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ORIGINAL ARTICLE

The evaluation of search range assignment in 300 mm automated material handling system (AMHS)

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Abstract In the 300 mm AMHS with a connected loops layout, the vehicle can travel not just in one loop but all around the wide fab to execute tool-to-tool delivery. Determining how far the waiting FOUPs (*WFs*) or idle vehicles (*IVs*) should be considered before selecting a dispatching rule might make dispatching more efficient. A two-phase approach with simulation has been developed to assign the search range (SR) for studying this idea. The model of a simplified 300 mm AMHS was built using eM-Plant and Design Expert to design experiments and analyse the results. In phase I, the number of *WF* and *IV* in the system at the time of dispatching will affect the distance of the vehicle's empty trip (*DVemp*). Further, the SR was assigned and evaluated based on the average and standard deviation of *DVemp* under different numbers of *WF* and *IV* in phase II. The results indicated that the SR significantly affects the performance, and a longer SR used in a light system is feasible; a shorter SR is applicable for a heavy system.

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Abbreviations

AMHS	automated material handling system
OHT	overhead hoist transporter
OHS	overhead shutter
FOUP	front-opening unified pod
MES	manufacturing execution system
FEFS	dispatching rule based on foremost encounter first served
NV	dispatching rule based on the nearest vehicle
MR	moving rate
SR	search range
FSV	FOUP search vehicle
VSF	vehicle search FOUP
Dvemp	distance of vehicle's empty trip
WF	waiting FOUP
IV	idle vehicle
LSD	the least significant difference

1 Introduction

Increasing the size of wafer production from 200 to 300 mm introduces many new issues in transportation. Therefore an automated material handling system (AMHS) becomes a critical support for wafer fabrication. The two major sub-systems for the 300 mm AMHS are interbay and intrabays. Interbay is responsible for transporting the wafer between different bays and intrabays take charge within bay transportation. The current trend with the transport tracks of both systems is located overhead to attain zero footprints in transport and minimise the fab footprint. Generally, two kinds of track system are designed in interbay. These are tracks for vehicle overhead shutter (OHS) and for vehicle

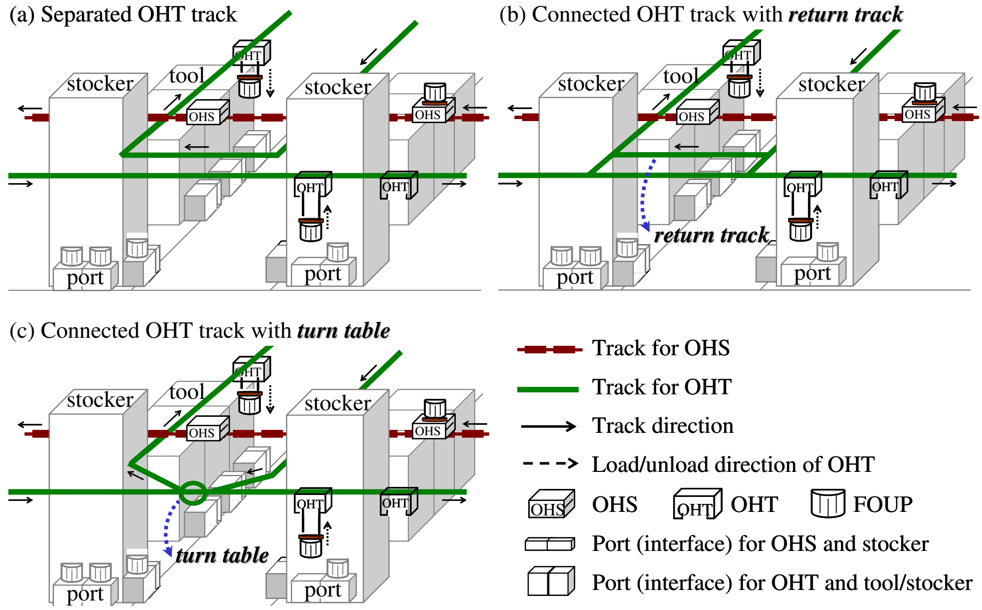


Fig. 1 Configurations of the 300 mm AMHS

overhead hoist transporter (OHT). The track system for OHS is a uni-directional, single-loop overhead system, through which vehicles are capable of carrying one carrier at a time. The track system for the OHT vehicle is the same except that this vehicle has a hoisting mechanism to load and unload one carrier automatically. The wafer carrier, or front-opening unified pod (FOUP), is a kind of closed carrier with an automated door at the front side as well as a cassette structure which is an integral part of the carrier [1]. Track systems for intrabays are designed as separate loops spread up from an interbay with a uni-directional OHT system.

Three kinds of combination of interbay and intrabay layout were represented in Fig. 1. In Fig. 1a, these two systems were separated loops and the transport tasks between different bays involved transferring by stocker. In Fig. 1b, these tracks were connected in front of each bay, and the return track made the within-bay transport more efficient. In Fig. 1c, the tracks were connected in front of each bay by turntable, but this turntable is a kind of resource restriction, because there might be some vehicles waiting for a turntable to move to interbay or intrabay, or even wait for a straight move in interbay or return to intrabay. Hence, traffic congestion occurs. Besides, overhead space management of these track heights becomes a complicated issue. Typically, the track of vehicle OHS is positioned higher than the track of OHT.

Under these combination layouts, not only can the wafer be delivered without labour for transport loading but also the number of faults during transporting is reduced. Especially in Fig. 1b and c, transport tasks can be delivered directly tool-to-tool without transferring by stocker and so decreasing delivery variation. Furthermore, five types of transport operation between different bays utilising different facilities are shown in Fig. 2. The suffix number in OHT refers to the vehicle used in transporting. All types, except type 5, involve another complex stocker selection issue; hence only type 5 and OHT behaviour will be considered for focus in this study.

The track layout and transport facility in the 300 mm AMHS is a breakthrough which can be known from the above descriptions. Once the hardware is determined, the number of vehicles required follows. As well, many operational issues need to be evaluated with the aim of finding the optimal strategy for best transportation performance and maximum value from the hardware investment, include the path-finding algorithm, traffic control methodologies, transport logic, and even the dispatching rule. The related issues are described briefly in Table 1.

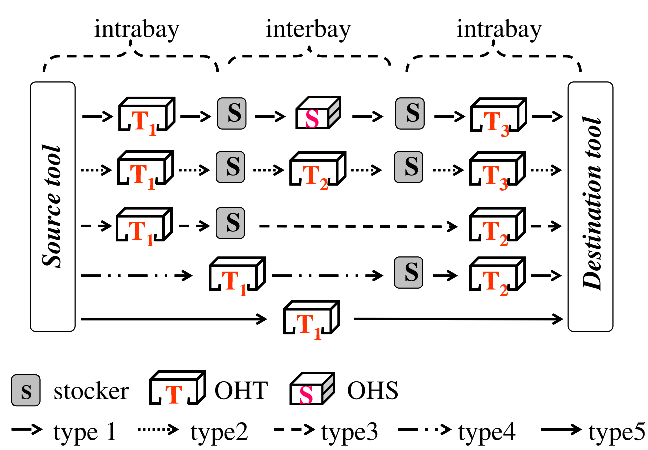


Fig. 2 Types of the tool-to-tool transport operation

Table 1 Literature review list

Authors	Subject	Main contribution	Applied system				
			Wafer fab				FMS
			A	B	C	D	
1) track layout and transport facility							
Kaempf [2]	The "zero footprint" solution for automated wafer transport in wafer Fab was introduced.	The various overhead AMHS architectures and transport facility was illustrated.			V	V	
Kurosaki et al. [3]	The transport methods: isolated lines and interconnected lines were compared for 300 mm AMHS.	The lead time of the interconnected line was better than the isolated line.			V	V	
Campbell and Ammenheuser [4]	The 300 mm AMHS equipment models were introduced.	The AMHS with the track loops, vehicle, stocker and their operations were demonstrated.			V		
Bahri et al. [5]	The two configurations: unified and segregated AMHS for 300 mm fabs were compared.	The system reliability and delivery times of the unified AMHS would be better than segregated.			V	V	
2) the number of vehicles required							
Maxwell and Muckstadt [6]	A mathematical model using the shortest route algorithm was defined.	The minimum vehicle number was obtained by the minimum travel time of empty vehicle's trip.					V
Egbelu [7]	Four analytical approaches were proposed to estimate the number of vehicles required in an AGV system.	These approaches were able to estimate the initial number of vehicles for implementation.					V
Arifin and Egbelu [8]	An analytical model using regression was developed to estimate the number of vehicles required.	The significant factors for estimating vehicle number were identified.					V
Lin et al. [9]	A decomposing approach was addressed to determine the number of vehicles in a 300 mm AMHS.	The number of vehicles under various vehicle types was calculated by this approach.				V	
Wang and Lin [10]	The simulation and response surface method were used to determine the vehicle numbers for AMHS.	The vehicle numbers in an intrabay system (photoarea) was determined.		V			
3) Operation issues							
3.1) Path-finding							
Fukunari et al. [11]	A dynamic path-finding algorithm for a vehicle-based AMHS was proposed. Two approaches for calculating node penalty were compared: node-type and data-based.	The data-based approach by feeding historical data improved the performance when system suffers from heavy traffic.	V*				
3.2) Traffic control							
Bahri and Gaskins [12]	A traffic control method which balances the flow between load/unload nodes of interbay was proposed.	The unnecessary free vehicle trip was reduced and available vehicle was allocated efficiently.	V				
Lin et al. [13]	The strategies for controlling the upper and lower limits of the number of vehicles in intrabays were proposed.	The traffic congestion was avoided in intrabays and vehicles were fully utilized.				V	
3.3) Transport logic							
Lin et al. [14]	Four vehicle types for transporting tasks in their respective area in the 300 mm AMHS was proposed.	Making the transport logic uncomplicated.				V	
Lin et al. [15]	Types of vehicle can be changed based on different task requests and the type's vehicle number was proposed.	Let each type of vehicle be fully utilized and made dispatch flexibly.				V	

Table 1 (continued)

Authors	Subject	Main contribution	Applied system Wafer fab A	B	C	D	FMS
3.4) dispatching rule							
Lin et al. [16]	Performance evaluation of dispatching rules in a double loop interbay with three decision points: loop selection, cassette-initiated and vehicle-initiated dispatching rule.	The rules of shortest distance, nearest vehicle and first encounter first served for above points respectively outperformed the other rules.	V				
Wang and Liao [17]	The pre-emptive policy (PHP) of highest priority job first for OHT dispatching was proposed.	The movement of high priority lot was expedited with acceptable time delay in regular ones.		V			
Wang and Liao [18]	The differentiated pre-emptive dispatching (DPD) rule for hot lot and against blocking by normal lot transport was proposed.	The delivery time of both hot and normal lot were reduced compared with nearest job first rule.		V			
Lin et al. [19]	A hybrid push and pull dispatching rule was proposed for a photobay in a 300 mm wafer fab.	The WIP level and cycle time can be improved. The number of input/retrieve operation in stocker and unnecessary transport could be decreased.		V			

A: interbay only; B: intrabay only; C: separated interbay and intrabay; D: connected interbay and intrabay; *: Inter-Floor

Previously, the dispatching issues of AMHS have been discussed separately for interbay or intrabay, or even both systems, but the range for search is just in the respective loop (see Table 1 and Fig. 3). However, the tracks are interlaced in the connected loops 300 mm AMHS and vehicles can travel, not just in one loop, but also all around the wide fab. Currently in a Taiwan's fab, the range for search is set as a fixed distance which is the length of all the tracks of the wide fab. If the assigned FOUP is far from the vehicle, not only FOUP might wait a long time for a vehicle to pick it up but also the vehicle is utilized for a long ineffective trip.

Hence, determining how far or the range in which to search and assign the FOUP or vehicle before selecting a dispatching rule is an important issue. This also indirectly limits the distance of a vehicle's empty trip (defined as *DVemp*) and then makes the resource/vehicle work effectively. The *DVemp* means the distance which the vehicle travels to the location of the FOUP without load, by which the vehicle is assigned. This is defined as a search range (SR) assignment issue and is the topical subject in this study.

In the following sections, the problem statement is addressed first. The simulation model is conducted in Sect. 3. The approach of the two-phase SR assignment and simulation experiments is presented in Sect. 4. Conclusions are made in the final section, along with suggestions for further research.

2 Problem statement

The dispatching operation in this study is separated into two categories: vehicle searches FOUP (VSF) and FOUP searches vehicle (FSV). VSF resembles vehicle-initiated task assignment and FSV resembles work-centre-initiated task assignment in Egbelu and Tanchoco [20]. When a vehicle completes a task and triggers VSF to search a waiting FOUP (defined as *WF*) for the next task, the SR of VSF is used to "determine how far the *WFs* from that vehicle will be considered for dispatching, and then indirectly limit the *DVemp* between that vehicle and the assigned *WF*" while dispatching successfully. If the SR is set too narrow, the vehicle might find no *WF* in the range, while there are actually many waiting to be transported. In addition, if the SR is set too wide and the vehicle assigns a farther *WF* successfully, the empty trip of that vehicle will be increased a significant distance from its location.

The other situation is when a FOUP completes the process step and triggers FSV to search an idle vehicle (defined as *IV*) to transport it to the next process tool or destination. The SR of FSV is used to "determine how far the *IVs* from that FOUP will be considered for dis-

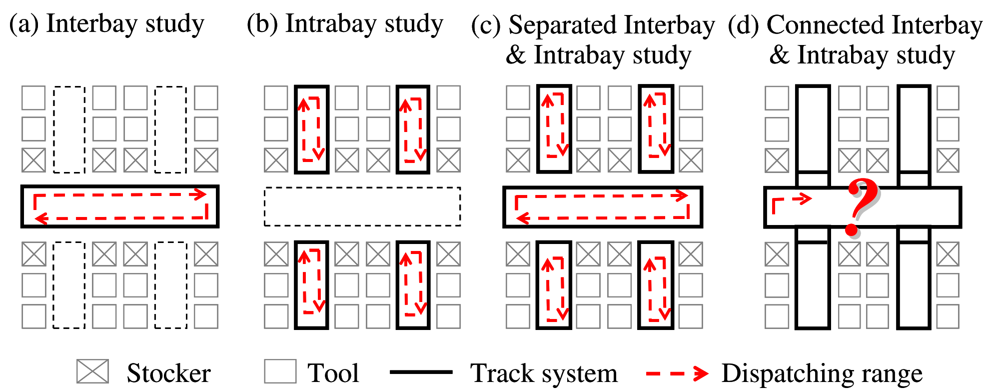


Fig. 3 The range of search for dispatching in AMHS studies

patching, and then indirectly limit the *DVemp*” too. The range for search, whether too narrow or wide, will not only increase the time of FOUP to wait for being assigned or wait for vehicle to pick it up, but also affect vehicle utilisation and traffic conditions. For this reason, an applicable SR for dispatching is required.

3 Simulation model descriptions

3.1 Layout

The performance of SR assignment was evaluated by a discrete event simulation model built using the object-oriented simulation software eM-Plant™ [21]. The simpli-

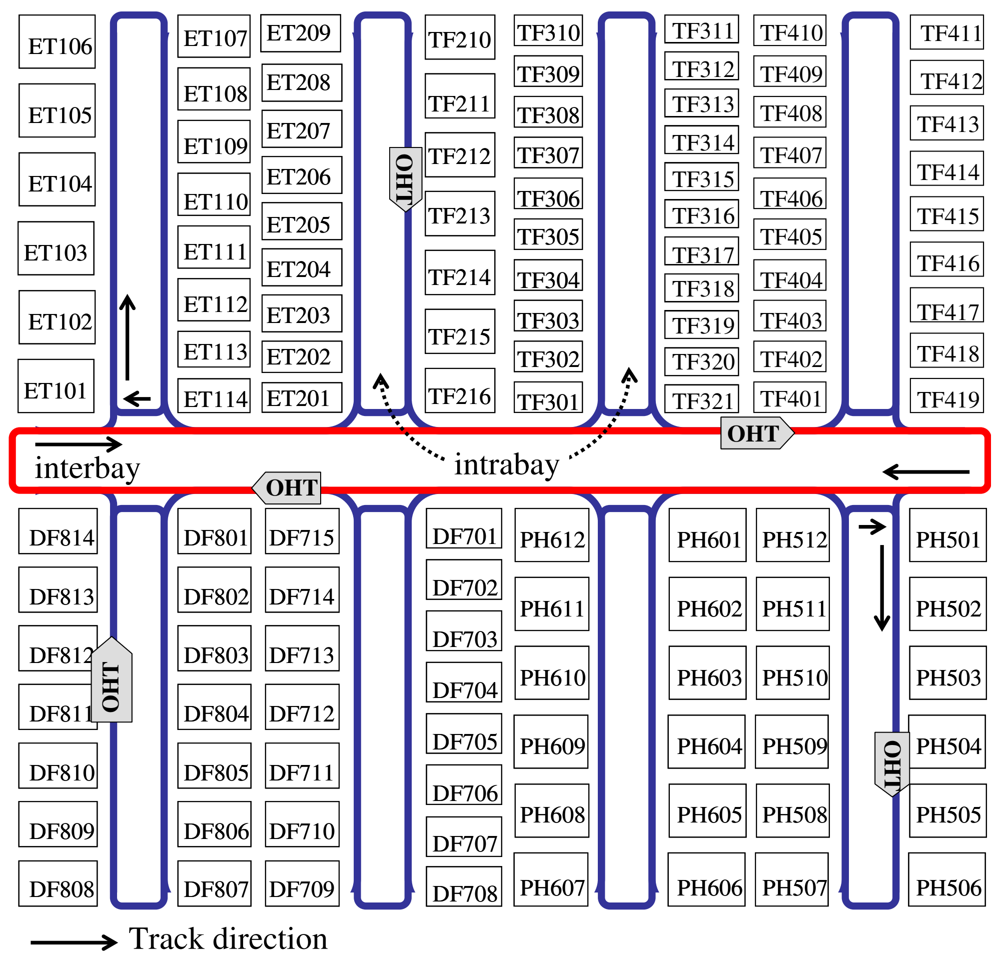


Fig. 4 The simplified layout of a 300 mm AMHS

Table 2 Examples of tools' average inter-arrival time

MR (lots/hr)	Tools									
	ET101	ET102	ET103	ET104	ET105	ET106	ET107	ET108	ET109	ET110
70	1:02:10	1:02:10	1:02:10	1:02:10	26:08	35:02	3:38:00	3:38:00	3:38:00	4:23:49
105	41:26	41:26	41:26	41:26	17:25	23:21	2:25:20	2:25:20	2:25:20	2:55:52
140	31:05	31:05	31:05	31:05	13:04	17:31	1:49	1:49	1:49	2:11

Note: (a) The time is the mean of exponential distribution. (b) Time format is hh: mm: ss.

fied layout is a reference from Lin et al. [13], which portrays a 300 mm wafer fab from Taiwan, R.O.C. There are a total of 123 tools and the AMHS includes one interbay and eight intrabay systems, as depicted in Fig. 4. Zone control is used to prevent traffic collision.

3.2 Transport information

The transport information includes (1) from-to distance; (2) from-to quantity; (3) system average moving rate (defined as MR) per hour, which is the average arrival rate of all the tools; and (4) inter-arrival time of each tool, which is the average time interval of transport task requests from tools and follows exponential distribution. These data were calculated from the moving records in the manufacturing execution system (MES) over two months. Some examples are shown in Tables 2 and 3.

3.3 Model assumptions

The following assumptions are made to facilitate the simulation model:

1 Four ports of each tool.
2 Average batch size of furnace tool is 4~6 lots randomly.
3 Inter-arrival time of tools is an exponential distribution (examples see Table 2).
4 Travelling speed of OHT is 1 m/sec, and the acceleration and deceleration of OHT is neglected.
5 Time to load/unload FOUP between vehicle and tool is 20 s.
6 Idle OHT (wait for request) travels in interbay system.
7 Efficiency of each OHT is equal to 100%, and no battery recharge is required.

3.4 Number of vehicles required

The number of vehicles required is an important factor, as it indicates the transport capability. Egbelu [7] introduced the idea to calculate the initial number of AGV required by performing empty and loaded runs. The exact formulas are:

1 The number of empty runs from station i to station j is given by g_{ij}.

$$g_{ij} = \frac{(Expected\ no.\ of\ deliveries\ to\ i) \times (Expected\ no.\ of\ pickups\ from\ j)}{Expected\ total\ no.\ of\ pickups\ throughout\ the\ system}$$
$$= \left[\left(\sum_{k=1}^{n} f_{ki}\right) * \left(\sum_{k=1}^{n} f_{jk}\right)\right] \Big/ \left(\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}\right)$$

Table 3 Examples of from-to moving quantity

From (Tools)	To (Tools)								
	ET201	ET202	ET203	ET204	ET205	ET206	ET207	ET208	...
ET201	0	4	4	5.5	5.5	39.5	39.5	39.5	
ET202	5	0	14.5	0.25	0.25	0.63	0.63	0.63	
ET203	5	14.5	0	0.25	0.25	0.63	0.63	0.63	
ET204	15	0	0	0	35	0.5	0.5	0.5	
ET205	15	0	0	27	0	0.5	0.5	0.5	
ET206	25.5	0.5	0.5	0.75	0.75	0	40	40	
...									

where n is number of stations in the facility; f_{ij} is expected number of loaded trips required between station i and station j during the period.

2 The total distance traveled from station i to station j is given by D_{ij}.

$$D_{ij} = D'_{ij} + \overline{D_{ij}} = \left[g_{ij} * d(\alpha_i, \beta_j)\right] + \left(f_{ij} * d(\beta_i, \alpha_j)\right)$$

where D'_{ij} is empty runs distances; $\overline{D_{ij}}$ is loaded runs distances; α_i is node label corresponding to the delivery station i, i =1, 2, ..., n; β_j is node label corresponding to the pickup station j, j =1, 2, ..., n; $d(\beta_i,\alpha_j)$ is distance between node β_i and node α_j.

3 The number of vehicles required is calculated according to

$$N = \left[\left(\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}/V\right)\right] + \left(\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}\right)(t_u + t_t)/(60T - t)$$

where T is length of the period during which the f_{ij} exchanges occur (hours); V is average vehicle travel speed; t_u is mean time to unload a vehicle; t_t is mean time to load a vehicle; t is mean expected lost time by each vehicle during a time period of T due to battery change.

In this study, n=123; T is two months which is 86,400 minutes; V=1 m/sec; t_u=t_t =20 sec; t=0. From the formulae and the moving data described above, we can obtain N (vehicle's initial number)=4.18; however the number was underestimated because the formulae did not estimate the time increase caused by traffic problems like congestion, nor the vehicle's idle time. Therefore, experiments to evaluate what the multiples of N to set as vehicle number in the model were performed. The experiment evaluated four levels of multiples, as 1.5, 2, 2.5 and 3 for N with the simulation model described above. The result showed that if the vehicle number is $\lfloor N \times 2(multiples) \rfloor =$ 9, it would make the system stable and the indices performed better than other multiples. These indices are described as follows, except vehicle empty utilisation was replaced by vehicle utilisation to be fully utilised. The bigger the vehicle utilisation, the better. For the analysis procedure, please refer to Sect. 4.2.2.

3.5 Performance indices

The performance indices are outlined as follows. (1) Throughput (TP, lots): the total quantity of transport tasks completed; (2) Waiting time (WT, sec): the time that FOUP waits for a vehicle to assign, not including the time of the vehicle's empty trip to pick it up; (3) Standard deviation of delivery time (stdDT, sec): standard deviation of delivery time, which is the time from FOUP requests to move to when that FOUP is loaded on the destination by vehicle; (4) Vehicle empty utilisation (Vemp, %): the utilisation of vehicle for empty trips. The standard deviation of delivery time is used to obtain expected and stable status, where a smaller number is better. The lower the vehicle empty utilisation is, the better.

3.6 Dispatching definition

Some definitions of dispatching are: (1) *FSV successfully* means that when FSV occurs, the FOUP finds an appropriate *IV* and assigns it to transport. On the contrary is *FSV unsuccessfully*; (2) *VSF successfully* means when VSF occurs, the vehicle finds an appropriate *WF* and assigns it for the next task. On the contrary is *VSF unsuccessfully*. The dispatching rules are a combination of the nearest vehicle (NV) for FSV and foremost encounter first served (FEFS) for VSF, which are the outstanding rules in a double loop interbay [16]. Furthermore, the statuses of vehicles include: (1) loaded, which was assigned a task and was executing that task now; (2) empty, which was assigned a task and just moves to pick up that task; (3) idle, which has no task to transport and waits for assignment.

4 The approach for SR assignment

A two-phase approach is used to develop the SR assignment. Phase I is to observe the trend and distribution of *DVemp*. Phase II evaluates levels of SR and the level's design inspired from the phase I results. The dispatching procedures in this two-phase approach are shown in Fig. 5.

4.1 Phase I: DVemp's trend and distribution analysis

Some factors might affect the *DVemp* such as dispatching rules, vehicle travel path and so forth. In this phase, the effect of "the number of *IVs* and *WFs* at the time when dispatching occurs" will be discussed. An observation of *DVemp*'s trend and distribution were made by simulation to interpret that effect. The SR setting in the phase I model is currently described in Sec. 1, FOUP/vehicle searches all the wide fab and evaluates all the *WFs* or *IVs* when dispatching occurs. The dispatching procedure is shown in Fig. 5a.

4.1.1 Simulation experiment

Three levels of MR as MR_i, i=1, 2, 3 are designed to vary the system loadings, where MR_1, MR_2, MR_3 is 70 lots/hr, 105 lots/hr, 140 lots/hr, respectively. Four indices are

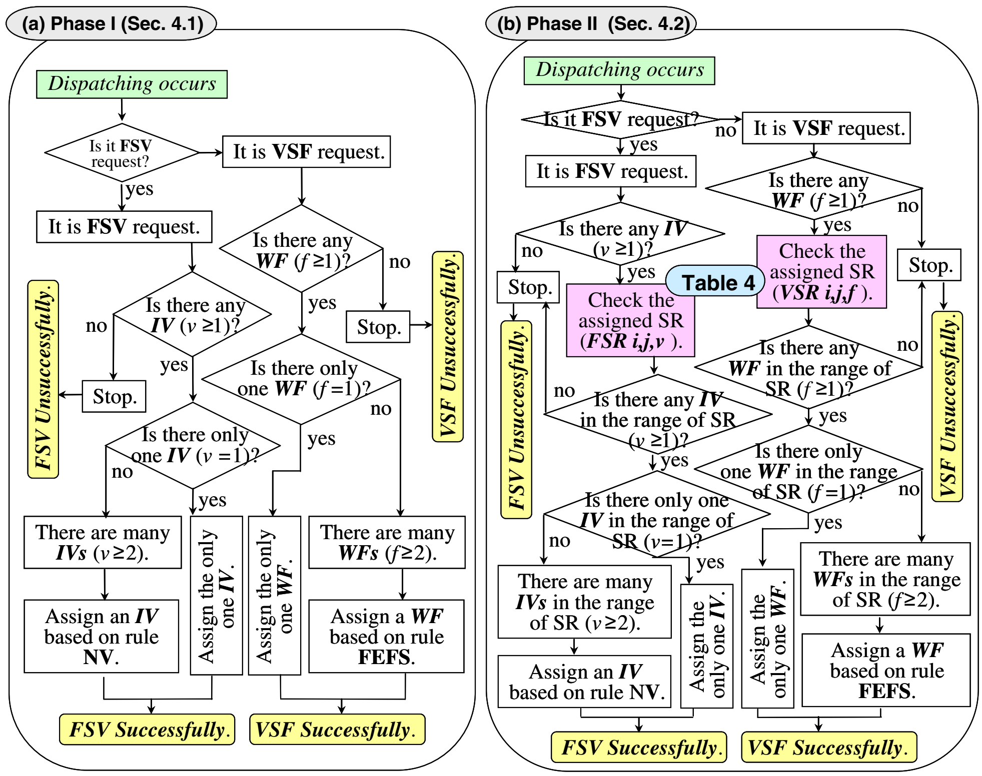


Fig. 5 The dispatching procedures in SR assignment

measured to verify whether or not the system is stable. Records needed to collect include: (a) the number of *IVs* and "*DVemp* between FOUP and the assigned *IV*" when FSV successfully; (b) the number of *WFs* and "*DVemp* between vehicle and the assigned *WF*" when VSF successfully. The notations to define the records are listed as follows.

(1) FOUP and vehicle related:

- (a) *F*: FOUP, which initials a FSV request.
- (b) *WF*: waiting FOUP, which waits for a vehicle to assign.
- (c) *V*: vehicle, which initials a VSF request.
- (d) *IV*: idle vehicle, which waits for an FOUP to assign.

(2) FSV related:

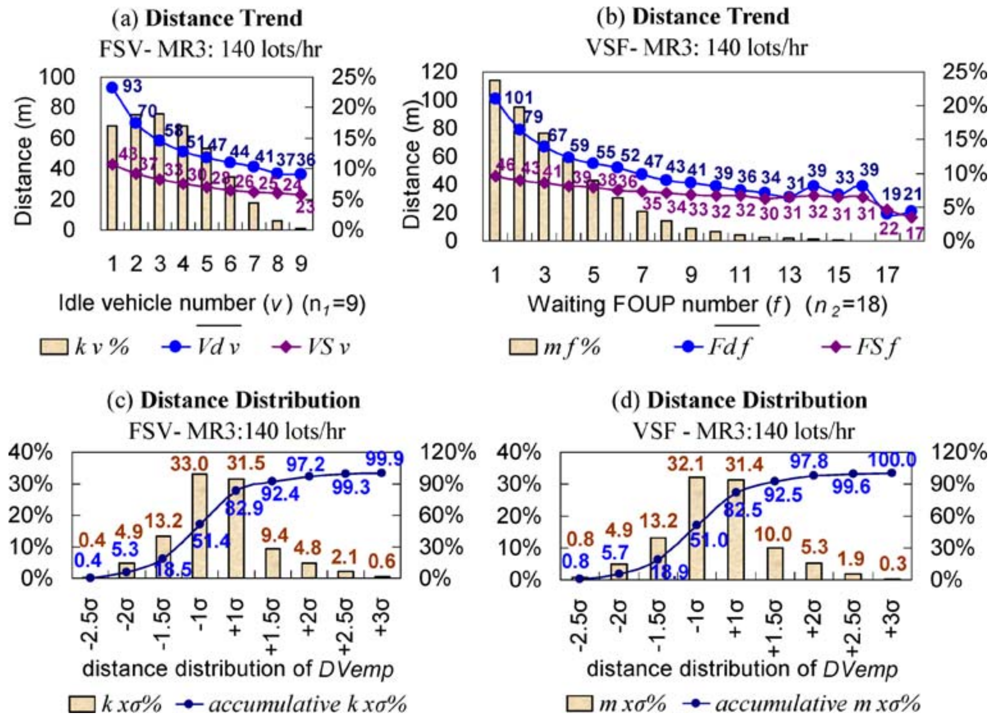
- (a) v: the number of *IV* when FSV occurs. v=1, 2, ..., n_1; n_1 is equal to the number of vehicle in the model; n_1=9.
- (b) k_v: the accumulated number of FSV requests under v. k_v=1, 2, ..., k; $1 \le v \le n_1 = 9$.
- (c) $D_{x,v,k_v}(F, IV)$: the *DVemp* between F and assigned *IV* under the x^{th} *IV*, v and k_v. x=1, 2, ..., v; $1 \le v \le n_1$; k_v=1, 2, ..., k.
- (d) $Vd_{v,k_v} = Min\left[d_{x,v,k_v}(F, IV)\right]$. x=1, 2, ..., v; $1 \le v \le n_1$; k_v=1, 2, ..., k.
- (e) $\overline{Vd_v}$: the average distance of Vd_{v,k_v}. $1 \le v \le n_1$; k_v= 1, 2, ..., k.
- (f) VS_v: the standard variation of Vd_{v,k_v}. $1 \le v \le n_1$; k_v=1, 2, ..., k.

(3) VSF related:

- (a) f: the number of *WF* when VSF occurs. f=1, 2, ..., n_2; n_2 is equal to the biggest number of *WF* in the system.
- (b) m_f: the accumulated number of VSF under f. m_f =1, 2, ..., m; $1 \le f \le n_2$.
- (c) $d_{y,f,mf}(V, WF)$: the *DVemp* between V and assigned *WF* under the y^{th} *WF*, f and m_f. y=1, 2, ..., f ; $1 \le f \le n_2$; m_f =1, 2, ..., m.
- (d) $Fd_{f,mf} = Min\left[d_{y,f,mf}(V, WF)\right]$. y=1, 2, ..., f; $1 \le f \le n_2$; m_f =1, 2, ..., m.
- (e) $\overline{Fd_f}$: the average value of $Fd_{f,mf}$. $1 \le f \le n_2$; m_f =1, 2, ..., m.
- (f) FS_f: the standard variation of $Fd_{f,mf}$. $1 \le f \le n_2$; m_f =1, 2, ..., m.

When v=0 or f=0, which was FSV or VSF unsuccessfully, no information needs to be recorded. The experiment was designed as one factor, MR, with three levels. The total number of experiments performed was 3(MR)*10 (replications)=30. The simulation interval was 30 days, and warm-up was 2 days.

Fig. 6 The *DVemp*'s trend and distribution



4.1.2 Simulation results and analysis

From the indices measured by simulation, the residual analysis of these data satisfied the model assumptions (normality, independence of error term, constant variance) [22] and there is no significant difference between the replications at each level of moving rate (MR). The transport records from one replication were picked out randomly, and the average and standard deviation of *DVemp* under different numbers of *WF* (f) and *IV* (v) were summarised for observing the *DVemp*'s trend. See Fig. 6a and b. The trends under levels of MR were all the same; hence the result of MR_3 was displayed only. Some discussions are as follows.

(1) The *more IV* was, the *shorter* $\overline{Vd_v}$ and VS_v when FSV occurs. See Fig. 6a; the *more WF* was, the *shorter* $\overline{Fd_f}$ and FS_f when VSF occurs. See Fig. 6b.

(2) *F* or *V* may find and assign the *nearerIV* or *WF* and make the *shorter DVemp* if there are *more IVs* or *WFs*; *F* or *V* may find and assign the *farther IV* or *WF* and make the *longer Dvemp* if there are *fewer IVs* and *WFs*.

(3) The number of *IV* and *WF* at the time when dispatching occurs will affect the *DVemp*.

(4) Another, n_1 is equal to 9 at both MR_1 and MR_2, and n_2 is equal to 6 and 11 at MR_1 and MR_2 respectively, which weren't shown in the figure.

Furthermore, to observe the *DVemp*'s distribution, the distance intervals of *DVemp* were recorded and the percentages of the accumulated number of each interval under MR were calculated based on the following rules. If the *DVemp* satisfied following distance interval, then record the distribution with "$x\sigma$". Some notations were described as follows and the outcome is summarised in Fig. 6c and d. Also, the result of MR_3 was displayed only.

(1) The rules to define the distance interval

(a) FSV records

(i) If $\overline{Vd_v} + (x-1) * VS_v \leqq DVemp < \overline{Vd_v} + x * VS_v$; x=1, 1.5, 2, 2.5, 3.

(ii) If $\overline{Vd_v} + x * VS_v \leqq DVemp < \overline{Vd_v} + (x+1) * VS_v$; x=−3, −2.5, −2, −1.5, −1;

(b) VSF records

(i) If $\overline{Fd_f} + (x-1) * FS_f \leqq DVemp < \overline{Fd_f} + x * VS_f$; x=1, 1.5, 2, 2.5, 3;

(ii) If $\overline{Fd_f} + x * FS_f \leqq DVemp < \overline{Fd_f} + (x+1) * FS_f$; x=−3, −2.5, −2, −1.5, −1;

(2) Notations description

(a) $$k_{x\sigma}\% = \left(\frac{\textit{the accumulate of FSV's DVemp fell in the distance interval "}x\sigma\textit{"}}{\textit{the total number of FSV request}}\right) * 100\%$$

(b) $$m_{x\sigma}\% = \left(\frac{\textit{the accumulate number of VSF's DVemp fell in the distance interval "}x\sigma\textit{"}}{\textit{the total number of VSF request}}\right) * 10$$

Table 4 The six levels of SR assignment

$FSR_{i,j,v}$ (m)																		
v	i=1						i=2						i=3					
	j=1	j=1.5	j=2	j=2.5	j=3	j=0	j=1	j=1.5	j=2	j=2.5	j=3	j=0	j=1	j=1.5	j=2	j=2.5	j=3	j=0
1	131.4	151.9	172.3	192.8	213.2	608.5	131.5	152.2	173.0	193.7	214.4	608.5	134.8	155.9	177.0	198.0	219.1	608.5
2	103.5	120.8	138.1	155.4	172.8	608.5	103.7	121.2	138.8	156.3	173.9	608.5	105.3	123.4	141.5	159.6	177.7	608.5
3	89.6	105.2	120.8	136.4	152.0	608.5	89.6	105.4	121.2	137.0	152.8	608.5	89.7	105.8	121.8	137.9	153.9	608.5
4	81.7	96.1	110.5	125.0	139.4	608.5	81.3	96.0	110.7	125.5	140.2	608.5	79.9	94.5	109.2	123.8	138.4	608.5
5	74.8	88.2	101.7	115.1	128.6	608.5	74.4	87.9	101.4	115.0	128.5	608.5	74.3	88.0	101.7	115.4	129.1	608.5
6	69.9	82.6	95.3	108.0	120.7	608.5	69.2	81.9	94.7	107.4	120.1	608.5	69.0	81.9	94.7	107.6	120.4	608.5
7	65.8	77.9	89.9	101.9	113.9	608.5	65.5	77.7	89.9	102.1	114.3	608.5	64.6	76.8	89.0	101.2	113.3	608.5
8	63.3	75.0	86.7	98.4	110.1	608.5	62.4	74.0	85.6	97.2	108.7	608.5	60.6	72.5	84.4	96.2	108.1	608.5
9	60.3	71.4	82.6	93.7	104.9	608.5	58.3	69.4	80.4	91.5	102.6	608.5	57.7	68.9	80.0	91.1	102.3	608.5
$VSR_{i,j,f}$ (m)																		
f	i=1						i=2						i=3					
	j=1	j=1.5	j=2	j=2.5	j=3	j=0	j=1	j=1.5	j=2	j=2.5	j=3	j=0	j=1	j=1.5	j=2	j=2.5	j=3	j=0
1	143.9	165.0	186.2	207.3	228.4	608.5	144.5	166.9	189.3	211.7	234.1	608.5	146.4	169.2	192.0	214.8	237.6	608.5
2	120.3	141.4	162.5	183.6	204.7	608.5	121.4	142.5	163.5	184.5	205.6	608.5	122.1	143.8	165.4	187.0	208.6	608.5
3	99.3	117.4	135.5	153.6	171.8	608.5	107.5	127.5	147.6	167.6	187.6	608.5	107.8	128.3	148.7	169.2	189.7	608.5
4	94.4	112.7	130.9	149.2	167.4	608.5	101.0	121.1	141.2	161.3	181.4	608.5	98.5	118.0	137.5	156.9	176.4	608.5
5	80.9	97.1	113.3	129.5	145.7	608.5	92.1	111.6	131.0	150.5	170.0	608.5	93.1	112.3	131.6	150.8	170.1	608.5
6	46.3	56.2	66.2	76.1	86.1	608.5	86.4	104.6	122.8	141.0	159.2	608.5	88.2	106.4	124.6	142.8	161.0	608.5
7							91.4	110.0	128.5	147.1	165.6	608.5	81.7	99.1	116.5	133.9	151.2	608.5
8							64.3	78.0	91.8	105.5	119.3	608.5	77.0	94.0	111.1	128.1	145.1	608.5
9							71.2	87.4	103.7	119.9	136.1	608.5	73.9	90.6	107.3	124.0	140.7	608.5
10							53.6	65.3	77.1	88.8	100.6	608.5	71.1	87.3	103.4	119.6	135.7	608.5
11							31.5	32.9	34.2	35.5	36.8	608.5	68.6	84.8	101.0	117.2	133.4	608.5
12													63.9	78.8	93.7	108.6	123.5	608.5
13													62.4	78.0	93.6	109.2	124.8	608.5
14													70.9	87.1	103.3	119.5	135.6	608.5
15													64.0	79.4	94.8	110.1	125.5	608.5
16													70.1	85.6	101.1	116.6	132.1	608.5
17													40.4	51.3	62.2	73.1	84.0	608.5
18													37.9	46.3	54.6	63.0	71.4	608.5

We can see from Fig. 6c and d that the *DVemp*'s distribution gathered between the intervals from −2.5σ to 3σ and almost all the *DVemp* of transport records fell into these intervals.

Consequently, the *DVemp*'s trend and distribution inspired to develop the SR assignment. The main idea is that *more WFs* or *IVs* in the system made the *shorter DVemp*, so *shorter* SR is adequate. Otherwise, *fewer IVs* or *WFs* in the system made the *longer DVemp*, so a *longer* SR is required and has a higher chance to dispatch successfully. Hence we will design an appropriate SR under a different number of *IV* (v) and *WF* (f), and the range of search should be set no longer than 3σ of $\overline{Vd_v}$ or $\overline{Fd_f}$.

4.2 Phase II: The evaluation of SR assignment

4.2.1 Simulation experiment and SR definition

Two factors are designed to evaluate the appropriate SR under a different number of *IV* (v) and *WF* (f), and only the *WFs* or *IVs* in the assigned range will be considered when dispatching occurs. The dispatching procedure is shown in Fig. 5b. The factors and levels selected were as follows.

(a) Factor A: moving rate (MR); numeric factor, three levels. Levels of MR were Mr_i, i=1, 2, 3, where MR_1, MR_2, MR_3 is 70 lots/hr, 105 lots/hr, 140 lots/hr respectively.

(b) Factor B: search range (SR); categorical factor, six levels. Levels of SR were SR_j, j=1, 1.5, 2, 2.5, 3, 0. The SR definition was made as follows.

The SR_j proposed are separated into two parts, FOUP-initiated search range (FSR) and vehicle-initiated search range (VSR). Developing the levels of SR is based on records from phase I and designed as the average distance of $DVemp\left(\overline{Vd_v}, \overline{Fd_f}\right)$, plus the multiple of *DVemp*'s standard deviation (VS_v, FS_f) while $j \neq 0$. The SR_0 (j=0) represents the current way described in Sec. 4.1, which is the total length of tracks around the fab. The purpose to set SR_0 is to test if SR is required in dispatching. The notations are described as follows and the levels of SR are shown in Table 4.

(1) $FSR_{i,j,v}$: the SR of FSV under MR_i and SR_j when *IV* number is v.

$$FSR_{i,j,v} = \begin{cases} \overline{Vd_v} + (j * VS_V)\ (m)\ if\ j \neq 0 \\ 608.50\ (m)\ if\ j = 0 \end{cases}$$

(2) $VSR_{i,j,f}$: the SR of VSF under MR_i and SR_j when *WF* number is f.

$$VSR_{i,j,f} = \begin{cases} \overline{Fd_f} + (j * FS_f)\ (m)\ if\ j \neq 0 \\ 608.50\ (m)\ if\ j = 0 \end{cases}$$

Where i=1, 2, 3; j=1, 1.5, 2, 2.5, 3, 0; v=1, 2, ..., n_1; n_1=9; f=1, 2, ..., n_2; n_2=6, 11, 18 at i=1, 2, 3 respectively.

A traditional statistical experimental design with two-factor full-factorial [22] was used in this study. The total number of combinations was 3(MR)*6(SR)=18, and the number of experiments performed was 18(combination)*10 (replications)=180. The simulation interval was 30 days, and warm-up was 2 days.

4.2.2 Simulation results and analysis

The ANOVA analysis as summarised in Table 5 indicates that the MR significantly affects all indices. Also, the SR and the interaction significantly affect all indices except the TP at 95% confidence level. The response trend under levels of MR and SR can be observed from the interaction graphs, as depicted in Fig. 7.

Further, the post hoc multiple comparisons were done with the least significant difference (LSD) method to compare all pairs of the six SR under each of the three MR, as summarised in Table 6. The value is the mean of performance, measured from the 10 replications, and the rank in the different alphabet means the effects of SR were significant at 95% confidence level. Table 6 implied that the shorter SR made for a longer WT because the narrow range decreased the chance for the vehicle to find the *WFs*, and then the *WFs* need more time to wait for being assigned; the Vemp would be lower (better) and indicates vehicle work more efficiently while SR is shorter. However, no SR outperforms the others in all indices.

Therefore, a multiple response method called desirability (Myers & Montgomery, Stat Ease) [23, 24] is used to integrate multiple indices into one. The method makes use of an objective function $D(X)$, called the desirability function.

$$\boldsymbol{D} = (\boldsymbol{d}_1 \times \boldsymbol{d}_2 \times \ldots \times \boldsymbol{d}_{\boldsymbol{n}})^{\frac{1}{n}} = \left(\prod_{i=1}^{n} \boldsymbol{d}_i\right)^{\frac{1}{n}}$$

where n is the number of responses; di is the desirable range for each response, $0 \leqq d_i \leqq 1$; and D(X) is a geometric mean of all transformed responses. The desirability of SR_j under MR_i is shown in Fig. 8, and some discussions are as follows.

(1) SR_1 is not applicable in any system loading. Too narrow a range decreases the chance for dispatching successfully, and then makes more WT and higher stdDT for FOUP, even if it can enable lower Vemp; see Fig. 8 and Table 6.

(2) In a light system (fewer *WFs*) such as MR_1, a shorter SR is not appropriate. Responses to the phase I result in fewer *WFs* making a longer *DVemp*. Hence a longer SR such as $SR_{2.5}$ or SR_3 or SR_0 makes for better performance; see Fig. 8a.

Table 5 The P-values of two factors with interaction on the performances in phase II experiment

Indices	Factors				R^2
	MR	SR	MR^2	MR*SR	
TP (lots)	<0.0001*	0.4611	0.0122*	0.2997	0.9999
WT (sec)	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.9715
stdDT (sec)	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.9825
Vemp (%)	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.9996

*=significant at 95% confidence level

(3) In a heavy system (more *WFs*) such as MR_2 and MR_3, the longer SR is not required. Responses to the phase I result in more *WFs* making a shorter *DVemp*. Hence a shorter SR such as $SR_{1.5}$ makes for better performance; see Fig. 8b,c.

(4) The *WFs* or *IVs* far from *V* or *F* could be ignored by setting an appropriate SR. For instance, ignoring 7.5% (4.8%+2.1%+0.6%) IVs for FSV and 7.5% (5.3%+1.9%+0.3%) *WFs* for VSF, of which the *DVemp* is longer than the interval +1.5σ under MR_3 to improve performance; see Fig. 6c,d and Fig. 8c.

(5) The result of testing if SR is required also can be seen. SR_0 might be used in a light system such as MR_1 because of its simpler control logic and performance is close to the optimal SR_3; see Fig. 8a. However, if system loading is increasing to MR_2 or MR_3, SR_0 is not applicable; see Fig. 8b,c.

Finally, the model equations in terms of coded factors (because there is a category factor) can be used to predict the response at an interesting point, where code for factor A: MR is −1, 0, 1 at MR_1, MR_2, MR_3 respectively, and B[1],

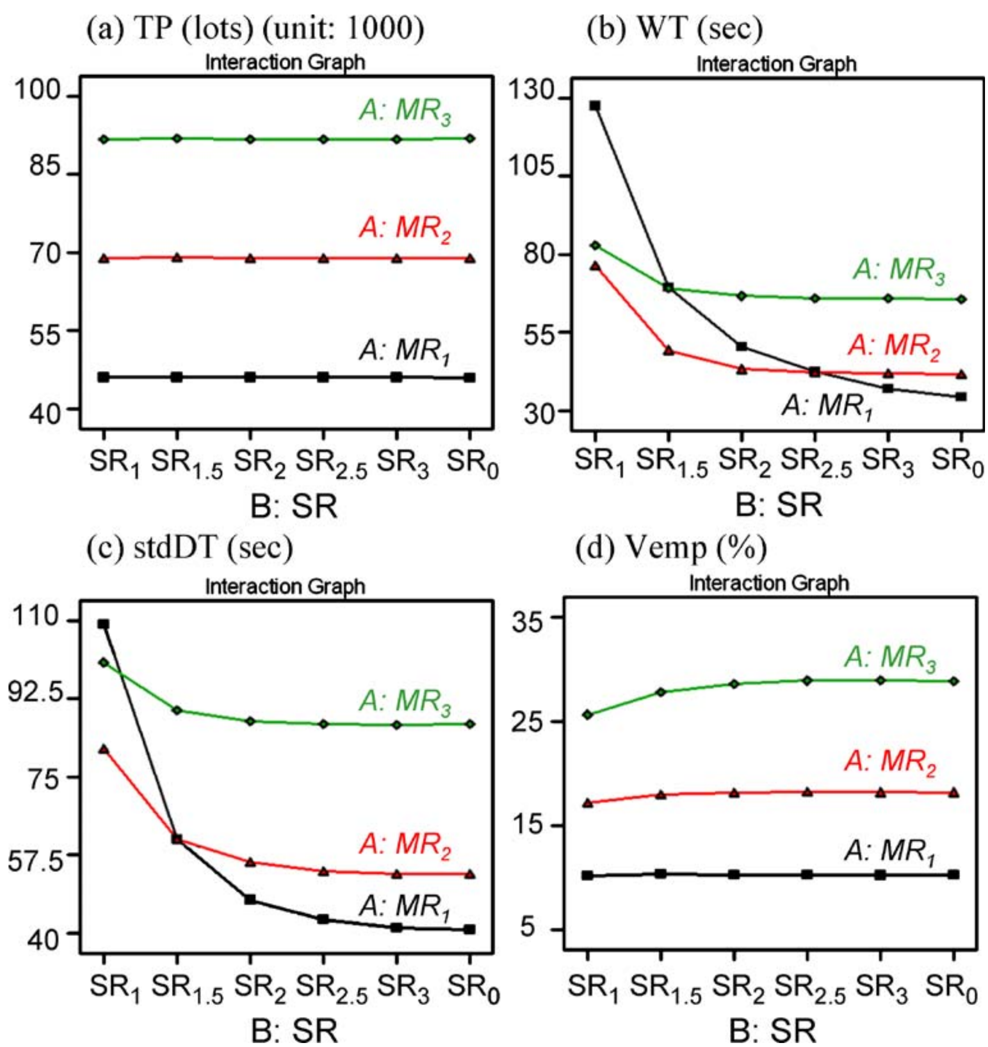


Fig. 7 The Interaction graphs of MR and SR

Table 6 Post hoc multiple comparisons in phase II experiment

MR (lots/hr)	SR	Indices							
		TP (lots)		WT (sec)		stdDT (sec)		Vemp (%)	
		rank	Mean	rank	mean	rank	mean	rank	mean
70	SR_1	A	46016.6	F	126.461	E	110.121	A	10.141
	$SR_{1.5}$	A	46016.5	E	69.673	D	60.955	C	10.296
	SR_2	A	46016.8	D	50.376	C	47.398	BC	10.251
	$SR_{2.5}$	A	46016.7	C	42.346	B	43.070	AB	10.216
	SR_3	A	46016.4	B	36.860	A	41.220	AB	10.196
	SR_0	A	45965.8	A	34.192	A	40.803	AB	10.203
105	SR_1	A	68946.5	D	76.295	D	81.238	A	17.167
	$SR_{1.5}$	A	69011.8	C	49.328	C	60.999	B	17.951
	SR_2	A	68946.9	B	43.230	B	55.840	C	18.116
	$SR_{2.5}$	A	68947.1	A	42.111	A	53.778	D	18.195
	SR_3	A	68946.7	A	41.930	A	53.278	D	18.182
	SR_0	A	68948.8	A	41.565	A	53.178	CD	18.173
140	SR_1	A	91687.7	C	82.731	C	100.732	A	25.629
	$SR_{1.5}$	A	91890.4	B	69.161	B	89.929	B	27.789
	SR_2	A	91687.9	A	66.607	A	87.376	C	28.579
	$SR_{2.5}$	A	91688.5	A	65.974	A	86.772	D	28.849
	SR_3	A	91687.6	A	65.944	A	86.638	D	28.886
	SR_0	A	91824.9	A	65.611	A	86.744	D	28.866

B[2],..., B[5] is to represent factor B: SR as SR_1, $SR_{1.5}$,..., SR_3 respectively. The code for factor B: SR is 0 or 1. The model equations also can provide guidance for practitioners in selecting the preferable setting based on the changeable environment and performance measures.

(1) TP (lot)=68958.0+22868.2*A-19.9*B[1]+69.4*B[2]−19.7*B[3]−19.4*B[4]−20.0*B[5]−81.6*A^2−32.6*AB[1]+68.8*AB[2]−32.6*AB[3]−32.3*AB[4]−32.6*AB[5]

(2) WT (sec)=49.1+4.7*A+35.7*B[1]+3.3*B[2]−6.1*B[3]−9.3*B[4]−11.2*B[5]+15.6*A^2−26.5*AB[1]−4.9*AB[2]+3.4*AB[3]+7.1*AB[4]+9.9*AB[5]

(3) stdDT (sec)=59.7+16.2*A+28.5*B[1]+1.7*B[2]−5.4*B[3]−7.7*B[4]−8.5*B[5]+13.8*A^2−20.9*AB[1]−1.7*AB[2]+3.8*AB[3]+5.6*AB[4]+6.5*AB[5]

(4) Vemp (%)=17.96%+8.94%*A−1.12%*B[1]−0.08%*B[2]+0.22%*B[3]+0.33%*B[4]+0.33%*B[5]+1.19%*A^2−1.20%*AB[1]−0.20%*AB[2]+0.22%*AB[3]+0.38%*AB[4]+0.40%*AB[5]

5 Conclusion and future research

SR assignment is an important issue in 300 mm AMHS due to the connected loops layout. A two-phase approach with simulation was used to develop an appropriate SR. In phase I, the *DVemp*'s trend showed that the number of *WF* (*f*) and *IV* (*v*) in the system will affect the *DVemp* when dispatching successfully. The *DVemp*'s distribution showed

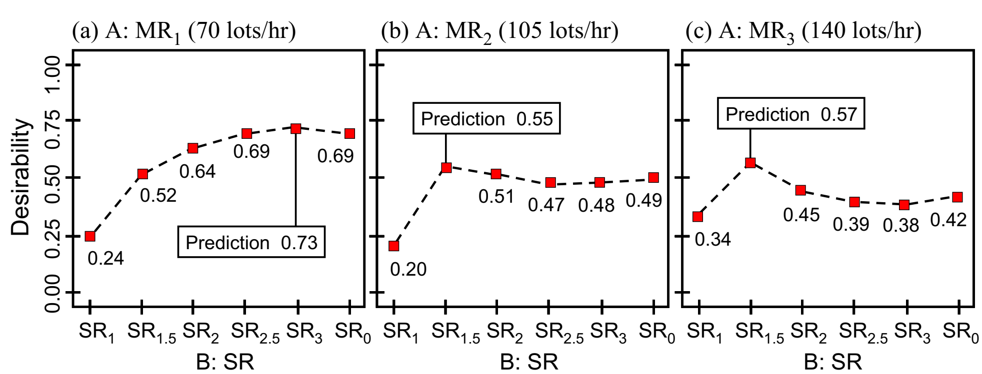


Fig. 8 The desirability of SR for each MR

that *DVemp* gathered between the intervals from −2.5σ to 3σ of the average distance of *DVemp*. Further, phase II extends this result and uses historical records obtained from phase I to design and evaluate levels of SR. The SR are designed by average *DVemp* plus multiples of standard deviation of *DVemp* under different numbers of *WF* (*f*) and *IV* (*v*) in each MR, and also to test if SR is required for dispatching (SR_0). The simulation results showed that SR affects performance significantly, and the longer SR like SR_3 is applicable in a light system such as MR_1, and in a heavy system such as MR_2 and MR_3, the shorter SR like $SR_{1.5}$ is appropriate. That also means ignoring the *WFs* or *IVs* far from *V* or *F* by assigning an appropriate SR can improve performance.

After determining the appropriate SR under different system loading, the transport performance can be further improved by using a better dispatching rule, which takes into account traffic conditions. Furthermore, the applicable dispatching rule under the SR could be researched.

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References

1. Binder H, Honold A (1999) Automation and fab concepts for 300 mm wafer manufacturing. Microelectron Eng 45(2/3):91–100
2. Kaempf U (1997) Automated wafer transport in the wafer Fab. Advanced Semiconductor Manufacturing Conference and Workshop, IEEE, pp 356–361
3. Kurosaki R, Nagao N, Komada H, Watanabe Y, Yano H (1997) AMHS for 300 mm wafer. Proc International Symposium on Semiconductor Manufacturing Conference, pp D13–D16
4. Campbell E, Ammenheuser J (2000) 300 mm factory layout and material handling modeling: Phase II report. International SEMATECH, technology transfer # 99113848B-ENG
5. Bahri N, Reiss J, Doherty B (2001) A comparison of unified vs. segregated automated material handling systems for 300 mm fabs. Proc International Symposium on Semiconductor Manufacturing Conference, pp 3–6
6. Maxwell WL, Muckstadt JA (1982) Design of automatic guided vehicle systems. IIE Trans 14(2):114–124
7. Egbelu PJ (1987) The use of non-simulation approaches in estimating vehicle requirements in an automated guided vehicle based transport system. Mater Flow 4:17–32
8. Arifin R, Egbelu PJ (2000) Determination of vehicle requirements in automated guided vehicle systems: a statistical approach. Prod Plan Control 11(3):258–270
9. Lin JT, Wang FK, Wu CK (2003a) Connecting transport AMHS in a wafer fab. Int J Prod Res 41(3):529–544
10. Wang FK, Lin JT (2004) Performance evaluation of an automated material handling system for a wafer fab. Robot Comput Integr Manuf 20(2):91–100
11. Fukunari M, Rajanna S, Gaskins RJ, Sparrow ME (2002) Data-based node penalties in a path-finding algorithm in an automated material handling system. Proc 2002 Winter Simulation Conference, pp 1383–1386
12. Bahri N, Gaskins RJ (2000) Automated material handling system traffic control by means of node balancing. Proc 2000 Winter Simulation Conference, pp 1344–1346
13. Lin JT, Wang FK, Yang CJ (2005) The performance of the number of vehicles in a dynamic connecting transport AMHS. Int J Prod Res 43(11):2263–2276
14. Lin JT, Wang FK, Wu CK (2003.b) Simulation analysis of the connecting transport AMHS in a wafer fab. IEEE Trans Semiconductor Manuf 16(3):555–564
15. Lin JT, Wang FK, Young JR (2004) Virtual vehicle in the connecting transport automated material-handling system (AMHS). Int J Prod Res 42(13):2599–2610
16. Lin JT, Wang FK, Yen PY (2001) Simulation analysis of dispatching rules for an automated interbay material handling system in wafer fab. Int J Prod Res 39(6):1221–1223
17. Wang CN, Liao DY (2003) Effective OHT dispatching for differentiated material handling services in 300 mm wafer foundry. Proceedings of the 2003 IEEE international conference on Robotics and Automation, pp 1027–1032
18. Wang CN, Liao DY (2004) Differentiated automatic materials handling services in 300 mm semiconductor foundry. Conference 2004 of Operations Research Society in Taiwan, pp 105–113
19. Lin JT, Wang FK, Chang YM (2006) A hybrid push/pull-dispatching rule for a photobay in a 300 mm wafer fab. Robot CIM-Int Manuf 22:47–55
20. Egbelu PJ, Tanchoco JMA (1984) Characterization of automatic guided vehicle dispatching rules. Int J Prod Res 22(3):359–374
21. Plant EM (2001) Objects manual, version 4.6. Tecnomatix Technologies GmbH & Co, Stuttgart, Germany
22. Montgomery DC (2001) Design and analysis of experiments. Wiley, New York
23. Myers RH, Montgomery DC (1995) Response surface methodology: process and product optimization using designed experiments. Wiley, New York
24. StatEase (2001) Design expert user's manual, version 6.04. StatEast, Minneapolis