A Novel Route Selection and Resource Allocation Approach to Improve the Efficiency of Manual Material Handling System in 200-mm Wafer Fabs for Industry 3.5

Chen-Fu Chien, *Member, IEEE*, Che-Wei Chou, and Hui-Chun Yu

***Abstract*—Motivated by realistic needs to enhance the productivity for 200-mm wafer fabs, this paper aims to propose a novel approach for manual material handling system (MMHS) to mimic functionalities of the automated material handling system in the advanced fabs without intensive capital investment to deliver the wafer lots manually and systematically. In particular, a mathematical model is developed to optimize the routing plan with two objectives that minimize the total traveling distance in all routes or minimize the number of manpower needed in all routes. Furthermore, a route planning approach is proposed to utilize the routes that reduce the technician traveling distance and transportation time for implementation. Also, a manpower loading index was developed for evaluating the number of needed technicians in the proposed MMHS. To estimate the validity of the proposed MMHS, we developed a simulation environment based on empirical data with different transportation requirement scenarios for comparison. The results have shown practical viability of the proposed approach.**

***Note to Practitioners*—As advanced manufacturing strategies such as Industry 4.0 are proposed for smart production, 200-mm wafer fabs cannot be equipped with fully automation facilities such as the automated material handling system to enhance overall productivity. To address the needs in real settings, a disruptive innovation manual material handling system was developed, on the basis of existing 200-mm fab facility, to organize the technicians to mimic the setting of a virtual material handling system manually to enhance productivity. Indeed, the developed solution has been implemented in this case company, in which the results have validated the proposed approach that can be a hybrid between the existing Industry 3.0 and to-be Industry 4.0.**

***Index Terms*—Fab economics, Industry 3.5, manpower allocation, manual material handling system (MMHS), productivity, route planning.**

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The authors are with the NTHU-TSMC Center for Manufacturing Excellence, Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 30013, Taiwan (e-mail: cfchien@mx.nthu.edu.tw).

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I. Introduction

SEMICONDUCTOR fabrication facilities (fabs) are the most capital-intensive and complex manufacturing plants that consists of lengthy re-entrant processes including cleaning, oxidation, deposition, metallization, lithography, etching, ion implantation, photoresist strip, inspection, and measurement [1]. The wafers pass through approximately several hundred processing steps for wafer fabrication, in which operational efficiency and productivity enhancement via maximizing the throughput and yield, while minimizing cycle time, are critical for maintaining competitive advantages [2], [3].

Automation in modern fabs enables efficient material handling between resources to reduce cycle time and manufacturing cost [4]. In particular, the advanced 300-mm fabs rely on automated material handling system (AMHS) to manage the wafer transportation in fabs [5], [6]. Furthermore, Germany has proposed a manufacturing strategy, Industry 4.0 [7], for smart factory via cyber-physical systems and decentralized decisions within a smart and networked platform. However, most existing 200-mm fabs that find it difficult or cost effective to install AMHS employ technicians maneuvering the trolleys for moving the wafer lots [8].

Motivated by realistic needs to empower 200-mm wafer fabs, this paper aims to propose a disruptive innovation via manual material handling system (MMHS) that mimics the AMHS functionalities by technicians and reduces the trolley accidents effectively. However, since the technicians may decide by themselves the wafer lots and the corresponding transportation route, some lots may be delayed causing cycle time increase, while serious trolley accidents happen causing injuries and yield loss. It is important to determine the standard operating procedures and manage the transportation routes for the technicians to avoid these issues. In particular, a mathematical model is developed to optimize the routing plan with two objectives that minimize the total traveling distance in all routes or minimize the number of manpower needed in all routes. Furthermore, a route planning approach is also proposed to utilize the routes that reduce the technician traveling distance and transportation time in a short time for implementation. Also, a manpower loading evaluation model is developed for determining the appropriate number of technicians for the MMHS. In order to estimate the validity of the proposed MMHS approach, a simulation model was developed based on empirical data collected in the largest 200-mm fab in a leading semiconductor manufacturing company in Taiwan for comparison under different scenarios. The results have shown practical viability of the proposed approach. Indeed, the proposed MMHS has been employed in the case study. Indeed, the proposed approach can be Industry 3.5, namely, a hybrid approach between the existing Industry 3.0 and the to-be Industry 4.0 platform.

The remainder of this paper is organized as follows. Section II reviews related approaches for material handling for semiconductor manufacturing. Section III describes the proposed approaches for route planning and manpower evaluation. Section IV estimates the validity of the proposed approach with simulation and scenario analyses. Section V discusses the implementation of this approach. Section VI concludes this paper with a discussion of contributions and future research directions.

II. Literature Review

The wafers pass through hundreds of production steps of reentrant processing flows in the fab, in which material handling of the wafers is critical to enhance productivity. Thus, AMHS is effectively employed in advanced fabs to enable efficient delivery of the wafer lots [5], [6]. In particular, the facility design and material handling system design are two major designs that will influence the fab productivity [5]. Many studies have addressed the design of the AMHS. For example, Peters and Yang [9] proposed a network flow formulation to integrate the layout and material handling system design for both spine and perimeter layout configurations. Moreover, Ting and Tanchoco [10] proposed two rectilinear layout configurations, the unidirectional loop and bidirectional loop layout, which connected the tools to stockers to minimize the total loaded travel distances in fabs.

Indeed, the spine unidirectional configuration has no intersection and the involved traffic management, vehicle routing, and dispatching decisions are simple [11]. Therefore, the spine configuration is a general layout of the AMHS with a loop in one direction.

Similar to a general tandem configuration, segmented flow configuration design consists of one or more mutual zones that are nonoverlapping segments with a single vehicle serving each segment [12]. Indeed, the segmented flow configuration design has higher efficiency than conventional systems by eliminating the congestion and blocking of vehicles [13]. However, the segmented flow configuration design requires additional transfer stations [14]. Hsieh *et al.* [15] proposed a segmented configuration design for AMHS which used a dual-track bidirectional loop design to eliminate congestion and blocking to reduce the cycle time and increase stocker utilization.

Yu and Egbelu [16] developed a partitioning algorithm that grouped the workstations into a number of single-vehicle zones based on variable path routing for nonoverlapping tandem configuration while minimizing the number of vehicles and satisfying the total workload. In addition, meta-heuristic approaches were employed to deal with the partitioning problem of the tandem configuration design [17], [18]. Aarab *et al.* [19] developed a hierarchical classification approach to group the workstations based on a similarity coefficient considering the flows and the distances between workstations.

Vehicle fleet sizing problem for determining the number of vehicles is critical for achieving the performance and minimizing the vehicle cost for AMHS. A number of studies have developed mathematical programming models [20]–[22], queuing models [23]–[25], or simulation models [26]–[28] to solve the vehicle fleet sizing problem. Furthermore, multiload vehicles were proposed to picks up additional wafer lots while transferring a previously assigned load, indicating better performance than single-load vehicles via simulation [29], [30]. Hung and Liu [31] modified previous single-load vehicle studies and proposed a model to estimate the number of multiload vehicles needed to improve the system performance. However, a complicated material handling control system is required to employ multiload vehicles [14].

The material handling control systems [12], [14] were developed to fulfill transportation demands and avoid traffic conflicts among the vehicles with the following functions:

1) vehicle dispatching rule to select a vehicle to execute a transportation demand;
2) vehicle scheduling to dispatch the vehicles for transportation demands under certain constraints such as capacity and priority;
3) vehicle routing to find a suitable path for a pickup or delivery of a dispatched wafer lot.

It is difficult to schedule the vehicles over a long horizon in a fab with high arraival stochasticity. In order to quickly respond to transporation requests, heuristic dispatching rules are employed to reduce cycle time, wafer waiting time, and delivery time, as well as to improve throughput, vechicle utilization, and machine utilization [32], [33]. A number of studies have been done to address route planning that decides the route for a vehicle to picks up the working pieces and the visiting sequence with the most efficient resource utilization and the minimum traveling distance and cost [34]–[36].

In conventional unidirectional (CU) route planning, Sinriech and Tanchoco [37] proposed the optimal single-loop route planning based on integer programming in an automated guided vehicle system. While the vehicles ran with the same direction path and uniform speed, the material handling system would not congest with the optimal single-loop route. However, the automated guided vehicle system may not be suitable for a large-scale material handling system with great number of vehicles and stations [34]. Asef-Vaziri *et al.* [38] developed an optimal unidirectional loop route to serve manufacturing cells in an automated guided vehicle system, in which the vehicle transported working piece following the assigned loop route including corresponding pickup and delivery stations.

In AMHS, the material flow is influenced by routing strategies such as static routing [39] and dynamic routing [40], [41]. In particular, Kim *et al.* [39] proposed a simple blocking prevention method for a path-based AMHS based on swapping the load assignments between retrieval vehicles on the same path. The simulation showed that their approach could improve productivity under various vehicle dispatching rules.

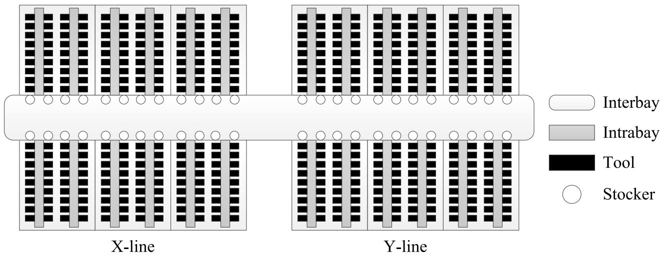

Fig. 1. Illustration of MMHS configuration in a 200-mm fab.

Bartlett *et al.* [40] proposed a congestion-aware dynamic routing approach to efficiently reroute vehicles as congestion status changes such as vehicle breakdowns and thus reduced the frequency of heavy congestion. Lau and Woo [41] developed an agent-based dynamic routing strategy for a loop-based network including the generation of feasible routes, reconfiguration of system parameters, and management of fault situations that can generate good routes in terms of cycle time, utilization, and ability to balance network loading.

However, the present problem addressed material handling in 200-mm fabs that cannot install the AMHS and in which the technicians maneuver the trolleys to carry the wafer lots dynamically. There is a need to determine manpower allocation and route planning. For example, Faaland and Schmitt [42] developed a cost-based heuristic to determine the manpower and machines needed in the assembly workshop. Süer *et al.* [43] focused on the cell loading and product sequencing problems and proposed a three-phase methodology to allocate manpower to the operation cells. Guyon *et al.* [44] proposed an approach to simultaneously assign a work pattern to each operator and form a feasible schedule to solve the employee scheduling and production scheduling problems. Chien *et al.* [45] employed genetic algorithm and response surface methodology to determine the operator–machine assignment under different product mix to minimize machine interference time and labor cost in the IC final testing facility.

Indeed, there is no study to address related issues for the MMHS problem for 200-mm wafer fabs in real settings. Therefore, a mathematical model and an analytical model were developed in this paper to address the routing plan and manpower evaluation.

III. Methodology

A. Problem Description

Focusing on real needs in the largest 200-mm fab in a leading semiconductor company in Taiwan that consists of two production lines equipped with tools in six production bays: diffusion (DIF), chemical vapor deposition, physical vapor deposition, etching (ETH), photo lithography (PHO), and ion implant (IMP). The proposed MMHS has a loop layout that connects twin fab tools with a length of more than 200 m as shown in Fig. 1. Although the X-line and Y-line can be treated as independent production lines, they can back up each other to enhance overall productivity. Therefore, it is inevitable to have cross-line transportation of the wafer lots.

TABLE I

From–To Flow Table

from \ to	1	2	3	4
1	-	f_{12}	f_{13}	f_{13}
2	f_{21}	-	f_{23}	f_{24}
3	f_{31}	f_{32}	-	f_{32}
4	f_{41}	f_{42}	f_{43}	-

The wafer material handling system is a single-loop interbay design to deliver the wafer lots manually by technicians. A number of stockers are located among the production bays to store temporary wafer lots before they are transported. A stocker has 32 temporary racks to store the output wafers from tools and the input wafers waiting for next processing tool. The wafer lot was first placed onto a stocker by technician. Each stocker is regarded as an entry (or exit) point to (from) an intrabay.

The trolleys used in the MMHS are multiload trolleys that can store up to 12 wafer lots. According to the priority information provided by the manufacturing execution system (MES), the technicians load the wafer lots from the beginning stockers to the terminal stockers in the unidirectional loop configuration following the interbay design of the AMHS. Then, another technician in charge of the corresponding production bay will move the wafer lots from stockers to the tools within the production bay following the intrabay design of the AMHS.

The from–to flow table was employed to denote the wafer lot that moved among stockers. f_{ij} denotes the number of wafer lots that are expected in the planning period to be moved from stocker i to stocker j, where $i \neq j$. An example of four stockers in the material handling system is illustrated. Given the number of technicians, Table I extracts the from–to flows indicating the relationships among stockers, which illustrates the demands via CU transportation.

The efficiency of the MMHS is difficult to evaluate through the number of technicians and from–to flow table. Therefore, when the technicians cannot fulfill the transport demand, the conventional approach will add technicians to resolve the shortage problem, yet will increase the manpower cost.

It is difficult to control and manage the MMHS system. Since there are many stockers, numerous multiload trolleys, and cross-line transportation in the 200-mm fab, the route planning is complicated. The transportation control system of MMHS is not similar to AMHS which could receive all the transportation requests and assign vehicles immediately by the computational control system. In addition, the technicians are not automatic vehicles. They could not execute the complicated routing plan accurately. The technician tends to have his or her discretion for transporting the wafer lots and thus may cause traffic accidents and wafer damages. Hence, it is very important to develop a simple and highly efficient routing plan to meet the transportation request in MMHS.

This paper focused on the interbay design of the MMHS to assign the route and allocate the corresponding stockers to the technicians to improve the efficiency and reduce the average transportation time of the MMHS. Based on domain knowledge, three indices including efficiency (E), minimal number of manpower needed (G), and average transportation time *(TT)* were used to evaluate the MMHS performance and thus derive the optimal solution. In particular, the efficiency is calculated by dividing the total transportation demand (F) by the total traveling distance (D) in the planning period as follows:

$$E = \frac{F}{D} \tag{1}$$

where F denotes the total transportation demand, which is the sum of all wafer lots from stocker i to stocker j, i.e., $F = \sum_i \sum_j f_{ij}$. D indicates the total traveling distance, which is the sum of all trolley's traveling distance, i.e., $D = \sum_g d_g$, where d_g represents the traveling distance by technician (g). That is, the more wafer lots are transported per distance, the more efficient the MMHS is.

The manpower needed is the minimal technicians required to fulfill transportation demand while keeping the MMHS uncongested. The average transportation time is the sum of the average waiting time on the stocker *(ws)* and the average transportation time on the trolley *(wt)*. The waiting time begins from the wafer lot put on stocker until the wafer lots are loaded onto the transportation trolleys. The transportation time on the trolley is from the time the wafer lots are loaded onto the trolleys to the time they arrive at the terminal stocker. The transportation time is regarded as the service level of the MMHS.

B. Mathematical Model

Before further discussion, the notations used below are summarized as follows.

Indices:

i, j, p, q	Index of stockers, $i, j, p, q = 1, 2, \ldots, N$.
s	Index of beginning stockers, $s = 1, 2, \ldots, N$.
r	Index of routes, $r = 1, 2, \ldots, R$.

Parameters:

f_{ij}	Number of wafer lots expected to be moved from stocker i to stocker j in the planning period, where $i \neq j$.
λ_r	Trolley's traveling frequency in route r in the planning period.
v_{ijr}	Wafer transported from stocker i to stocker j in route r.
t_{si}	Transportation time from beginning stocker s to stocker i.
d_{si}	Distance between stocker s and stocker i.
v	Transportation velocity of a trolley.
L_{ir}	Number of wafer lots on a trolley while it stops at an intermediate stocker i in route r.
A_r	Total trip time of trolley in route r.
tl	Loading time from beginning stocker to trolley.
tu	Unloading time from trolley to destination stocker.
LD_r	Total wafer loading time by technician in route r.
ULD_r	Total wafer unloading time by technician in route r.
OT	Operation time for transportation technician.
d_r	Total trip distance of all trolleys based on route r.
c	Trolley capacity.
M	Large positive number.

Decision Variables:

g_r Number of trolleys needed in route r.

$$x_{ir} = \begin{cases} 1, & \text{if trolley picks up wafer from stocker } i \text{ in route } r \\ 0, & \text{otherwise} \end{cases}$$

$$x_{sr} = \begin{cases} 1, & \text{if trolley stops at stocker } s \text{ in route } r \\ 0, & \text{otherwise.} \end{cases}$$

The mathematical programming formulation of the MMHS routing problem is described as follows:

Objective function

$$\text{Min} \sum_{r=1}^{R} d_r \tag{2}$$

or

$$\text{Min} \sum_{r=1}^{R} g_r \tag{3}$$

subject to

$$d_r \geq 2d_{si}\lambda_r - M(1 - x_{ir}) \quad \forall r, s, i = s+1, \ldots, N \tag{4}$$

$$L_{ir} \geq \sum_{p=s}^{i-1} \sum_{q=i+1}^{N} v_{pqr} + \sum_{q=i+1}^{N} \sum_{p=s}^{i-1} v_{qpr} - M(1 - x_{ir}) \quad \forall r, s, i = s+1, \ldots, N-1 \tag{5}$$

$$\sum_{r=1}^{R} v_{ijr} = f_{ij} \quad \forall i, j \tag{6}$$

$$\sum_{i=s+1}^{N} x_{ir} \leq (N - s)x_{sr} \quad \forall r, s \tag{7}$$

$$\lambda_r \leq M x_{sr} \quad \forall r, s \tag{8}$$

$$\sum_{j=1}^{N} v_{ijr} + \sum_{j=1}^{N} v_{jir} \leq M x_{ir} \quad \forall r, s \tag{9}$$

$$\sum_{p=s}^{j-1} \sum_{q=j}^{N} v_{pqr} \leq c\lambda_r \quad \forall r, s, j = s+1, \ldots, N \tag{10}$$

$$\sum_{p=s}^{j-1} \sum_{q=j}^{N} v_{qpr} \leq c\lambda_r \quad \forall r, s, j = s+1, \ldots, N \tag{11}$$

$$A_r \geq 2\lambda_r \max_i \{t_{si} x_{ir}\} - M(1 - x_{ir}) \quad \forall r, s, i = s+1, \ldots, N \tag{12}$$

$$\mathrm{LD}_r = tl \sum_{i=1}^{N} \sum_{j=1}^{N} v_{ijr} \quad \forall r \tag{13}$$

$$\mathrm{ULD}_r = tu \sum_{i=1}^{N} \sum_{j=1}^{N} v_{ijr} \quad \forall r \tag{14}$$

$$g_r \geq (A_r + \mathrm{LD}_r + \mathrm{ULD}_r)/\mathrm{OT} \quad \forall r \tag{15}$$

$$x_{ir} \in \{0, 1\} \quad \forall i, r \tag{16}$$

$$x_{sr} \in \{0, 1\} \quad \forall s, r \tag{17}$$

$$g_r \geq 0, \quad \text{and integer } \forall r \tag{18}$$

$$\lambda_r \geq 0, \quad \text{and integer } \forall r \tag{19}$$

where

$$E = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} f_{ij}}{\sum_{r=1}^{R} d_r} \tag{20}$$

$$G = \sum_{r=1}^{R} g_r. \tag{21}$$

Objective function (2) is used to minimize the total traveling distance in all routes. Alternatively, objective function (3) arms to minimize the number of manpower needed in all routes. Constraint (4) specifies the total trip distance d_r based on route r. d_r is obtained by multiplying two (for round trip), the distance between the beginning stocker s and the end stocker i of the route r, and its service frequency λ_r together. The large positive number M and the 0–1 variable x_{ir} in constraint (4) ensure that d_r is the maximum of the distance d_{si} between stocker s and all stockers i in the route r. If a route r is not formed, i.e., all $x_{ir} = 0$, the large positive number M will make $d_r = 0$. Constraint (5) defines L_{ir} that is determined by the wafer lots pickup at a previous stocker p and alight at a subsequent stocker q, i.e., L_{ir} is the total wafer lots (v_{pqr} and v_{qpr}) served by the round trip of the route r between stocker p and stocker q. Constraint (6) denotes the transportation demand f_{ij} between stockers i and j which must be fulfilled by all wafer lots v_{ijr} served by all routes. Constraints (7) and (8) obtain route r. All trolley trips based on route r start from a beginning stocker s, where $x_{sr} = 1$, i.e., the trolley stops at stocker s, and load and unload wafer lots. If $x_{sr} = 0$, route r cannot be formed while trolley does not stop at stocker s, i.e., all x_{ir} in constraint (7) and the trip frequency λ_r in constraint (8) are equal to zero. Constraint (9) ensures that no wafer lot can load or unload at stocker i, if route r does not stop at stocker i. Constraints (10) and (11) are capacity limitation constraints that denote total wafer lots served by a one-way trip of route r which must be accommodated by the trolley capacity of the corresponding trips. Constraint (12) defines the total trip time of trolley A_r in route r which is restricted by multiplying its traveling frequency λ_r and its running time of round trip between the beginning stocker s and ending stocker i ($\max_i\{t_{si}x_{ir}\}$), i.e., considering the running time by maximal distance of a round trip. Constraints (13) and (14) denote the total wafer loading and unloading time by technician in route r. Constraint (15) determines the minimum number of trolley needed, g_r, in route r. For each route r, the number of trolley required is the sum of total trolley traveling time, loading time, and unloading time, divided by operation time of transportation technician. Constraints (16) and (17) define the binary variables of decision variables x_{ir} and x_{sr}. Constraint (18) obtains decision variable g_r as a nonnegative real number. Constraint (19) denotes the trolley's traveling frequency λ_r as a nonnegative real number. Constraint (20) obtains the efficiency of a MMHS system which is calculated by dividing the total transportation demand by the total traveling distance. Constraint (21) indicates the minimal manpower needed which is the sum of number of trolleys that maneuvered by technicians in route r.

TABLE II

FROM–TO FLOW TABLE OF THE SMALL-SCALE NUMERICAL EXAMPLE

from \ to	1	2	3	4	5	6
1	-	0	59	0	7	119
2	0	-	2	0	0	1
3	68	161	-	14	4	39
4	0	0	72	-	12	28
5	4	7	3	2	-	5
6	2	7	1	5	3	-

TABLE III

DISTANCE BETWEEN EACH STOCKER OF THE SMALL-SCALE NUMERICAL EXAMPLE

from \ to	1	2	3	4	5	6
1	-	4.8	13.8	17.4	27	31.8
2	4.8	-	9	12.6	22.2	27
3	13.8	9	-	3.6	13.2	18
4	17.4	12.6	3.6	-	9.6	14.4
5	27	22.2	13.2	9.6	-	4.8
6	31.8	27	18	14.4	4.8	-

TABLE IV

RESULT OF THE SMALL-SCALE NUMERICAL EXAMPLE

Route	Minimize total distance			Minimize total manpower		
	Route plan	λ_r	g_r	Route plan	λ_r	g_r
1st	1-2-3-4-5-6	18	1	1-2-3-4-5-6	21	1
2nd	2-3	3	1			
$\sum_{r=1}^{R} d_r$	1306.8			1335.6		
E	0.478			0.468		
G	2			1		

To validate the mathematical model, a small-scale numerical example was demonstrated. In this case, there are six stockers in the MMHS. The transportation demand of MMHS is shown in Table II, and the distance between each stocker is listed in Table III. The transportation velocity of a trolley (v) was set at 0.56 m/s. The operational time for loading (tl) and unloading (tu) of wafer lots from stockers was set as 10 s. The capacity limitation of trolley is 12 wafer lots. In this paper, the small-scale test problem was solved through the mathematical model by using LINGO software.

First, we considered objective function (2) to minimize the total traveling distance in all routes that were subject to constraints (4)–(21). Then, LINGO was used to generate the optimal solution to the mathematical model. Second, we alternatively considered objective function (3) to minimize the manpower needed in all routes that were also subject to constraints (4)–(21). Table IV illustrates an optimal route plan that includes the manpower needed, total traveling distance, and the efficiency of the MMHS system.

In Table IV, there are two routes allocated to two technicians for minimizing total traveling distance, 1306.8 m, in objective function (2). One technician transported wafer lots in round trip with first route (1-2-3-4-5-6) that stops at each stocker. The other technician transported wafer lots only between stocker #2 and stocker #3 with the second route (2-3). Alternatively, one route was allocated to one technician for minimizing total manpower in objective function (3). The technician was assigned to the route (1-2-3-4-5-6) to transport wafer lots with total traveling distance in MMHS. In conclusion, the optimal route plan was determined by the objective function. The proposed mathematical model can address the present MMHS problem.

However, the proposed mathematical model may not be able to generate the optimal route plan in real settings because of computational limitations. Indeed, the MMHS problem in 200-mm fab is a complex and large-scale problem. It takes much computational time to solve the mathematical model in MMHS. It is not efficient in semiconductor manufacturing environment. Furthermore, the mathematical model that is formulated with different objectives could solve the MMHS problem to minimize the total traveling distance in all routes or minimize the manpower needed in all routes. However, it is crucial to simultaneously consider multiple and conflicting objectives to optimize the route plan and manpower allocation in real MMHS settings. Therefore, this paper proposed an analytical model to solve the MMHS problem in real setting.

C. Proposed Analytical Model

This paper proposes a route planning approach to determine the routes and to allocate the corresponding number of technicians simultaneously. Two types of transportation flows are considered: forward transportation (FWDT) and backward transportation (BWDT). A technician starts the FWDT by moving forward in a loop configuration to transport the wafer lots from the left-side stocker to the right-side stocker. When a technician reaches the end of the lane, he or she starts the BWDT that rolls over to deliver the wafer lots from the right-side stocker to the left-side stocker. The BWDT needs to confirm all the transportation demands to be fulfilled, while the demands arise from left-side stockers to right-side stockers.

The path flow (p_{ij}) is the total number of wafer lots that pass along the corridor between stocker i and the next stocker j in the planning period, that is

$$p_{ij} = \sum_{p \le i} \sum_{q \ge j} f_{pq} \quad \forall i, j, p, q = 1, 2, \ldots, N;\ i \ne j \tag{22}$$

where f_{pq} is the wafer lots needed to be transported from stocker p to stocker q, and N denotes the total number of stockers. While f_{pq} is given in this paper, the path flow is not only a metric to measure the congestion of the MMHS, but is also regarded as a consequence of routing decision.

Fig. 2 shows an example of path flows. A technician carries wafer lots from stocker 1 which consists of different destination stockers. The path flow p_{12} is the accumulated number of wafer lots that transport from stocker 1 to stocker 2, which is equal to $f_{12} + f_{13} + f_{14}$ based on (22). When the technician passes through stocker 2, he or she unloads (f_{12}) and loads wafer lots ($f_{23} + f_{24}$) to next stocker. Then, the path flow p_{23} is $f_{13} + f_{14} + f_{23} + f_{24}$. Finally, before arriving at stocker 4, the path flow p_{34} is $f_{14} + f_{24} + f_{34}$, where the wafer lots are delivered to stocker 4.

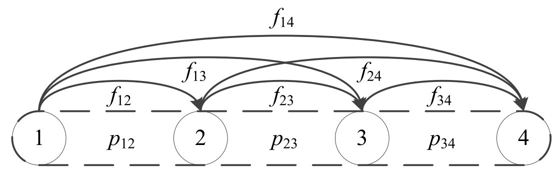

Fig. 2. Illustration of path flow.

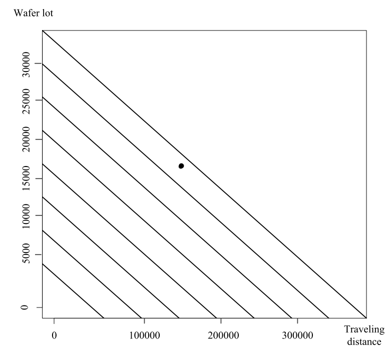

Fig. 3. Illustration of the manpower work loading of the MMHS.

This paper also evaluates the manpower workload for people productivity by considering two indices: the traveling distance and the number of wafer lots for transportation in the planning period. This evaluation assumes that each technician follows a repetitive working procedure of first loading the wafers from the stockers, then transporting the wafer lots by trolleys, and finally unloading the wafer lots to stockers. Fig. 3 illustrates manpower workload, where the x-axis represents the total traveling distance by all technicians and the y-axis stands for the total number of wafer lots the technicians transported. Each line represents the cumulative transportation capacity as each additional technician is added. The dot shows the workload of the technicians. When the dot is located on the diagonal line, denoting a specific number of technicians, they are all working at full capacity. The manpower workload is evaluated by the transported wafer lots and the corresponding traveling distance. The optimal number of needed technicians can thus be derived. As shown in Fig. 3, the minimal manpower needed to satisfy the transportation requirements is eight technicians in the MMHS.

Based on the transportation requirements from a given from–to flow table, the manpower can be determined for the MMHS. In addition, this paper develops a novel route planning (NRP) approach to design the routes to be assigned to each of the corresponding technicians that satisfied technician workload limitation with high transportation efficiency and good service without congestion.

Following the route planning in Fig. 4, the ranges of routes can be generated, in which the technicians have been assigned a distinct route that defined the corresponding beginning and ending stockers. While the route is assigned with a wide range,

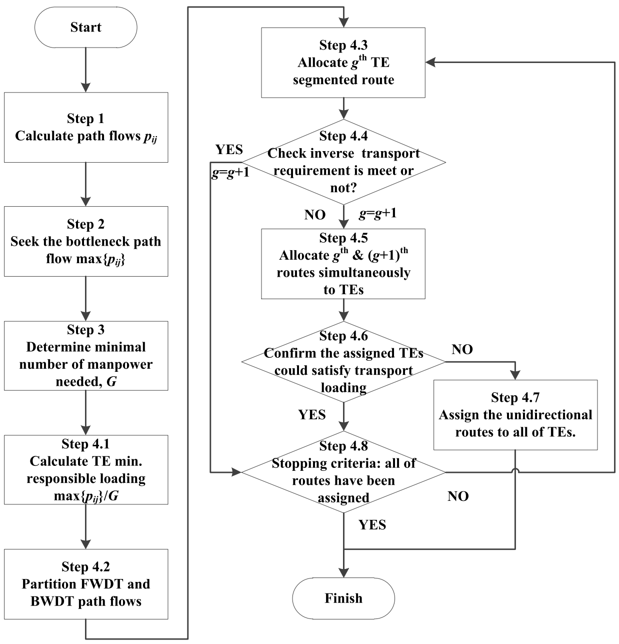

Fig. 4. Proposed route planning procedures.

the technicians can load and unload wafer lots from more stockers, which confirms that wafer lots could be delivered in a reasonable waiting time. On the other hand, the technicians that were assigned a route with a narrow range can move more wafer lots contributing to the increase in the frequency of round trip. That is, the technicians with a wide route could cover all stockers fulfilling transportation demand. The technicians with a narrow route can transport more lots to increase efficiency. Hence, the MMHS efficiency can be improved. The proposed route planning procedures are as follows.

Step 1) Calculate the path flow p_{ij} for stocker i and the next stocker j based on (22). According to the from–to table, the transportation flow can be specified for each demand. The overall transportation flow can be derived by computing the path flow of FWDT and BWDT. Note that p_{ij} can be converted into $p_{i,i+1}$ in FWDT and $p_{i,i-1}$ in BWDT.

Step 2) Identify the bottleneck path flow, $\max\{p_{ij}\}$, that contains the maximal accumulated wafer lots from stocker i to next stocker j. Indeed, stocker i is the earliest stocker to be blocked when using CU route planning in which technicians traverse from the first left-side stocker to the last right-side stocker.

Step 3) Determine the total number of technicians needed (G) using the manpower loading evaluation approach based on the from–to flow table without considering route planning, i.e., all technicians transport in the same unidirectional loop routes. First, calculate the minimal traveling frequency (λ) based on trolley capacity (c) considering the bottleneck path as follows:

$$\lambda = \left\lceil \max_{i,j}\{p_{ij}\}/c \right\rceil. \tag{23}$$

Note that the technician is at least loaded $\lambda - 1$ times with full loads plus one more load with (0, full] load, so that Stocker i will not be congested. Then, the total traveling distance (D) is determined by multiplying two (for round trip), the distance between the first stocker and the end stocker ($d_{1,N}$), and its minimal traveling frequency (λ) together as follows:

$$D = 2d_{1,N}\lambda. \tag{24}$$

Then, compute the total traveling distance and obtain all transportation flows from the from–to flow table to derive the total workload of the technicians in the MMHS. Finally, derive the total manpower workload and thus determine the minimal number of needed technicians based on their loading including traveling distance and transportation flows. In addition, the slope that formed by the dot and the origin in Fig. 3 is derived by total taking wafer lots ($\sum_i \sum_j f_{ij}$) divided by total traveling distance (D). The slope denotes the efficiency which measures the transportation efficiency, i.e., an assigned flow route, where the shorter the traveling distance is, the more the efficiency is.

Furthermore, the following procedures are employed to assign the route to the technician, respectively.

Step 4.1) Calculate the minimal responsible loading for each technician, i.e., $\max\{p_{ij}\}/G$. That is, each technician needs to transport at least $\max\{p_{ij}\}/G$ wafer lots from stocker i; otherwise, stocker i will be blocked and congested.

Step 4.2) Path flows of both FWDT and BWDT are partitioned by dividing with the minimal responsible loading. After splitting the path flows of the stockers, the overall traffic flow in the MMHS can be estimated, in which the minimal required wafer lots for the stockers to be transported are managed to avoid congestion.

Step 4.3) Determine the route for each technician based on the corresponding transportation flow of technician g, $(G - g/G) \cdot \max\{p_{ij}\}$. In FWDT, the route of technician g starts at stocker i, where the path flow is greater than $(G - g/G) \cdot \max\{p_{ij}\}$, and ends at stocker N of the loop configuration. Thus, the initial stocker and the end stocker for FWDT and BWDT are derived as follows:

$$\text{FWDT}: \left\{\min\left\{i \mid p_{ij} \geq \frac{G-g}{G} \cdot \max\{p_{ij}\}\right\}, N\right\} \tag{25}$$

$$\text{BWDT}: \left\{\max\left\{i \mid p_{ij} \geq \frac{G-g}{G} \cdot \max\{p_{ij}\}\right\}, 1\right\}. \tag{26}$$

Note that the gth technician was assigned to be in charge of the boundary stocker at the end of the configuration. It is designed to let the technician load as many wafer lots as possible, while the trolley still has empty space in one trip. Hence, the gth technician can improve utilization and share the transportation loading of other $(G - g)$ technicians.

Step 4.4) Ensure $(G - g)$ technicians can handle the transportation flows of inverse transportation, i.e., when the first assigned is FWDT, the inverse transportation is BWDT. While the gth technician has been assigned a route, his traveling distance can be reduced by reducing the transportation scope. Thus, the other $(G - g)$ technicians need to transport the wafer lots in the inverse transportation that the gth technician has not covered. Go to Step 4.8 and check the other technicians that have been assigned routes; otherwise, continue to Step 4.5 to assign the next route allocation for the $(g + 1)$th technician.

Step 4.5) Assign the gth and $(g + 1)$th technicians to take charge of the routes according to (25) and (26), respectively, where $g = g+1$. If the gth technician cannot fulfill the transportation demands with the corresponding gth route in both FWDT and BWDT flows, the inverse transportation will be congested while using the gth route and the other unassigned routes. Thus, we need to assign both the gth and $(g + 1)$th technicians to satisfy the transportation requirements.

Step 4.6) Confirm that the assigned gth technician, the $(g+1)$th technician, and the other unassigned technicians can satisfy the transportation requirements. If not, go to Step 4.7. Otherwise, go to Step 4.8. As the gth and $(g + 1)$th technicians are assigned to the corresponding routes in Step 4.5, confirm that the gth technician can back up transportation requirements for the $(g+1)$th technician who is in charge of the inverse transportation, respectively. That is, the gth technician should be able to carry out twice the required transportation in the range of his corresponding route that substitutes the $(g+1)$th transportation flow. Also, the inverse transportation should be checked at the same time. The gth route and $(g + 1)$th route are determined to ensure that the transportation system will not be congested, since the gth and $(g + 1)$th technicians may share the loading of other technicians. Therefore, the other technicians who were not given assigned routes can still transport the wafer lots in the same unidirectional route.

Step 4.7) If the assigned technicians, gth and $(g + 1)$th, cannot satisfy the transportation requirements, the transportation system will be congested. Therefore, the unassigned technicians are all allocated to unidirectional routes to transport the wafer lots.

Step 4.8) Stop the route planning, if all routes have been assigned. Otherwise, return to Step 4.3.

IV. Simulation and Results

Given the complex and lengthy processing steps in the fabs, simulation has been widely used for analyzing the AMHS for semiconductor manufacturing [27], [46], [47]. A simulation model of the proposed MMHS was developed with eM-Plant based on empirical data collected in a 200-mm twin fab in a leading semiconductor manufacturing company in Taiwan to test the feasibility and estimate the validity of the proposed approach under different transportation requirement scenarios. The tradeoff among the performance indices are also illustrated in scenario analyses.

A. Simulation Assumptions

The proposed MMHS was employed for the largest 200-mm twin fab with two production lines in this empirical study. The material handling system consisted of 42 stockers, and the transportation requirements were obtained from real settings. For confidentiality issues, the data and transportation flow of the MMHS were transformed without loss of generality for validation. The settings are designed as follows.

1) The transportation velocity of a trolley (v) was set at 0.56 m/s.
2) The operational time for loading (tl) and unloading (tu) of wafer lots from stockers was set at 10 s.
3) The wafer lot output time was exponentially distributed.
4) The capacity limitation of stocker was 32 wafer lots.
5) The capacity limitation of trolley $c = 12$ wafer lots.
6) The trolley dispatch rule of the MMHS was set as the first come first serve (FCFS).
7) The wafer lot dispatch rule of the MMHS was designed as a weighted priority index (WP_m) considering lot priority (LP_m), remaining queue time index (QI_m), waiting time on the stocker (WI_m), and transportation distance index (DI_m) of wafer lots, that is

$$WP_m = y_m(\alpha_1 LP_m + \alpha_2 QI_m + \alpha_3 WI_m + \alpha_4 DI_m) \tag{27}$$

where there are m wafer lots on the stocker, and α_1, α_2, α_3, and α_4 denote the weight parameters, $\alpha_1+\alpha_2+\alpha_3+\alpha_4 = 1$, that were determined by the preference of the domain expert. LP_m represents the production priority of wafer lot, scoring from 0 to 1, which is determined by the production planner. QI_m is determined by the remaining queue time (RQ_m) divided by its processing limited queue time (LQ_m), i.e., $QI_m = RQ_m/LQ_m$. WI_m is equal to the maximum waiting time of wafer lots on the stocker ($\max_m\{WT_m\}$) subtracted from its waiting time (WT_m) and divided by $\max_m\{WT_m\}$, i.e., $WI_m = (\max_m\{WT_m\} - WT_m/\max_m\{WT_m\})$. DI_m defines the transportation distance of the wafer lot (TD_m) divided by the maximum transportation distance of wafer lots on the stocker, i.e., $DI_m = TD_m/\max_m\{TD_m\}$. y_m is the Boolean binary that controls the priority index. If the queue time (QT_m) of the wafer lot longer than its processing limited queue time, $y_m = 0$; otherwise, $y_m = 1$.

While the trolley stopped at a stocker, the technician checked the priority information of the wafer lot from the MES and then transports the wafer lots according to their priorities determined by the dispatch rule to satisfy multiple objectives. Note that the wafer lot with smaller priority index indicates higher priority. The technicians load and unload the wafer lots

TABLE V
SIMULATION SCENARIO

Scenario	Transportation Requirement
High utilization	22366
Medium utilization	18290
Low utilization	13111

from the stockers and use trolleys to move them in a clockwise direction.

The wafer lots whose processing from the tools in the production bay is completed will be moved to the preassigned stocker until they are ready to be transported by technicians for the next process. If the storage racks of the stockers are full, the stockers will not be available until technicians transport previously loaded wafer lots to their destination stockers. Meanwhile, the completed wafer lots will remain inside the tools if they cannot be moved to next location. The transportation will not be affected during the meal time in the simulation since other technicians can back up.

B. Experimental Design

To validate the proposed route planning approach, three scenarios of different utilization levels, i.e., high, medium, and low, were examined with historical data in 200-mm fab as shown in Table V. Six route planning approaches were employed to compare the performances of the proposed MMHS.

Hung and Liu [31] proposed an analytical model (AM) by modifying the vehicle fleet size estimation model [20] to estimate the multiload vehicle requirement in an automated guided vehicle system for minimizing empty vehicle travel time (see the Appendix). Thus, the AM approach can determine the manpower needed and assign the technician to transport wafer lots in the same direction in the 200-m fab.

The present approach (PS) assigns the technicians to transport wafer lots according to their corresponding production bay. For example, the technicians who are in charge of PHO production bay carry wafer lots from the stockers located in PHO production bay to its destination stockers (Fig. 1), i.e., the technician's route is assigned to only take the wafer lots from his or her corresponding production bay and transport them to the destination stocker in the loop configuration layout.

The CU approach computes the manpower needed by using the manpower loading evaluation approach which is proposed in this paper. However, the technician's route planning follows the CU path. i.e., CU approach assigns every technician to transport wafer lots in one direction in the loop configuration layout of the MMHS.

To comprehensively compare the route planning methods in this paper, we also ran Dijkstra's algorithm [48] which is used to solve the shortest path (SP) problem. We applied AM and CU approaches to determine the manpower needed and assigned the technicians to follow Dijkstra's algorithm for generating route plan that is named as AM-SP and CU-SP, respectively. When the technicians picks up wafer lots based on weighted priority index (WP_m), the system will calculate the shortest path by Dijkstra's algorithm. Then, the technician follows this request to move to the destination. In addition, while wafer lots are loaded and unloaded, the route plan will be updated depending on transported wafer lots that are loaded on a trolley.

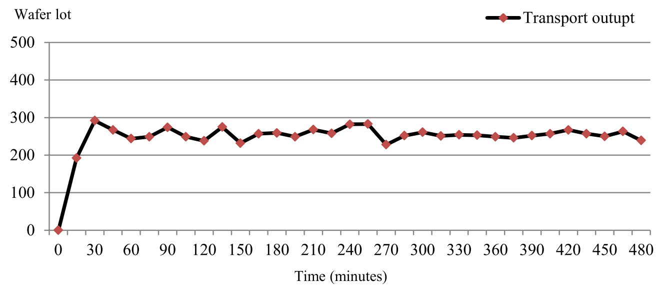

Fig. 5. Partial transport output of the MMHS.

The proposed NRP approach determines the needed manpower and allocates technicians who follow routes to transport wafer lots. To reduce the randomness of the simulation model, we ran ten replications for each scenario. The pilot run was designed to reach a steady state. Therefore, only after a steady state was reached, the warm-up period could be determined. As shown in Fig. 5, a transient period was for 60 min and then the data collection began and lasted for 10 days.

C. Route Planning

To demonstrate the proposed route planning approach, the medium utilization scenario of the MMHS is used for the following Illustration.

First, in Step 1, the path flows based on the given from–to flow table were calculated for FWDT and BWDT, respectively. In Step 2, $\max\{p_{ij}\} = 4132$ was specified, which was between the 17th stocker and the 16th stocker in the BWDT mode.

In Step 3, the minimal traveling frequency, $\lambda = \lceil 4132/12 \rceil = 345$, was computed based on the bottleneck path flow and the trolley capacity. Also, the total traveling distance, $D = 2d_{1,N}\lambda = 161\,561$, was determined. Then, we evaluated manpower workload based on traveling distance and transporting wafer lots. Fig. 3 shows the transformed working hour into the number of loaded wafer lots and the distance moved, respectively. Thus, the minimal manpower needed for the MMHS was derived to be eight technicians.

Second, the routes were designed as follows. In Step 4.1, the calculated $\max\{p_{ij}\}/G$ was 517 wafer lots, which was equal to the minimal responsible loading. In Step 4.2, both FWDT and BWDT were partitioned by dividing the path flows from the minimal responsible loading of 517 wafer lots. In Step 4.3, we assigned the first technician with the first route $\{28,1\}$ traveling in the BWDT mode using (26). In Step 4.4, we checked whether seven technicians can meet the transportation requirements at inverse transportation, FWDT. However, FWDT still had to be done by eight technicians. Thus, we needed to simultaneously allocate the first and second technicians to take charge of the respective BWDT $\{28,1\}$ and FWDT routes $\{14,42\}$ in Step 4.5. As the first technician had transported the wafer lots between the 28th stocker and the first stocker, the second technician transported

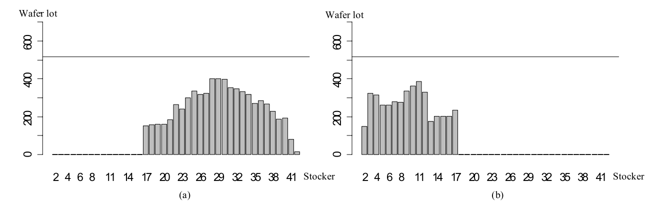

Fig. 6. Path flow chart of Step 4.6 for the medium utilization scenario.

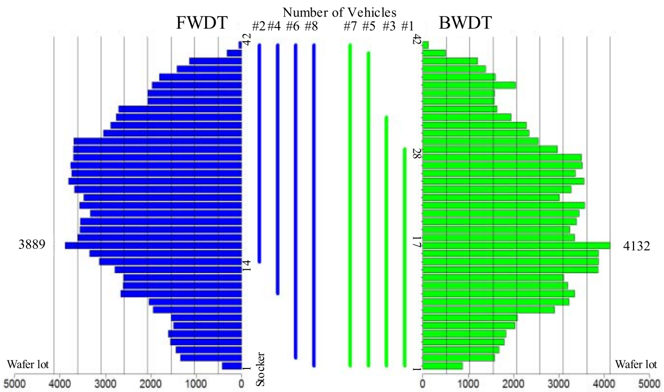

Fig. 7. Route planning result of medium utilization in the MMHS.

wafer lots between the 14th stocker and the 42nd stocker. To guarantee the assigned technicians fulfilling the minimal required wafer lots, we need to check, in Step 4.6, whether the assigned first and the second routes met the transportation requirements in the BWDT and FWDT modes simultaneously.

For the BWDT mode, seven technicians were needed to transport wafer lots in the range of $\{42, 28\}$, yet eight technicians were required to reach the bottleneck stocker of the range $\{17, 1\}$. However, the second technician had been assigned to be responsible for the range of $\{14, 42\}$ in the FWDT mode. Thus, it was necessary to confirm whether the first technician could transport two-eighths of the original transportation requirements in the bottleneck stocker of the range $\{17, 1\}$, and the other unassigned six technicians could deliver the remaining six-eighths of the transportation requirements in the BWDT mode. The path flows were recalculated based on the two-eighths transportation requirements of the from–to flow table in the range of $\{17, 1\}$. We found that the first technician could meet the transportation flow under his minimal responsible loading, i.e., 517 wafer lots. For the FWDT mode, the checking procedure is the same with different ranges, respectively. Fig. 6 shows the path flow chart of the two-eighths requirements. That is, it was confirmed that the assigned first and second routes could satisfy the transportation requirement in Step 4.6. The route planning procedures stopped after all of the technicians were assigned in Step 4.8.

That is, as shown in Fig. 7, the route planning of the eight routes in the MMHS is as follows: #1:$\{28, 1\}$, #2:$\{14, 42\}$, #3:$\{32, 1\}$, #4:$\{10, 42\}$, #5:$\{40, 1\}$, #6:$\{2, 42\}$, #7:$\{42, 1\}$, and #8:$\{1, 42\}$.

Thus, the range of the routes was narrowed down contributing to the increase in the frequency of round trip. The technicians moved the wafer lots on the stockers with higher transportation frequency in their corresponding routes. Consequently, the efficiency of the MMHS and the transportation time are improved with this proposed route planning approach.

TABLE VI
SIMULATION RESULTS OF THREE SCENARIOS

Scenario	Approach	G	E	TT (sec.)	$\sum_i \sum_j f_{ij}$	$\sum_g d_g$ (m)	ws (sec.)	wt (sec.)
High	AM	12	0.069	832	22576	327756	569	263
	AM-SP	12	0.063	1976	21541	339350	1723	254
	PS	12	0.080	740	22393	281427	505	235
	CU	10	0.096	1028	22396	233009	743	285
	CU-SP	10	0.085	2477	21033	248268	2200	277
	NRP	10	0.096	835	22389	233082	558	278
Medium	AM	10	0.067	832	18560	275963	590	242
	AM-SP	10	0.060	1974	17318	289883	1750	224
	PS	11	0.066	686	18337	278464	473	213
	CU	8	0.101	1045	18341	181656	779	266
	CU-SP	8	0.085	2713	16896	197840	2458	255
	NRP	8	0.101	827	18337	181692	569	258
Low	AM	8	0.056	817	13324	237847	583	234
	AM-SP	8	0.048	1990	12114	251397	1766	224
	PS	8	0.055	674	13153	239764	460	215
	CU	6	0.092	1034	13152	143001	769	265
	CU-SP	6	0.076	3206	11895	157075	2943	263
	NRP	6	0.092	845	13155	142973	587	258

D. Simulation Results

Six approaches were compared in the simulation model developed for the real setting MMHS problem under three scenarios. Table VI lists the comparison results with three measures, i.e., the efficiency (E), the manpower needed (G), and the average transportation time (TT), in which each result denotes the average of ten replications.

As shown in Table VI, the number of technicians determined by the proposed manpower loading approach was fewer than those derived from PS and AM approaches. Also, the results are all significantly different from the two approaches, PS and NRP, at the level $\alpha = 0.05$ in each scenario. Furthermore, the efficiency comparisons showed 20.7%, 53.3%, and 67.7% improvement rates for the high, medium, and low utilization scenarios, respectively, showing that the proposed NRP was more efficient than the PS approach.

In addition, the AM approach overestimates the manpower needed because of assuming that each time an empty trolley could load all wafer lots equal to its fully loading capacity with the same destination stocker. Alternatively, the technician may load wafer lots from different stockers and often have different destination stockers. In practice, the trolley may not be fully loaded during every trip because of the wafer lot output rate. Therefore, the AM approach has a long traveling distance that deteriorates the transportation efficiency.

Compared with the average transportation time, AM-SP and CU-SP have shorter transportation times on the trolley due to application of the shortest path for route plan. However, the traffic congestion happened in MMHS, which resulted in a long transportation time on the stocker. The wafer lots were queued on the stockers. The efficiency was worse than that obtained using other approaches. Indeed, AM-SP and CU-SP cannot fulfill the transportation demand of three scenarios even if the transport manpower is the same for AM and CU approaches, respectively.

Furthermore, the NRP approach had a shorter transportation time than the CU approach, implying that the waiting time on the stocker was reduced. Note that the NRP and CU approaches have used the same manpower loading evaluation approach except routing planning. The NRP approach considers the route planning that designed shorter empty trip for transportation of trolley, and thus the technician could visit the stockers and pick the corresponding wafer lots up as early as possible to reduce the wafer waiting time on stockers. Note that the transportation time of the PS was shorter than that of others. However, its efficiency was significantly worse than that of others at the level $\alpha = 0.05$.

Therefore, both the NRP and CU approaches were more efficient than the PS, AM, AM-SP, and CU-SP approaches. The NRP approach reduced the transportation time significantly compared with the CU approach. Indeed, the proposed NRP approach assigns the efficiency routes to the technicians reducing the transportation time with the best performance among other approaches.

V. DISCUSSION

The developed solution has been implemented in this case company. The results have shown practical viability of the proposed approach and performance indices to enhance the efficiency of the proposed MMHS and improve the overall fab productivity. In particular, each work shift can save two transport technicians in MMHS, i.e., 16% people productivity improvement, while the average transportation time is still keep at the same service level. Meanwhile, the efficiency is also improved by at least 20% subject to the transportation demands.

A number of studies have investigated the control strategies for AMHS. However, few studies have addressed similar control strategies for MMHS in real settings. While the proposed MMHS mimics AMHS, this paper developed effective approach and performance indices to determine the routes and allocate the corresponding manpower needed. The proposed approach provides an adaptive and flexible control policy for efficiently maintaining transportation performance of MMHS in the real setting of 200-mm fab.

While AMHS was constrained in 200-mm fabs due to fab configuration, the proposed approach provides an adaptive and flexible manpower allocation and route planning to empower the proposed MMHS. Table VII addresses the differences in features between AMHS and MMHS.

TABLE VII
COMPARISON OF AMHS AND MMHS

Features	AMHS	MMHS
Investment Cost	High [23]	Low
Guide-path Layout	Unidirectional, bidirectional loop configuration [9],[10],[15]	Unidirectional loop configuration
Number of Vehicle	Procurement when system is designed [12]	Dynamically adjust transportation technicians
Vehicle Capacity	Single-load (Typical) [22], [26]-[28]	Multi-load
Vehicle Dispatch Rule	Distance-based dispatch rules, time-based dispatch rules, and workload-based dispatch rules [14]	Time-based dispatch rule: FCFS
Route Planning	Static routing [39], and dynamic routing [40],[41]	Dynamic routing
Optimal Methodology	Mathematical optimization [36],[50], heuristic [39]-[41], and meta-heuristic [51]	Mathematical optimization and heuristic
Ergonomic Restrictions	No limitation [6],[52]	Yes, only in 200mm fabs
System Congestion (probability)	Low [14]	Low
Traffic Management System	Complicated [32],[33],[39], [40]	Adaptive, Flexible

An AMHS spends a significant share of a 300-mm fab investment cost, U.S. \$2–3 billion, as much as 3%–5% of the total fab cost [23], [49]. Alternatively, the proposed MMHS requires only labor cost for transportation and associated variable cost which are much lower than the capital investment of AMHS.

The AMHS should not be a bottleneck in wafer manufacturing fab, and thus AMHS design is critical for constraints and assumptions. The minimum number of vehicles has to be determined while AMHS is designed [12] considering different scenarios. However, a fab configuration, capacity portfolio, and product mix are often change as semiconductor manufacturing technologies migrate, causing difficult adjustments of the constructed AMHS. Alternatively, the proposed MMHS can adjust the needed manpower and the corresponding routing flexibly in light of the transportation demands considering production plan and product mix change.

The vehicle capacity is single load in AMHS [22]–[28]. However, the proposed MMHS employs multiload trolley to picks up additional lots while transferring a previously assigned wafer lot to improve system performance [29]–[31]. The AMHS in a 300-mm fab generally employs unidirectional loop configuration [9], while some AMHS studies [10], [15] designed bidirectional loop configuration to eliminate congestion and blocking.

Vehicle dispatch rules help AMHS and MMHS control vehicles when a vehicle picks up wafer lots, a vehicle reaches its destination stocker, and a vheicle unloads wafer lots. Depending on the objective of dispatch rules, three types of dispatch rules were addressed in AMHS [14].

1) Distance-based dispatch rules based on traveling distances or time, including shortest travel time first rule and nearest vehicle first rule.
2) Workload-based dispatch rules considered queue sizes of wafer lots in the stockers. There rules include maximum outgoing queue size rule and minimum remaining outgoing queue space rule.
3) Time-based dispatch rules depended on waiting time of wafer lots, such as the FCFS rule.

In MMHS, the time-based dispatch rule, FCFS, was applied. While a trolley stops at a stocker, the technician will follow a weighted priority index (WP_m) which determines the wafer lot priority to load. The technician usually takes several wafer lots onto the trolley due to multiload trolley design.

There are two types of routing strategies in AMHS such as static routing [39] and dynamic routing [40], [41]. The static route planning employs static strategies such as shortest distance, least utilization, random assignment, round robin, and CU algorithms for route planning. The dynamic route planning needs to change periodically to fulfill the transportation demands. The proposed MMHS has a central lane designed for multiload trolley transferring wafer lots in a 200-mm fab. The designed routing can be adjusted dynamically in light of new demands by using the proposed approach.

In general, the optimization methodologies of AMHS routing problem are classified into three catagories: mathematical optimization, heuristic, and meta-heuristic. Mathematical optimization approaches search optimal routing plan based on objective functions, such as transportation cost, vehicle cost, balancing of routes, and wait time [36], [50]. Heuristics are problem-specific approaches that take advantage of the problem properties to derive the routing plan [39], [40]. Meta-heuristics are general heuristic schemes that can be applied to many complicated and large-scale routing problems in AMHS [51]. In this paper, a mathematical model that is formulated with different objectives, minimizing the total traveling distance in all routes or minimizing the manpower needed in all routes, was addressed to solve the MMHS routing problem. However, this model cannot generate the optimal route plan because of computational limitations with real settings. And it is also crucial to simultaneously consider multiple and conflicting objectives to optimize the route plan and manpower allocation. Therefore, this paper also developed a novel heuristic approach to provide an efficient route planning.

AMHS traffic management is complicated due to large-scale stockers and vehicles used in fab [32], [33], [39], [40]. It is a very important task to prevent the traffic congestion and keep the wafer transportation efficient. In this paper, we provided an NRP approach to manage all trolley's routes with high efficiency. Besides, this routing plan is also adaptive and flexible, which was validated through a simulation model and really implemented on MMHS system in a 200-mm fab based on transportation request.

VI. Conclusion

To empower existing 200-mm fabs, this paper developed a novel MMHS approach as an illustration of Industry 3.5 as a hybrid strategy between the existing manufacturing for Industry 3.0 and to-be Industry 4.0. In particular, a mathematical model was constructed to address the MMHS routing problem that was formulated with two objectives to minimize the total traveling distance in all routes or minimize the manpower needed in all routes. Since it cannot generate the optimal route plan because of computational limitations in real settings, it is crucial to simultaneously consider multiple conflicting objectives to optimize the route plan and manpower allocation. This paper also developed a novel approach for route planning that considers the path flows of segmented configuration to obtain the route planning in light of transportation requirements and a data-driven from–to flow table and determines the manpower needed for the corresponding routes. Empirical data collected in the largest 200-mm fab of a leading semiconductor manufacturing company in Taiwan were used for validation. The results have shown that the proposed approach has fairly good performance than others under different transportation scenarios, showing practical viability of the developed solution. The proposed approach can dynamically adjust both the manpower needed and the routes in light of the change of production system to improve the efficiency and reduce the transportation time to enhance overall productivity of the fab. Indeed, the proposed approach has been implemented in this company.

Further research can be done to integrate the interbay and intrabay configurations of the MMHS while considering extra factors such as fab capacity, product mix, and various layout configurations. Furthermore, since most of the existing manufacturing facilities cannot easily adopt advanced manufacturing strategies such as Industry 4.0 platform, the proposed hybrid approach, i.e., Industry 3.5, should be extended to other industries that do not have fully automated systems for handling the materials to empower existing facilities to address the needs for smart production. Future research can be done to examine human–machine collaborations between humans, trolleys, and robotics with the information collected by multimode sensors and mobile devices in advanced manufacturing systems. In addition, AMs and big data analytics can be employed to structure the present problem to generate the optimal solutions, provide alternative estimates, and derive empirical rules to enhance the overall effectiveness of MMHS in real settings.

Appendix

The integer linear programming model [20], [31] for estimating the minimal number of multiload vehicles needed is as follows:

Objective function

$$\min T_e = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} x_{ij} \tag{A1}$$

subject to

$$\sum_{j=1}^{n} x_{ij} = \sum_{j=1}^{n} \lceil f_{ij}/c \rceil, \quad \forall i \tag{A2}$$

$$\sum_{j=1}^{n} x_{ji} = \sum_{j=1}^{n} \lceil f_{ij}/c \rceil, \quad \forall i \tag{A3}$$

$$x_{ii} \leq \left\lceil \left(\sum_{j=1}^{n} \lceil f_{ji}/c \rceil \right) \cdot \left(\sum_{j=1}^{n} \lceil f_{ji}/c \rceil \Big/ \sum_{k=1}^{n} \sum_{l=1}^{n} \lceil f_{kl}/c \rceil \right) \right\rceil, \ \forall i \tag{A4}$$

$$x_{ij} \geq 0, \quad \text{and integer } \forall i, j \tag{A5}$$

where

$$T_t = \sum_{i=1}^{n} \sum_{j=1}^{n} \lceil f_{ij}/c \rceil \, t_{ij} \tag{A6}$$

$$T_l = (tl + tu) \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \tag{A7}$$

$$G = \left\lceil \frac{T_t + T_l + T_e}{T_a} \right\rceil. \tag{A8}$$

Objective function (A1) aims to minimize the total empty travel time (T_e) that aggregates total empty trips from the ith stocker to the jth stocker (x_{ij}) multiplied by its traveling time (t_{ij}), where the vehicle can load with the maximal capacity (c). Constraint (A2) guarantees that the total number of empty trips departing from the ith stocker is equal to the number of multiload of wafer lots delivered there. Constraint (A3) denotes that the total number of empty trips terminating at the ith stocker is equal to the total number of multiload of wafer lots loaded from there. Constraint (A4) indicates that the number of empty trips depart from the ith stocker and stop there itself (x_{ii}). x_{ii} should not be more than the number of multiload of wafer lots delivered at the ith stocker multiplied by the fraction of multiload of wafer lots loaded from the same stocker. Therefore, at most x_{ii}-loaded trips ending at the ith stocker will again start as loaded from the same stocker. Constraint (A5) defines the positive integer variable of decision variable x_{ij}. Constraint (A6) denotes that the total vehicle traveling time (T_t) is equal to summation the traveling time of all loaded trips from the ith stocker to the jth stocker. Constraint (A7) represents the total loading and unloading time (T_l), i.e., the summation of accessing wafer lots loading time (tl) and unloading time (tu). Consequently, constraint (A8) derives the total vehicles needed (G) during the planning period, where T_a is the total vehicle effective time.

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Chen-Fu Chien (M'03) received the B.S. degree (Phi Tao Phi Hons.) in industrial engineering and electrical engineering from National Tsing Hua University (NTHU), Hsinchu, Taiwan in 1990, and the M.S. degree in industrial engineering and the Ph.D. degree in operations research and decision sciences from the University of Wisconsin–Madison, Madison, WI, USA, in 1994 and 1996, respectively.

He was a Fulbright Scholar with the University of California at Berkeley, Berkeley, CA, USA, from 2002 to 2003. He received the PCMPCL Training at the Harvard Business School, Boston, MA, USA, in 2007. From 2005 to 2008, he was on-leave as the Deputy Director of the Industrial Engineering Division at Taiwan Semiconductor Manufacturing Company (TSMC), Hsinchu. He is currently a Tsing Hua Chair Professor with NTHU. He is also the Director of the NTHU–TSMC Center for Manufacturing Excellence and the Principal Investigator for the Semiconductor Technologies Empowerment Partners (STEP) Consortium, Ministry of Science and Technology, Taiwan. He has received 20 invention patents on semiconductor manufacturing and published 4 books, more than 140 journal papers, and 12 case studies with the Harvard Business School. His current research interests include decision analysis, big data analytics, modeling and analysis for semiconductor manufacturing, manufacturing strategy, and manufacturing intelligence.

Dr. Chien received the National Quality Award, the Distinguished Research Awards and Tier 1 Principal Investigator (Top 3%) from NSC, the Distinguished University-Industry Collaborative Research Award from the Ministry of Education, the University Industrial Contribution Awards from the Ministry of Economic Affairs, the Distinguished University-Industry Collaborative Research Award, the Distinguished Young Faculty Research Award from NTHU, the Distinguished Young Industrial Engineer Award, the Best IE Paper Award, the IE Award from the Chinese Institute of Industrial Engineering, the Best Engineering Paper Award and Distinguished Engineering Professor by the Chinese Institute of Engineers in Taiwan, the 2011 Best Paper Award of the IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING, and the 2015 Best Paper Award of the IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING. He is an Area Editor of the *Flexible Services and Manufacturing Journal*, an Editorial Board Member of *Computers and Industrial Engineering*, an Associate Editor of the *Journal of Intelligent Manufacturing*, and an Advisory Board Member of *OR Spectrum*. He has been invited to give keynote speech in various conferences, including APIEMS, C&IE, IEEM, and IML, and leading universities worldwide.

Che-Wei Chou is currently pursuing the Ph.D. degree with the Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu, Taiwan.

He has published papers in the IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING and the *Journal of Management and System*. His current research interests include production planning and scheduling, modeling and analysis for manufacturing, intelligent manufacturing, and decision analysis.

Hui-Chun Yu received the Ph.D. degree in statistics from National Cheng Kung University, Tainan, Taiwan, in 2011.

He was a Research Fellow with the NTHU TSMC Center for Manufacturing Excellence, NTHU, Hsinchu, Taiwan. He is currently a Senior Data Scientist with TSMC, Hsinchu. He has published papers in the *International Journal of Computational Intelligence Systems* and the *Journal of Intelligent Manufacturing*. His current research interests include data mining, tool health, modeling and analysis for manufacturing, and intelligent manufacturing.