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# Dealing Order Determination for Various Simultaneous Device Failures for Material Circulation Control in ALSS by Hierarchical Approach.

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**This paper discusses the handling of device malfunctions in an advanced life support system (ALSS) that would be serious enough to cause a circulation system collapsed. This simulation was calculated using $O_2$ and $CO_2$ gas circulation model, and the malfunction handling procedure was the same procedure that used by previous report. Seven devices of from a total of 21 were designated at random as malfunctioning, and the order in which the failures were designated for repair was automatically determined. As calculation results, the material circulation system was not collapsed as whole, although the amount of $CO_2$ in $CO_2$ tank was almost lacked. From this result, our handling procedure was cleared to be useful for ALSS circulation system.**

## I. Introduction

AN advanced life support system (ALSS) is one type of environmental control and life support system (ECLSS) that provide self-contained environments within which humans can survive in outer space. An ALSS maintains a living environment by recycling and circulating the materials needed for human life within the system. Since an ECLSS must continually control its environment, it must also be capable of operating without stopping when the system expanded with new devices or the component was removed to maintain or to replace[1,2].

We have previously proposed a hierarchical approach to control that combines two control methods, a centralized control system, and an autonomous distributed control system, to handle flexibly ALS system expansions or a replacement of its component devices. By the numerical simulations, we have been cleared this approach enables us to both expand subsystems to enhance their capabilities and remove malfunctioning devices while the system continues to operate[3,4].

For the last some years, we had constructed a method for automatically determining in what order malfunctioning equipment should be repaired when some devices of the different types malfunction simultaneously. When equipment of different types malfunction simultaneously, it is not always obvious which devices should be removed or replaced first. In that time, it is serious problem how to prioritize the malfunction equipment to repair. We had proposed the method to determine the handling order automatically using the hierarchical model that was employed for material circulation control, and have verified its effectiveness in a computer simulation.

The validation of our method was calculated under many conditions, for example the condition of enough flexibility in its capabilities[5], or of catastrophically device failed. These cases were selected to represent conditions requiring swift action in order to prevent a complete collapse of the circulation system[6]. The probability of system collapsed when the number of failed devices is gradually increased was also calculated[7]. Our determination method was used two model; model of the whole circulation system (called upper model) and model of detail of each function part (call lower model). In our validate calculation, while the upper model considered $O_2$, $CO_2$, and waste circulations, the lower model dealt with only $O_2$ flow to simplify the discussion.

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In this paper, we discuss about the availability of our determination method for simultaneous malfunctions using the lower model that considered $O_2$, $CO_2$, and waste flows.

## II. Control Requirements, Control Procedures and Simulation Models

The contents of this section are nearly identical to that of previous report[6,7] except the section "**D** Lower layer model and its control procedure", so the description here will be brief. The reader is directed to that report for further explanations.

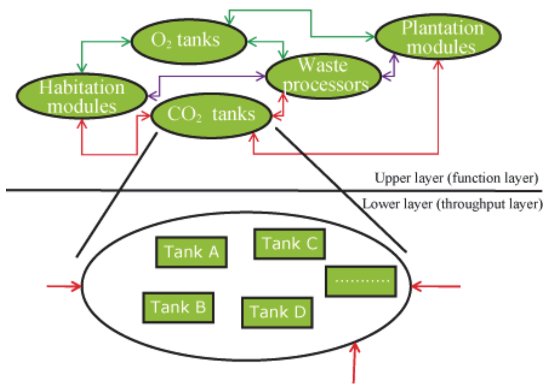
### A. Control Requirements

The following ALSS functionalities were required in this study:

1) Food is produced within the system, which includes plantation modules.
2) Control of material circulation within the system is completely automated.
3) The system includes human habitation modules in which two people can reside, and all the food they need is produced in the plantation modules.
4) The automated method by which component malfunctions are detected is excluded from consideration, and the simulation assumes no malfunction misidentifications.

### B. Basic Concepts of the Hierarchical Material Circulation Control

We believe our proposed hierarchical approach is the most suitable method for performing material circulation control in an ALSS in a manner that allows autonomous handling of modifications to system capabilities[3]. The system is conceived and control is performed as described below.




The first step is to group the devices making up the system by their functions (oxygen storage, waste processing, etc.). This organized grouping is called the "upper layer". The computer, which takes a bird's-eye view of the entire system, determines how much of what substance to move from which element cluster to which other element cluster using its automatic scheduling procedure. The lower layer, which is conceived as a decentralized autonomous system, responds to upper layer decisions regarding the inputs and outputs among the element clusters using a learning control procedure. Figure 1 shows a diagram of this control scheme.

This approach prevents the nearly inevitable computational explosion that would occur if the upper layer performed centralized control procedures in which the upper layer "sees" only a fixed number of functional units because the hierarchical approach assures stable overall control. Conversely, operating the lower level autonomously will allow for independent handling of process volume fluctuations that can occur due to variations in the number of available devices during expansions for redundancy and/or during shutdowns or restorations of existing devices.

### C. Model of Upper Layer Circulation System and Its Control Procedures

The material circulation model shown in Figure 2 was constructed for the upper layer based on the approach described above. However, since the main objective of this study is to examine the response characteristics of this procedure to device failures, the circulation model was simplified to just three components, gaseous $O_2$ and carbon dioxide ($CO_2$) and waste products (consisting of carbon atom (C)).

The parameters representing the contents of the plantation module and the metabolisms of the human occupants were estimated using software for calculating daily metabolic expenditures based on biochemical stoichiometry.[2] The plant growth parameters were calculated using the experimental results of Tako et al.[8] The parameters for the upper layer were appropriate compared with previous findings.[7] The total volume of waste products processable by the waste oxidation processor (WOP) was assumed to equal the daily volume of the metabolites generated by the human occupants and the plants, and that there was no extra margin in the processors.

The circulation in the system can be described as follows. First, $CO_2$ is converted into $O_2$ by photosynthesis in the plantation modules, stored in the $O_2$ tanks, and then pumped to the human habitation modules and the physical chemistry devices as necessary. Two people live in the human habitation modules subsisting on food from the plants grown in the plantation modules. The $O_2$ is turned into $CO_2$ by their respiration. The $CO_2$ is separated from the atmosphere, stored in tanks, and then provided to the plantation modules where it is again used by the plants in photosynthesis.

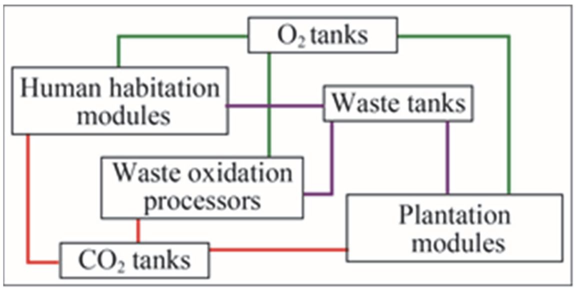



**Figure 2. Model of ALSS material circulation.** *Green lines represent $O_2$ flows, red shows $CO_2$, and purple, waste (carbon atoms) flows.*

Meanwhile, the inedible portions of the plants, human waste products, and other organic materials are stored in the waste tanks for oxidation treatment in the WOPs. In this model, which only accounts for gases, the role of the WOPs is to convert $O_2$ and other waste products to $CO_2$, which is then provided to the $CO_2$ tank cluster. The plant species and their respective areas of cultivation are determined in order to supply the nutritional needs of the human occupants.

The volumes of materials to be transferred on the upper layer at each time interval are determined by generating an operation schedule automatically. We employed Lagrangian Decomposition and Coordination method to create that schedule. To evaluate the schedule, we used a function that minimizes the deviations of $O_2$ and $CO_2$ from their desired concentrations in the human habitation and plantation modules.

### D. Lower Layer Model and its Control Procedure

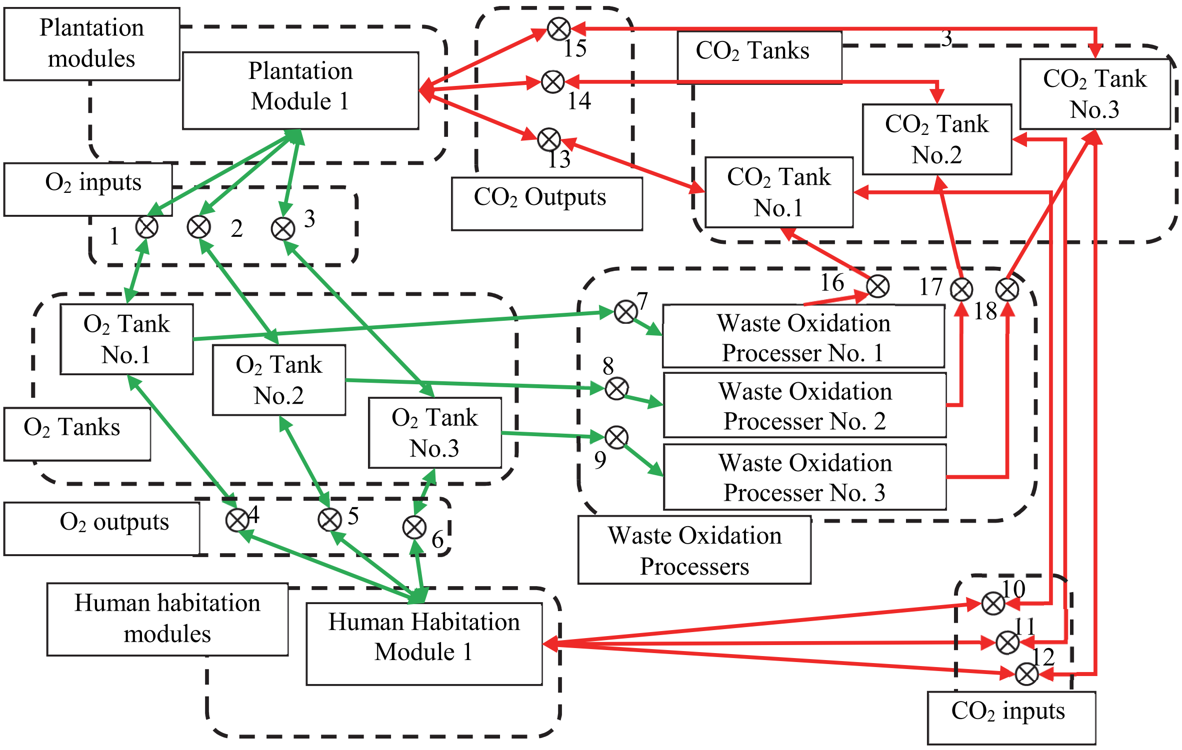



**Figure 3 Model of ALSS lower layer (normal operating conditions).**
*⊗ indicates a material transport pump (MTP). The number near ⊗ indicates serial number of MTP.*

In shown Figure 3, every group of devices, considered as a unit on the upper layer, is modeled on the lower layer in its specific physical layout. However, waste flow was omitted in Figure 3 because of no failure device in the waste flow. In this study, calculations were begun by assuming the system consisted of three oxygen tanks, three carbon dioxide tanks, three waste oxidation processors (WOPs), and 18 material transportation pumps (MTPs) and that all of these components were connected to each other. The tanks had same capacities for each material, as did the pumps. Additionally, as mentioned in the previous section, the capacity of the three WOPs operating together was sufficient for one day. The values for all of these are given in Table 1.

**Table 1. $O_2$ tank, $CO_2$ tank, MTP, and WOP abilities**

| | | |
|---|---|---|
| $O_2$ tank capacity, g | | 7926 |
| $CO_2$ tank capacity, g | | 13628 |
| MTP capacity, g/min | | 20 |
| Waste oxidation processor | Process time, min/batch | 480 |
| | Required $O_2$, g/batch | 876 |
| | Required waste, g/batch | 1090 |
| | $CO_2$ produced, g/batch | 297 |

Device failures could occur in 18 MTPs and 3 WOPs. It was assumed that no leaks of substances out of the devices occurred due to malfunctions, which one day was required for repair or replacement of an MTP, and that two days were required for repair or replacement of a WOP.

The lower layer control system model operated the MTPs and the WOPs to obtain the volumes of material transport between the device groups designated by the upper layer control device. This was accomplished by treating each device and MTP as an agent in a multi-agent system. As the learning control procedure, a rule-based control scheme was employed in the process initiation algorithm for the WOPs and to control material transport among the tank modules.[3]

## III. Procedure for Determining Order of Malfunction Corrections

The content of this portion of the report is nearly identical to that of previous papers[5-7], so the description here will be brief. The reader is directed to that report for further explanations.

### A. Hierarchical Method of Handling Malfunctions

The reader is directed to the paper by Miyajima et al.[2] for an explanation of the hierarchical method of handling malfunctions. This approach is a hierarchical modification of Rasmussen's skill-rule-knowledge (SRK) model[10] of a material circulation system in which the system upper layer model and the control system were treated at the knowledge level. In this scheme, the upper layer can calculate how much influence the reduction in processed volume (that would result from a malfunction in a part of a device cluster) would have on the circulation of materials through the entire system.

In this calculation, the upper layer employs data on the maximum total storage capacities, the maximum substance processing capacities, and the current capacities of the malfunctioning device clusters. It then uses that data to determine the extent to which the capacities need to be restored and the order of priorities for effecting those repairs. The upper layer has the ultimate authority for the handling of device clusters. In contrast, the control system for the lower layer model corresponds to the rule level of the SRK model, and this system determines the actions that need to be taken to accomplish the degree of repairs set by the upper layer.

The procedure used here was designed to provide convenient scalability to the ALSS control system while allowing handling of malfunctions autonomously from the highest levels of the system[5].

### B. Details of Calculations Performed by the Upper and Lower Levels

In the procedure we have constructed for setting the repair order, the upper layer determines which device will be repaired, and to what extent. The extent to which repairs will be pursued is calculated in the same manner as described in previous papers[5,6]. The maximum storage capacity, or maximum processing capacity, of each device cluster is, divided by five, and the recovery of each fifth of that capacity is considered a single repair unit. For example, if a device cluster is "halfway broken" (in other words, its capacity has degraded to half its maximum capacity), the extent of repair will be from one to three units. In contrast, the system will consider repairs from one to five units in extent if the cluster is completely inoperable.

Next, the authority for control of the repairs of one of the multiple malfunctioning clusters will be handed over to the lower layer, and the question of which cluster will be selected first is addressed as follows. Each malfunctioning cluster and each level of repair to that cluster, from one unit to the maximum number of actually needed units, are selected, and the benefit to material circulation in the ALSS after each level of repair is calculated over the next three days. The repair priorities of the clusters are then assigned based on the order whose repair results in the least degree of risk to the modules. The function used to assess modules for their degree of danger is the same one used to create the schedule for the material circulation control system.

The next decision (which device to repair first) is made by the lower layer based on an auction scenario. The bid price is calculated by each agent using the sum of (1), which is the per-day processed amount of material assumed after (i) partial or (ii) complete repair of the device, normalized to the standard per-day processed amount of material. This is combined with (2), which is the reciprocal of the number of days for the repair. The repair is concluded when the volume processed by the repaired unit exceeds the volume set by the upper layer, after which the number of the repair unit where this occurs is recorded and control is returned to the upper layer.

## IV. Conditions of Numerical Calculations and Calculation Results

### A. Numerical Calculation Flow and Its Conditions

The following numerical calculation was performed to validate the hierarchical procedure for handling malfunctions. First, a material circulation simulation was carried out until noon of the third day (the 2.5-day mark on the graph). At that point, multiple devices were randomly selected to malfunction. Of the 21 devices for supply of materials and processing of wastes, seven devices were selected to malfunction. The upper layer sets the order of malfunctions based on this timing and the target number of repairs and then passes authority to the lower layer along with instructions regarding the target number of repairs. On the upper layer, the MTPs connected to the WOPs are treated as integral to those WOPs. In other words, if any single device of MTPs No. 7, No. 16 or WOP No. 1, MTPs No. 8, No. 17 or WOP No. 2, and MTPs No. 9, No. 18 or WOP No. 3 has a malfunction, it is handled as a WOP malfunction.

The lower layer determines then uses the abovementioned auction algorithm to determine the repair order for the devices and returns authority to the upper layer when repairs are complete.

Once all the devices have been repaired, material circulation is calculated for a further 1.5 days. However, it was determined that the circulation system had failed and calculations had stopped in all four cases. Specific problems included oxygen concentrations exceeding 22% in one of the plantation modules, oxygen concentration falling below 20% in the human habitation modules (at which point humans cannot survive), oxygen amounts in the oxygen tanks reaching zero, and a case where the amount of oxygen in the oxygen tanks exceeded their capacities.

### B. Calculation Results: Upper Layer Time History of Filling Fraction for $O_2$ Tanks and $CO_2$ Tanks

Figure 4 shows the upper layer time history of the filling fraction of the $O_2$ tanks and $CO_2$ tanks with repair events. The following results, including those shown in this graph, indicate the case where MTPs Nos. 1, 5, 7, 12, 13 and 15, as well as WOP No.3, failed.

As shown Figure 4, the amount of $O_2$ tanks was gradually increase and the amount of $CO_2$ tanks was decrease under devices malfunction period. This was due to the fact that the WOPs were no longer able to meet their requirement to treat a full day's processing volume of waste products. Thus leaving unused gas in the $O_2$ tanks and untreated waste products in the waste tanks, and as a result, no $CO_2$ was produced. This rise and descent ceased once the repairs were completed, but the tanks concentration never returned to its previous level. This was because the daily processing volume of the WOPs was equal to the daily output of waste, so the processors were never able to eliminate the untreated volume that remained in their tanks.

We calculated the simulation at 50 times, but no circulation collapse occurred although the amount of $CO_2$ in $CO_2$ tanks was almost lacked. This is because, when the amount of $CO_2$ in $CO_2$ tanks was almost reached to zero, the controller stopped to supply $CO_2$ to plantation module. As a result, $CO_2$ concentration in plantation module was a little decreased. In this calculation's photosynthesis model, $CO_2$ concentration dose not affect plant growings, as well production amount of $O_2$. However, if photosynthesis model changed, $O_2$ production problems may arise because of this concentration down.

The root reasons of above results were that the amount of $CO_2$ circulating in the system was low and the performance of the waste oxidation processor had little room to recover. For that the system can controlled to recover the margin like the history of 0 to 2.5 days in Figure 4, it seems to be effective to add more waste oxidation processors to system (system expansion) and to add the tank concentration term to evaluation function in Lagrangian decomposition and coordination method.

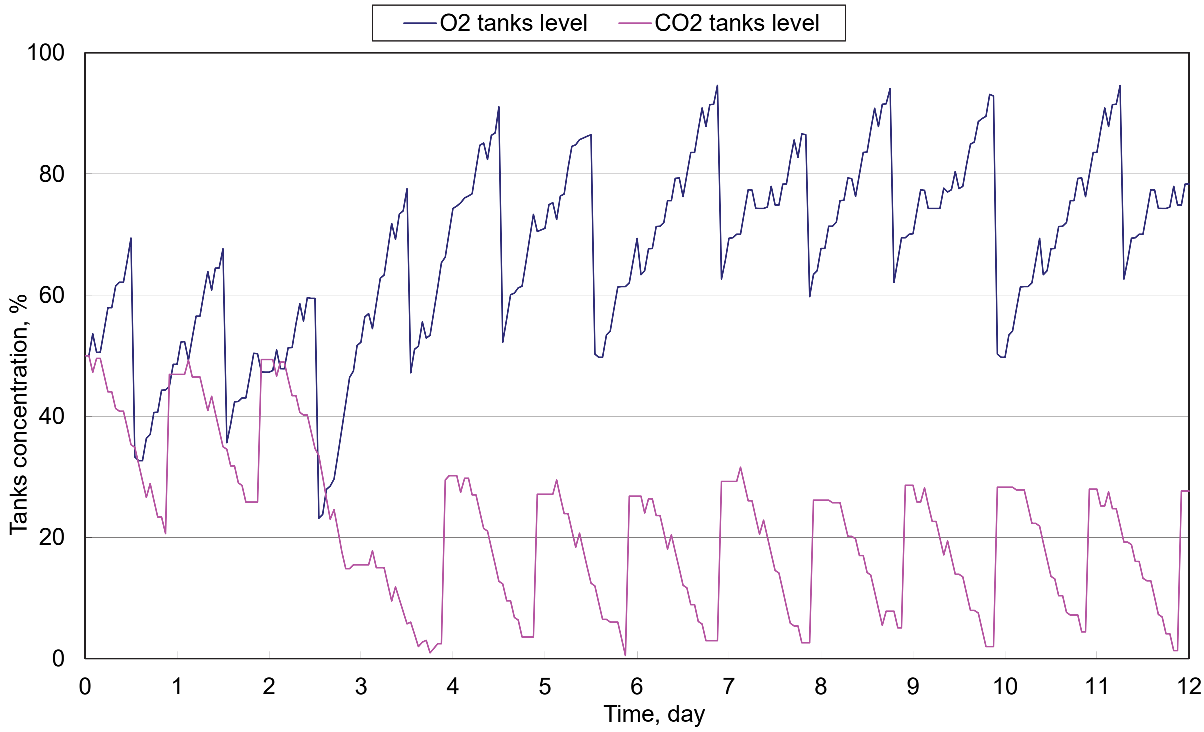



**Figure 4. Upper Layer Time History of Filling Fraction for $O_2$ Tanks and $CO_2$ Tanks.**

### C. Results of Upper Layer Order Determination Calculations

Table 2 provides the results for repair order in the upper layer.

**Table 2 Prioritization of repairs by upper layer.**

| Device cluster | Max capacity | Current capacity | Repair stage | Assessed handling value | Priority |
|---|---|---|---|---|---|
| $O_2$ inputs | 60 | 40 | 1 | 1.168 | **4**(6) |
| | | | 2 | 0.830 | (8) |
| $O_2$ outputs | 60 | 40 | 1 | 1.202 | **3**(3) |
| | | | 2 | 1.164 | (7) |
| $CO_2$ inputs | 60 | 40 | 1 | 1.201 | (4) |
| | | | 2 | 1.223 | **2**(2) |
| $CO_2$ outputs | 60 | 20 | 1 | 0.829 | **5**(9) |
| | | | 2 | 0.810 | (10) |
| | | | 3 | 0.809 | (11) |
| | | | 4 | 0.808 | (12) |
| Waste oxidation processors | 3270 | 1090 | 1 | 1.195 | (6) |
| | | | 2 | 1.196 | (5) |
| | | | 3 | 1.237 | **1**(1) |

In the upper layer, the system contains 5 parts; total $O_2$ input capacity from plantation modules to $O_2$ tanks ($O_2$ inputs), total $O_2$ output capacity from $O_2$ tanks to human habitation modules ($O_2$ outputs), total $CO_2$ input capacity from human habitation modules to $CO_2$ tanks ($CO_2$ outputs), total $CO_2$ output capacity from $CO_2$ tanks to plantation modules, and total waste processing capacity (WOPs). In Table 2, the repair stage with the highest assessed value within each device cluster is marked in bold, with the overall rank based purely on the assessed value in parentheses. The order of priority, by the simple calculation of assessed value, is indicated in parentheses. In the present study, complete repair of the waste oxidation processors was calculated to have the highest priority. The biggest problems in these calculations were $O_2$ overfill and $CO_2$ lack in the each tank part. These two difficulties could be solved at the same time if waste oxidation processors repaired completely. This is why to repair waste processors completely was calculated to highest priority.

Repair of $CO_2$ inputs was estimated as the second highest priorities. It is small effect to supply $CO_2$ from human habitation modules, which was produced by human breathing, as compared with to produce $CO_2$ by oxidation the waste. However, the lack of $CO_2$ in $CO_2$ tanks causes the decrease in the $CO_2$ concentration in the plantation modules. In order to avoid this situation, it seems that the repair of $CO_2$ inputs was prioritized.

### D. Results of Lower Layer Determination Calculations

Tables 3 and 4 show the evaluations by the lower layer determination at the same time as those by the upper layer. It was $CO_2$ outputs and waste oxidation processors that need to make order decision in the lower layer.

**Table 3. Prioritization of repairs by lower layer ($O_2$ outputs)**

| Device cluster | Device name | Bid value | Priority |
|---|---|---|---|
| $CO_2$ outputs | MTP 14 | 1.5 | 1 |
| | MTP 15 | 1.2 | 2 |

**Table 4. Prioritization of repairs by lower layer (WOPs).**

| Device cluster | Device name | Bid value | Priority |
|---|---|---|---|
| WOPs | MTP 7 | 1.3 | 1 |
| | WOP 3 | 0.8 | 2 |

As shown Tables 3, it was determined that MTP 14 was repaired before MTP 15. This reason was as follows: $CO_2$ tank No. 2, witch connected to MTP 14, was tend to store large amount of $CO_2$ because connected equipment (waste oxidation processor No 2 and MTP 11) were not malfunction neither. By repairing MTP 14, stored $CO_2$ in $CO_2$ tank No. 2 could sent to plantation module. Therefore, even though the repair ease (number of days) was identical, the bid price for MTP 14 was higher, and that pump was prioritized for repair.

On the other hand, since both of the devices listed in Table 4 would have processed the same volume of materials once they were completely repaired, the terms representing the recovered volume in the bid price for both took an identical value of 0.3. Accordingly, the repair priority was determined purely on the basis of ease of repair (number of days).

## V. Conclusion

We had proposed a hierarchical procedure for automatically handling malfunctions of devices in an ALSS and employed it in a numerical simulation of a material circulation control system for keeping human survival environment. The numerical model consisted of 21 devices, of which seven were assumed to have malfunctioned simultaneously, and the procedure was employed to automatically determine the order in which repairs must be performed. Even though the obtained results indicated extremely dangerous conditions in some cases, these results was showed to be able to deal with device failures. As these results, our determination method was shown to be effective for the devices malfunction in the ALSS.

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