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ORIGINAL ARTICLE

Real-time OHT Dispatching Mechanism for the Interbay Automated Material Handling System with Shortcuts and Bypasses

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Abstract As a key to improve the performance of the interbay automated material handling system (AMHS) in 300 mm semiconductor wafer fabrication system, the real-time overhead hoist transport (OHT) dispatching problem has received much attention. This problem is first formulated as a special form of assignment problem and it is proved that more than one solution will be obtained by Hungarian algorithm simultaneously. Through proposing and strictly proving two propositions related to the characteristics of these solutions, a modified Hungarian algorithm is designed to distinguish these solutions. Finally, a new real-time OHT dispatching method is carefully designed by implementing the solution obtained by the modified Hungarian algorithm. The experimental results of discrete event simulations show that, compared with conventional Hungarian algorithm dispatching method, the proposed dispatching method that chooses the solution with the maximum variance respectively reduces on average 4 s of the average waiting time and average lead time of wafer lots, and its performance is rather stable in multiple different scenarios of the interbay AMHS with different quantities of shortcuts. This research provides an efficient real-time OHT dispatching mechanism for the interbay AMHS with shortcuts and bypasses.

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1 Introduction

The semiconductor wafer fabrication system (SWFS) is one of today's most complex discrete manufacturing systems featured with re-entrant flows, large-scale and multi-species work-in-process (WIP), enormous manufacturing processes, long cycle times and tight due dates [1]. Due to the growing wafer size and weight and high-level transportation requirement in the 300 mm semiconductor wafer fabrication line, the automated material handling system (AMHS) is widely adopted to guarantee high tool utilization and system performances, such as wafer lots' throughput and due dates [2]. According to the working area, AMHSs used in SWFSs are generally classified as interbay or intrabay AMHS. As the name implies, the interbay AMHSs transport wafer lots (25 wafers are grouped and transported in a standard container, called a wafer lot) between processing bays and the intrabay AMHSs transport wafer lots within one process bay. Compared with intrabay AMHSs, interbay AMHSs are the hub of the entire AMHS and involves much more automated guided vehicles, more types of transportation tasks, and more stochastic transportation demands with higher risk of vehicle conflicts [3]. Therefore, an efficient control of interbay AMHS is of significant importance to improve the performance of the semiconductor wafer fabrication system.

In an interbay AMHS, the overhead hoist transporter (OHT) is used to respond to transportation demands and accomplish tasks in real-time. Thus, dispatching strategies for OHTs are the key to control the interbay AMHS, which have received much attention over the last few years. These dispatching methods stimulated better interbay AMHS performances such as OHT's utilization, wafer lot's waiting time and lead time. Current OHT dispatching methods are mainly classified into three categories: direct dispatching polices based on single- or multi-attribute heuristic rules, optimal dispatching polices based on mathematical programming and adaptive dispatching polices usually based on fuzzy logic control. The literature review presents all mentioned methods in the following.

In one of the earliest papers on automated guided vehicle (AGV) dispatching, EGBELU and TANCHOCO [4] concluded a variety of dispatching heuristics, which can be classified as either vehicle initiated or workstation initiated. After that, BOZER and YEN [5] proposed two dispatching rules, MOD-STTF and B2D2, which combined *shortest travelling time first* (STTF) rule with re-assignment mechanism. In addition, B2D2 rule is an improved version of MOD-STTF rule, which introduces bidding rule and allows each vehicle accepting more than one transportation requests simultaneously. In 2001, some researches [6] were conducted on dispatching vehicles in a double-loop interbay AMHS and proved that the combination of the *nearest vehicle first* and the *first encounter first served* rules outperformed the other heuristic rules. In addition, given wafer lots' waiting time and delivery time, LIN, et al [7], established a pull/push dispatching mechanism based on the *first encounter first served* rule and the *nearest vehicle first* rule. By LE-ANH, et al [8], the performances of several single- and multi-attribute rules with re-assignment mechanism were evaluated in warehouse transportation scheduling problem and it was concluded that the combined dispatching rules which integrates multi-attribute dispatching and vehicle reassignment yields the best performance overall. To solve a matching problem in the modified miniload automated storage/retrieval system, WANG, et al [9], proposed a multi-stage heuristic algorithm minimizing the transportations of items. KIM, et al [10], proposed *reassignment based dispatching* (RBD) mechanism similar to MOD-STTF. Then, this RBD rule was combined with Hungarian algorithm to simultaneously deal with the assignment problem of multiple OHTs and wafer lots [11].

Mathematical programming was used to find the optimal solutions usually with high computational complexity. CORREA, et al [12], decomposed the AGVs dispatching problem in FMS into task scheduling problem (major problem) and route optimization problem (sub problem), which were respectively solved by constrained programming and mix-integer programming. TAVANA, et al [13], focused on the performance measures and proposed a bi-objective stochastic programming to optimize the time and cost objectives considering the uncertainties inherent in the AMHS. Given that earliness and tardiness are significant in satisfying the expected cycle time, FAZLOLLAHTABAR, et al [14], proposed a mathematical program to minimize the penalized earliness and tardiness in a manufacturing system with multiple automated guided vehicles. Since the mathematical program is difficult to solve with a conventional method, an optimization method in two stages was designed to find optimal solutions accordingly.

Further, to fulfill the requirement of the multi-objective optimization in a dynamic environment, WU, et al [3], and QIN, et al [15], offered real-time multi-objective OHT dispatching methods which combined Hungarian algorithm with fuzzy logic control. According to their dispatching policies, multiple system parameters were simultaneously considered and these parameters' weight coefficients were adjusted adaptively by fuzzy logic method. Similarly, MORANDIN, et al [16], suggested a heuristic AGVs dispatching police based on fuzzy logic and genetic algorithms, which included prediction task, multi-objective and modeling Petri nets realizing the closest simulation of real environment. Through introducing a simultaneous detection and tracking framework, WANG, et al [17], established a multi-vehicle detection and tracking system. BINHARDI et al [18], came up with a multi-agent AGV system which uses a fuzzy system to decide what task should be assigned to the AGV fleet. And compared with two other decision methods, FCFS and Contract Network (CNET), the fuzzy method enabled a greater average task waiting time reduction and completed tasks in less time.

However, different from previous researches focused primarily on complex control strategies in AMHSs, some researchers dealt with details of OHT dispatching problems. To reduce each vehicle's arrival time, LIN, et al [19], proposed the novel vehicle pre-dispatching method which calls several idle vehicles to move to a load port simultaneously. Since the blocking issue is inevitable in a typical bay type path-based AMHS with no bypasses, KIM, et al [20], proposed a simple blocking prevention method based on the swapping of load assignments between retrieval vehicles on the same path. IM, et al [21], also analyzed a kind of traffic congestion event caused by OHTs in single-loop interbay AMHS with no bypasses and pointed out that the Hungarian algorithm could be modified to avoid this kind of event. However, they [21] did not rigorously proved the conclusions related to solutions obtained by Hungarian algorithm and the proposed method needs to be validated more sufficiently in the interbay AMHS with shortcuts and bypasses, which is the motivation of this study.

In order to be distinguished from the interbay AMHS in Ref. [21] and verify the conclusions related to Hungarian algorithm in different cases, the interbay AMHS with shortcuts and bypasses [22] is adopted as a main purpose of this study. Furthermore, two propositions on the characteristics of solutions obtained by Hungarian algorithm are completely proved in the interbay AMHS with shortcuts and bypasses: 1) multiple optimal assignments of multiple OHTs and wafer lots are achieved by Hungarian algorithm; 2) there are strict inequality relations among these optimal assignments' variances regarding any real number. Finally, based on the conclusions on Hungarian algorithm, a new real-time OHT dispatching method is proposed.

2 Description and Formulation of OHT Dispatching Problem in interbay AMHS

As shown in Fig. 1, there are 22 intrabay AMHSs and one spine-type interbay AMHS with shortcuts and bypasses in a 300 m SWFS. The interbay AMHS is indirectly connected with the intrabay AMHSs through stockers acting as buffers of wafer lots.

Specifically, the interbay AMHS consists of three parts: transportation track, stockers and OHTs. The transportation track is a unidirectional closed-loop monorail system with perimeter of 480 m and total length of 560 m. Basically, there are four shortcuts in the track and eight turntables that change the directions of OHTs in the intersection of main track and shortcuts. Each stocker has one input port and one output port and its capacity is set unlimited so that the deadlock problem is not existed when OHTs load/unload wafer lots from/to stockers. OHTs move in the clockwise direction and transport wafer lots from one stocker to another stocker. Because of no dwell place, idle OHTs should continue moving on the track until receiving new tasks. When it is assigned a new task, the OHT will always choose the paths with the shortest distance between its current place and the destination. And with the bypasses, the blocking events when OHTs load/unload wafer lots from/to stockers are significantly reduced.

Supposed that at scheduling moment, there are m available OHTs and n wafer lots waiting to be transported in the interbay AMHS. The problem of OHT dispatching is a special form of assignment problem with the objective to minimize the sum of OHTs' travel time and it can be formulated as a 0-1 integer programming model shown as follows [11]:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij}, \tag{1}$$

$$\sum_{i=1}^{n} x_{ij} = 1, \tag{2}$$

$$\sum_{j=1}^{m} x_{ij} = 1, \tag{3}$$

$$\boldsymbol{C} = \begin{pmatrix} c_{11} & \cdots & c_{1m} \\ \cdots & c_{ij} & \cdots \\ c_{n1} & \cdots & c_{nm} \end{pmatrix}, \tag{4}$$

where $x_{ij} \in \{0, 1\}$, $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. x_{ij} is the decision parameter indicating whether waiting wafer lot n is assigned to available OHT j and if it is true, x_{ij} equals 1, otherwise 0. And c_{ij} is the time cost for OHT j to travel to waiting wafer lot i, which is derived from the distance between OHT j and waiting wafer lot i and all of c_{ij} make up the time cost matrix $\boldsymbol{C}$ in Eq. (4).

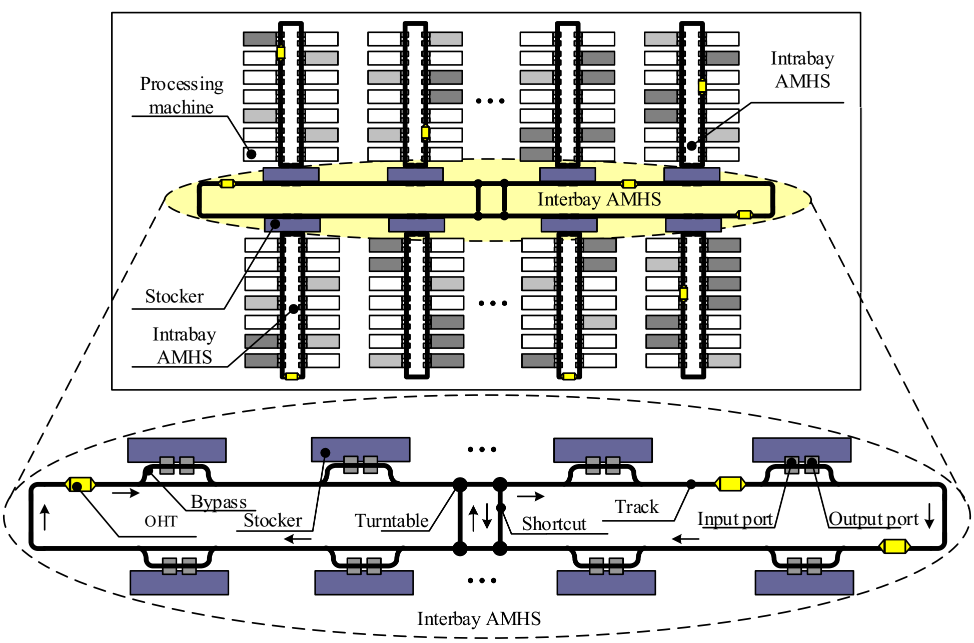

Fig. 1 Configuration of the interbay AMHS with shortcuts and bypasses

The assignment problem can be efficiently solved by Hungarian algorithm [23] and the time complexity is O(N^3), where $N = \max\{n, m\}$ [24]. The procedure of Hungarian algorithm is briefly described as follows [21].

Step 1: A cost matrix $\boldsymbol{C}$ is constructed first in the form of Eq. (4).
Step 2: For each row of $\boldsymbol{C}$, subtract the minimum number in that row from all numbers in that row.
Step 3: For each column of $\boldsymbol{C}$, subtract the minimum number in that column from all numbers in that column.
Step 4: Draw the minimum number of lines to cover all zeroes. If this number equals the size of cost matrix, stop and an assignment can be made. Otherwise go to Step 5.
Step 5: Find the minimum uncovered number γ, and perform following operations: 1) subtract γ from the uncovered numbers; 2) add γ to the twice-covered numbers; 3) the once-covered numbers remain the same; 4) go to Step 4.

At the end, the pairs of row index and column index of the independent zeros are the optimal assignment of OHTs and wafer lots [23]. However, in many situations, the Hungarian algorithm results in multiple optimal solutions for the OHT dispatching problem.

3 Analysis of the Interbay AMHS Scheduling Based on Hungarian Algorithm

To analyze the interbay AMHS scheduling based on Hungarian algorithm, an interbay AMHS with two shortcuts is illustrated, as shown in Fig. 2. To make the analysis operable, without loss of generality, suppose that the quantity of *idle* OHTs and that of wafer lots waiting to be transported are equal. As presented in Fig. 2, there are 4 *idle* OHTs and 4 wafer lots waiting to be transported in the scheduling moment. According to Hungarian algorithm, the sum of OHTs' travel time is minimized and under this objective the OHTs are assigned to their nearest wafer lots as possible. Observing the distribution of OHTs and wafer lots in Fig. 2, it can be easily obtained that OHT$_2$ is assigned to transport the wafer lot in Stocker 2 and the OHT$_3$ is assigned to transport the wafer lot in Stocker 3. However, how to assign OHT$_1$ and OHT$_4$ to Stocker1 and Stocker4 cannot be easily determined by Hungarian algorithm. To make it straightforward, the interbay AMHS with two shortcuts in Fig. 2 is equivalently divided into two interbay AMHSs without shortcuts shown in Fig. 3. And in Fig. 3, it is much easier to determine the assignment of OHT$_2$ and OHT$_3$.

Next, in order to describe the dispatching process of OHT$_1$ and OHT$_4$ based on Hungarian algorithm, the single-loop track in Fig. 3 is "cut off" with the "split line" and "straightened", as depicted in Fig. 4(a). Then the cost matrix can be formulated as

$$\boldsymbol{C} = \begin{pmatrix} c_{11} & c_{41} \\ c_{14} & c_{44} \end{pmatrix}.$$

In Fig. 4, $c_{11}(c_{14})$ indicates the time cost for OHT$_1$ travel to Stocker 1(4) and so is $c_{41}(c_{44})$. Therefore, it is obviously defined:

$$c_{11} < c_{14}, c_{41} < c_{44}, c_{11} < c_{44}, \tag{5}$$

$$c_{14} - c_{11} = c_{44} - c_{41} > 0, \tag{6}$$

$$\text{also} \quad c_{11} + c_{44} = c_{14} + c_{41}. \tag{7}$$

Thus, according to Hungarian algorithm, two optimal solutions shown in Fig. 4(b) and 4(c) can be obtained, which are named as *solution b* and *solution c*. Obviously, the sum (or average) of OHTs' travel times in *solution b* and *solution c* are the same, but OHT$_1$ in *solution b* will respond to the transport request of wafer lots in the shortest time.

Based on the analysis of the situations described in Fig. 2, when there are two OHTs on the track between two consecutive Stockers, the situation in Fig. 4 is triggered. To popularize this conclusion in a generalized environment, a

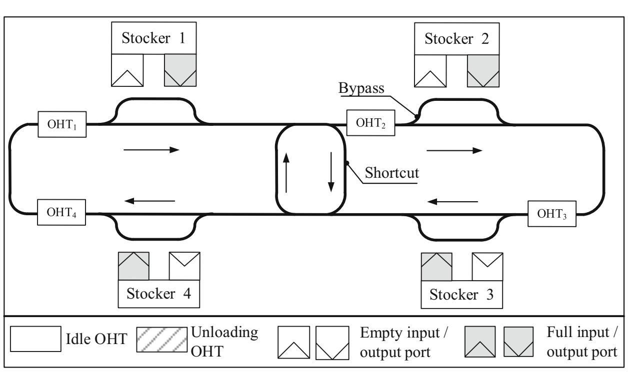

Fig. 2 Interbay AMHS with two shortcuts

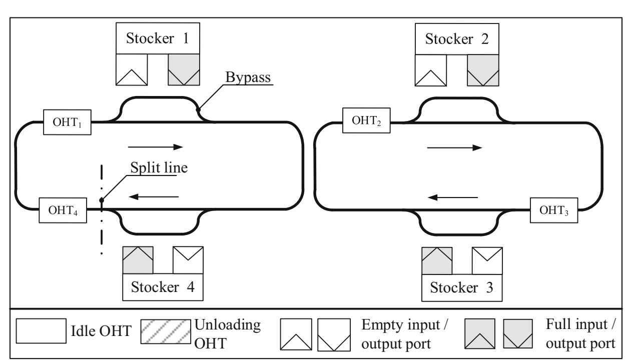

Fig. 3 Interbay AMHSs without shortcuts

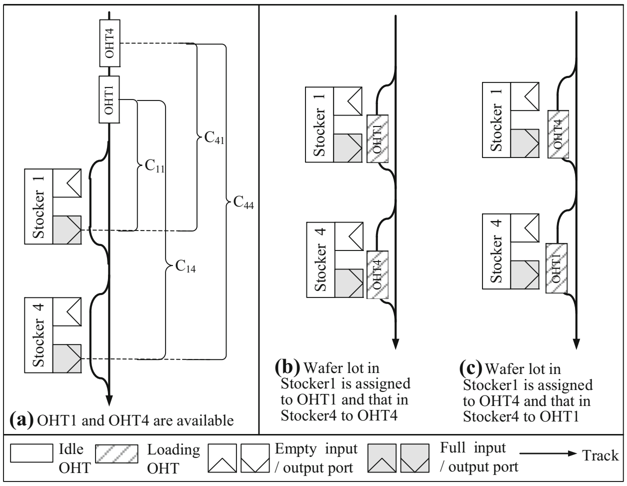

Fig. 4 Dispatching of OHTs in interbay AMHS

single-loop interbay AMHS with k shortcuts is given in Fig. 5. Accordingly, there are performed the following actions:

First, check the OHTs between each pair of two consecutive wafer lots. If there is only one OHT between them, the OHT is assigned to its nearest wafer lots (in moving direction) and “omitted” from the system.

Second, check consecutive OHTs and consecutive wafer lots and make them as a group meeting three conditions: 1) the consecutive OHTs are next to the consecutive wafer lots; 2) the quantity of consecutive OHTs and that of wafer lots are equal; 3) the quantity of consecutive OHTs (or wafer lots) is as many as possible.

With the above two operations, the OHTs and wafer lots are divided into many groups similar to the situation in Fig. 6. Obviously, the situation in Fig. 4 is the special case of the situation in Fig. 6. So, it is reasonably concluded that when there are two or more OHTs on the track between two consecutive Stockers, the situation in Fig. 6 is triggered.

From the above derivation, the Hungarian algorithm is not influenced by the quantity of shortcuts in the interbay AMHS, or more precisely speaking, the shortcuts only affect the average distance between OHTs and wafer lots. And the larger the number of shortcuts is, the shorter the average distance will be.

As the situation described in Fig. 4 occurs frequently in the interbay AMHS, it is necessary to distinguish these two kinds of solutions and compare their performance. So, two propositions on the characteristics of these solutions are proposed and related rigorous mathematical proofs are described in detail.

4 Propositions and Proofs

As shown in Fig. 6, $c_{i,j}$, $v_{i,j}$, $s_{i,j}$ are defined, the distance between OHT j and waiting wafer lot i, the distance between OHT i and OHT j, the distance between waiting wafer lot i and waiting wafer lot j, where $i, j = 1, 2, \ldots, n$.

Without loss of generality, the velocity of OHTs is supposed to be 1, so $c_{i,j}$, $v_{i,j}$ and $s_{i,j}$ can separately represent time costs for OHTs to travel equivalent distances.

Proposition 1 If the positions of available OHTs and waiting wafer lots are shown in Fig. 6, and each OHT can transport only one wafer lot every time, then the sum of OHTs' travel time is independent of the assignment solutions and the total time cost is defined as

$$\sum_{i=1}^{n} c_{i,\sigma(i)} = \sum_{i=1}^{n} c_{i,i}, \tag{8}$$

where $\sigma(i) = 1, 2, \ldots, n$.

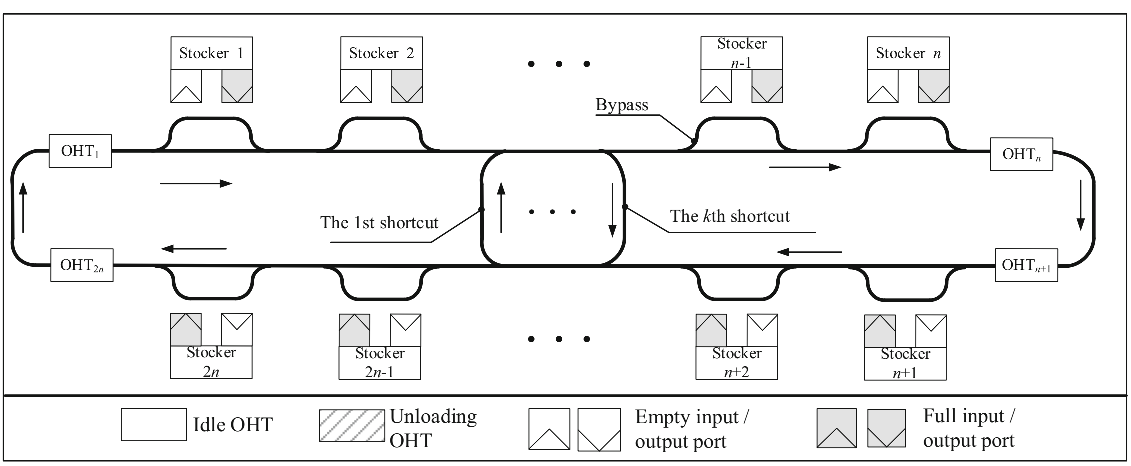

Fig. 5 Interbay AMHS with k shortcuts

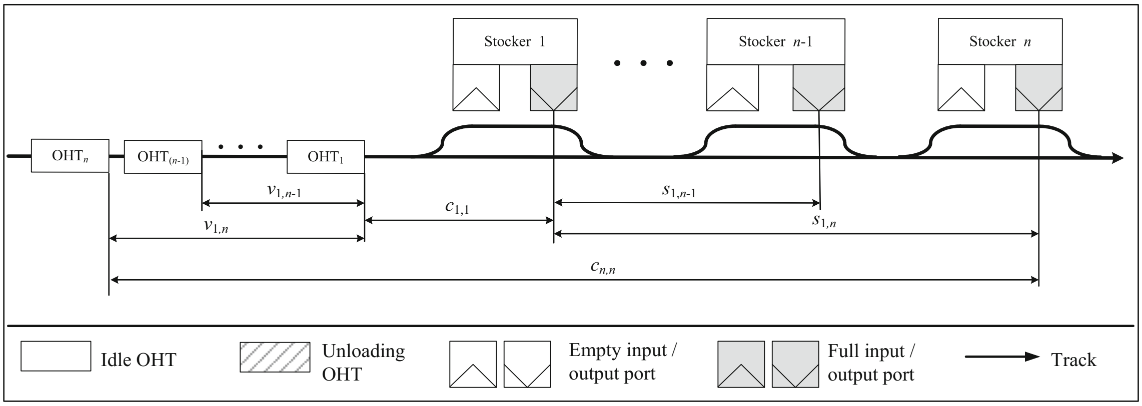

Fig. 6 Assignment problem of n OHTs and n wafer lots

Proof Based on information provided in Fig. 6, it is obvious that $c_{i,\sigma(i)} = v_{1,i} + c_{1,1} + s_{1,\ \sigma(i)}$. Then, we have

$$\sum_{i=1}^{n} c_{i,\sigma(i)} = \sum_{i=1}^{n} \left(v_{1,i} + c_{1,1} + s_{1,\sigma(i)}\right) = \sum_{i=1}^{n} v_{1,i} + nc_{1,1} + \sum_{i=1}^{n} s_{1,\sigma(i)} = \sum_{i=1}^{n} v_{1,i} + nc_{1,1} + \sum_{i=1}^{n} s_{1,i} = \sum_{i=1}^{n} \left(v_{1,i} + c_{1,1} + s_{1,i}\right) = \sum_{i=1}^{n} c_{i,i}\,.$$

So, **Proposition 1** is proved.

Proposition 2 If the positions of available OHTs and waiting wafer lots are as shown in Fig. 6, and each OHT can transport only one wafer lot every time, then the following inequalities for any real number μ is held

$$\sum_{i=1}^{n} \left(c_{i,n-i+1} - \mu\right)^2 \le \sum_{i=1}^{n} \left(c_{i,\sigma(i)} - \mu\right)^2 \le \sum_{i=1}^{n} \left(c_{i,i} - \mu\right)^2, \tag{9}$$

where $\sigma(i) = 1,\ 2,\ \ldots,\ n$.

Proof Expanding the second expression in Eq. (9), we have

$$\sum_{i=1}^{n} \left(c_{i,\sigma(i)} - \mu\right)^2 = \sum_{i=1}^{n} \left(c_{i,\sigma(i)}^2 - 2\mu c_{i,\sigma(i)} + \mu^2\right) = \sum_{i=1}^{n} c_{i,\sigma(i)}^2 + 2\mu \sum_{i=1}^{n} c_{i,\sigma(i)} + n\mu^2. \tag{10}$$

According to Eq. (8) in proposition 1, the second and third term in Eq. (10) are constants, and thus only the first term needs to be further analyzed. Continuing expanding the first term in Eq. (10), we have

$$\sum_{i=1}^{n} c_{i,\sigma(i)}^2 = \sum_{i=1}^{n} \left(v_{1,i} + c_{1,1} + s_{1,\sigma(i)}\right)^2 = \sum_{i=1}^{n} \left(v_{1,i} + s_{1,\sigma(i)}\right)^2 + 2c_{1,1} \sum_{i=1}^{n} \left(v_{1,i} + s_{1,\sigma(i)}\right) + nc_{1,1}^2. \tag{11}$$

Obviously, the second and third terms in Eq. (11) are also constants. Continuing expanding the first term in Eq. (11), it is obtained

$$\sum_{i=1}^{n} \left(v_{1,i} + s_{1,\sigma(i)}\right)^2 = \sum_{i=1}^{n} v_{1,i}^2 + 2\sum_{i=1}^{n} v_{1,i} s_{1,\sigma(i)} + \sum_{i=1}^{n} s_{1,\sigma(i)}^2. \tag{12}$$

In addition, according to the positions of OHTs and wafer lots in Fig. 6, it can be concluded as $v_{1,1} < v_{1,2} <$ - $v_{1,3} < \ldots < v_{1,n}$, $s_{1,1} < s_{1,2} < s_{1,3} < \ldots < s_{1,n}$, and meanwhile based on the rearrangement inequality [25], we have

$$\sum_{i=1}^{n} v_{1,i} s_{1,n-i+1} \le \sum_{i=1}^{n} v_{1,i} s_{1,\sigma(i)} \le \sum_{i=1}^{n} v_{1,i} s_{1,i}. \tag{13}$$

Thus, according to Eqs. (11)–(13), it is naturally concluded as follows

$$\sum_{i=1}^{n} c_{i,n-i+1}^2 \le \sum_{i=1}^{n} c_{i,\sigma(i)}^2 \le \sum_{i=1}^{n} c_{i,i}^2. \tag{14}$$

Finally, considering Eqs. (10) and (14) simultaneously, the conclusion of proposition 2 is obtained, which is

$$\sum_{i=1}^{n} \left(c_{i,n-i+1} - \mu\right)^2 \le \sum_{i=1}^{n} \left(c_{i,\sigma(i)} - \mu\right)^2 \le \sum_{i=1}^{n} \left(c_{i,i} - \mu\right)^2.$$

In Sect. 5, the method distinguishing *solution b* and *solution c* is proposed based on the two characteristics described in propositions 1 and 2. In addition, both solutions are used in the OHT dispatching separately and then their performance are carefully compared in Sect. 6.

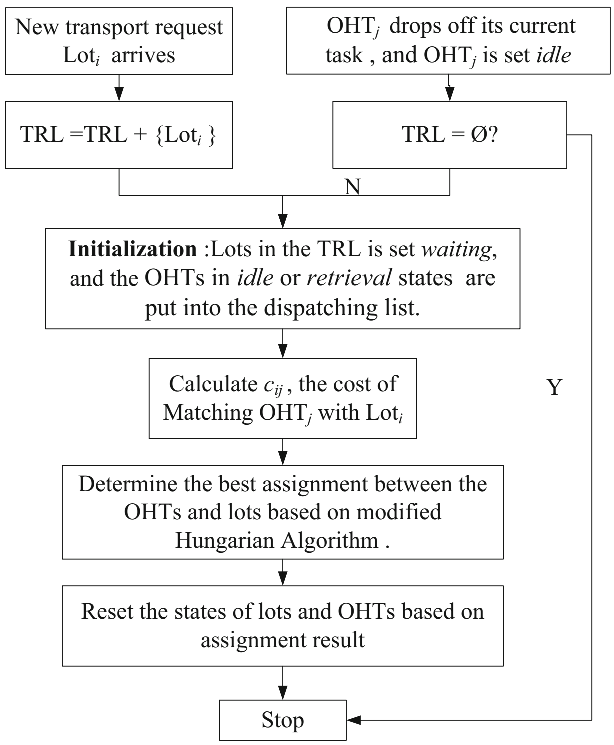

Fig. 7 Flowchart of the OHT dispatching process

5 Real-time OHT Dispatching Mechanism

When a wafer lot enters the stocker connected with the interbay AMHS, its information will be recorded in Transport Request List(TRL) and after it is moved on to the assigned OHT, the wafer lot's information will be removed from TRL.

The states of OHTs in the interbay AMHS are classified into three types: *idle*, *retrieval* and *delivery* [10] which respectively indicates the OHT is not assigned, assigned but empty, and delivering a wafer lot. And correspondingly, the wafer lots also have three states [21] which are *waiting*, *assigned* and *loaded*. The states of *waiting* and *assigned* respectively indicate the wafer lot is waiting for or already assigned an OHT, and *loaded* indicates the wafer lot is transported by the assigned OHT to its destination for successive processing.

A new dispatching is triggered when a new wafer lot enters the stocker connected with the interbay AMHS or an OHT finishes its transportation task. The complete dispatching process is divided into three steps describe in detail as follows.

Step 1: Determine the OHTs that should be dispatched and then calculate the cost matrix
When a new dispatching is launched, check each OHT's state and put the OHTs in *idle* or *retrieval* states into the dispatching list. The states of wafer lots in TRL are set *waiting*. Afterward, calculate the time costs for each OHT in the dispatching list travelling to the wafer lots in TRL.

Step 2: Determine the optimal assignment of available OHTs and waiting wafer lots.

In order to get different solutions similar to *solution b* and *c*, the Hungarian algorithm is modified. ***Co*** and ***Cr*** are respectively denoted an original cost matrix and a reduced cost matrix obtained by Hungarian algorithm, which are illustrated in Eqs. (15) and (16).

$$\boldsymbol{Co} = \begin{pmatrix} Co_{11} & Co_{12} & Co_{13} & Co_{14} \\ Co_{21} & Co_{22} & Co_{23} & Co_{24} \\ Co_{31} & Co_{32} & Co_{33} & Co_{34} \\ Co_{41} & Co_{42} & Co_{43} & Co_{44} \end{pmatrix}, \tag{15}$$

$$\boldsymbol{Cr} = \begin{pmatrix} 0 & 0 & Cr_{13} & Cr_{14} \\ Cr_{21} & 0 & Cr_{23} & 0 \\ Cr_{31} & Cr_{32} & 0 & Cr_{34} \\ Cr_{41} & 0 & Cr_{43} & 0 \end{pmatrix}. \tag{16}$$

According to the Hungarian algorithm, the final assignment solution is the pairs of row index and column index of the independent zeros in the reduced cost matrix ***Cr***, so two optimal solutions are obtained: 1-1, 2-2, 3-3 4-4 (called S1) and 1-1, 2-4, 3-3, 4-3 (called S2).

Considering proposition 2, S1 and S2 can be further distinguished. There is defined a real number μ which denotes the average value of the maximum element $C_{\max}$ and minimum element $C_{\min}$ i.e. $\mu = (C_{\max} + C_{\min})/2$. More, there is also defined a normalized variance σ^2 and its formulation is

$$\sigma_{ij}^2 = (Co_{ij} - \mu)^2 \Big/ (C_{\max} - C_{\min})^2. \tag{17}$$

Perform the following operations:The element in original cost matrix is added (or subtracted) by its normalized variance if it becomes zero in the reduced cost matrix; otherwise, this element is replaced with $C_{\max}$. Through these operations, a new cost matrix $\boldsymbol{C_N}$ (or $\boldsymbol{C'_N}$) is obtained as shown in Eqs. (18) and (19):

$$\boldsymbol{C_N} = \begin{pmatrix} Co_{11} + \sigma_{11}^2 & Co_{12} + \sigma_{12}^2 & C_{\max} & C_{\max} \\ C_{\max} & Co_{22} + \sigma_{22}^2 & C_{\max} & Co_{24} + \sigma_{24}^2 \\ C_{\max} & C_{\max} & Co_{33} + \sigma_{33}^2 & C_{\max} \\ C_{\max} & Co_{42} + \sigma_{42}^2 & C_{\max} & Co_{44} + \sigma_{44}^2 \end{pmatrix}, \tag{18}$$

or

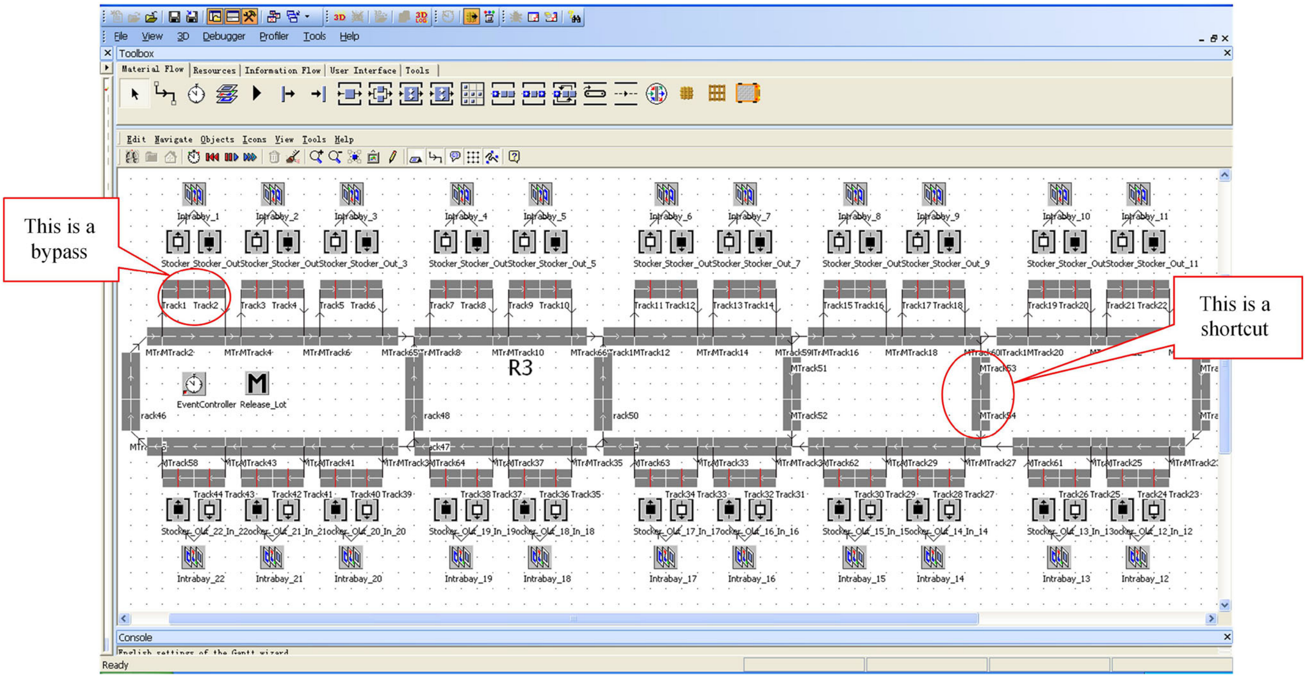

Fig. 8 Simulation model of interbay material handling system with 4 shortcuts based on eM-Plant 7.5

$$\boldsymbol{C'}_N = \begin{pmatrix} Co_{11} - \sigma_{11}^2 & Co_{12} - \sigma_{12}^2 & C_{\max} & C_{\max} \\ C_{\max} & Co_{22} - \sigma_{22}^2 & C_{\max} & Co_{24} - \sigma_{24}^2 \\ C_{\max} & C_{\max} & Co_{33} - \sigma_{33}^2 & C_{\max} \\ C_{\max} & Co_{42} - \sigma_{42}^2 & C_{\max} & Co_{44} - \sigma_{44}^2 \end{pmatrix}, \tag{19}$$

Because S1 and S2 are both optimal solutions obtained by Hungarian algorithm, their total costs are the same in $\boldsymbol{Co}$, or specifically $Co_{22} + Co_{44} = Co_{42} + Co_{24}$. Due to that the positions of OHTs and wafer lots are different, it is obvious that Co_{22} does not equal Co_{24} and Co_{42} does not equal Co_{44}. Without loss of generality, there is assumed that $Co_{22} <$ - $Co_{24}, Co_{42} < Co_{44}$. And according to proposition 2, we have $\sigma_{22}^2 + \sigma_{44}^2 > \sigma_{42}^2 + \sigma_{24}^2$ and thus, the total cost of S2 in $\boldsymbol{C_N}$ is less than that of S1 in $\boldsymbol{C_N}$ (or the total cost of S2 in $\boldsymbol{C'_N}$ is more than that of S1 in $\boldsymbol{C'_N}$). Again, $\boldsymbol{C_N}$ is calculated with Hungarian algorithm, and finally, only one optimal solution S2(similar to *solution c*) is obtained (or $\boldsymbol{C'_N}$ is calculated with Hungarian algorithm, and finally, only one optimal solution S1 (similar to *solution b*) is obtained).

Step 3: Modify the states of OHTs and wafer lots according to the final solution obtained in Step 2.

For OHTs, if the OHT is assigned to a waiting wafer lot, then set its state *retrieval*, otherwise, set its state *idle*. For wafer lots, if the wafer lot is assigned an OHT, then set its state *assigned*, otherwise, set its state *waiting*.

The whole process of the OHT dispatching is shown in Fig. 7.

6 Simulation Experiments and Case Study

To evaluate the efficiency of the proposed method, a simulation model of the interbay AMHS in the 300 mm SWFS described in Sect. 2 is established based on the discrete event simulation software eM-Plant 7.5, shown in Fig. 8. The Hungarian algorithm and its modified version is programmed with C++ language and embedded into the simulation model as a dynamic link library (DLL) file.

There are three types of wafer lots a, b, and c being processed in the 300 mm SWFS and their quantity is equal to each other. In addition, the breakdown of all equipment such as OHTs, stockers and processing machine is not in consideration. In order to observe the performance of proposed OHT dispatching method in different scenarios, the number of OHTs and loading ratios are respectively set 10 OHTs, 11 OHTs, 12 OHTs, 13 OHTs, 14 OHTs and 3lot/3.0 h, 3lot/3.5 h. Therefore, there are totally 10 experiment scenarios. Then 4 OHT dispatching methods are tested in these scenarios:

(1) Reassignment based dispatching(RBD) [10] method: When a new transport request (wafer lot) arrives at the interbay AMHS, the nearest *idle* OHT, if any, is allocated to transport this wafer lot. Otherwise, the wafer lot will wait for *idle* OHTs. On the other hand, if an OHT becomes *idle*, it is assigned to the nearest *waiting* wafer lot. And if there is no *waiting* wafer lot, then it searches for *assigned* wafer lots, which are waiting for *retrieval* OHTs, and to which the

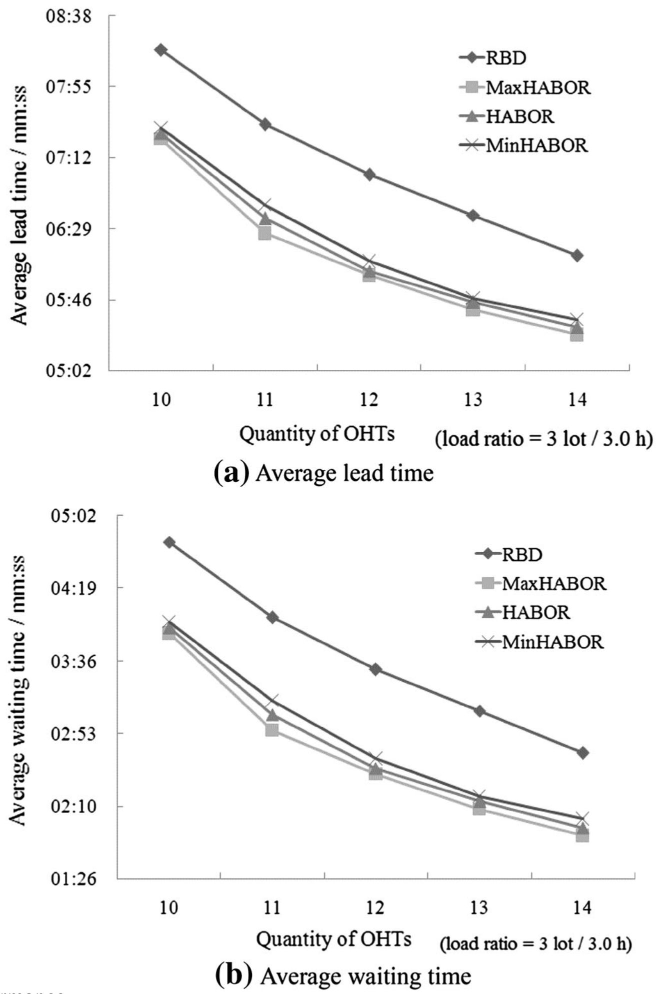

Fig. 9 Dispatching methods' performance

distance from the OHT is shorter than the distance from the *retrieval* OHT. If there are multiple such wafer lots, the OHT is assigned to the most suitable one, and releases the OHT originally assigned to this wafer lot. The released OHT is set to *idle*. If there is no such wafer lot, the vehicle is set to *idle* and keep moving on the track.

(2) Hungarian algorithm based OHT reassignment (HABOR) [11]: Different from RBD rule, whenever an OHT becomes *idle*, an assignment problem is formulated and solved by Hungarian algorithm with the consideration of all *idle* and *retrieval* vehicles and *waiting* and *assigned* wafer lots.

(3) Hungarian algorithm based real-time OHT dipatching with the minimum variance (MinHAROD): Base on the proposed method in Sect. 5, the solution with minimum variance (similar to *solution c*) is always selected as the optimal assignment of OHTs and wafer lots.

(4) Hungarian algorithm based real-time OHT dispatching with the maximum variance (MaxHAROD): In contrast to MinHABROD, the solution with maximum variance (similar to *solution b*) is always selected as the optimal assignment of OHTs and wafer lots.

When the simulation starts, all OHTs are stochastically distributed on the track and their initial states are set *idle*. As the simulation time goes on, the system will enter the steady state after a warm-up period. By multiple simulation experiments, it is determined that the warm-up period is a little less than 20 days (simulation time). So, the statistics of the simulation model is gathered after 20 days(simulation time) and the duration is 10 days (simulation time). The performance indicators are average lead time and average waiting time of wafer lots [10]. Figure 9(a) and Fig. 10(a) depict the relationship between average lead time of wafer lots and the quantity of OHTs while load ratios are 3 lot/3.0 h and 3 lot t/3.5 h respectively. And similarly, Fig. 9 (b) and Fig. 10(b) present the relationship between average waiting time of wafer lots and the quantity of OHTs. Based on the results of Fig. 9 and Fig. 10, it is concluded

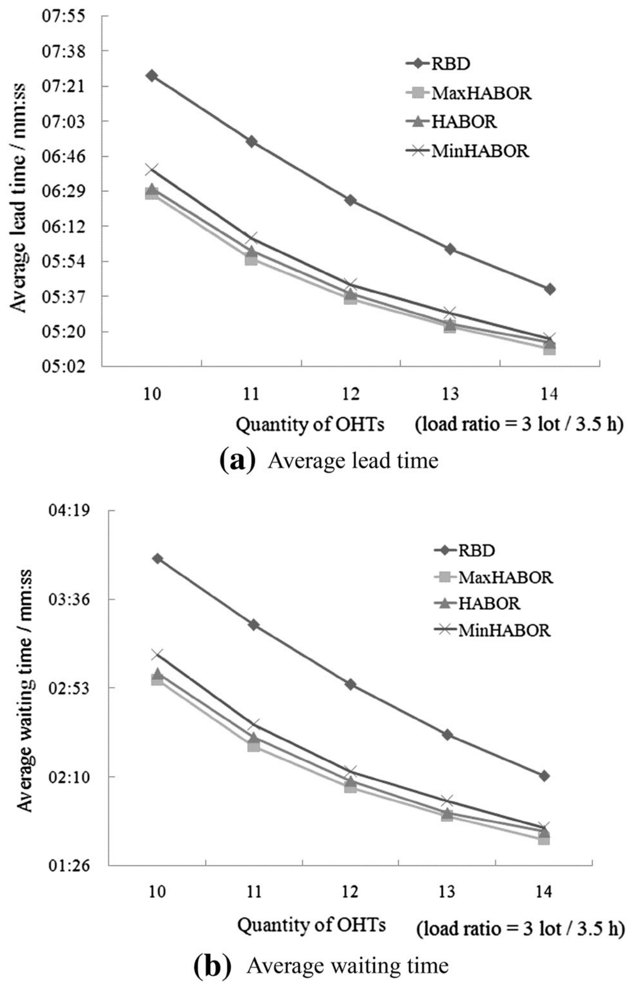

Fig. 10 Dispatching methods' performance

that HABOR, MinHAROD, and MaxHAROD, which lead to less average lead time and average waiting time of wafer lots, perform much better than RBD. And it also proves that Hungarian algorithm is effective in solving OHT dispatching problem. Furthermore, compared with HABOR and MinHAROD, MaxHAROD leads to less average lead time and average waiting time and its performance is rather stable in all these scenarios. And it is reasonable that the performance of HABOR is quite close to that of MaxHAROD. By HABOR, one of the solutions obtained by Hungarian algorithm is always stochastically chosen, which is much probably the same with the solution of MaxHAROD.

Especially, it is most noteworthy that the performance of MinHAROD is obviously worse than that of MaxHAROD. Recalling the analysis on *solution b* and *solution c* in Sect. 3, it is obvious that the sum (or average) of OHTs' travel times in MaxHAROD and MinHAROD are equal, but some of OHTs in the interbay AMHS scheduled by MaxHAROD will respond to the transport requests in much shorter time than OHTs in MinHAROD and the remaining OHTs with long response time may be adjusted quickly due to the reassignment mechanism. Therefore, MaxHAROD is more adapted to the highly dynamic and stochastic environment of the interbay AMHS.

In addition, to verify the stability of MaxHABOR, two-factor analysis of variance (ANOVA) tests with significance level of $p = 0.05$ are conducted. Both of Table 1 and Table 2 declare that load ratio and quantity of OHTs have significant influence on the average lead time and waiting time of wafer lots in the interbay AMHS. Therefore, combined with the results of of Fig. 9 and Fig. 10, the

Table 1 Two-factor ANOVA for average lead time

Source	*SS*	*DF*	*MS*	*F*	*p*-value	*F*crit
Load ratio	2.71×10^{-7}	1	2.71×10^{-7}	14.19	0.020	7.71
Quantity of OHTs	1.59×10^{-6}	4	3.97×10^{-7}	20.84	0.006	6.39
Error	7.63×10^{-8}	4	1.91×10^{-8}			
Total	1.94×10^{-6}	9				

(*SS*—sum of squares, *DF*—degree of freedom, *MS*—mean square, *F*—*F* ratio, *p*—*p*-value, *F*crit—*F* critical value.)

Table 2 Two-factor ANOVA for average waiting time

Source	*SS*	*DF*	*MS*	*F*	*p*-value	*F*crit
Load ratio	2.64×10^{-7}	1	2.64×10^{-7}	13.90	0.020	7.71
Quantity of OHTs	1.62×10^{-6}	4	4.05×10^{-7}	21.37	0.006	6.39
Error	7.59×10^{-8}	4	1.90×10^{-8}			
Total	1.96×10^{-6}	9				

Table 3 Average lead time of dispatching methods

Quantity of shortcuts	Quantity of OHTs	RBD/mm:ss	MaxHABOR/mm:ss	HABOR/mm:ss	MinHABOR/mm:ss
Without shortcuts, load ratio = 3 lot/3.0 h	10	44:49.4	42:47.0	41:48.9	42:44.0
	11	22:23.0	21:49.0	22:15.3	22:36.6
	12	14:41.7	13:46.1	13:55.0	14:09.4
	13	12:05.3	11:11.7	11:07.2	11:16.6
	14	11:06.0	09:54.3	10:02.1	10:03.1
With 2 shortcuts, load ratio = 3 lot/3.0 h	10	10:47.9	09:59.1	10:02.1	10:10.6
	11	09:17.5	08:07.8	08:17.6	08:17.5
	12	08:28.7	07:18.0	07:23.8	07:31.1
	13	07:56.3	06:46.4	06:45.9	07:00.9
	14	07:33.2	06:23.6	06:24.1	06:33.8
With 4 shortcuts, load ratio = 3 lot/3.0 h	10	08:17.3	07:23.4	07:26.5	07:30.2
	11	07:32.0	06:25.7	06:34.9	06:42.9
	12	07:01.4	06:00.3	06:03.0	06:08.8
	13	06:36.7	05:39.4	05:43.8	05:46.6
	14	06:12.1	05:24.0	05:28.6	05:33.4

Table 4 Average lead time of dispatching methods

Quantity of shortcuts	Quantity of OHTs	RBD/mm:ss	MaxHABOR/mm:ss	HABOR/mm:ss	MinHABOR/mm:ss
Without shortcuts, load ratio = 3 lot/3.5 h	10	19:56.5	19:04.1	20:01.8	19:53.2
	11	13:43.2	12:52.3	13:02.0	13:15.6
	12	11:34.6	10:54.7	11:04.9	10:43.8
	13	10:47.2	09:37.0	09:46.6	09:42.9
	14	10:16.0	09:02.0	09:03.0	09:12.1
With 2 shortcuts, load ratio = 3 lot/3.5 h	10	09:10.0	08:02.8	08:16.2	08:15.3
	11	08:21.0	07:05.0	07:15.5	07:26.5
	12	07:45.3	06:39.9	06:41.8	06:50.4
	13	07:19.2	06:17.6	06:19.4	06:24.9
	14	06:47.1	06:04.6	06:02.7	06:07.7
With 4 shortcuts, load ratio = 3 lot/3.5 h	10	07:25.6	06:27.3	06:30.1	06:39.2
	11	06:53.1	05:55.2	05:59.4	06:05.4
	12	06:24.4	05:35.6	05:38.3	05:42.8
	13	06:00.0	05:21.8	05:23.2	05:28.7
	14	05:40.3	05:10.9	05:14.2	05:15.8

OHT dispatching method MaxHABOR proves to have stable performance in multiple different environments of the interbay AMHS.

Furthermore, to analyze what influences the quantity of the shortcuts has on the performance of the interbay AMHS and different dispatching rules, several simulation experiments were carried out in the interbay AMHSs with 0, 2 and 4 shortcuts respectively. The results of the experiments are presented in Table 3 and Table 4.

According to these results, the quantity of shortcuts has significant impact on the average lead time and the lager the quantity of the shortcuts is, the smaller the average lead time will be. It is also observed that the average lead time in the interbay AMHS without shortcuts is much larger than that with shortcuts, especially when the quantity of OHTs is 10 and 11. In addition, in almost all these scenarios, HABOR, MinHAROD, and MaxHAROD perform much better than RBD regardless of the quantity of shortcuts. Similarly, compared with HABOR and MinHAROD, MaxHAROD leads to less average lead time in all these scenarios, respectively reducing 4 s and 10 s on average.

Based on all these statistics, it is concluded that the real-time OHT dispatching mechanism MaxHABOR presents superior and stable performance in various environments of the interbay AMHS even with different quantities of shortcuts.

7 Conclusions

(1) Multiple optimal assignments of multiple OHTs and wafer lots are achieved by Hungarian algorithm in the interbay AMHS with shortcuts and bypasses and it is proved that strict inequality relations exist among these optimal assignments' variances regarding any real number.

(2) Hungarian algorithm is modified with the introduction of normalized variances and able to distinguish two solutions with opposite characteristics. Moreover, a real-time OHT dispatching mechanism based on modified Hungarian algorithm is proposed to obtain better OHT dispatching solutions accordingly.

(3) The proposed real-time OHT dispatching mechanism is presented through two methods MaxHAROD and MinHAROD. Together with RBD and HABOR, four OHT dispatching methods are tested in simulation models of the interbay AMHS with shortcuts and bypasses in the 300 mm SWFS. Results of simulation experiments demonstrated that, compared with RBD, HABOR and MinHAROD, MaxHAROD has high efficiency in OHT dispatching and is more stable in multiple different scenarios of the interbay AMHS even with different quantities of shortcuts.

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