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APPLICATION SYSTEMS OF KNOWLEGE ENGINEERING IN WATER AND SEWAGE WORKS

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1. FOREWORD

Water and sewage works are part of the water circulation cycle aimed at the world of nature and human society. High reliability as the foundation of life and efficient and stable operation of the water distribution process for a wide area and biological chemical filtering treatment process are essential in the operation and management of facilities. However, realizing all these conditions with conventional operation control techniques only is difficult. Much is expected of new technology and knowledge engineering, especially of expert systems. Actually, these are being applied to actual plants and noticeable effects are being achieved. Examples of application of these to water and sewage works are introduced here.

2. APPLICATION OF KNOWLEDGE ENGINEERING

2.1 Aims and effects of application

When the site of operation control of water and sewage works is considered, conventional techniques offered by manufacturers only are insufficient and there are many examples in which smooth operation is performed by adding the experience and know-how of skilled operators. This reason for this is that obtaining a complete knowledge of the objects of control is difficult and the control system is designed based on a limited partial knowledge. The conventional control techniques for design are sequence control, PID control, modern control heory (regulator, non-interference, Kalman filter), and mathematical planning (dynamic programming, linear programming). The flexible contemplating faculty and knowledge of man fill in the gap between the necessary complete of man fill in the gap between the necessary complete knowledge and the partial knowledge which can be obtained. Supporting this activity is the aim of application of knowledge engineering. The areas at which this knowledge gap is created and the reason for it are described below.

(1) Control field in which the objective model is complex and a numerical model cannot be made.
(2) Abnormal phenomena cannot be forecast and countermeasures cannot be decided in the system design stage.
(3) There points which are unclear at the time of specifications consultations and design and are first judged at the start of operation.

An advanced operation control system is realized by incorporating the advanced knowledge and know-how of the experienced operator regarding these problems. The fields of application of knowledge engineering to the water and sewage works fields are shown in *Table 1.* The types of problems are control problems and diagnostic problems. Control problems which handle fuzziness and

Table 1 Fields of application of knowledge engineering to water and sewage works

Type		Water works	Sewage works	Tool
Control	Cooperation of numerical model	• Water operation control • Filtration plant operation control	• Sludge transfer between multiple sludge treatment plants	EIXAX (KOCP)
	Fuzziness	• Filtration plant operation control • Water intake and distribution con control • Chemical feed control • Pump operation control	• Pump operation control • Forecast for rain water inflow • DO control	FRUITAX
Diagnosis		• Facility diagnosis (independent power plant, pump, etc.) • Operation support (treatment for power outage and restoration) • Detection of water interruption point	• Facility diagnosis (independent power plant, pump, etc.) • Operation support (treatment for power outage and restoration, sludge treatment)	COMEX

Table 2 Features of knowledge engineering software tools

Comparison item \ Tool name		Programming type EIXAX	FRUITAX	COMEX
Development concept	Basic theory	Production system	Fuzzy theory	Criteria logic
	Existing theory	Mathematical programming	Deterministic numerical formula model	Production system
	Problems with existing theory	Operator logic is difficult to represent.	Fuzzy information cannot be incorporated in numerical formula.	Expert's knowledge is difficult to represent.
	Objective	Fragmentary collection of logic and arrangement into rules.	Use of fuzzy control rules.	Use of knowledge representation actually used in medicine.
Scheme	Knowledge representation	Rules, numerical formula, frame	Fuzzy rule, membership function	Criteria frame
	Handling of fuzziness	Coping by external program (membership function scheduled to be introduced shortly)	Building into membership function	Coping by 3-stage certainty factor of criteria frame
Use	Field	Planning (sequence plant establishment)	Control (for diverse, voluminous results data can be collected)	Diagnosis (knowledge can be acquired from experts)
	Development and execution by personal computer	X	O (F9450, L25, etc.)	O (possible if MS-DOS personal computer)
	Development and execution by A Series	O	O	O

problems which are solved in concert with mathematical models.

The following effects can be expected from the application of knowledge engineering:

(1) Reduction of maintenance management costs (power cost, chemical consumption, etc.)
(2) 24-hour (including the time when a skilled operator is absent) stable operation is possible.
(3) Transmission of technology: Coping with the transfer, retirement, etc. of skilled operators
(4) Acquisition of new knowledge: Incorporation of new knowledge into the system by the user in interactive form

2.2 Knowledge engineering software tools

Fuji Electric has developed four knowledge engineering software tools (AI tools): EIXAX, FRUITAX, COMEX, and ΦNET. EIXAX and FRUITAX are control-type expert system tools. COMEX is a diagnostic-type expert system tool. ΦNET is used in the FA field.

The development concept, scheme, and use of EIXAX, FRUITAX, and COMEX which are used in the water and sewage works field are shown in *Table 2.*

Application of EIXAX to water works water operation control, application of FRUITAX to sewage works rain water pump control, and application of COMEX to sludge treatment operation support are described below as examples of application of each tool.

3. APPLICATION OF KNOWLEDGE ENGINEERING TO WATER WORKS

An abundant real-time use, simulation use, and operation use software library based on linear programming and dynamic programming is available for the operation and control of the water supply. An expert system: Knowledge and Optimal Control Package (KOCP) for water supply operation that uses these proven package groups and the process control-type AI tool, EIXAX, was developed and introduced into the water supply operation system of a large water distribution system.

3.1 Water operation expert system introduction background

Water works are responsible for supplying water to area users. Water demand differs regionally and variation with time is noticeable. To supply this with limited water resources, a suitable amount of water must be supplied at a suitable timing to a suitable distribution pond by forecasting demand beforehand.

To establish this water distribution plan, mathematical programming methods (the linear programming method etc.) have been used from times past. However, for large scale water distribution systems including many distribution ponds and water conveyance tunnels as seen in water works for wide area, a strict solution method takes a long time and the solution may change considerably even though the conditions changed very little and not matching the feeling of the site engineer was a disadvantage.

Therefore, many skilled operators actually performed the water distribution operation by judging the general trend of demand and the water distribution system and there were problems from the standpoints of technology transmission and uninterruption stable operation.

Moreover, with water works for a wide area, which are becomes increasingly complex, the physical and mental load on the operator is heavy and lightening of the load has becomes a serious problem.

Here, a method which prepares an amply practical plan in a short time by incorporating the know-how of operation of a skilled operator was made, in addition to the conventional mathematical programming method, to prepare the water distribution plan dynamically.

3.2 Features of expert system

(1) Operation by process control computer

The system is operated by a process control computer provided at the center. Therefore, it can be used easily by the site engineer and on-line data can be immediately reflected in the plan.

(2) Block unit optimization

Attention is focused on blocked subsystems in a large water conveyance and distribution system and the optimum water distribution plan is established with this as the unit.

(3) Use of mathematical programming in block optimization

Block units plan establishment uses linear programming and dynamic programming. Which is used is divided into the valves whose operating device can be changed continuously and pumps whose number of units can be controlled. For the former, LP method is used and for the latter, DP method is used.

(4) Possession of knowledge related to the order in which blocks are solved

If the order in which blocks are solved is changed, the planned obtained changes also. Therefore, things which decide this order are important. The know-how of skilled operator is used at this part.

(5) Correction is easy even if the structure of the water conveyance and distribution system changes

The structure of a water conveyance and distribution system changes if there are accidents or other system changes. Modulization is performed with the water conveyance and distribution system information as one knowledge so that this information is quickly reflected in the plan and even accidents can be dealt with. Since this knowledge can be represented as a system diagram on the screen, the site operator can make corrections easily and even system modifications can be dealt with.

3.3 Expert system structure and knowledge representation

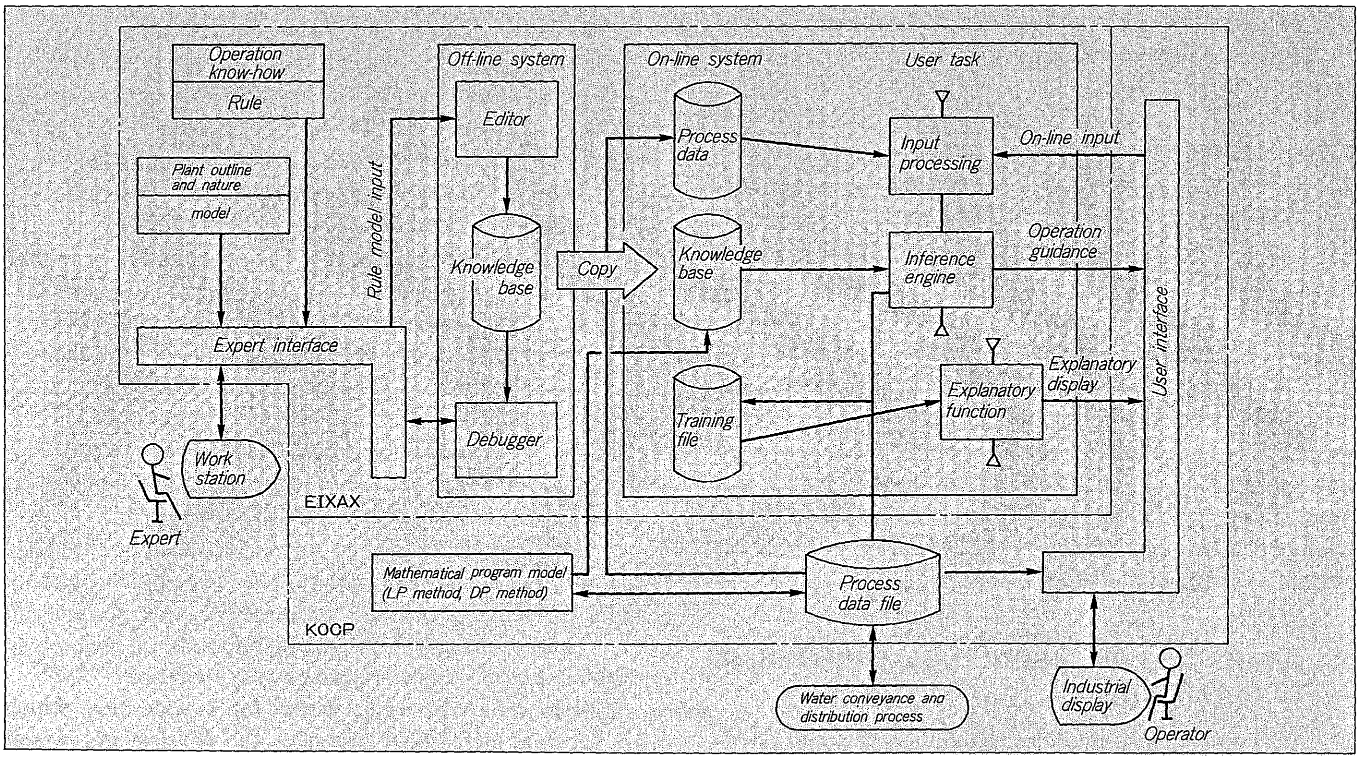
(1) KOCP structure

The structure of a water operation expert system (KOCP) is shown in *Fig. 1*.

Two environments are provided: on-line system and off-line systems. Knowledge base building and maintenance are performed by off-line system even during on-line system processing. Since the off-line system knowledge base can be reflected immediately at the on-line system after reliability was amply confirmed, uninterruptible operation of the system is guaranteed. Since frames are used, the connection structure of the water conveyance can be easily referenced from rules that can be represented in a computer. Furthermore, existing subroutines can be started freely from in rules. This is an essential condition for using mathematical programming in block units planning.

(2) Knowledge representation

Fig. 1 Structure of water operation expert system (KOCP)



(a) Rules

As a result of analyzing operator know-how, the rules related to the order of the solution blocks are:

(1) Since a water distribution pond with a large capacity is a margin and is adjusted easily, solving is performed from small capacity distribution ponds.

(2) When deciding the water distribution amount, solving is performed from the lower distribution ponds.

(3) Since a water distribution pond with a valve as the operating device is easier to adjust than a distribution pond with a pump as the operating device, solving is performed from water distribution ponds with a pump as the operating device.

(4) The solution method of water distribution ponds with a valve as the operating device is the block division type linear programming.

(5) The solution method of water distribution ponds

Fig. 2 **Procedure control problem rules**

Main rules

IF On planning
THEN Subrule 1 (pond=ALL)
Subrule 2 (pond=ALL, LOOP)
Subrule 3 (junction well=ALL, LOOP)

IF On checking
THEN Subrule 1 (pond=ALL)
Subrule 4 (pond=ALL, LOOP)

IF On planning
AND Review tunnel plan
THEN Subrule 1 (pond=ALL)
Subrule 2 (pond=ALL, LOOP)
Subrule 3 (junction well=ALL, LOOP)

Rule which initially sets pond (Subrule 1)

IF Absolutely execution
THEN Find (pond) capacity
Find lower pond and parallel ponds of (pond)

Rule which solves pond problem at planning (Subrule 2)

IF Intake device) of (pond) is (valve)
AND Intakes of lower pond of (pond) are all decided
AND Intakes off small capacity parallel ponds of (pond) are all decided
AND Intakes of parallel ponds with pump at inlet are of(pond)
THEN Solve (pond) by block-decomposition-type linear programming

IF (Intake device) of (pond) is (pump)
AND Intakes of lower ponds of (pond) are all decided
AND Intakes off parallel ponds with pump of smaller capacity than (pond) at inlet are all decided
THEN Solve (pond) by dynamic programming.

Rule that solves tunnel problem (Subrule 3)

IF (ponds) lower than (junction well) are all solved
THEN Find inflow of (junction well)

IF Inflow of junction well are all decided
THEN Fine inflow of tunnel

Rule which solves pond problem at checking (Subrule 4)

IF Actual value and expected value of demand of (pond) substantially (different)
THEN Review (pond) plan

IF Reviewed plan of (pond) effects (higher pond) of (pond)
AND (higher pond) of (pond) is not (junction well)
THEN Review (higher pond) of (pond)

IF Reviewed (pond) plan effects (higher pond) of (pond)
AND (higher pond) of (pond) is (junction well)
THEN Review (junction well) plan

IF Review (junction well) plan effects tunnel
THEN Review tunnel plan

Fig. 3 **Pond frame structure**

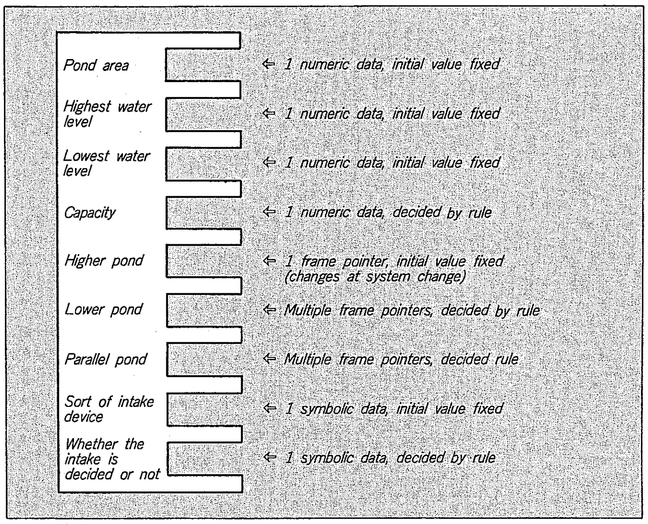


Table 3

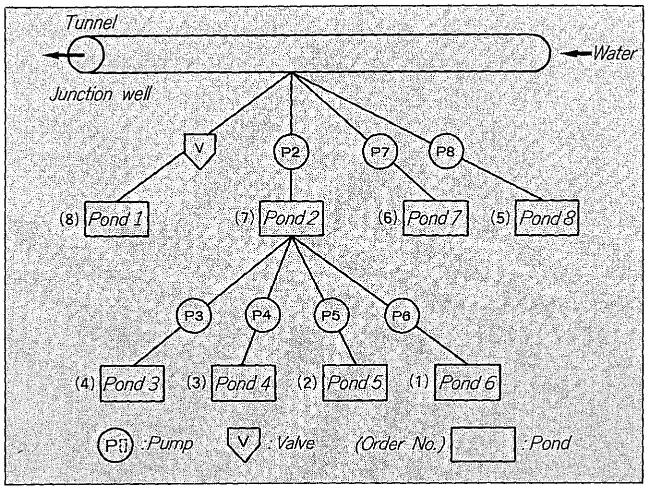
(a) Distribution pond

Pond No. / Specification	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	Pond 6	Pond 7	Pond 8
Pond area (m^2)	800	210	267	156	506	233	229	67
Absolutely highest water level (m)	17.1	5.0	3.0	3.5	3.0	3.0	3.0	2.8
Absolutely lowest water level (m)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Highest water level (m)	14.9	4.5	2.43	2.43	2.34	2.79	3.0	2.66
Lowest water level (m)	5.8	1.7	1.07	1.7	1.61	1.26	0.0	1.4
Initial water level (m)	13.7	4.49	1.0	2.89	2.29	2.6	2.01	2.31
Capacity (m^3)	7,280	588	363	212	369	356	687	84

(b) Pump

Pump No. / Specification		P2	P3	P4	P5	P6	P7	P8
Number of operable pumps		3	2	2	2	2	2	2
Pump capacity (m^3/h)	No.1	120	41	118	179	120	215	32
	No.2	120	42	116	186	120	218	32
	No.3	120	–	–	–	–	–	–

Fig. 4 Water conveyance and distribution system model



with a pump as the operating device is the dynamic programming.

This is represented by EIXAX rules in *Fig. 2*.

(b) Frame

The frame which shows a pond was planned as shown in *Fig. 3*. This places all the necessary information related to the pond in a frame.

3.4 Simulation result

When this system was applied to a model (*Fig. 4*, *Table 3*) of a water conveyance and distribution system with ponds laid out hierarchically, the order in which the ponds are solved coincided with the judgment of the operator and the demanded operating quantity was also a small number of modifications and valid results were obtained.

This system was introduced into an actual operation system based on this evaluation.

4. APPLICATION OF KNOWLEDGE ENGINEERING TO SEWAGE WORKS

4.1 Fuzzy control system for rainwater pump control

4.1.1 Introduction background

Regarding operation of sewage works facilities in cities, safer and positive handling of the increase of the area over which rain water is not absorbed due to urbanization and city type storm water by the heat island phenomena and the sudden rain water inflow by the greater depth, increased complexity, etc. of sewage sewer pipes has becomes a big problem.

Of sewage works facilities, the facilities which are the center of the problem are storm water pumping stations installed in cities. However, they are generally near housing areas and there are many stations which do not have sufficient capacity to deal with sudden rain water inflow because of area and environment and other restrictions. Therefore, in many cases, operation of such stations when it rains is advanced and complex and is currently entrusted to manual operation based on the experience and intuition of the operator. Specifically, the operator performs operation by using the full capacity of the pump station by overall judgment from the rainfall amount and inflow state and pumping-up ability to meteorological information and operating the number of operated pumps and speed and the inflow gate.

However, since the individual error due to operator experience is also large and the work creates a lot of stress over many hours, including the night, automation is desirable from the standpoint of the work environment also.

4.1.2 Process modeling and control system

The pumping station was modeled based on the actual data of the pumping station and a comparative study was made of control operation by actual operator and PID feedback control by water level and fuzzy control, which is an expert controller, by using that model. The control block diagram of the objective storm water pumping station is shown in *Fig. 5*. The pumping station model is shown in *Fig. 6*.

Rainwater that flowed down a 2km long, 3.5m diameter, 1% gradient sewer pipe flows into pump well 1 and pump well 2 through the inflow gate and the former is discharged by one speed control pump and the latter is discharged by four number of units control pumps.

Each pump has the same rated draft of $1.8m^3$. The rainfall runoff model finds the amount of rain water which flows into the sewer pipe from the rainfall strength by a 1-stage tank model. Regarding the sewer pipe model, handling the flow of rain water in the sewer pipe, including the effect of storage in the pipe, was made possible by means of an open channel varying flow linked equations and continuous expressions. Regarding the pumping station model, the pump well was made a storage tank model which finds the change of water level from the inflow and runoff difference and is a model which finds the pump draft by approximating the head curve and pipe resistance curve by secondary expression.

Next, the conventional control systems are PID control, which makes pump well water level 1 constant, and number of units control, which starts and stops the pumps according pump well water level 2.

As shwon in *Fig. 7*, the fuzzy control system was built by dividing it into a controller consisting of control

Fig. 5 Storm water pumping station control block diagram

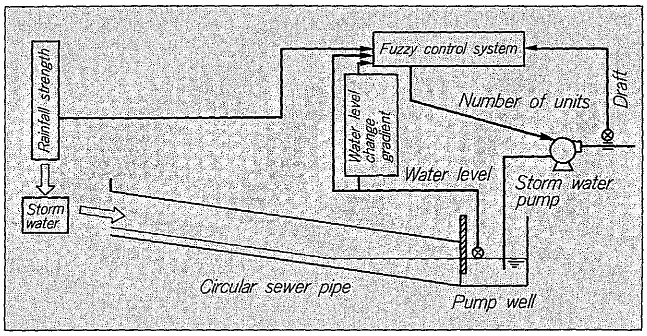


Fig. 6 Storm water pumping station model

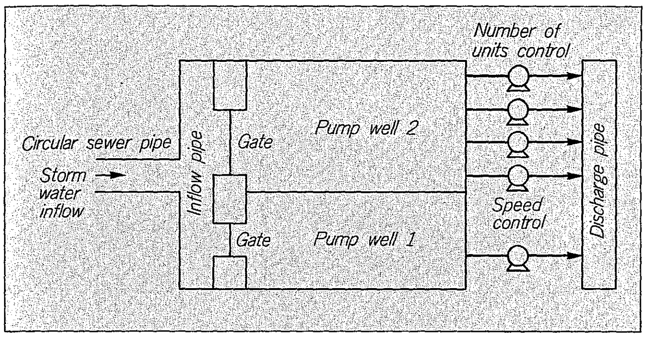


Fig. 7 Composition of fuzzy control system

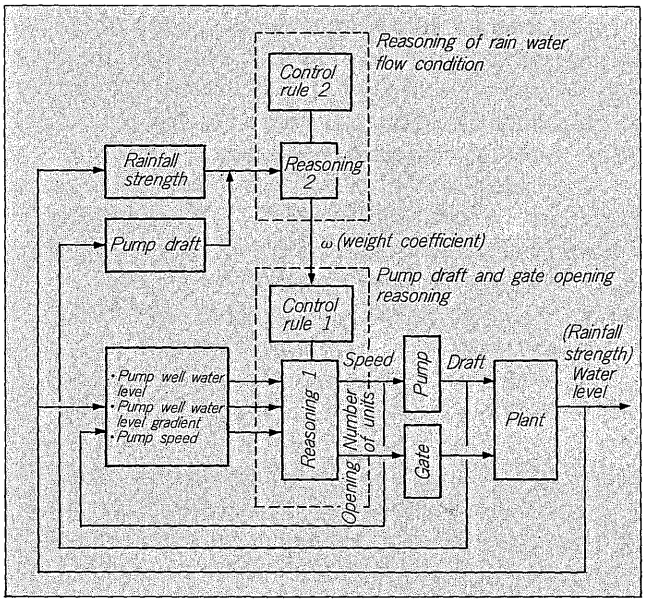
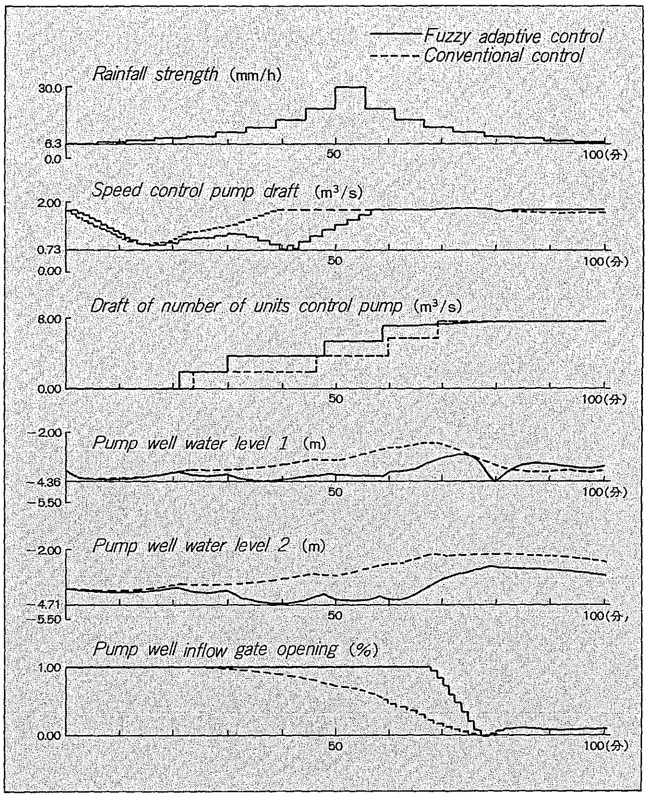


Fig. 8 Simulation result by model



rule 2 and reasoning 2 which reason the rain water inflow state based on the rainfall strength and pump draft and a controller that performs coordinated control of the pumps and gates based on its judgment value.

4.1.3 Simulation result

The simulation result of *Fig. 8* is the result of pump control described above for the pumps and control that suppressed the rain water inflow to pump well 1 for the inflow gate.

With the conventional control shown by the broken line, gate control is performed by a rise of the water level. However, reduction of the inflow from the inflow gate becomes a drop of pump well water level and generation of operation that suppressed the speed of the pump motor as a result can be seen from the pump draft change.

The cause is because gate control is performed by water level only and the operating status of the pumps is not seen.

Conversely, a fuzzy control system can be realized by incorporating operation including pump well water level and pump operating status in the control rule. The result is shown by the solid line of *Fig. 8.* When the pump speed was suppressed while performing gate control by pump well water level, it is learned that the pump is operated at almost 100% capacity by coordination control which increases the inflow by opening the gate a little.

It was confirmed that control using a fuzzy control system like this performs control approaching human operation that was impossible by PID control by water level in more detail than humans. As also learned from this simulation, since it is difficult to make a mathematical model of the sewage treatment process or becomes uniform with conventional PID control and on-off control, fuzzy control that automates operation by modeling the operation method of a skilled operator by control rule (if ~ then ~ IF THEN format), is said to be very effective with processes that require operator intervention.

4.2 Expert System for sludge treatment operation

4.2.1 Introduction background

The sludge treatment facility is a plant which treats the sewage sludge generated continuously from the water treatment facility and ships "sludge cake" as the product.

Since the properties and amount of incoming sludge differ substantially with the weather and the day of week, a knowledge and intuition of a skilled operator are indispensable in facility operation which produces a uniform product.

An expert system was introduced at such a plant for the following purposes:

(1) Arrangement and transmission of the operation know-how of a skilled operator

(2) Effective use of the operation know-how of a skilled

Fig. 9 Themes related to plant operation

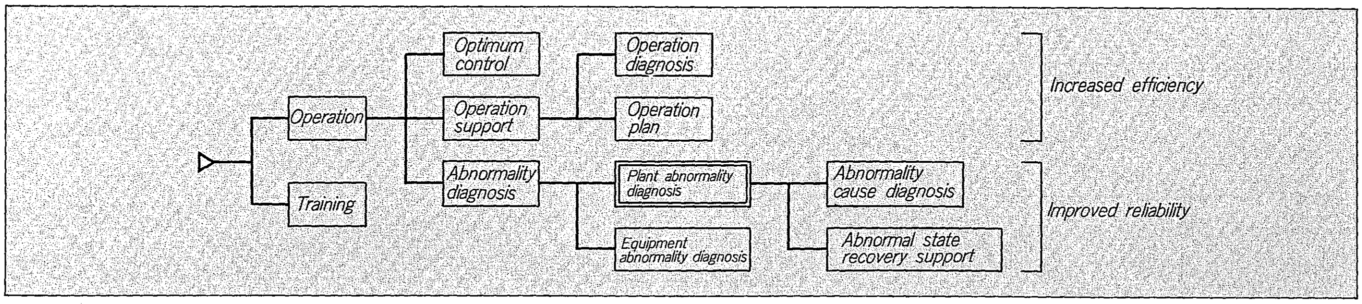
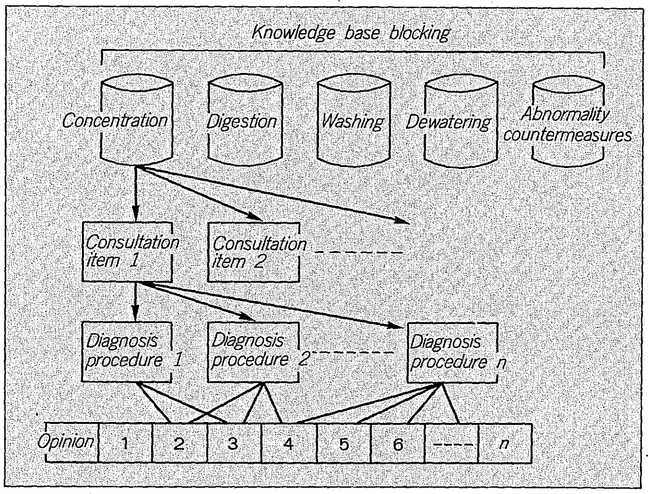


Fig. 10 Knowledge base hierarchy



operator in actual operation

(3) New operator training

4.2.2 Kinds and structure of knowledge base

Even through the system is changed by arranging the knowledge of a skilled operator, systems are divided into may branches by system use theme. The system introduced here built a knowledge base with "plant abnormality diagnosis" as the theme. The theme classification related to plant operation is shown in *Fig. 9*.

To build a knowledge base, the Tokyo Sewage Works Service Co., Ltd. Shibaura Office arranged the relationship with the factors (dehydrator malfunction, unsuitable dosage, etc.) that cause the abnormal state and the opinions obtained by the normal observation method, with the abnormal state "sludge cake water content is high", for example, as one consultation item.

The arranged knowledge was made a knowledge base by the Fuji Electric AI tool COMEX. Moreover, the knowledge base was blocked and made a hierarchy to increase operation efficiency. This is shown in *Fig. 10*.

4.2.3 System manufacturing refinements

The manufactured expert system was operated on a personal computer (FACOM 9450Σ) and the man-machine interface and other parts were refined to make it easier to use by the operator, including beginners.

(1) To show the opinion or diagnosed result in an easy to understand manner, display of the image scanner input/output image at the side of the explanation on the CRT was made possible.

(2) Operation by one-touch operation after the personal computer power was turned on without taking key operation in multiple procedures was made possible.

(3) Retrogressive input and input correction of opinion input, diagnosis procedure, consultation item, etc. was made possible.

5. CONCLUSION

Knowledge engineering application examples were introduced, however there are considered to still be many problems such as:

(1) Research on method of efficiently acquiring knowledge

(2) Development of training type tools (tools that make the system independently firm)

(3) Development of design type tools

There problems will be tackled positively in the future.