Integrated Operational Techniques for Efficient Robotic Batch Manufacturing Systems

Satoshi Hoshino, Hiroya Seki, Yuji Naka, and Jun Ota

***Abstract*— This paper focuses on a batch manufacturing system with multiple industrial robots. In this system, material-handling robots (MHRs) and material-processing robots (MPRs) are operating. Inappropriate operations of these robots might cause a bottleneck. In addition, a bottleneck is a constraint that dominates the entire system performance, that is, the productivity. Therefore, for an efficient system, these robots have to operate appropriately while relating to each other. This is a challenge in this study. We propose the following operational techniques: route planning approaches for the MHR and operation dispatching rules for the MPR on the basis of task-assignment to the robots that will reduce the effect of a bottleneck. Furthermore, reactive cooperation among the MPRs, so that the robots respond to a fluctuating heavy workload caused by the shifting bottleneck, is an essential operational technique. Throughout the simulation experiments, each combination of the operational techniques is examined; finally, the integrated operational techniques are shown.**

I. INTRODUCTION

Generally, in manufacturing systems for high-mix low-volume production, a number of different machines are operating. In order to improve the throughput of the whole of the operation in the system, it is not enough to use each of the machines efficiently, but an efficient operational technique, based on the careful consideration of the operations of all the machines, is required.

A pipeless batch manufacturing plant [1] in chemical process industries is an applicable environment of a flexible batch manufacturing system from the standpoint of the reasonable and multi-product production of chemical products, such as lubricants, adhesives, pharmaceuticals, paints, and inks, in addition to adaptation to a fast-changing market. The reason for this trend is that materials are transported by movable vessels and production processes are conducted at a number of fixed process stations. Thus, compared to a general batch manufacturing plant, which consists of a pipe network, a pipeless batch plant is able to prevent material contamination when materials or products are switched from batch to batch. Furthermore, each recipe for a production process is different from others; herewith, a multi-product production in one plant is made possible. However, since advanced control technology for the equipment is required, only a few plants have started operations so far.

With regard to this issue, we focus on a robotic batch manufacturing system. Each industrial robot is able to perform a task agilely according to its control law and to respond to the changing circumstances flexibly by sharing information via communication. In this regard, let us notice that a manufacturing system is usually located in a closed plant facility; thus, a heavy workload for a robot that arises from a bottleneck at a place in the system affects productivity as a whole. Moreover, the bottleneck may shift to another place in the system even if it is corrected [2]. Therefore, for an efficient system, robots have to operate appropriately while relating to each other and tracking the shifting bottleneck.

We propose the following operational techniques: route planning approaches and operation dispatching rules on the basis of task-assignment that will reduce the effect of a bottleneck. Furthermore, reactive cooperation, so that the robots respond to a fluctuating heavy workload caused by the shifting bottleneck, is an essential operational technique. Throughout the simulation experiments, each combination of the operational techniques is examined; finally, the integrated operational techniques are shown.

II. PREVIOUS AND RELATED WORKS

Many previous studies that focused on pipeless batch manufacturing systems have addressed a production scheduling problem. The scheduling problem has been formulated mainly with the use of the Mixed Integer Linear Programming, MILP [3] [4] [5]. However, a main weakness of the MILP approach is that, as the complexity of a plant increases, the scheduling problem becomes very hard to formulate properly [6]. Huang *et al.*, using constraint satisfaction techniques, have proposed an integrated scheduling methodology in consideration of the behavior of movable vessels [7] [8]. In industrial robotics, Yang *et al.* have proposed a robotic system that assists production in flexible manufacturing environments [9]. In the system, off-line robots work exclusively to support on-line robots.

These previous and related works, however, have been based on the following assumptions: (I) fewer movable vessels with large capacity ($\geq$10 [m^3]); (II) deterministic transport time of a vessel between process stations; (III) deterministic operation (process) time at a station; (IV) a specific process equipment installed in every station; and (V) two categorized robots, directly operating and indirectly operating ones. Hence, (I’) it has been difficult to control the vessels agilely and flexibly; (II’) and (III’) as the case may be, an expected production volume according to the scheduling result is not achieved in the event that the vessel speed or the operation time at a process station fluctuates due to a disturbance [10]; (IV’) low system reconfigurability and multi-productivity result; and (V’) low resource utilization takes place due to these assumptions.

In view of the above reasons, (I’) $\sim$ (V’) , in this paper, (I”) instead of a vessel, we use a large number of robots with small volume, namely, a material-handling robot with high mobility; (II”) and (III”) we take into account the actual robot’s behavior including uncertainty, i.e., variable moving and operation times; (IV”) instead of specific processing equipment, we use fewer movable robots, namely, material-processing robots, and the robots have various equipment; and (V”) both of the robots perform tasks directly.

S. Hoshino, H. Seki, and Y. Naka are with the Chemical Resources Laboratory, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, JAPAN `hosino@pse.res.titech.ac.jp`

J. Ota is with Research into Artifacts, Center for Engineering (RACE), The University of Tokyo, Kashiwa, Chiba, 277-8568, JAPAN

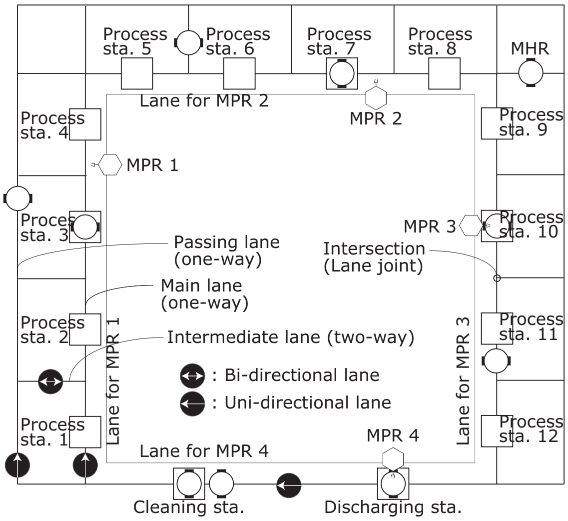


Fig. 1. Robotic Batch Manufacturing System with a Cyclic Layout Structure in a Pilot Plant Facility (top view)

III. CHALLENGES

In this paper, there are two types of robots performing their own tasks, which are material handling and processing. These robots must cooperatively execute the assigned task. In other words, even if one robot's efficiency improves, the other experiences a bottleneck and, as a result, a heavy workload. This phenomenon is a so-called shifting bottleneck, as described in I. Of course, this workload sometimes occurs due to a bottleneck resulting from the given tasks and layout structure. Furthermore, since the heavy workload for the robot caused by the shifting bottleneck affects the overall system productivity, it is necessary to balance the fluctuating workload among the robots.

To tackle the challenge, we propose the following operational techniques for the robots and synthesize them as integrated operational techniques. 1) Route planning for the material-handling robot; 2) operation dispatching for the material-processing robot; 3) task assignment to the robots; and 4) reactive cooperation among the material-processing robots depending on the situation.

IV. ROBOTIC BATCH MANUFACTURING SYSTEM

In this decade, most new automated material-handling systems have usually been designed with a spine- or perimeter-type of configuration that formed a material flow loop within a plant facility [11]. Several layouts that have single-loop and cyclic structures have been reported [12] [13]. For this reason, we adopt a cyclic layout structure, as shown in Fig. 1. This layout is based on the well-known cyclic operations. In the system, the Material-Handling Robot (MHR) moves to transport materials and a product, and the Material-Processing Robot (MPR) moves to a station and conducts production processes, such as coupling, feed, blending, separation, discharge, and cleaning, at the station.

In order for the MHR to move agilely, three types of lanes, i.e., main (one-way), passing (one-way), and intermediate (two-way), are provided. Process stations are placed on the main lanes. Materials circulate through the process stations with the MHR; then, a final product is produced. Inside the main lanes, four bi-directional lanes for the MPRs are provided. Each MPR basically works at its own station (e.g., MPR 1 works at stations $1 \sim 4$). In this paper, assuming that each robot has a radio communication device, the robots are able to share and exchange information via distributed blackboards installed on them. This is a sign board model [14]. Using this communication model, the MHR is able to move on the lanes flexibly while selecting lanes and changing a suitable route to a destination, and the MPR is able to move to its own stations or other MPRs' stations to support them depending on the circumstances.

At each station, $1 \sim 12$, since the MPR provides various equipment, such as a coupler, stirrer, reactive and separation meters, and a scrubber, for the production processes as assumed in II, all processes can be conducted. As for the discharging of a final product and cleaning of the MHR, these are the requisite processes in one batch; therefore, exclusive stations are set up for each of them. In the system, the MHR moves from the cleaning station to the discharging station in the clockwise direction through any of the stations, $1 \sim 12$.

V. OPERATIONAL TECHNIQUES FOR THE ROBOTS

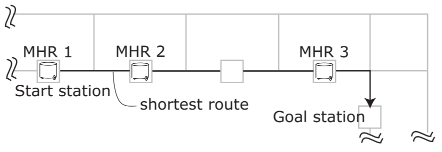
A. *Route Planning for the MHR*

In order for the MHR to move adequately on the three types of lanes, we apply the following three route-planning approaches to the MHR: (a) shortest-path routing; (b) dynamic routing looking ahead to one station; and (c) dynamic routing looking ahead to all the stations to a destination. As for approaches (b) and (c), the breadth-first search method with an objective function regarding the distance to the destination is applied. Hence, the MHR does not detour any more than is necessary. In addition, these two approaches are repeatedly applied each time the MHR passes through a station on the planned route.

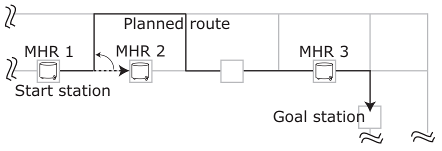
Fig. 2 shows that MHR 1 is planning a route to the destination (goal station) from the current position (start station). At the start station, if MHR 1 plans a route to the goal station with the use of the shortest-path routing (a), it has to stop on the planned route due to impeditive robots, such as MHR 2 and MHR 3 (see Fig. 2(a)). On the other hand, by applying planning approach (b) to the MHR, MHR 1 determines whether an MHR is present at the next station via communication and then changes the lane to detour MHR 2 (see Fig. 2(b)). However, as shown in Fig. 2(c), MHR 1 needs to plan a route once again through the passing lane due to an obstacle, MHR 3. To avoid this waste of time, MHR 1 selects a route to the destination, as shown in Fig. 2(d), by planning a route with the use of planning approach (c) on the basis of the situation of all stations with regard to the destination.

B. *Operation Dispatching for the MPR*

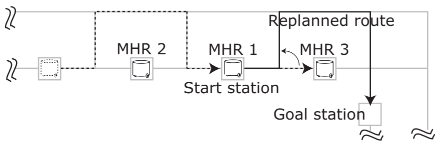
MPRs $1 \sim 3$ work for the production processes at four stations, i.e., $1 \sim 4$, $5 \sim 8$, and $9 \sim 12$, respectively. Therefore, when multiple MHRs arrive at different stations (e.g., the 1st, 2nd, 3rd, and 4th stations) at the same time, it is required to appropriately dispatch the MPR (e.g., MPR 1) to the operations in order to improve the robot's operating efficiency. For this purpose, we focus on the operation execution sequence among the MHRs and MPR; the MPR determines the next operation partner (MHR) and station on the basis of the following three dispatching rules: (a') First-In First-Out (FIFO); (b') nearest-neighbor; and (c') minimization of the total moving distance using the full-search method. This execution sequence is repeatedly determined each time a task



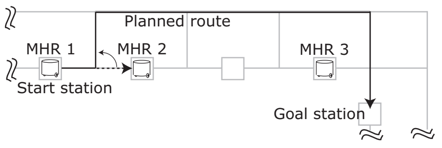
(a) Planned shortest route



(b) Planned route considering one station ahead

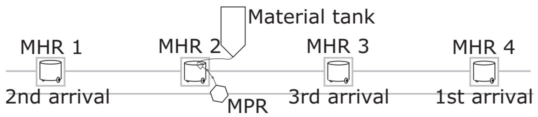


(c) Replanned route considering one station ahead



(d) Planned route considering all stations with regard to a destination

Fig. 2. MHR Route Planning with the Use of Each Approach



Ex.) Production processes: tank coupling
--> material feed and blending by the MPR

Fig. 3. Operation Dispatching

is finished according to the state of other stations if there is an MHR stopping at a station for the task.

Fig. 3 shows a case in which, while an MPR is conducting the production processes to MHR 2 at a station, MHRs arrived at all other stations in the following sequence: MHR 4, MHR 1, and MHR 3. In this case, the MPR reciprocates to the right and left unnecessarily if rule (a') is applied. On the other hand, the operations are performed smoothly in the following order: MHR 2 → MHR 3 → MHR 4 → MHR 1 by using rule (b') and MHR 2 → MHR 1 → MHR 3 → MHR 4 by using rule (c'). These dispatching rules are, similarly, applied to MPR 4.

C. Task Assignment to the MHRs

After an MHR is washed at the cleaning station, the next production recipe is assigned as a task to the MHR. In a material-handling system, task assignment policies for Automated Guided Vehicles (AGVs) have been proposed [15]; additionally, these assignment policies have been applied to a previous pipeless batch plant [16]. However, in the proposed heuristic rules, only the next destination of the AGV has been considered. In other words, a "single task [17]" has been assumed so far.

In contrast, it is impossible to address an MHR equipped with a vessel and its content (materials or product) separately in the robotic batch manufacturing system. Moreover, each product is produced on the basis of its own recipe, which consists of a series of processes. All of the processes for one product are carried out by the same (one) MHR. Namely, this is a "multi task [17]" problem. Therefore, a suitable production task, in consideration of all destinations, needs to be selected from other tasks and then assigned to an MHR. For this purpose, we propose the following objective function; a task ($Task_k$) is assigned to the MHR based on the function. The objective function denotes that a task with the lowest similarity to the execution state of all the tasks in the system is assigned to the MHR. By doing this, a heavy workload due to the bottleneck that arises from the given tasks is made as uniform as possible.

$$minimize \sum_{k} \sum_{n} Task_{n,k}(ExeTask_n - Task_{n,k}),$$

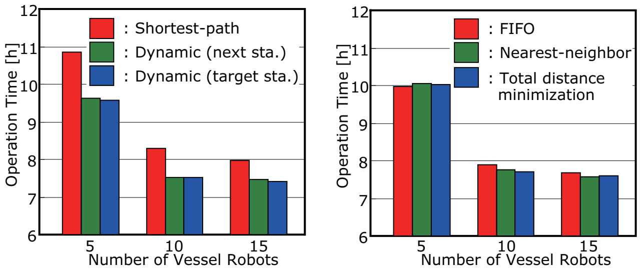
where k is a reference task number and n represents a station number. $ExeTask_n$ represents the total number of MHRs that are being and going to be processed at stations n following the production recipes. As for $Task_{n,k}$, a binary variable, 0 or 1, is given whether station n of the k-th reference task is a destination in the recipe for a product.

In this regard, however, if a task is selected and assigned to an MHR by referring to all other unexecuted tasks on the basis of the objective function, tasks with fewer processes are gathered in the first half of the production activity, while tasks that have many processes remain in the second half. For this problem, we propose the following three assignment policies: (a") in sequence ($k = 1, 2, 3, \cdots$); (b") the whole task reference ($\forall k \in K$); and (c") a partial task reference ($\forall k \in K_p$). Policies (b") and (c") are applied on the basis of the proposed objective function.

VI. SIMULATION EXPERIMENT

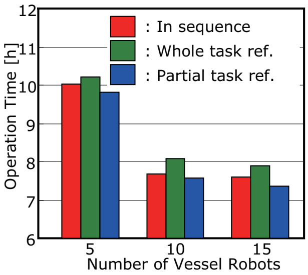
A. Experimental Condition

From V-A, V-B, and V-C, in total, $3 \times 3 \times 3 = 27$ combinations of the operational techniques are simulated. As a case study, the total number of tasks, K, is 200, and the process time at stations 1 $\sim$ 12 is determined to be 30 $\sim$ 80 [s] with a uniform distribution in a random manner. In the production recipe, a 0-1 binary variable is given by one-third and two-thirds for each station. If a 1 is given to a station, the MHR goes to the station. At the discharging and cleaning stations, 10 $\sim$ 40 [s] and 20 $\sim$ 80 [s] with a uniform distribution are required in a random manner. With regard to the assignment policy (c") described in V-C, the partial task reference range is 10 tasks (i.e., $K_p = 10$).



(a) Route planning

(b) Operation dispatching



(c) Task assignment

Fig. 4. Comparison and Evaluation of Each Operational Technique

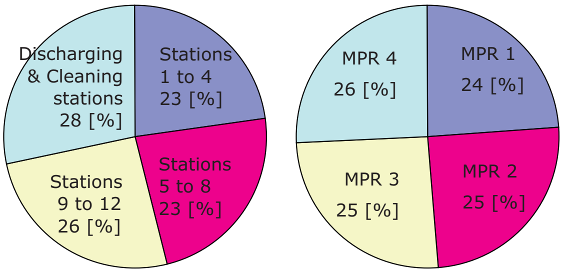
B. Impact Evaluation of Each Operational Technique

The system operation time with the use of the route planning, operation dispatching, and task assignment is shown in Fig. 4. This operation time is equal to the system throughput by dividing the time by the number of tasks, 200. In order to compare and evaluate the impact of each of the three techniques, (a) $\sim$ (c), (a’) $\sim$ (c’), and (a”) $\sim$ (c”), on the operating efficiency, for instance, the averaged operation time obtained through the simulations with fixed route planning (a), (b), or (c) and nine other combinatorial techniques ((a’) $\sim$ (c’) $\times$ (a”) $\sim$ (c”)) are shown in Fig. 4(a).

We can see that the route planning approaches, (b) and (c), and task assignment policy, (c”), resulted in an efficient system regardless of the number of MHRs (see Fig. 4(a) and Fig. 4(c)). This result indicates that the synthesized operational techniques reduced the effect of the bottleneck and increased the production volume. Here, it must be noted that operational techniques with task assignment policy (b”) resulted in the most inefficient system (see Fig. 4(c)) due to the heavy workload caused by the given tasks. Moreover, while the operation time decreased as the number of MHRs increased from 5 to 10, the results of the operation time with 10 and 15 MHRs were almost the same. This is because that the fleet size was the factor that decides the throughput before the bottleneck occurred. To discuss the reason of this result, we analyze the robots utilization ratio.

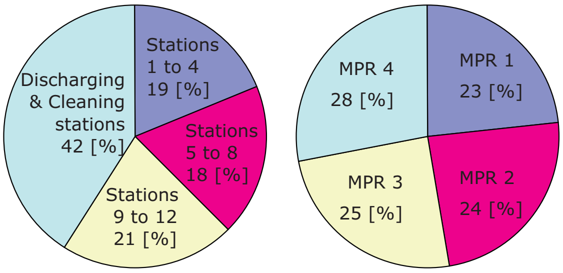
C. Bottleneck Analysis

In Fig. 5, as the robots utilization ratio, the sojourn time ratio of the MHRs (5, 10, and 15) at each station and the operation time ratio of the MPRs (1 $\sim$ 4) are shown on the basis of the combination of the operational techniques that achieved the given 200 tasks in the shortest time, namely, the best system.



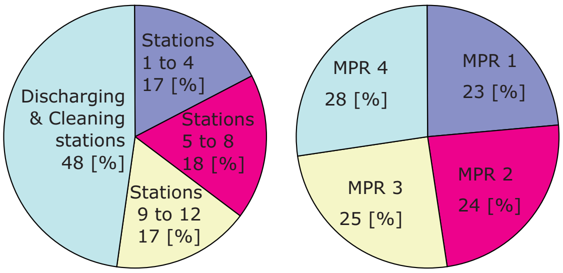
(a) Sojourn ratio (5)

(b) Operating ratio (5)



(c) Sojourn ratio (10)

(d) Operating ratio (10)



(e) Sojourn ratio (15)

(f) Operating ratio (15)

Fig. 5. Robots Utilization Ratio in the Best System (# of MHRs)

From the results of Fig. 5(a), Fig. 5(c), and Fig. 5(e), it is noticeable that the sojourn time ratio at the discharging and cleaning stations increases as the number of MHRs increases from 5 to 10 and then to 15. For this reason, the system throughput at the stations, 1 $\sim$ 12, increased as a result of the use of efficient operational techniques, and the MHRs often arrived at the discharging and cleaning stations in which no passing lane is provided. On the other hand, from a comparison of the results shown in Fig. 5(b), Fig. 5(d), and Fig. 5(f), it is evident that each MPR operated almost evenly. That is to say, in spite of the fact that all MPRs fully operated at their two or four stations, a bottleneck occurred at two stations due to the layout structure; eventually, MPR 4 had a heavy workload.

In order to improve the bottleneck, it is general practice to add an MPR to the discharge or cleaning station. However, as discussed previously, this is an insufficient approach to the shifting bottleneck. Therefore, it is obvious that reactive cooperation among the MPRs over their own process stations is necessary for the shifting bottleneck. In other words, if there is an MPR that has a heavy workload, other MPRs will support it by performing its task in order to balance the workload as called for by the particular situation.

VII. OPERATIONAL TECHNIQUE FOR REACTIVE COOPERATION

A. Workload Balancing

Tewolde *et al.* have proposed a distributed workload-balancing algorithm to assign tasks to robots evenly [18]. They, however, have assumed a single task under a static environment, and the proposed algorithm was thus executed only at the beginning of the operation. This is insufficient for a multi-task and shifting bottleneck. For such an environment, we have shown the effectiveness of reactive robot behavior [19]. Therefore, we focus on this robot's reactivity for workload balancing, and we then propose the following reactive cooperation technique among adjacent MPRs. The detailed algorithm of the proposed technique is listed in Algorithm 1.

Algorithm 1 ReactiveCooperation (MHR, MPR)

```
if $flagOperation_{MPR_i}$ = false then
    if $x_{MPR_i} = x_{S_{MPR_i}}$ then
        if $x_{MHR} = x_{S_{MPR_{i-1}}}$ then
            if $flagOperation_{MPR_{i-2}}$ = true then
                Set $NT_{MPR_i} \leftarrow$ Cooperation
            else
                if $x_T - x_{MPR_i} < x_T - x_{MPR_{i-2}}$ then
                    Set $NT_{MPR_i} \leftarrow$ Cooperation
                end if
            end if
        else if $x_{MHR} = x_{S_{MPR_{i+1}}}$ then
            if $flagOperation_{MPR_{i+2}}$ = true then
                Set $NT_{MPR_i} \leftarrow$ Cooperation
            else
                if $x_T - x_{MPR_i} < x_T - x_{MPR_{i+2}}$ then
                    Set $NT_{MPR_i} \leftarrow$ Cooperation
                end if
            end if
        end if
    else
        if $x_{MHR} \neq x_{S_{MPR_i}}$ then
            Set $NT_{MPR_i} \leftarrow$ Maintain cooperation
        else
            Set $NT_{MPR_i} \leftarrow$ Return to $x_{S_{MPR_i}}$
        end if
    end if
else
    if $x_{MHR} \neq x_{S_{MPR_i}}$ then
        Set $NT_{MPR_i} \leftarrow$ Maintain cooperation
    else
        Set $NT_{MPR_i} \leftarrow$ Return to $x_{S_{MPR_i}}$
    end if
end if
```

The MPR decides the cooperation reactively to support other MPRs on the basis of the information of the MHR and other MPRs, MHR and MPR. MPR_i represents the host MPR that has its own process stations, denoted as S_{MPR_i}. x shows a position; thus, x_{MHR}, x_{MPR_i}, and $x_{S_{MPR_i}}$ represent the positions of the MHR, MPR, and its stations, respectively. x_T is the position of the target station. Note that MPR_{i-1} and MPR_{i+1} are the MPRs adjacent to MPR_i and $S_{MPR_{i+1}}$ and $S_{MPR_{i-1}}$ are their own process stations. $flagOperation_{MPR}$ shows whether an MPR is operating ($true$ represents operating, and $false$ represents free). NT_{MPR} indicates the next task of an MPR.

TABLE I

SIMULATION RESULT ON THE OPERATION TIME

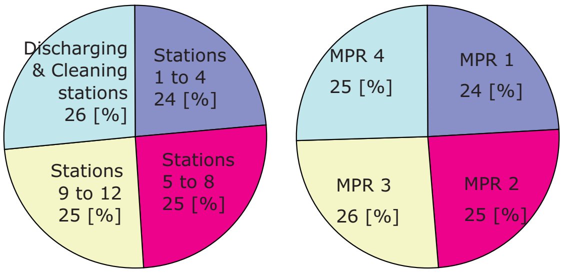
	Total operation time [h]			
	Non-reactive cooperation		Reactive cooperation	
# of MHRs	Best	Worst	Best	Worst
5	9.23 (b)(c')(c")	11.18 (a)(b'/c')(b")	9.38 (b)(b'/c')(a")	11.32 (a)(b'/c')(b")
10	7.16 (b)(c')(c")	8.62 (a)(a')(b")	6.89 (c)(c')(c")	7.94 (a)(a')(b")
15	7.12 (c)(b')(c")	8.27 (a)(c')(b")	6.46 (c)(c')(c")	7.4 (a)(b')(a")

In a case in which the MPR, MPR_i, is free at its own station and an MHR arrived at the adjacent MPR's station, $x_{S_{MPR_{i-1}}}$, the MPR begins to move to the station to support MPR_{i-1} if the other adjacent MPR, MPR_{i-2}, to MPR_{i-1} is operating. In this regard, we presuppose that the adjacent MPR, MPR_{i-1}, is also operating. If MPR_{i-2} is also free, a closer MPR to the target position begins to cooperate. In the same way, reactive cooperation among the MPRs, MPR_i, MPR_{i+1}, and MPR_{i+2}, takes place if an MHR arrived at the adjacent MPR's station, $x_{S_{MPR_{i+1}}}$. If MPR_i is already at the adjacent MPR's station, it stays at the station to support MPR_{i-1} or MPR_{i+1} as long as an MHR does not arrive at $x_{S_{MPR_i}}$. If the MHR arrived at $x_{S_{MPR_i}}$, MPR_i returns to its own station. On the other hand, in a case in which MPR_i is already operating at another MPR's station, MPR_i continues operating at $x_{S_{MPR_{i-1}}}$ or $x_{S_{MPR_{i+1}}}$ to support MPR_{i-1} or MPR_{i+1} if no MHR arrives at $x_{S_{MPR_i}}$. If an MHR arrived at $x_{S_{MPR_i}}$, MPR_i returns to its own station after the current cooperative task. The MPR does not perform the reactive cooperation if it is operating at its own station.

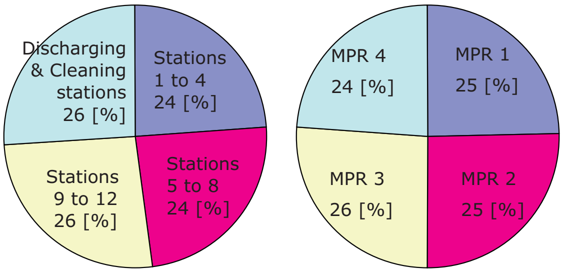
B. Simulation Result Including Reactive Cooperation

Table I shows the simulation result for 5, 10, and 15 MHRs. Under the non-reactive cooperation, the results in VI are listed, and the other ones under reactive cooperation show the results including the reactive cooperation technique. In the columns labeled "best" and "worst," the shortest and longest operation times are respectively described. Under the best and worst operation times, the combination of the applied operational techniques is shown.

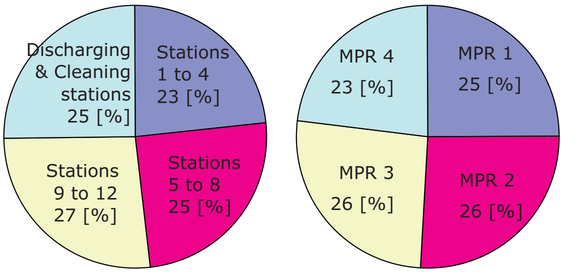
From this result, we can see that the best and worst times with 5 MHRs obtained by using the reactive cooperation technique were 0.15 and 0.14 [h] longer than the results without the technique. The reason for this result is that no bottleneck occurred in this system; accordingly, reactive cooperation for workload balancing was not necessary. Therefore, the integrated operational techniques, when a small number of MHRs is used, are (b), (c'), and (c") without reactive cooperation. On the other hand, the best and worst times are improved (10 MHRs: 0.27 and 0.68 [h], 15 MHRs: 0.66 and 0.87 [h]) as the number of MHRs increases by using the reactive cooperation technique. Furthermore, the best operation time with 15 MHRs is reduced by 0.43 [h] from the result with 10 MHRs. These results indicate that workload balancing for a shifting bottleneck was appropriately performed. The integrated operational techniques for



(a) Sojourn ratio (5) (b) Operating ratio (5)



(c) Sojourn ratio (10) (d) Operating ratio (10)



(e) Sojourn ratio (15) (f) Operating ratio (15)

Fig. 6. Robots Utilization Ratio with the Use of the Operational Techniques Including the Reactive Cooperation in the Best System (# of MHRs)

more MHRs are, therefore, (c), (c'), and (c") with reactive cooperation.

For the analysis of the bottleneck, Fig. 6 shows the robots utilization ratio with the reactive cooperation technique on the basis of the best result in Table I. In a comparison of the results of Fig. 6(a) and Fig. 6(b) with the results of Fig. 5(a) and Fig. 5(b), the robots utilization ratio at each station is almost the same and even (about 25 [%]). For more MHRs, 10 and 15, workload balancing was performed sufficiently well with the use of the reactive cooperation technique; eventually, the shifting bottleneck around the cleaning and discharging stations (see Fig. 5(c) and Fig. 5(e)) was successfully improved, as can be seen in Fig. 6(c) and Fig. 6(e). Moreover, from the results of Fig. 6(d) and Fig. 6(f), the operation ratio of MPR 4 was reduced from 28 (see Fig. 5(d) and Fig. 5(f)) to 24 and 23 [%]. This is because the adjacent MPRs, 1 and 3, supported MPR 4; then, MPR 2 supported MPR 1 and MPR 4; eventually, heavy workloads among the MPRs were made uniform.

VIII. CONCLUSIONS

In this paper, we focused on a robotic batch manufacturing system with a cyclic layout. In order for the robots, MHR and MPR, to operate appropriately while relating to each other, we proposed operational techniques, such as route planning for the MHR and operation dispatching for the MPR on the basis of task-assignment to the robots to reduce the effect of the bottleneck and increase the production volume, in addition to reactive cooperation technique among the MPRs for workload balancing. From the simulation results, we showed that these techniques could effectively improve the shifting bottleneck and evenly spread a heavy workload. Finally, integrated operational techniques suitable for the number of MHRs were shown. In future work, we will address a fault-tolerant issue in consideration of the robot reliability.

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