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Design of Intelligent Control Software for Mini-Earth

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ABSTRACT

In this paper, we describe the design of intelligent control software required for operating the Closed Ecology Experiment Facilities (CEEF) that we call Mini-Earth. We will develop intelligent control software by reconfiguring functions of a Control Computer System (CCS) for controlling the CEEF into three layers that consist of planning & scheduling, task, and control levels. In the last half of this paper, we will focus on the planning & scheduling level, and describe the operation scheduling problem of a CEEF gas circulation system using a Planning and Scheduling Language (PSL) to develop an Operation Schedule Interactive Generation system (OSIG).

INTRODUCTION

A habitation experiment using the Closed Ecology Experiment Facilities (CEEF) was started in 2005, and three experiments were conducted in which two persons stayed in the CEEF for one week. In the future, stays will be gradually extended. In 2009, a habitation experiment with two persons staying for four months will be carried out [1]. Although the CEEF has a challenging target of developing an advanced life support system technology, its system has been developed based on existing conventional plant system technologies. For monitoring and control systems, almost no automation has been introduced. This system has many manually operated parts that require operators to determine whether to start and stop operations as well as parts requiring offline measurements (i.e. analyses that should be executed manually, etc.). At present, as the first step for managing such a system, a CEEF behavioral prediction system (CPS) is under development [2]. In the CPS, an operator creates an operation schedule for the CEEF. It is not easy to create a complex operation schedule. Creating an operation schedule exceeds the operator's ability to consider all the possible variations of conditions during a long-term habitation experiment.

Therefore, we will develop an Operation Schedule Interactive Generation system (OSIG) to be installed in the CPS by 2009 when long-term habitation experimenting will start. This system will enable interactive generation of operation schedules that currently need to be created by operators. In this research, we will develop intelligent control software consisting of three layers for a Controlling Computer System (CCS) of the CEEF that is a conventional plant system. In this paper, we will describe the development of the OSIG, especially focusing on the planning and scheduling level.

DESIGN OF INTELLIGENT CONTROL SOFTWARE

The CEEF has been developed based on conventional technologies for plant systems. Likewise, conventional technologies have also been used for the monitoring and control system. Here, we reconfigure the functions of the CCS for controlling the CEEF into three layers as an ideal hierarchy as shown on the left-hand side of Fig. 1 [3]. They are, from the top, the planning & scheduling, task, and control levels. In the planning & scheduling level, planning and scheduling are executed. In planning, a design for the experiments is determined, and the required tasks (basic factors constituting the schedule) for the design of experiments are generated. In scheduling, the execution sequence of the tasks is determined. Among the above, the scheduling part will be developed this time. The operator now executes the planning and also makes the final decisions. In the task level, the progression management of events (operation, etc.) that construct the tasks is executed. In this level, sequencers that are attached to individual hardware items fill this role. In the control level, controllers attached to individual hardware items monitor and control the states of the objective. In this level, although there is a case in which existing controllers are upgraded, controllers attached to individual hardware fill this role. However, all the hardware is not necessarily classified clearly into task and control levels. In addition, these levels correspond to unit time differences of management. That is, in the planning & scheduling level, task management is carried out in terms of units of several hours or several days. In the task level, event management is executed in terms of units of several seconds or several minutes. In the control level, state management is executed in terms of units of several milliseconds or several seconds.

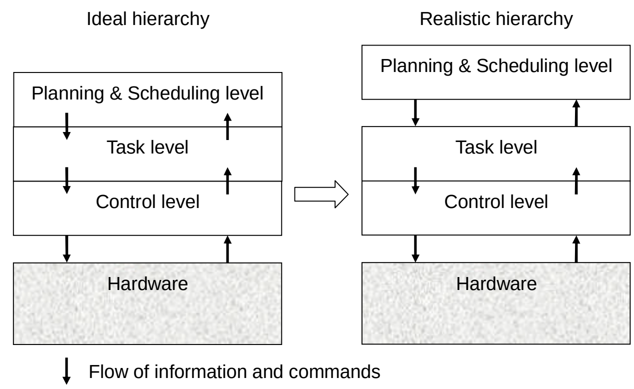

Fig. 1 CEEF monitoring and control system concept

It would be ideal to develop intelligent control software in three layers that are integrated, as shown on the left-hand side of Fig. 1, since the current CCS is a conventional monitoring and control system that needs manual operations. However, it is now difficult to develop such intelligent controlling software. We have thus decided to develop intelligent controlling software as shown on the right-hand side of Fig. 1 as a realistic hierarchy. The planning & scheduling level shown on the right-hand side is not integrated with the lower two layers, but is software just for supporting the operator's tasks. That is, in order to execute a generated schedule, it requires manual operation performed by the operator. Fig. 2 shows the expanded CCS of the CEEF in which a monitoring and control system as shown on the right-hand side of Fig. 1 has been adopted. While the control and task levels correspond to the CEEF equipment and CCS, the scheduling & planning level corresponds to the OSIG that will be newly developed. Fig. 2 shows parts surrounded by dotted lines that will be developed this time. According to the operation schedule generated by the OSIG, an operator operates a first master board, a second master board, and each piece of equipment. The operator must walk several tens of meters from the operation room to execute these operations.

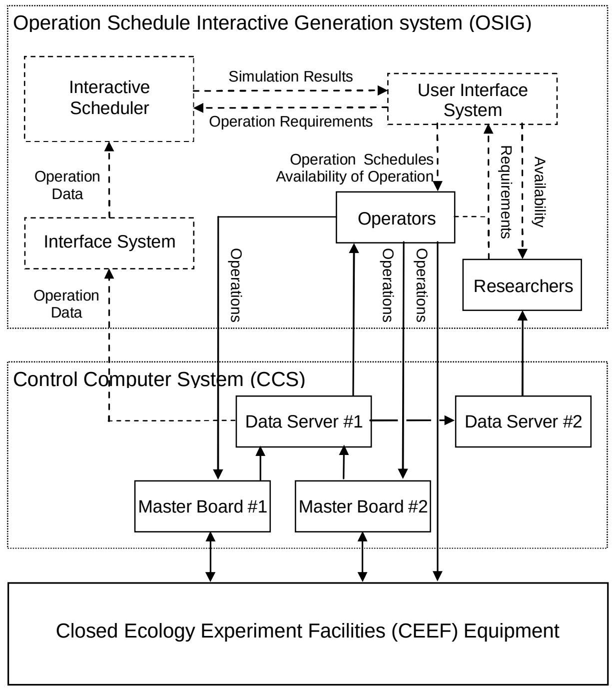

Fig. 2 Expanded CCS of the CEEF

DESIGN OF OPERATION SCHEDULE INTERACTIVE GENERATION SYSTEM

Recently, Advanced Planning and Scheduling (APS) with highly integrated planning and scheduling have been introduced in the manufacturing industry. Hence, it becomes possible to execute planning that assures enabling the execution of scheduling, thus greatly expanding the flexibility of planning. We will design our OSIG based on the concept of APS.

Fig. 3 shows the flow of information and decision-making in the OSIG. The OSIG consists of an Interactive Scheduler and an operator. The operator creates an operation schedule based on the design of experiments using an Interactive Scheduler before starting the experiments, and confirms the results of those experiments. When altering the schedule is required, or when any abnormality occurs in the facilities, the operator must regenerate the operation schedule according to the operation data and confirm the results. Even if immediate schedule modification is required, the operator can easily regenerate the schedule based on the existing schedule by using the Interactive Scheduler. A generated operation schedule is implemented by the operator's instructions. For the method to interactively create a schedule, we will adopt a simulation scheduling method that is effective to solve dynamic problems in which not all data have been given from the first, and that is best fitting to process problems in real time.

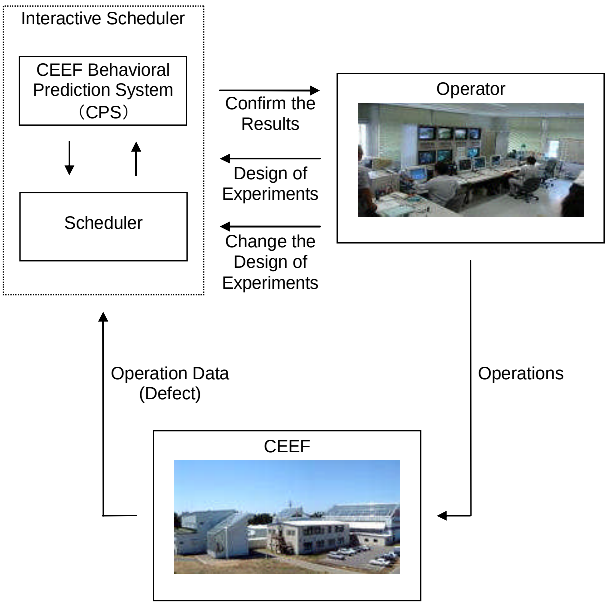

Fig. 3 Flow of information and decision-making in the OSIG

SCHEDULING METHOD

SIMULATION SCHEDULING

Simulation scheduling evaluates tasks stored in the queue of each machine using a priority rule, allocating the task having the highest priority to the relevant machine. By repeating this process, it creates the operation schedule. A priority rule used in this process is called a dispatching rule. For simulation, a forward simulation technique in task allocation in the forward direction of time axis is used.

DISPATCHING RULE

As the dispatching rule, we adopted a Shortest Processing Time (SPT) in which a task having the shortest processing time is selected among tasks to be allocated. However, given the purpose of the CEEF to realize material circulation that can support human life, there should be a more appropriate dispatching rule. We will discuss this in the conclusion of this paper.

SCHEDULING ALGORITHM

Scheduling is a problem to obtain the closest solution to the optimum that is as realistic as possible in circumstances where constraints are intricately interwoven. If we try to solve one constraint violation, it may cause another constraint violation relating to the same problem. As an algorithm to solve such a scheduling problem, we are using a penalty propagation network developed by Y. Nishioka [4]. This is a methodology that searches for constraints currently being violated. Then, while making the amount of penalty for the constraint violation to propagate over the neighboring constraints in turn, gradually reduces the total amount of penalties as a whole. This method does not require re-scheduling for correcting small constraint violations.

If we formulate this scheduling algorithm, it can be expressed as the following. The objective function minimizes the sum of constraint violation penalties, and the decision variable is an event time used as a trigger task for events such as the start and end time of each task. Constraint conditions include constraints such as processing times and precedence relationships.

$$min \quad \sum_{\forall i,\forall j \in M} \left(\alpha_{i,j} + \lambda_{i,j}\beta_{i,j}\right) \qquad (1.1)$$

$$subject \quad to \quad t_i - t_j \geq d_{i,j} \quad \forall i, \forall j \in M \qquad (1.2)$$

$$t_i = c_i \quad \forall i \in E^{fix} \qquad (1.3)$$

where, i, j are event numbers, t is event time, c, d are constant numbers, M is an aggregation of constraint relations, E^{fix} is an aggregation of fixed events, α is a penalty generated by constraint violation, β is the penalty quantity corresponding to the degree of constraint violation, and $\lambda_{i,j} = d_{i,j} + t_j - t_i > 0$.

DESCRIPTION OF SCHEDULING PROBLEM

In order to develop the OSIG, we describe the scheduling problem utilizing Planning and Scheduling Language (PSL) [5]. PSL is a general purpose language for scheduling manufacturing processes that can express large scale and complex problems by using only declarative descriptions. In addition, PSL can be easily expanded to a Planning and Scheduling Language on XML based representation (PSLX), enabling exchanging data through the World Wide Web.

Fig. 4 shows a modeling method in PSL. In PSL, scheduling problems are described by basic elements such as tasks, events, items, resources and orders. Task constructs the schedule and is a meaningful abstract with a certain time width. Event is an instantaneous happening, operation, or change without any time width. Item is something manufactured, such as products, parts, and materials. Resources such as machines and workers produce things. Order is an action to require a certain amount of an item at a certain time point. Item has an attribute of the stock, and resource has an attribute of the amount of load. Using PSL, we describe the relationships between task and event, task and item, task and resource, task and time, item and order, and resource and order. Also, we describe a precedence constraint (time constraint between two tasks or events which are related to each other through common items) for task, stock constraint for item, and switching constraint for resource (time constraint between two tasks which are related to each other though common resources), load and state constraints.

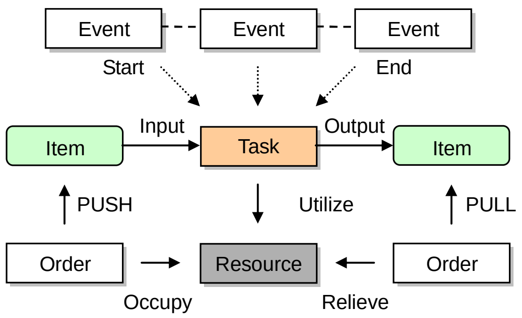

Fig.4 PSL modeling method

CEEF GAS CIRCULATION SYSTEM EXAMPLE

We will develop an OSIG using the aforementioned modeling method. Here, first before starting full-scale development, we executed a simulation where this method was applied to a CEEF gas circulation system and discussed the problems. The simulation was carried out by using an Apstomizer, which was developed by Y. Nishioka, and MS-Excel.

Fig. 5 shows the CEEF gas circulation system used in this simulation. This system consists of an Animal Breeding and Habitation Module (ABHM); 4 Plant Cultivation Modules (PCM) A, B, C, and F; O_2 and CO_2 tanks; O_2 separator; CO_2 separator (H); CO_2 separator (P); O_2 supply unit; CO_2 supply unit; and a solid waste processor. Although the O_2 and CO_2 tanks are expressed as one unit in Fig. 5, there are multiple tanks. The specifications and environmental conditions of modules are shown in Table 1 [6]. The volume of the ABHM is 340m^3. O_2 concentration is set as 20.3% (target), 23.5% (high) and 19.5% (low). CO_2 concentration is set as less than 5000 μLL^{-1}. As for the PCMs, volumes of A, B, C are each 146.3 m^3, and the volume of F and the preparation room are 239 m^3 and 332.2 m^3. The O_2 concentration is the same as the ABHM. CO_2 concentration is set as 700±70μLL^{-1} for light periods and less than 1500□μLL^{-1} for dark periods.

Table 1 Specifications and environmental conditions of modules

ABHM	Volume	340m^3 (Habitation Area, Animal Breeding Area, Access Aisle)
	O_2 Concentration	Target :20.3%, High: 23.5% Low: 19.5%
	CO_2 Concentration	High: less than 5000 μLL^{-1}
PCMs	Volume	146.3 m^3 (A,B,C) 239 m^3 (F) 332.2 m^3 (Preparation Room)
	O_2 Concentration	Target 20.3% High 23.5% Low 19.5%
	CO_2 Concentration	Light Period: 700±70μLL^{-1} Dark Period: less than 1500 μLL^{-1}

Here we describe the scheduling problem using a PSL. First, we define the tasks and items shown in Fig. 5. The items are O_2 and CO_2 quantities in ABHM (O2:ABHM and CO2:ABHM), CO_2 quantity in CO_2 Tank (CO2:CO2_TANK), O_2 and CO_2 quantities in PCMs (O2:PCM_A, B, C, F and CO2:PCM A, B, C, F), O_2 quantity in O_2 Tank (O2:O2_TANK). The tasks are respiration (O2:RES and CO2:RES), CO_2 separation (CO2:SEP), CO_2 supply to PCMs (CO2:SUP_A, B, C, F), photosynthesis (CO2:PHO_A, B, C, F and O2:PHO_A, B, C, F), O_2 separation from PCMs (O2:SEP_A, B, C, F), O_2 supply to ABHM (O2:SUP), CO_2 separation from PCMs (CO2:SEP_A, B, C, F), and solid waste process (SWP). Then, we define the stocks, stock constraints, events, precedence relationships, resources, and orders. The stocks are the initial quantities of the O_2 and CO_2 tanks, ABHM, and PCMs, and the stock constraints are the capacities of the O_2 and CO_2 tanks, ABHM, and PCMs. The events are the start and end time of the solid waste process. The precedence relationships are the precedence constraints of the tasks. The resources are O_2 separator, CO_2 separator (H), CO_2 separator (P), O_2 supply unit, CO_2 supply unit, and a solid waste processor. The orders are dummy actions for management of the tasks.

The description of the scheduling problem consists of 10 lines of stocks, 10 lines of stock constraints, 25 lines of tasks, 2 lines of events, 8 lines of precedence relationships, 38 lines of items, 13 lines of resources, and 36 lines of orders. These descriptions in Fig. 6 are written in an Excel worksheet and converted to a PSL format using a program written in VBA. Next, we read in this PSL file using an Apstomizer and execute task allocation so as to satisfy the constraint conditions as much as possible. If we did not get a task allocation that was satisfied with the first calculation, we would change the task allocation interacting with the Apstomizer until the operator was satisfied with the results. The Apstomizer shows constraint violations with the orange task. We changed the task allocation by drug-drop until the tasks turned into green task.

Table 2 shows the setup values for the simulation. Two persons (Eco-Nauts) live, cultivating rice and soybeans to produce their own food for themselves. The scheduling of human activity was given before the scheduling by the OSIG. The individuals sleep from 0 to 6 o'clock. They cultivate rice in PCM A (the light period is 0 to 14 o'clock) and PCM B (the light period is 4 to 18 o'clock), and soybeans in PCM C (the light period is 8 to 22 o'clock). They do not cultivate in PCM F. The values of stocks (Stocks), stock constraints (Stock Levels), and load constraints (Load Levels) of the items are shown in Table 2.

In this setting, we generated a schedule for one day. The results are shown in Fig. 7. The schedule was regenerated manually by changing task allocation in the event of constraint violations. Generating and regenerating the schedule took a few minutes. This Gantt Chart gives an operation schedule of a solid waste processor, CO_2 separator (H), CO_2 supply unit, CO_2

separator (P), O_2 separator, and O_2 supply unit. In this figure, A, B, and C express the PCMs connected. Fig. 8 shows changes of the quantitative state of items, that is the change of CO_2 and O_2 concentration in ABHM, CO_2 and O_2 concentration in PCMs A, B, and C, and the quantitative state in the CO_2 and O_2 tanks. All the states except for the CO_2 concentration in PCM satisfy the constraint requirements. One reason that it couldn't keep the CO_2 concentration within the required range was because it judged the ON/OFF switching every hour. In actual operation, since PID control is utilized in the control level, the state can be controlled more precisely by adjusting the flow rate.

Table 2 Setup values for the simulation

Eco-Nauts	2 persons, CO_2 : 1402.6 g/day, O_2 : 1077.4 g/day They sleep from 0 to 6 o'clock, and their metabolism is two thirds that of normal activity while sleeping.
Plants	PCM A and B : Rice (442.0 g/day) Light Period (14h) CO_2 : 1884.1 g/day, O_2 : 1454.4 g/day Dark Period (10h) CO_2 : 198.7 g/day, O_2 : 164.5 g/day PCM C : Soybeans (194.0 g/day) Light Period (14h) CO_2 : 992.7 g/day, O_2 : 897.0 g/day Dark Period (10h) CO_2 : 118.0 g/day, O_2 : 114.7 g/day PCM F : No Plant
Stocks	CO_2 Tank : 5000 g, O_2 Tank : 5000 g ABHM; O_2 : 84550 g, CO_2 : 125 g PCM A, B, and C; O_2 : 36435 g, CO_2 : 125 g
Stock Levels	CO_2 Tank : Min 0 g, Max 10000 g O_2 Tank : Min 0 g, Max 10000 g ABHM; O_2 : Min 81218 g, Max 97878 g, CO_2 : Min 0 g, Max 2083 g PCM A, B, and C; O_2 : Min 34947 g, Max 42116 g, CO_2 : Min 0 g, Max 896 g
Load Levels	CO_2 Separator : 58.4 g/h O_2 Separator : 423 g/8h CO_2 Supply Unit : 942.1 g/12h O_2 Supply Unit : 44.9 g/h

O_2 and CO_2 are expressed in grams in normal atmosphere.

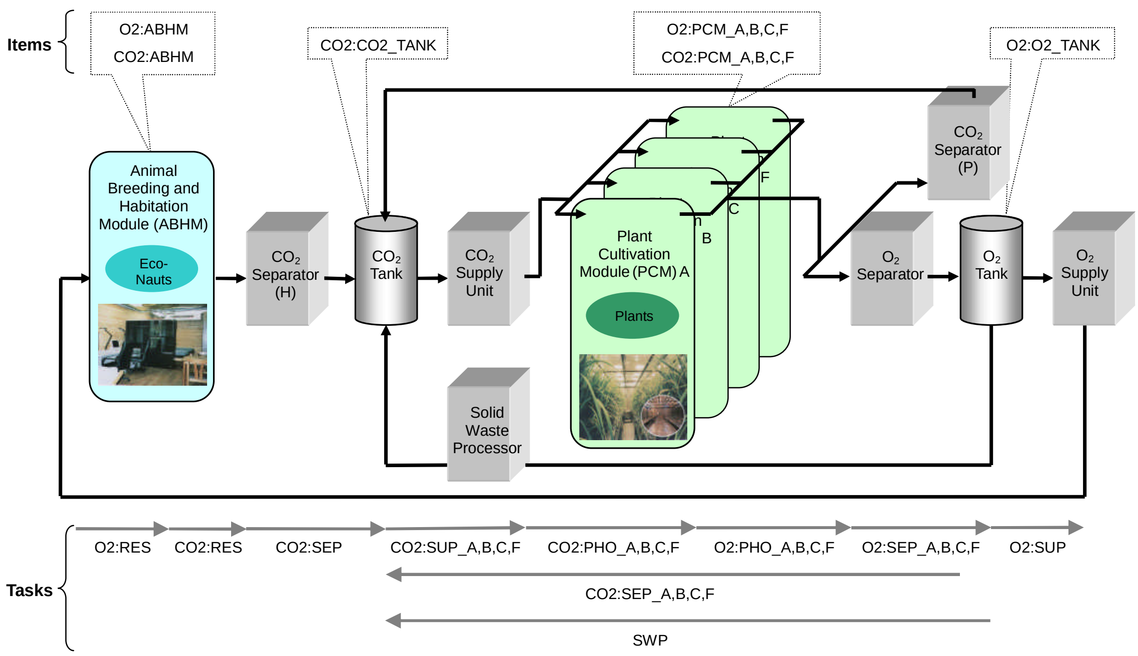

Fig. 5 CEEF gas circulation system

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PROBLEM  CEEF          210

TIMEUNIT  60
CELLTIME  60

TIMEMIN   2006         7          1
TIMEBASE  2006         7          1
TIMEMAX   2006         7          2

%          Item                    Quantity   %
STOCK      O2:ABHM                 84550
STOCK      CO2:ABHM                125
STOCK      O2:PCM_A                36435
STOCK      O2:PCM_B                36435
STOCK      O2:PCM_C                36435
STOCK      CO2:PCM_A               125
STOCK      CO2:PCM_B               125
STOCK      CO2:PCM_C               125
STOCK      O2:O2_TANK              5000
STOCK      CO2:CO2_TANK            5000

%              Item             Lower     Upper     %
STOCKLEVEL     O2:ABHM          81218     97878
STOCKLEVEL     CO2:ABHM0        2083
STOCKLEVEL     O2:PCM_A         34947     42116
STOCKLEVEL     O2:PCM_B         34947     42116
STOCKLEVEL     O2:PCM_C         34947     42116
STOCKLEVEL     CO2:PCM_A        0         896
STOCKLEVEL     CO2:PCM_B        0         896
STOCKLEVEL     CO2:PCM_C        0         896
STOCKLEVEL     O2:O2_TANK       0         10000
STOCKLEVEL     CO2:CO2_TANK     0         10000

%              Task             Process   Time (h)  Type     %
OPERATION      CO2:RES_S        RES       6         CONS
OPERATION      CO2:RES_A        RES       18        CONS
OPERATION      CO2:SEP          PROC 1    1         CONS
OPERATION      CO2:SUP_A        PROC 3    2         CONS
OPERATION      CO2:SUP_B        PROC 3    2         CONS
OPERATION      CO2:SUP_C        PROC 3    2         CONS
OPERATION      CO2:SEP_A        PHO_A     1         CONS
OPERATION      CO2:PHO_C        PHO_C     14        CONS
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%              Precedence task    Successive task    Type    Time
PRECEDENCE     CO2:PHO_A          CO2:SEP_A          ESR        6
PRECEDENCE     CO2:PHO_B          CO2:SEP_B          ESR        6
PRECEDENCE     CO2:PHO_C          CO2:SEP_C          ESR        6
PRECEDENCE     O2:SEP_A           CO2:SEP_A          SSS
PRECEDENCE     O2:SEP_B           CO2:SEP_B          SSS
PRECEDENCE     O2:SEP_C           CO2:SEP_C          SSS
PRECEDENCE     CO2:SUP_A          CO2:SUP_B          SS
PRECEDENCE     CO2:SUP_B          CO2:SUP_C          SS
PRECEDENCE     CO2:RES_S          CO2:RES_A          SS
PRECEDENCE     O2:RES_S           O2:RES_A           SS

%      Item              Task          Qty (g/h)   Type     %
ITEM   CO2:ABHM          CO2:RES_S     255         C
ITEM   CO2:ABHM          CO2:RES_A     1147.6      C
ITEM   CO2:ABHM          CO2:SEP       -58.4       D
ITEM   CO2:CO2_TANK      CO2:SEP       -58.4       D
ITEM   CO2:CO2_TANK      CO2:SUP_A     -628        C
ITEM   CO2:CO2_TANK      CO2:SUP_B     -628        C
ITEM   CO2:CO2_TANK      CO2:SUP_C     -330.9      C
ITEM   CO2:CO2_TANK      CO2:SEP_A     198.7       D
ITEM   CO2:CO2_TANK      CO2:SEP_B     198.7       D
ITEM   CO2:CO2_TANK      CO2:SEP_C     118         D
                   .
                   .
                   .
                   .
%              Resource             Task           %
RESOURCE       CO2_SEPARATOR        CO2:SEP
RESOURCE       CO2_SUPPLY           CO2:SUP_A
RESOURCE       CO2_SUPPLY           CO2:SUP_B
RESOURCE       CO2_SUPPLY           CO2:SUP_C
RESOURCE       CO2_SEPARATOR_P      CO2:SEP_A
RESOURCE       CO2_SEPARATOR_P      CO2:SEP_B
RESOURCE       CO2_SEPARATOR_P      CO2:SEP_C
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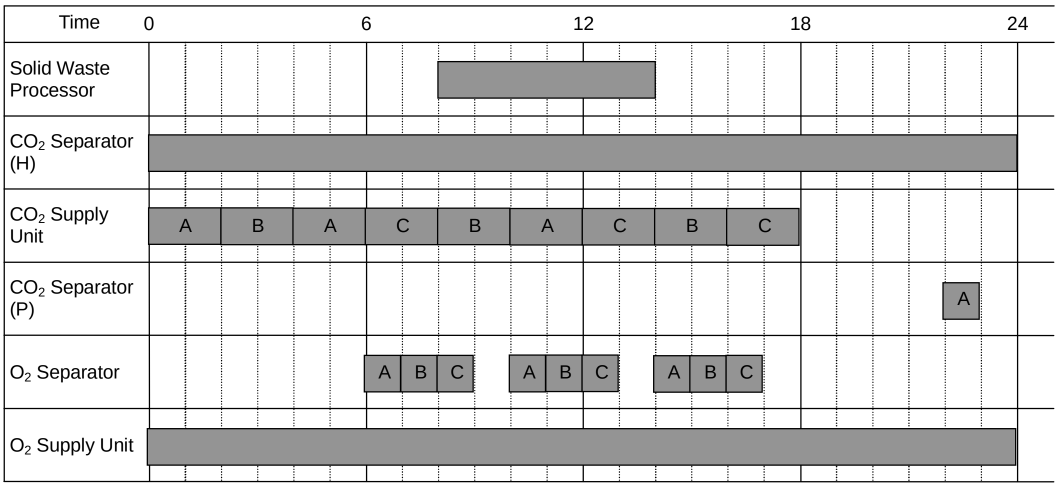
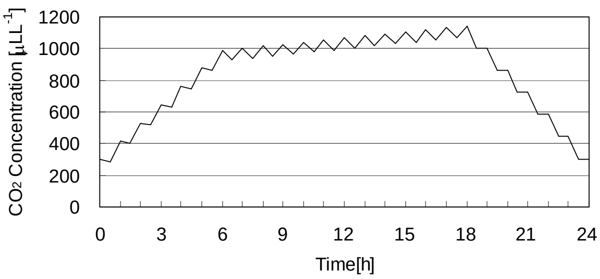
Fig. 6 Scheduling description using PSL

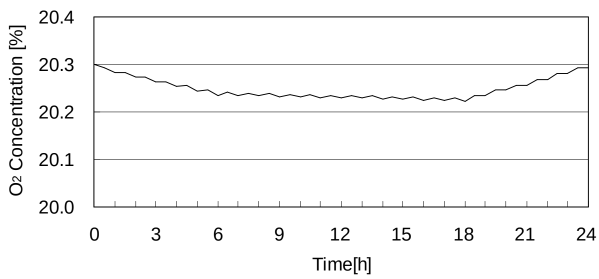


A, B, and C express the PCMs connected.

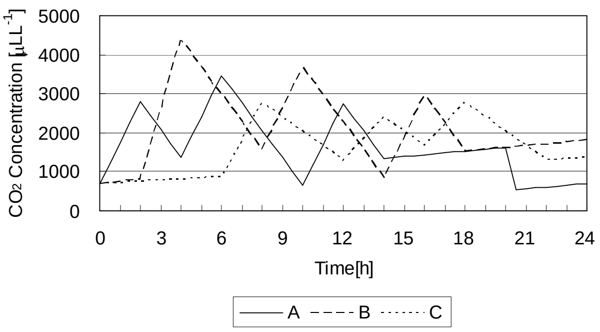
Fig. 7 Gantt Chart of CEEF gas circulation system



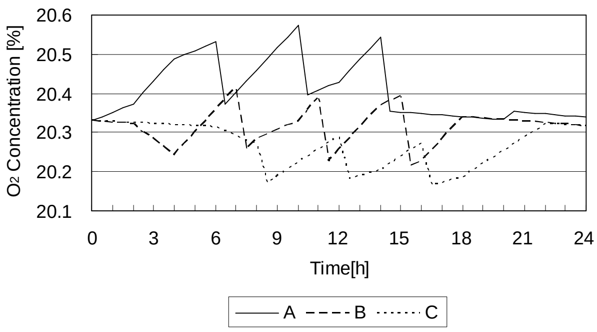
(a) Change of carbon dioxide concentration in ABHM



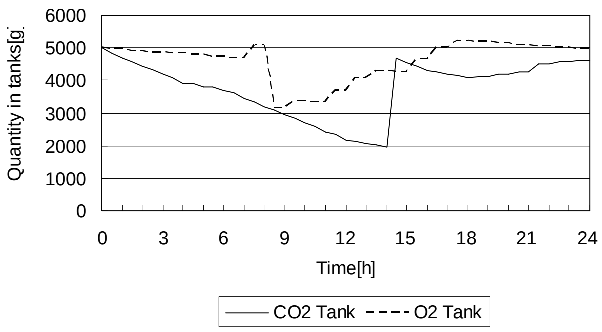
(b) Change of oxygen concentration in ABHM



(c) Change of carbon dioxide concentration in PCM



(d) Change of oxygen concentration in PCM



(e) Change of quantity in tanks

Fig. 8 Change of quantitative state in CEEF gas circulation system

CONCLUSIONS

We described the development of the intelligent control software consisting of three layers of planning & scheduling, task and control levels. Among these layers, in this paper, we focused on the planning & scheduling level, and described the operation scheduling problem of a CEEF gas circulation system using a PSL to develop the OSIG. As the result, we have addressed the following issues in areas such as constraint conditions, dispatching rules, and software and algorithm development.

CONSTRAINT CONDITIONS

In order to describe the scheduling problem using a PSL, it is necessary to understand the operational characteristics of individual CEEF equipment and to define the constraint conditions relating to operation. In constraint condition, there are constraints such as the processing time of each process, precedence relationship between processes, simultaneous starting or finishing between processes, and continuous usage of the same equipment. For example, for the CEEF gas circulation system, the CO_2 separator and the O_2 separator in PCM can operate only when these are connected to the same module.

Each piece of equipment in the CEEF has been modified many times and their specifications have been updated each time. We are currently surveying the accuracy of the specifications of each piece of equipment. This survey will make it possible to describe the constraint conditions for operating the entire CEEF system.

DISPATCHING RULES

In our simulation, we used an SPT for the dispatching rule. However, when we think about the true purpose for operating the CEEF, which is to realize a material circulation that can support human life, the dispatching rule should not be determined by SPT. In actual development, we will adopt a dispatching rule that generates a schedule able to equalize the fluctuation of material circulation. In general, tank capacity is determined by the time interval between the input and output of material. A longer interval means that the amount of input or output for each time becomes large. That is, if the time interval is short, it becomes possible to use small capacity tanks. It is the solid waste processor that has the longest time interval and the lowest flexibility of operation in the material circulation system. Although the water circulation system is not a rate controlling process, the gas circulation system becomes a rate controlling process. We will first determine the schedule of the solid waste processor. Plant cultivation that has a long cultivation cycle may become a candidate for the rate controlling process. However, it will probably not become an actual rate controlling process because there are many types of plants and sequential cultivation is adopted. In addition, it is impossible to control the metabolism of a human or plant. Thus, we will first determine the operation schedule of the solid waste processor and adopt a dispatching rule that shortens the time interval between input and output in the future.

SOFTWARE DEVELOPMENT

In this paper, we described a scheduling problem of a CEEF gas circulation system by using a PSL and obtained an operation schedule by using Apstomizer. Although PSL is very good at describing scheduling problems, it is not sufficient to establish the state constraints of items. For this reason, we couldn't make a description that can determine the task allocation based on given state quantity. Since Apstomizer, which was used this time is a scheduling tool for research use developed by Y. Nishioka, it will not be available in developing CEEF OSIG for practical use. Therefore, it is necessary to develop a new and advanced scheduling tool as its replacement. At this time, we must integrate a structure that can describe the constraint conditions for operation that was not able to describe using a PSL.

ALGORITHM DEVELOPMENT

At present, we are developing a new scheduling algorithm utilizing multi-agent reinforcement learning, based on knowledge obtained from description of scheduling problems using a PSL. Using this algorithm will enable generating a schedule that can shorten the time interval between input and output of material. This new algorithm will be able to automatically study new schedules corresponding to changing situations. We will publish another paper in the future about this new algorithm.

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DEFINITION, ACRONYMS, ABBREVIATIONS

ABHM: Animal Breeding and Habitation Module

APS: Advanced Planning and Scheduling

CCS: Control Computer System

CEEF: Closed Ecology Experiment Facilities

CPS: CEEF behavioral Prediction System

OSIG: Operation Schedule Interactive Generation system

PCM: Plant Cultivation Module

PSL: Planning and Scheduling Language

PSLX: Planning and Scheduling Language on XML based representation

SPT: Shortest Processing Time