Examination of Deep Knowledge in Knowledge Compilers

Shinji YOSHIKAWA*, Akira ENDOU
Power Reactor and Nuclear Fuel Development Corporation
4002 Narita-cho, O-arai-machi, Ibaraki-pref. 311-13, Japan
Telephone:+81-292-67-4141 ext. 3121
Facsimile:+81-292-66-3868

Yoshinobu KITAMURA, Munehiko SASAJIMA, Mitsuru IKEDA,
and Riichiro MIZOGUCHI
The Institute of Science and Industrial Research
Osaka University
8-1, Mihogaoka, Ibaraki, 567 Japan
Telephone:+81-6-877-5111 ext. 3565
Facsimile:+81-6-877-4977
E-mail:miz@ei.sanken.osaka-u.ac.jp

Length:4078 words(excluding the abstract and references)
8 figures

Abstract

A new method is proposed to examine a deep knowledge in knowledge compilers based on qualitative reasoning(QR)[1]. It is profitable if a knowledge compiler can examine a deep knowledge base to judge whether a thorough shallow knowledge can be generated or not, and can request the knowledge engineer to add some knowledge to the deep knowledge base if necessary, just like ordinary compilers check program source lists before generating executable objects and let the programmer know about defects of the source lists. Deep knowledge in QR-based knowledge compilers can be represented as simultaneous qualitative equations(SQEs). And the examination method reported in this paper is based on a structure analysis of a set of SQEs, and enables compilers to suggest necessary additional qualitative equation(QE)s. The way how this examination function works is explained with a sample model of a heat transport system of a nuclear power plant.

Background

In the conventional numerical calculations, the device under consideration is analyzed using numerical models, and analysis accuracy can be improved as the models become sophisticated. However, such a method doesn't show us how the device behaviors are determined by its descriptions. For example, we cannot know "why this temperature increases when this pump stops". And we need another whole analysis to know "how this behaves if this pipe were 1cm shorter than it is".

In contrast with numerical analyses, qualitative reasoning can be viewed as aiming at "to make it clear how the device behaviors are determined by its descriptions, in exchange for a compromise on the behavior accuracy."

Advantages of qualitative reasoning[2][3][4] has been claimed that reasoning can be started from incomplete information, and all possible behaviors can be derived. And explanation generation capacity has been recognized as one of the greatest advantages. However, combinatorial explosion is the heaviest drawback and makes crucial tradeoffs with the advantages described above. There are many efforts to achieve disambiguation and to maintain explanation capability and simplicity of qualitative reasoning, mostly by combining qualitative reasoning/simulation with numerical processing. Within most of these researches, disambiguation is done by choosing one among all qualitative solutions by matching with numerically obtained result or human intuitive knowledge.[5] It is undoubtedly profitable if disambiguation process is explained also in a qualitative manner. In other words, qualitative reasoning will be much more effective if it shows why the other solutions should be denied as spurious ones, even when the conflicting change propagations have comparable effect[6]. For this reason, some systems employ additional qualitative constraints for disambiguation. However, identification of the additional constraints is done manually in an ad hoc manner. And, in case that qualitative reasoning is done using insufficient information, users may need to know what information can determine the system behavior uniquely. If a deep knowledge base is viewed as a set of qualitative constraint, there should be a clear condition to attain disambiguation. However, researches to identify this condition and to utilize this condition for examining deep knowledge are hardly found[7]. What the authors want to do in this research is to enable the system to examine initially given set of qualitative knowledge base and to suggest additional qualitative constraints useful for disambiguation of the solution. In this paper, an attempt to realize this suggesting function is presented. The proposed method deals with equilibrium equations. First, a qualitative model of a heat transport system of nuclear plant is shown, which has plural feedback loops, to emphasize the importance of additional qualitative constraints. Then, mechanism of ambiguity is analyzed. Finally, the method to check the initial deep knowledge and to suggest additional knowledge effective for disambiguation is explained and demonstrated.

A Qualitative Model of Heat Transport System of Nuclear Power Plant

A qualitative model of a heat transport system in a nuclear power plant is shown below.

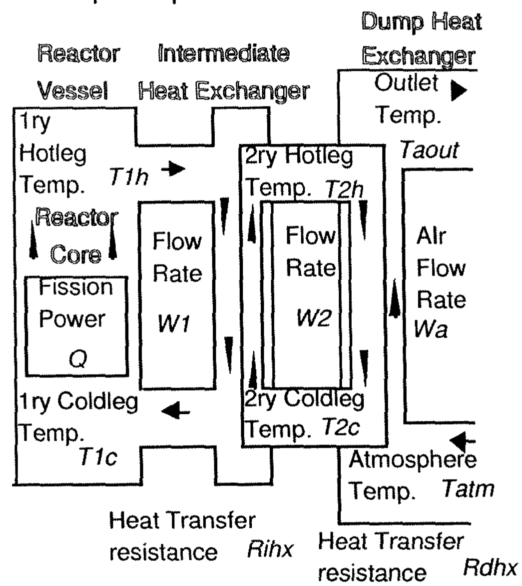

Fig.1 One loop Heat Transport System Model of A Nuclear Plant

The knowledge of change propagation in each component of the model, which can be primarily acquired easily, is shown below:

Reactor

1ry hotleg coolant temperature(T1h) increases if:(1) 1ry coldleg coolant temperature(T1c) increases,

(2) reactor fission power(Q) increases, or

(3) 1ry coolant flow rate(W1) decreases.

— QK-1

Intermediate Heat Exchanger(IHX)

1ry coldleg coolant temperature(T1c) increases if:(1) 1ry hotleg coolant temperature(T1h) increases,

(2) 2ry coldleg coolant temperature(T2c) increases,

(3) 1ry coolant flow rate(W1) increases,

(4) 2ry coolant flow rate(W2) decreases, or

(5) heat transfer resistance of IHX(Rihx) increases.

—QK-2

2ry hotleg coolant temperature(T2h) increases if:(1) 1ry hotleg coolant temperature(T1h) increases,

(2) 2ry coldleg coolant temperature(T2c) increases,

(3) 1ry coolant flow rate(W1) increases,

(4) 2ry coolant flow rate(W2) decreases, or
(5) heat transfer resistance of IHX(Rihx) decreases. --- QK-3

Air Dump Heat Exchanger(DHX)

2ry coldleg coolant temperature(T2c) increases if:(1) 2ry hotleg coolant temperature(T2h) increases,
(2) Atmosphere temperature(Tatm) increases,
(3) 2ry coolant flow rate(W2) increases,
(4) air flow rate(Wa) decreases, or
(5) heat transfer resistance of DHX(Rdhx) increases. --- QK-4

Air outlet temperature(Taout) increases if:(1) 2ry hotleg coolant temperature(T2h) increases,
(2) Atmosphere temperature(Tatm) increases,
(3) 2ry coolant flow rate(W2) increases,
(4) air flow rate(Wa) decreases, or
(5) heat transfer resistance of DHX(Rdhx) decreases. --- QK-5

Now we can try to determine the qualitative value of the 1ry coldleg temperature(T1c) when the primary coolant flow rate(W1) decreases. However, too many qualitative value combinations of the endogenous parameters(T1h,T1c,T2h,T2c,Taout) are derived:----
([-],[-],[-],[-],[-]),([0],[-],[-],[-],[-]),([+],[-],[-],[-],[-]),
([+],[0],[-],[-],[-]),([+],[+],[-],[-],[-]),([+],[-],[0],[0],[0]),
([+],[0],[0],[0],[0]),([+],[+],[0],[0],[0]),
([-],[-],[+],[+],[+]),([0],[-],[+],[+],[+]),
([+],[-],[+],[+],[+]), and ([+],[+],[+],[+],[+]) ----from which we get no meaningful result:

From causal network of this model shown in Fig.2, it is easily observed that this model has many feedback loops and that most of endogenous parameters cannot be causally ordered[8]. In case that a device under consideration has a particular characteristic like this model, qualitative reasoning can hardly be applied without additional qualitative constraints.

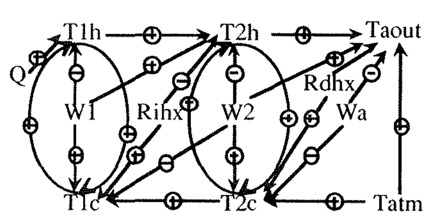

Fig.2 Causal Network of the Heat Transport System Model

Knowledge Representation by Qualitative Equation

Before the detailed discussions, representative equations has to be presented.
QK-1 means that:
a)if (T1h=[+]or[0])and(Q=[+]or[0])and(W1=[-]or[0]) and(not (T1c=Q=W1=[0]))
then T1h=[+]
b)if (T1c=[-]or[0])and(Q=[-]or[0]) and(W1=[+]or[0])and(not (T1c=Q=W1=[0]))
then T1h=[-]
c)if (T1c=Q=W1=[[0]) then T1h=[0]
These propositions can be transformed as:
a')(T1h=[0]or[-])and(T1c=[+]or[0])and(Q=[+]or[0]) and(W1=[-]or[0])and(not(T1h=T1c=Q=W1=[0]))
IS FALSE
b')(T1h=[0]or[+])and(T1c=[-]or[0])and(Q=[-]or[0]) and(W1=[+]or[0])and(not(T1h=T1c=Q=W1=[0]))
IS FALSE

In this paper, this set of propositions is represented as an qualitative equation as shown below:

[-]T1h+[+]T1c +[+]Q+[-]W1=0 --- QE-1

This equation means that:
"there is at least 1 pair of terms having opposite signs, or all the terms are zero".
In case that the right-hand side is [+], this equation means that:
"At least one term is plus".

Above transformation of a qualitative knowledge(QK-1) into a qualitative equation(QE-1) is called transposition thereafter. And a set of qualitative knowledge can be represented as a set of simultaneous qualitative equations(SQE) by transposition. Knowledge representation in the form of SQE is convenient for visualizing the mechanism of ambiguity and for discussion of the method of disambiguation. Furthermore, this representation method leads to a new qualitative reasoning algorithm, which derives the solution(s) based on qualitative constraint satisfaction. This algorithm can deal both with local change propagation knowledge and other kind of qualitative constraint effective for disambiguation , in the same manner. From a viewpoint of explanation generation, this algorithm may have a disadvantage to the standard method of qualitative reasoning which traces change propagation along with causal network[1]. However, the focus of this paper is to analyze the given deep knowledge base, to check whether a thorough shallow knowledge can be obtained with satisfactory disambiguation, and to suggest about necessary additional qualitative knowledge, if any.

The qualitative knowledge from QK-1 through QK-5 can be represented as follows by transposition and in the form of matrix calculus similar to that of ordinary linear equations:

$$\begin{pmatrix} [-]T_{1h}+[+]T_{1c} & & & \\ [+]T_{1h}+[-]T_{1c} & +[+]T_{2c} & & \\ [+]T_{1h}+ & +[-]T_{2h}+[+]T_{2c} & & \\ & [+]T_{2h}+[-]T_{2c} & & \\ & [+]T_{2h} & +[-]T_{aout} & \end{pmatrix} +$$

Endogenous Parameter Part

$$\begin{pmatrix} & [+]Q+[-]W_1 & \\ & [+]W_1+[+]R_{ihx}+[-]W_2 & \\ & [+]W_1+[-]R_{ihx}+[-]W_2 & \\ [+]T_{atm} & & [+]W_2+[+]R_{dhx}+[-]W_a \\ [+]T_{atm} & & [+]W_2+[-]R_{dhx} \end{pmatrix}$$

Exogenous Parameter Part

$$= \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Fig. 3 Initial Qualitative Knowledge about the Heat Transport Model Represented as a Set of Simultaneous Qualitative Equations

In the above figure,parameters affected by no other parameter in the whole model are classified as exogenous parameters, and parameters affected by other parameter(s) in this model are classified as endogenous parameters.

Mechanism of Ambiguities

In order to identify the method for checking initially constructed SQEs and for suggesting about additional QEs effective for disambiguation, We need to observe and formulate ambiguity generation mechanism.

In QE-1 and QE-2 as follows:

[-]T1h+[+]T1c +[+]Q+[-]W1 =0
--- QE-1

[+]T1h+[-]T1c+[+]T2c +[+]W1+[+]Rihx+[-]W2 =0
--- QE-2

,suppose that only W1 becomes [-] among the exogenous parameters. Then QE-1 and 2 are transformed as follows for the endogenous parameters:

[-]T1h+[+]T1c =[-]
--- QE-1'

[+]T1h+[-]T1c+[+]T2c =[+]
--- QE-2'

QE-2' is always satisfied as long as QE-1' is satisfied. In other words, QE-2 cannot contribute to suppress the ambiguity when reasoning about W1 deviation.

This observation can be generalized as:

"In case that all the endogenous terms and one term of exogenous parameter Ve of QE-m are involved in another equation QE-n, QE-n does not represent any effective constraint when Ve deviates."
---- Condition-1

Condition-1 can be used for checking ambiguities specific to particular parameter's deviation. Now we need another method for checking common ambiguities among all the exogenous deviation. In numerical calculus, it is apparen that a set of independent equations represents enough constraint if the set is as large as the number of the endogenous parameters, and that no endogenous parameter can deviates when no exogenous parameter deviates. However, this is not applicable to qualitative calculus. For example, all the endogenous parameters in Fig.3 can have qualitative values:([+],[+],[+],[+],[+]) when the exogenous parameters take [0]. It can be proven that some endogenous parameter is allowed to deviate when no exogenous parameter deviates, this parameter canno have unique qualitative value against any exogenous deviation. Therefore, a necessary condition for SQE to suppress the ambiguity is:

"None of the endogenous parameters can be other than zero when no exogenous parameter deviates."
---- Condition-2

It is worth emphasizing that Condition-1 is to inhibit a par of spurious solutions specific to each exogenous deviation, and that Condition-2 is to inhibit common spurious solutions for all exogenous deviations. These 2 conditions can be used to examine originally constructed SQE, and to suggest the user/KE to add QEs, by showir candidate QEs which can suppress the ambiguity. The detailed procedures are shown in the next section.

Suggestion Method of Additional QEs

Condition-1 can be used for checking independent effectiveness of a particular QE's qualitative constraint, in comparison to another QE. On the other hand, Conditio 2 is for checking the whole SQE. If Condition-2 is appliec first for checking the initially given SQE, followed by filteri by Condition-1, Condition-2 must be applied again, because filtering by Condition-1 can throw away QEs necessary for satisfying Condition-2.

Therefore, Condition-2 has to be checked and satisfied the set of QEs after filtered by Condition-1. The propos method to suggest additional QEs consists of 2 steps: 1)excluding QEs which cannot contribute to suppressior of ambiguity when one particular parameter deviates,applying condition-1, 2)derivation of candidate additional QEs to inhibit nonzero qualitative values for th endogenous parameters when no exogenous paramete deviates. And Condition-1 is checked whenever a new C is added.

It should be noticed that excluded QEs by Step-1 shoul be included in knowledge compilation because these ca contribute for disambiguation when deviated exogenous parameter differs from one corresponding to Ve in Condition-1.

Demonstration of Suggestion about Adding Ql

In this section, the method for suggesting about adding QEs is demonstrated about the heat transport system model, assuming that only QK-1 through QK-5 representing local change propagations are initially included in the deep knowledge.

The procedures of these 2 steps are explained below fo the heat transport model of a nuclear power plant describ before:

Step-1)
About exogenous parameter Tatm,Q,Rihx,Rdhx and Wa,there is no pair equations to match the condition-1.
About W1, QE-2 represents no additional constraint to QE-1. then QE-2 is excluded.
About W2, QE-3 represents no additional constraint to QE-4. then QE-3 is excluded.

Then QE-1,4, and 5 are handed to Step-2.

Step-2)
When no exogenous parameter deviates, the SQE for the endogenous parameters are as follows:

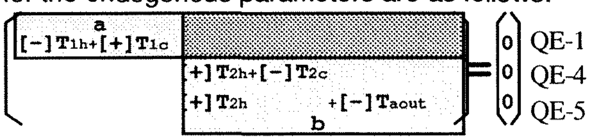

Fig.4 SQEs of QEs 1,4, and 5

If the block-b) satisfies Condition-2, the dark shaded area can be neglected to judge whether the whole matrix satisfies Condition-2. Only block-a) has to be judged. Thus it is seen that a SQE satisfies Condition-2 if and only if every diagonal block satisfies Condition-2. In this case, examination of Condition-2 need to be done on 3 blocks.

Examination of diagonal block-b) in Fig.4:
Solutions of :
[+]T2h+[-]T2c =[0], and
[+]T2h +[-]Taout=[0]
are ([-],[-],[-]),([0],[0],[0]), and ([+],[+],[+]).
The candidate QEs to inhibit ([-],[-],[-]) and ([+],[+],[+]) are:
[+]T2h +[?]Q+••••+[?]Wa=0,
[+]T2c +[?]Q+••••+[?]Wa=0,
+[+]Taout+[?]Q+••••+[?]Wa=0,
[+]T2h+[+]T2c +[?]Q+••••+[?]Wa=0,
[+]T2h +[+]Taout+[?]Q+••••+[?]Wa=0,
[+]T2c+[+]Taout+[?]Q+••••+[?]Wa=0, and
[+]T2h+[+]T2c+[+]Taout+[?]Q+••••+[?]Wa=0,
Note that [?] stands for any of [-],[0], and [+]and that description "[?]Q+••••+[?]Wa" in each of above list means :
"[?]Q+[?]W1+[?]Rihx+[?]W2+[?]Rdhx+[?]Tatm+[?]Wa".

Therefore, these candidate EQs are not concrete yet. For example, the first candidate EQ can match many EQs:[+]T2h+[-]Q=0, [+]T2h+[+]Q+[-]Tatm+[-]Wa=0, and so on. Each candidate in the above list can match 3^7=2187 possible concrete EQs. In this sense, candidate EQs like those in the above list are called just "type" of EQ hereafter. What the user has to do at this point is to inspect the candidate EQ types one by one, carefully suspecting whether he/she has a qualitative knowledge to match the type.
In this case, the following knowledge matches the third type:

"About Air flow of DHX,
heat reduction rate by air flow in DHX is proportional to (air outlet temperature - atmosphere temperature)*(air flow rate)
—QK-6
,and the heat reduction rate is equal to the fission power of the reactor".
, and the following QE is obtained by transposition:
[+]Taout+[-]Tatm+[-]Q+[+]Wa=0
—QE-6

It is important that the new set of SQEs consisting QE-1,4,5, and 6 has to be examined about Condition-1, because constraint of newly added QE-6 can make some of the constraints of QE-1,4, and 5 ineffective about some exogenous deviation. In this case, QE-5 is excluded from the SQE for the examination about Condition-2, and the SQE for the endogenous parameters change as follows:

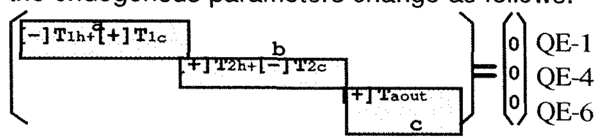

Fig.5 SQEs of QEs 1,4, and 6

In this case, diagonal blocks-b) and a) have to be examined, because diagonal block-c) apparently satisfies Condition-2, and cannot be excluded by Condition-1 when new EQs are added in diagonal blocks-b) and a).

Examination of diagonal block-b) in Fig.5:
The solutions to inhibit are ([-],[-]) and ([+],[+]). The candidate QEs to add are:
[+]T2h +[?]Taout+[?]Tatm+[?]Q+••••+[?]Wa=0,
[+]T2c+[?]Taout+[?]Tatm+[?]Q+••••+[?]Wa=0
, and
[+]T2h+[+]T2c+[?]Taout+[?]Tatm+[?]Q+••••+[?]Wa=0.
This time, the user can be expected to pick up the following knowledge from his/her brain when checking the third QE type in the above list :

"About DHX,
energy transport rate through DHX is proportional to (2ry average temperature - air side average temperature)/(heat transfer resistance of DHX)
—QK-7
, and the heat transport rate is equal to the fission power"
, and transposed QE is:
[+]T2h+[+]T2c+[-]Taout+[-]Tatm+[-]Q+[-]Rdhx=0
—QE-7

, and no EQ is excluded by Condition-1 this time, and the SQE to be examined is now:

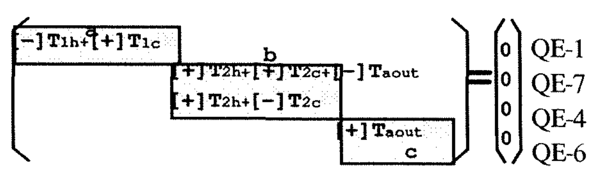

Fig.6 SQEs of QEs 1,7,4, and 6

Examination of diagonal block-a) in Fig.6:

The solutions to inhibit are again ([-],[-]) and ([+],[+]). The candidate QEs to add are:

[+]T1h+ [?]T2h+[?]T2c+[?]Taout+•••=0,

[+]T1c+[?]T2h+[?]T2c+[?]Taout+•••=0, and

[+]T1h+[+]T1c+[?]T2h+[?]T2c+[?]Taout+•••=0.

This time the following knowledge can be reminded by the user when checking the third type:

"About IHX,

energy transport rate through IHX is proportional to (1ry average temperature - 2ry average temperature)/(heat transfer resistance of IHX) —QK-8

,and the energy transport rate is equal to the fission power."

and transposed EQ is:

[+]T1h+[+]T1c+[-]T2h+[-]T2c+[-]Q+[-]Rihx=0 —QE-8

, and no EQ is excluded by Condition-1 this time, and Condition-2 is finally satisfied by the set of SQEs:

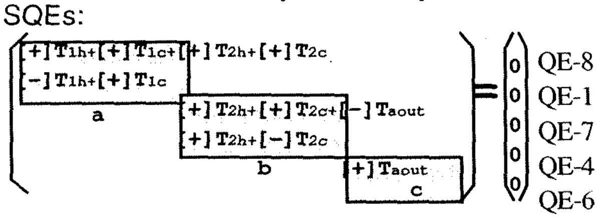

Fig.7 SQEs of QEs 8,1,7,4, and 6

The final set of QEs resulted from above procedures are:QE-1,4,6,7, and 8, and whole SQE for reasoning consists of QE-1,2,3,4,5,6,7, and 8. Ambiguity is drastically reduced by newly added EQs(:QK-6,7, and 8) as follows.

Deviation of dependent variables / exogenous deviation	T1h	T1c	T2h	T2c	Taout
Tatm=[+]->	(+)	(+)	(+)	(+)	(+)
Q=[+]->	(+)	(+)	(+)	(+)	(+)
W1=[+]->	?	?	?	?	?
Rihx=[+]->	?	?	?	?	?
W2=[+]->	?	?	?	?	?
Rdhx=[+]->	(+)	(+)	(+)	(+)	?
Wa=[+]->	(-)	(-)	(-)	(-)	(-)

Reasoning result by initially constructed SQE

↓

Deviation of dependent variables / exogenous deviation	T1h	T1c	T2h	T2c	Taout
Tatm=[+]->	?	?	?	+	+
Q=[+]->	+	+	+	+	+
W1=[+]->	-	+	0	0	0
Rihx=[+]->	+	+	0	0	0
W2=[+]->	?	?	-	+	0
Rdhx=[+]->	+	+	+	+	0
Wa=[+]->	?	?	?	-	-

Reasoning result by enlarged SQE

Fig. 8 Disambiguation Effect of Additional Qualitative Equations

(note: (+) and (-) mean that these qualitative signs are determined only when reasoned along with the causal orders. This method assumes that the device is in perfectly normal condition before the assumed exogenous deviation, in contrast with that derived informations from SQE of the device's equilibrium state after the assumed deviation are independent of the prior states to the assumed deviation.)

Discussions

1) Conditions of qualitative matrix for disambiguation

It has been demonstrated that conditions-1 and 2 can be used to suggest necessary additional qualitative equations, but still have a weak point. There is one more qualitative knowledge as follows, which has not been picked up by the proposed method:

"About 2ry loop,

Energy transport rate through 2ry loop is proportional to (2ry hotleg coolant temperature - 2ry coldleg coolant temperature)*(2ry coolant flow rate), and the energy transport rate is equal to the fission power".

And, this knowledge suppresses the remaining ambiguities of the resulting SQE about deviations of Tatm and Wa.

This means that satisfying Conditions-1 and 2 is not enough to suppress the reasoning ambiguity, at least by the algorithm briefed in the section of "Knowledge Representation by Qualitative Equation".

More conditions of SQE structure to suppress ambiguity have to be identified, and, if possible, it is desirable that an efficient algorithm is available to judge all the conditions.

2) Identification of the right QE from suggested QE types

In the demonstration, the way to select right QE type and to identify right QE to match the type was not discussed. It is definitely impossible to derive concretely the right QE based only on the initially constructed knowledge base and the examination or reasoning algorithm. The purpose of this research is to support users of knowledge compilers in building more effective deep knowledge bases more easily. The method proposed in this paper can help to limit the space of knowledge to search for effective disambiguation, although this method cannot guarantee the successful knowledge building. And, there is still some room for improvements. First, parameter combinations in the suggested equation type can be limited based on the device topology. For example, about the heat transport system model shown before, if a suggested equation type has only T1h and Taout, excluding all the parameters in the secondary loop, this QE cannot represent naive knowledge and can be thrown away from the suggestion list. Second, suggested equation type can be more intuitive by introducing physical dimensions. In general, equations to represent physical laws are expressed in a form like "PV=nRT" or "F=ma". Physical dimensions can be useful to transform the suggested type of QE into the form like <Product of Parameters is equal/proportional to Product of Parameters>" For example, about the heat transport system model again, a suggestion like "Do you have any knowledge to show that 'Q[J/sec] are positively proportional to <product of T1h[K] and W1[kg/sec]> and inversely proportional to <product of T1c[K] and W1[kg/sec]>' ?" is expected to much more understandable than the other one like "Do you have any knowledge to show that '[+]T1h+[-]T1c+[+]W1+[-]Q=0' ?"

3) Possibility to support another knowledge category construction.

It has been considered that deep knowledge for knowledge compilation has to consist of a)physical principles and commonsense causalities, and b)informations of the device's topology. Category a) can be commonly used at least in the specific domain, and category b) is thought to be specific to the object device. However, category b) is still common in the sense that behaviors of devices having same configuration can differ to each other. This implies that a new knowledge category is necessary to reason particular device behavior without excessive ambiguity. Examples are demonstrated below:

In the previous heat transport system of a nuclear power plant, qualitative influence of 2ry coolant flow rate on 1ry coolant temperature cannot be determined from local change propagations, general principles and device topologies. This qualitative influence depends on initial plant heat balance. In other words, this qualitative influence depends on individual quantitative specifications. After complete condition of SQE is identified, the function to suggest necessary additional qualitative knowledge can derive the criterion to determine whether the influence is positive or negative. And it will be possible to efficiently construct a knowledge base for *qualitative knowledge depending on individual quantitative specifications* . Let us consider another example. In general, heat transfer coefficient is dependent on Reynolds number. Suppose that the secondary coolant were gas, which makes the net heat transfer ratio much more dependent on Reynolds number,. If so, both of the 2ry hotleg and coldleg temperature can decrease if 2ry flow rate increases. In this case, suggestion function of additional qualitative equations enables the user to make the qualitative model of heat exchanger more common, and to describe additional qualitative constraint dependent on whether the fluids are liquid or gas into a knowledge base for *qualitative knowledge depending on individual quantitative specifications* .

In case that it is necessary to develop a deep knowledge base for another similar plant, this new category can be separated, to enhance reusability of the deep knowledge base. As seen so far, this function improves re-usability of the whole deep knowledge base.

Conclusion

A method to examine deep qualitative knowledge and to suggest necessary additional knowledge has been proposed and demonstrated. Knowledge representation by qualitative equations plays an important role in this method. Currently derived conditions of simultaneous qualitative equations for disambiguation is still incomplete,Followings are thought to be the main works to reach the next step of this research:

1)Qualitative mathematics

In order to identify the complete condition of SQE for disambiguation , an integrated theory of qualitative mathematics has to be developed. As seen so far, it can happen that a set of SQEs larger than the number of endogenous parameters still remains under constraining. And, if a QE is viewed as a set of signs in an ordinary linear equations, a set of SQEs larger than the number of endogenous parameters involves some information about absolute values of the coefficients. Theory of qualitative mathematics has to deal with these special characteristics of SQEs.

2)Reasoning algorithm modification

In order to make sense of establishing a new knowledge category for *qualitative knowledge depending on individual quantitative specifications*, priorities among QEs have to be considered during the reasoning procedures. Knowledge used in the explanations generated along with reasoning process has to be shifted to deeper ones. In other words, shallow knowledge derivable from general principles only must not be explained by individual quantitative specifications.

After these works are completed, knowledge compilers based on QR will be greatly enhanced both in effectiveness of shallow knowledge to be generated, and in reusability of deep knowledge base, mainly due to being less dependent on heuristic approaches.

Acknowledgement

And the authors are greatly indebted to Mr. K. Suda of Power Reactor and Nuclear Fuel Development Corporation, who provide his original heat balance calculation and visualization software to enable the authors to verify the qualitative reasoning system.

References

[1]Hirai,K. and Mizoguchi, R. et al.;"The organization of the domain knowledge oriented to shareability - Domain-specific Tool Based on the Deep Knowledge (KCII-DST)", *Proceedings of the 5th Annual Conference of JSAI,* Vol.1, pp.325-328, 1991(in Japanese)

[2] de Kleer, J. and Brown, J. S.:"A Qualitative Physics Based on Confluences", *Artificial Intelligence,* Vol.24, pp7-83, 1984

[3] Benjamin Kuipers:"Qualitative Simulation",*Artificial Intelligence*, 29:289-338,1986.

[4] Kenneth D. Forbus:"Qualitative Process Theory",*Artificial Intelligence*,24:85-168,1984

[5] Yoshida, K. and Motoda, H.:"An Approach to Hierarchical Qualitative Reasoning"

[6] O. Raiman, "Order of Magnitude Reasoning," AAAI-86

[7] Jean-Luc Dormoy, et al,:"Assembling a Device", *Proceedings of AAAI-88*, pp.330-335, 1988

[8] Iwasaki, Y. and Simon, H. A.:"Causality in Device Behavior", *Artificial Intelligence*, Vol.29, pp3-32, 1986