parameter whose value is afffected by that of the parameter under consideration, then the flag C is associated with the parameter under consideration. If there is no such parameter, $\tilde{C}$ ($\tilde{E}$) is associated. Parameters with a constant value, for example, a resistance R in an electric circuit[4], have $C\tilde{E}$ as causal specification. The values of such parameters are changed only by influences of other components and/or factors external to the model of the system such as faults. Thus, a parameter is *exogenous*[4] to the model of the target system if and only if it has $C\tilde{E}$ as causal specification and has no connection with other components. The exogenous parameters are candidates of the faults in the diagnostic tasks.

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[3] As mentioned in No-Function-In-Structure principle[1], function of components is context-dependent. While we discuss a functional model in another paper[9], we concentrate on the modeling at the behavior level in this paper.

[4] On the assumption that the resistance R is not changed by heat.

### 3.3 Global Constraints and Time-Scales

In order to cope with global phenomena discussed in section 2.1, global constraints over local components are described. Such global constraints are justified by general properties of the physical entity such as heat and fluid. Since such properties are specified by the physical laws and the generic topologies of connections among components such as loop, they can be prepared beforehand for each generic topology as a part of the domain ontology. For example, such a general property for the generic loop topology holds in which changes of the temperatures in a loop are caused by the difference between the inflow and the outflow of thermal energy according to heat conservation law. Global constraints are instantiated according to concrete configurations.

*Time-scales* of phenomena enable the reasoning engine to distinguish *globally simultaneous* phenomena such as changes of flow-rate of incompressible fluid as T4. The global constraints representing such phenomena are called *globally simultaneous constraints* and marked with “simultaneous”. Other constraints and local component models are marked with “not-simultaneous”.

## 4 The Reasoning Method

The reasoning engine is designed to generate sequences of states representing changes of parameter values over time. A state consists of states of parameters, each of which consists of a qualitative value, a flag representing assignment of the value, three time counters: $T_f$,$T_s$,$T_v$. These time counters correspond to T4, T2 and T5 mentioned in section 2.1, respectively. The $T_f$ and $T_s$ counters increase when the values are propagated to other components. The $T_v$ counter increases when a value is changed by its derivative through the integral equation mentioned in section 3.1. The orders of states in the sequences mean causal orders among changes. A difference of the time counters between two states represents the cognitive length of the time interval of the two changes and the category of the causal relations. In the initial state, an abnormal value of an exogenous parameter must be specified. Other parameters are assumed to take normal values.

The reasoning engine has two processes, that is, intra-component reasoning and inter-component reasoning. Given abnormal values propagated from other components, the intra-component reasoning process determines values of other parameters in the component. According to constraints and causal specifications, abnormal values are propagated from parameters marked with “C” to those with “E”. If a value of a parameter marked with “CẼ” is not determined by other components, it can be assumed to remain an old value in the precedent state. Such assumptions enable to solve inherently simultaneous equations. In the inter-component reasoning process, on the other hand, abnormal values are propagated to parameters of neighboring components according to connections between ports. If values are propagated to *globally simultaneous constraints,* the $T_f$ time counter increases. If not, the $T_s$ time counter increases. The reasoning orders are according to the topology of connections among components and the time counters.

When a loop exists in the propagation path, a value of a parameter may cause a change of the parameter itself after propagating the loop around, so called feedback.

The new value of the parameter after the feedback may become ambiguous[4]. If the difference of the time counters between the new value and the original value is only $T_f$ representing instantaneous changes in T4, the reasoning engine determines the value the same as the original value, since there is no instantaneous feedback, according to the heuristics mentioned in section 2.3. If the difference of the time counters is greater than $T_f$, that is the time intervals of phenomena are grater than T4, the value remains ambiguous. We will see an example of a feedback in the next section.

## 5 Application to a Power Plant

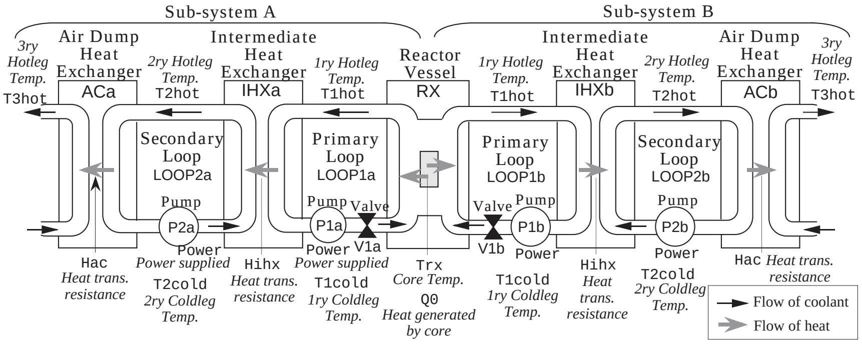

**Fig. 1.** Outline of the heat transportation system

This section describes the application of our method to a nuclear power plant. To concentrate on the behavior of the flow of thermal energy and the fluid, we built a model of the heat transportation system of the power plant. Figure 1 shows the outline of the system. The plant transports thermal energy generated in the reactor vessel(RX) into the open air[5] through two heat exchangers(IHX and AC). The system has two subsystems(called A and B) each of which has two loops(called primary and secondary) in which the coolant circulates.

The model of the whole system consists of 27 components, 143 parameters and 102 constraints. Major components and parameters[6] are shown in Figure 1. A component model is an instance of a component class, such as heat exchangers and pumps. The component class models are based on our domain ontology of fluid systems. Figure 2 shows the qualitative model of the heat exchanger in the primary loop in the subsystem A (called IHXa). Figure 3 shows that of the pump (called P1a). According to the ontology, the pump changes the flow-rate reacting to changes in the power supplied to the pump

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[5] Because this is a test plant, it has no power generator.

[6] The parameter name should be unique in each component. Thus, in Fig. 1, different parameters are shown as the same name.

and the total pressure-drop along the loop. We have identified four global properties of heat and fluid as a part of the domain ontology of fluid systems. In the case of the target system, 16 global constraints are derived according to them. Figure 4 shows a heat conservation law in the primary loop of the subsystem A.

**Name:** IHXa
**Time-Scale:** not-simultaneous
**Ports:**

| *symbol* | *connected comp.* | *connected port* |
|---|---|---|
| in1 | RX | out1a |
| out1 | P1a | in |
| in2 | P2a | out |
| out2 | ACa | in1 |
| heat1 | LOOP1a_HEAT | out |
| heat2 | LOOP2a_HEAT | in |
| flow1 | LOOP1a_FLOW | rst2 |
| flow2 | LOOP2a_FLOW | rst1 |
| dp1 | LOOP1a_DP | rst2 |
| dp2 | LOOP2a_DP | rst1 |

**Parameters:**

| *symbol* | *description* | *causal spec.* | *port* |
|---|---|---|---|
| `T1hot` | 1ry Coolant inlet Temp. | $C\tilde{E}$ | in1,heat1 |
| `T1cold` | 1ry Coolant outlet Temp. | $\tilde{C}E$ | out1,heat1 |
| `T2cold` | 2ry Coolant inlet Temp. | $C\tilde{E}$ | in2,heat2 |
| `T2hot` | 2ry Coolant outlet Temp. | $\tilde{C}E$ | out2,heat2 |
| `Q12` | Heat transported to 2ry coolant | CE | heat1, heat2 |
| `Hihx` | Heat trans. resistance. | $C\tilde{E}$ | |
| `Flow1` | Flow rate of 1ry coolant | $C\tilde{E}$ | flow1 |
| `Flow2` | Flow rate of 2ry coolant | $C\tilde{E}$ | flow2 |
| `P1io` | Pressure drop of 1ry coolant | $\tilde{C}E$ | dp1 |
| `P2io` | Pressure drop of 2ry coolant | $\tilde{C}E$ | dp2 |

**Constraints:**

```
Q12 = Hihx * ((T1hot + T1cold)/2
              - (T2hot + T2cold)/2)
Q12 = Flow1 * (T1hot - T1cold)
Q12 = Flow2 * (T2hot - T2cold)
P1io = Flow1
P2io = Flow2
```

**Fig. 2.** The qualitative model of IHXa

**Name:** P1a
**Time-Scale:** not-simultaneous
**Port:**

| *symbol* | *connected comp.* | *connected port* |
|---|---|---|
| in | IHXa | out1 |
| out | V1a | in |
| flow | LOOP1a_FLOW | driver |
| dp | LOOP1a_DP | driver |

**Parameters:**

| *symbol* | *description* | *causal spec.* | *port* |
|---|---|---|---|
| `Power` | Power supplied | CE | |
| `Flow` | Flow rate | $\tilde{C}E$ | flow |
| `Pio` | Difference of pressure between inlet and outlet | $C\tilde{E}$ | dp |
| `Tin` | Coolant Temp.(inlet) | $C\tilde{E}$ | in |
| `Tout` | Coolant Temp.(outlet) | $\tilde{C}E$ | out |

**Constraints:**

```
Power = Flow * Pio
Tin = Tout
```

**Fig. 3.** The model of the Pump in LOOP1a

**Name:** LOOP1a_HEAT
**Time-Scale:** not-simultaneous
**Port:**

| *symbol* | *connected comp.* | *connected port* |
|---|---|---|
| in | RX | heata |
| out | IHXa | heat1 |

**Parameters:**

| *symbol* | *description* | *causal spec.* | *port* |
|---|---|---|---|
| `Q01` | Heat transported from RX | CẼ | in |
| `Q12` | Heat transported to IHX | CẼ | out |
| `T1hot` | Coolant Temp.(hotleg) | C̃E | in,out |
| `T1cold` | Coolant Temp.(coldleg) | C̃E | in,out |

**Constraints:**

```
D(T1hot) = Q01 - Q12
D(T1cold) = Q01 - Q12
```

$\exists t,\ D(T1hot)_{(t)} = [0]$
$\exists t,\ D(T1cold)_{(t)} = [0]$

**Fig. 4.** The model of LOOP1a concerning heat conservation law

**Table 3.** Results of qualitative simulation

|  | RX Q0<br>[+] | IHXa Hihx<br>[-] | ACb Hac<br>[-] | P1a Power<br>[-] | P2b Power<br>[-] |
|---|---|---|---|---|---|
| Trx | (1)+ | (2)+ | (3)+ | (1)+ | (2)+ |
| A T1hot | (1)+ | (2)+ | (3)+ | (1)+ | (2)+ |
| T1cold | (2)+ | (1)+ | (4)+ | (1)- | (3)+,(4)? |
| T2hot | (2)+ | (1)- | (4)+ | (1)- | (3)+,(5)? |
| T2cold | (3)+ | (2)- | (5)+ | (2)- | (4)+,(6)? |
| T3hot | (3)+ | (2)- | (5)+ | (2)- | (4)+.(6)? |
| B T1hot | (1)+ | (2)+ | (3)+ | (1)+ | (2)+ |
| T1cold | (2)+ | (3)+ | (2)+ | (2)+ | (1)+,(4)? |
| T2hot | (2)+ | (3)+ | (2)+ | (2)+ | (1)+,(5)? |
| T2cold | (3)+ | (4)+ | (1)+ | (3)+ | (1)-,(6)? |
| T3hot | (3)+ | (4)+ | (1)- | (3)+ | (1)-,(6)? |

Table 3 shows the simulation results. Given one of the five anomalous perturbations in the top-most raw, the reasoning engine determines values of the other parameters when the system eventually reaches the heat balanced state. The numbers associated with the qualitative values[7] represent causal orders. All results in the table correspond to those of a domain expert. Although results when the system is subjected to decrease of the power suppied to pump2b are ambiguous, domain experts cannot determine the value without *quantitative* values of the flow-rate either.

Figure 5 shows a part of the causal relations generated by the reasoning engine in the case of decreasing the power supplied to P1a. When the power supply `Power` takes `[-]`, the reasoning engine derives the flow-rate `Flow` = `[-]` in T1 (see the sequence No.2 in Figure 5) by introducing an assumption that the difference of the pressure of the pump `Pio` specified as CẼ is `[0]`. The change of `Flow` is propagated to the all

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[7] The value “?” represents ambiguous values.

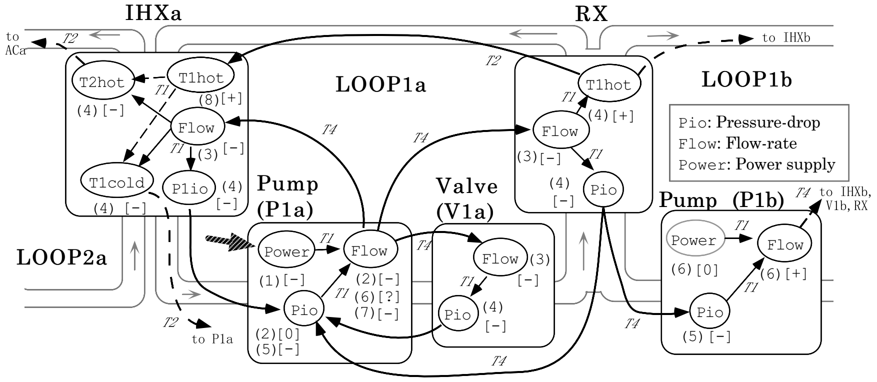

**Fig. 5.** A part of causal relations in the case of decreasing the power supplied to the P1a

components in LOOP1a, i.e. IHXa, RX and V1a, simultaneously in T4 by the globally simultaneous constraint concerning flow-rate. In each component, each pressure-drop decreases (No.4) because pressure-drop is proportional to flow-rate. Then, the total pressure-drop along LOOP1a changes to `[-]` by the globally simultaneous constraint concerning pressure-drop. Since the `Pio` of the pump equals to the total pressure-drop, `Pio` = `[-]` is derived (No.5) and then the assumed value is dismissed, so-called feedback. Then, value of `Flow` becomes ambiguous (No.6) because of `Power` = `[-]` and `Pio` = `[-]`[8]. Since the time delay along the feedback loop is T4+T1+T4+T1 representing instantaneous phenomena, according to the heuristics, that is, there is no instantaneous feedback, the system obtains `Flow` = `[-]` which matches reality (No.7). The decrease of the pressure-drop in RX, on the other hand, is propagated to the other pump P1b (No.5). It causes increase of the flow-rate in LOOP1b. Moreover, in RX and IHXa, the decrease of the flow-rate of LOOP1a also causes the changes in the temperatures of the coolant (No.4). Since these changes are not simultaneous, i.e. in T2, these are propagated to the other components after the simultaneous phenomena (No.8).

Figure 6 shows the causal relations when the heat transfer resistance `Hihx` of IHXa decreases[9]. Firstly, in IHXa, the reasoning engine derives `T1cold` = `[+]` and `Q12` = `[-]` (the sequence No. 2 in Fig. 6). The value of `T1cold` is propagated to RX through P1a and V1a, then `T1hot` = `[+]` and `Q01` = `[0]` (No.8) are derived in RX. When `Q01` = `[0]` and `Q12` = `[-]` are propagated to LOOP1a_HEAT (No.9), `D(T1hot)` = `[+]` and `D(T1cold)` = `[+]` are derived (No.10). These mean the temperatures in the loop are increasing in T3, caused by the difference between the inflow (`Q01`) and outflow (`Q12`) of thermal energy. Long enough time in T6 after the occurrence of anomaly, the loop achieves an equilibrium state, and hence the temperatures are stable. Thus, although `Q12` becomes ambiguous (No.12), the reasoning engine obtains `Q12` = `[0]` in the equilibrium state in T6 (No.14). This reasoning result shows the increase of the

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[8] Note that multiplication has the same effect as addition because the qualitative values represent not sign but deviation from a normal value.

[9] In contrast with the result shown in Table 3, Figure 6 shows the result in the case where the system has only the subsystem A without the subsystem B.

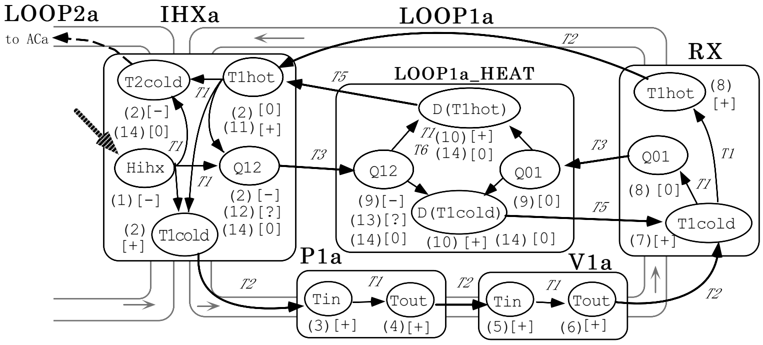

**Fig. 6.** A part of causal relations in the case where the heat transfter resistance of IHXa decreases (without the subsystem B)

temperatures of LOOP1a compensates the decrease of the heat transfer resistance of IHXa, and then the temperatures of LOOP2a become equal to the normal values[10].

The reasoning system has been implemented in Common ESP, an object-oriented Prolog, on a UNIX workstation.

## 6 Related Work

A lot of research has been carried out on qualitative reasoning for causal understanding [1, 2, 4, 6, 10, 11, 12, 13, 14]. In [1] and [12], although general causal properties of devices have been identified, causal relations generated by their methods are ambiguous in the case of inherently simultaneous equations. The TQ analysis[14] provides heuristics to analyze limited kinds of feedback involving integration. A part of our causal specification corresponds to the descriptions of “exogenous parameters”[4] of each component. Skorstad discusses context-dependence (“instability”) of such descriptions[11]. In [2] and [13], causal properties of physical processes are described.

The concept of time-scale itself is not new and has been proposed in other papers such as [5] and [7]. The global constraint about heat presented in section 5 corresponds to an energy constraint[3] (a global filter) for QSIM.

## 7 Summary

A new method of qualitative reasoning and causal ordering is proposed. The method is based on ontologies of causality and time-resolution and a domain ontology of fluid systems. The reasoning engine generates complex causal relations originated in various configurations of components according to causal specifications independent of the context. The generated causal relations include those among the transitional states between

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[10] In the case where the system also has the subsystem B, these phenomena do not happen as shown in Table 3

completely-satisfied-states constrained by the inherently simultaneous equations. Moreover, its performance evaluation through application to the power plant is described. The reasoning result matches exactly those of a domain expert.

The assumptions underlying the model and the reasoning engine are explicitly discussed in section 2.3. The experiment suggests appropriateness of the assumptions. Understanding the limitation of the method remains as future work. In the application mentioned in section 5, global constraints are manually described as global components. Currently, investigation on mechanism which automatically generates global constraints from general properties is in progress.

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