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Optimising the location of crossovers in conveyor-based automated material handling systems in semiconductor wafer fabs

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This research presents several heuristics to optimise the location of crossovers in a conveyor-based automated material handling system (AMHS) for a semiconductor wafer fabrication facility. The objective is to determine the location of crossovers that minimises the total cost of the expected work-in-process on the conveyor and the cost of installing and operating the AMHS with the crossovers. The proposed heuristics are integrated with a queuing-based analytical model incorporating practical hardware considerations of the AMHS, such as turntables and crossovers. To illustrate the proposed heuristics' practical application they are applied to SEMATECH's virtual wafer fabrication facility. Experimental results demonstrate that under a wide variety of operating conditions and cost scenarios the local improvement heuristic is able to identify the optimal solution and outperform other commonly used heuristics for layout design such as genetic algorithms.

Keywords: wafer fabrication; AMHS; conveyors; analytical models; heuristics; crossovers; facility design

1. Introduction

In most industries, such as the semiconductor wafer manufacturing industry, the material handling system is an enabler for high-volume manufacturing. A state-of-the-art wafer fab can process between 30,000 and 100,000 wafers per month (Brown and Linden 2009). The cost to build such a wafer fab is currently \$3.5–\$4.0 billion (Myers 2007); the cost of the equipment represents approximately 80% of the total costs (Johnson 2001). In general, wafer fabrication is highly complex and automated, consisting of several hundred steps that require different types of equipment (also referred to as tools). The wafer cycle time is between 30–60 days (Brown and Linden 2009). Since they are manufactured in layers, wafers enter the same process several times during their manufacturing recipe (route), creating a re-entrant effect (Uzsoy *et al.* 1992). Consequently, each wafer can travel several hundred miles before completing its route. Most advanced wafer fabs use automated material handling systems (AMHSs) for moving and storing wafers because of their fast

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delivery speeds and high reliability. Typically, the AMHS is based on asynchronous vehicle-based overhead systems, such as overhead hoisted vehicles. Since their introduction in wafer fabs, vehicle-based AMHSs have improved equipment utilisations and increased fab productivity. For more background related to AMHS in semiconductor manufacturing, readers are referred to Agrawal and Heragu (2006).

Under the existing 300 mm technology, wafers are typically processed in groups of 25 stored in a front opening unified pod (FOUP). However, next-generation 450 mm wafer technology is expected to improve wafer cycle times by reducing the wafer lot size to no more than 12 wafers per carrier (Marshall *et al*. 2007, Bass and Wright 2008). Under these conditions, the AMHS would be required to process twice as many moves to maintain the same wafer starts per month. The problem is that existing AMHS technologies may represent a potential productivity detractor because the vehicle's delivery speed and the stocker capacity may be insufficient to meet the requirements of smaller lot size operations (SEMATECH 2009). Conveyor-based continuous flow transport (CFT) is starting to gain support with the expectations that this type of transport technology will be capable of providing high-speed, high-throughput deliveries (Pettinato and Pillai 2005). Conveyors offer some advantages over asynchronous material handling systems due to the following characteristics:

- Storage capabilities – when space is available on the conveyor, its continuous flow allows its use for storage, as opposed to sending the load to a storage unit. This eliminates loading and retrieval delays, which might lead to throughput improvement.
- High availability – in contrast to asynchronous systems, loads do not need to wait for the conveyor once a move request has been issued. Instead, loads must simply wait for a clear space on the conveyor. This eliminates the time spent waiting for vehicles. It is important to highlight that the time spent waiting for vehicles will increase dramatically as the number of move requests (and hence the number of vehicles) is increased.

Another benefit is that CFTs add local buffering near the tool. While local buffering is possible in vehicle-based AMHS, there are several drawbacks. If under track buffering locations are added, there are additional delays introduced by the loading and unloading time to place the FOUP in the under track location. If local buffering is implemented by having small track loops where vehicles can recirculate near the tool, this reduces the number of vehicles available to move FOUPs between tools. Thus, CFTs can achieve local buffering without either of these drawbacks. Local buffering reduces the average time for the transporter to deliver lots to the tool, plus reduces the need for large stockers. Previously the use of conveyors had not been widely adopted because there were concerns about the loading and unloading process. Further the motors required to power the conveyors created vibrations which if severe enough could damage the wafers. Conveyors have been criticised because they are less flexible than vehicle systems. Finally, turntables were seen as a potential bottleneck for conveyor-based system. While most of the concerns are being addressed through mechanical developments, the potential delays created by turntables have been investigated by Nazzal *et al*. (2010) and have been found to be insignificant relative to the throughput gains for a wide range of settings. For more detailed discussion of the advantages and drawbacks of using conveyors as the primary AMHS technology in future 450 mm wafer fabs, the reader is referred to Pettinato and Pillai (2005).

According to Pillai (2006), it is difficult to adapt a conveyor-based transport system into a fab using existing tools and techniques since there is a lack of work regarding the evaluation of the CFT's peak transport capabilities, as well as the integration of CFTs with high-speed stocker robots and virtual bay buffers.

2. System description

This paper considers a spine layout similar to the one illustrated in Figure 1. The spine layout is composed of bays interconnected by a central closed-loop conveyor (referred to as the interbay system). The bays, referred to as intrabay systems, are also closed-loop conveyors. There are two distinct operating scenarios: (1) the spine and the loops are decoupled using stockers, in which case lots moving between loops (or bays) require three different transportation steps and two stocker moves; or (2) the spine and the bays are integrated, where loads can freely move from the spine interbay system to the intrabay systems and vice versa, and loads moving between two loops require only a single transportation step. The results presented here address the second case, which is more general and represents the trend in most modern wafer fabs.

Figure 1 also illustrates a detailed description of the material handling system under study. The system is composed of a central unidirectional closed-loop conveyor and

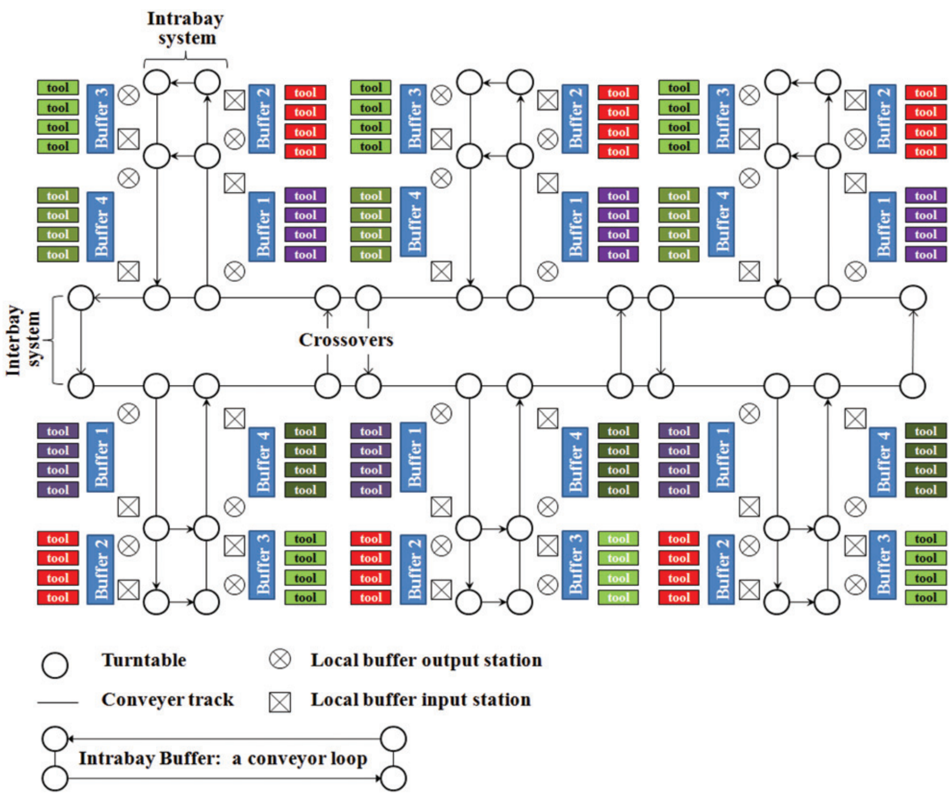

Figure 1. An illustration of the conveyor system.

N functional bays, where production tools are located. Each of the N bays is served by a unidirectional conveyor loop, each referred to as an intrabay system. The conveyor loops include crossovers, located perpendicular to the longer sides of each loop with two turntables for each crossover. Crossovers are used to reduce the travel distances of the lots. Located at the track intersections (i.e., corners of the interbay and intrabay systems, and intersections between the main path and a crossover), turntables change the lot's travelling direction by 90°. A turntable cycle consists of receiving a lot, changing the lot's direction, releasing the lot, and returning to home position. The time required to complete such a cycle is assumed to be deterministic. It is also assumed that all turntables operate at the same speed. A queue develops in front of the turntable if lots arrive to the turntable at a faster rate than the turntable cycle. Turntables are only activated when loads need to make a 90° turn, whereas loads that pass through a turntable without making the 90° turn do not experience turning delays, but they may be delayed due to the queueing effects as a result of other loads waiting to turn.

A conveyor is described in terms of its speed and length. The length can be measured in units of '*windows*'. A window is defined as the size of one lot plus a small gap on either side to allow for spacing between lots on the conveyor. Windows are of equal size provided the lots have the same dimensions as is the case with FOUPs in semiconductor manufacturing. The windows are stationary and the conveyor speed is the time required for the conveyor to move the length of one window.

Local buffers in the bays are essentially a conveyor loop that acts as a storage area for a group of tools in similar proximity, as illustrated in Figure 1. A load that is headed to one of the tools served by a local buffer is transferred to the buffer through an input station (represented by $\otimes$) and then to the tool, after the load completes processing on a tool, it goes back to the buffer and is transferred to the intrabay conveyor loop through the output station (represented by $\boxtimes$) when the first open window arrives in front of the output station. For details on the local buffering concept in the bays see Arzt and Bulcke (1999). Local buffers in the bays are assumed to have sufficient capacity so that loads are never blocked from entering the buffer. The loading time onto the conveyor is assumed to be constant and less than the conveyor cycle time. Therefore, it is assumed that the conveyor continues to move while lots are being loaded onto or unloaded from the buffers.

A wafer lot will follow a process recipe or route, which defines the sequence of tools that a lot needs to visit for processing. The demand on the material handling system is a function of both the throughput required for the fab and the routing of the lots. Such demand is modelled using 'from-to' matrices representing the average rate of moves between pairs of tools.

Crossovers decrease the wafer lot's travel distance, thus reducing the AMHS's work-in-process (WIP) and delivery time (DT). However, we note that some crossovers will provide greater benefits than others. Therefore, a ranking system is used in order to identify the crossover that results in the greatest benefit. The novelty of our approach is that we evaluate the different design alternatives based on congestion delays due to the added intersection points in addition to the traditional method of evaluating the improvement in delivery times as a result of the reduced travel distances. Analytical models of closed-loop conveyor systems have been recently proposed in Nazzal *et al.* (2010). These analytical models enable the performance evaluation of a conveyor (in terms of expected WIP and DT) at computational speeds that are significantly lower than those obtained by existing simulation methods. The application of these analytical methods allows the exploration of a larger solution space when making decisions concerning the AMHS configuration.

With this in mind, the goal of this paper is to integrate a stochastic analytical model for closed-loop conveyors with a heuristic to determine the optimal location of crossovers in a spine layout to minimise the total cost of the expected WIP on the conveyor and the cost of installing and operating the AMHS with the crossovers.

The remainder of this paper is organised as follows. Section 3 presents a review of past-published literature that is relevant to our problem. Section 4 summarises the analytical model of the conveyor-based transport system. Section 5 describes the proposed solution methodologies for determining the optimal crossover location. Section 6 describes a design of experiments using the virtual fab from SEMATECH, and reports the corresponding results of the crossover location optimisation for several different operational scenarios. Finally, Section 7 states our conclusions and briefly explains our future planned work.

3. Literature review

Several studies focus on optimising the layout in a semiconductor fabrication facility, including Meller (1997), and Ting and Tanchoco (2000, 2001). However, very few publications address the problem of determining the number and location of crossovers in semiconductor wafer fabs. Yang and Peters (1997) propose a solution procedure for the fab layout design problem with guided vehicles (i.e., optimise the location of bays using a spine layout) based on a modified quadratic set covering problem. Given a set of crossovers, the procedure determines the optimal layout for the facility. Hence, by iterating over alternative sets of crossovers, the authors are able to search for the best overall solution. Peters and Yang (1997) propose a methodology to simultaneously optimise the semiconductor fab's layout and interbay material handling system design (i.e., crossover quantities and location). The layout problem is solved using steepest descent pairwise interchange. Given a layout, the optimal number and location of crossovers are computed by solving a simple network flow formulation. Their objective function minimises the trade-off between the increase in crossover construction cost and the decrease in material handling costs. The authors consider spine and perimeter layouts. Yang *et al.* (1999) propose a hybrid tabu search-simulated annealing procedure to solve the problem in Peters and Yang (1997). Johnson *et al.* (2009) addresses determining location of crossovers in conveyor material handling systems for semiconductor wafer fabs. Their heuristic uses the analytical model from Nazzal *et al.* (2010) to determine which crossovers to incorporate using a greedy strategy. Besides these four publications, no other publications address the crossover location problem in semiconductor fabrication facilities or in the general context of closed-loop conveyors.

In Peters and Yang (1997), and Yang *et al.* (1999) the authors seek to optimise the layouts by balancing the total material handling effort and the cost of installing crossovers. However, the authors do not consider the effect that installing crossovers might have on the amount of WIP, system throughput, etc. Other authors use discrete event simulation to be able to consider these types of system behaviour. Unfortunately, simulation models are expensive to build and maintain. Also, evaluating alternatives using simulation models is time consuming. The reader is referred to Nazzal and El-Nashar (2007) for a survey of existing publications using simulation.

In this study, the analytical model for conveyor-based AMHS in semiconductor fabrication facilities from Nazzal *et al.* (2010) is used to optimise the quantity and location of crossovers. The objective is to minimise the weighted cost of the average WIP and installing crossovers. The model from Nazzal *et al.* (2010) is described in Section 4. The current paper is an extension of the work in Johnson *et al.* (2009).

4. Analytical model

The objective of this study is to develop a methodology that quantifies the impact of adding crossovers in conveyor-based material handling layouts. Given a closed-loop conveyor, this work identifies which crossovers should be added to improve the performance of the AMHS. The criteria for performance in this study are the expected work-in-process (WIP), measured in front opening unified pods (FOUPs), on the conveyor. These criteria are a function of input parameters such as the move requirements, the number of crossovers, the conveyor speed, the layout of the stations on the AMHS closed loop track, the turntables delays, and the window size for each lot.

To quantify the benefits, the overall WIP on the conveyor is estimated using the analytical model in Nazzal *et al.* (2010). This section briefly introduces the three phase analytical model from Nazzal *et al.* (2010) and how the model can be used to estimate the total expected WIP on the interbay loop and the intrabays loops.

4.1 *Phase I – no turntables*

The outcome of Phase I is an estimate of the travelling WIP on the conveyor. The approximation is based on the work of Bozer and Hsieh (2005) for the performance of closed-loop conveyors in a general manufacturing setting. Bozer and Hsieh make several assumptions that will be maintained for the models developed here. Namely:

(1) Conveyors travel at a constant speed.
(2) Move requests follow a Poisson process.
(3) No queueing of the loads is possible at pick-up and drop-off locations;
(4) The conveyor is continuous.
(5) The conveyor can be divided into equal size windows; each window holds $\leq$ one load (lot). The windows are stationary while the conveyor and FOUPs move between window locations.
(6) The conveyor is divided into segments that are not necessarily of equal size, each segment ends with a load drop-off station or an intersection point either with a crossover segment or another conveyor loop, as illustrated in Figure 2.

Define α_i to be the mean arrival rate of loads to segment i, V as the speed of the conveyor in terms of windows per time unit, and let q_i denote the probability that each window of segment i is occupied (provided that the conveyor system is stable). q_i can be calculated from the expression $q_i = \alpha_i / V$. Finally, defining S as the number of segments on the conveyor and w_i as the number of windows on segment i, the expected travelling WIP on the conveyor is estimated using the expression $WIP = \sum_{i \in S} w_i q_i$.

4.2 *Phase II – turntables analysis*

In Nazzal *et al.* (2010), turntables are analysed in pairs by considering two turntables located on the same crossover (the end of the interbay or intrabay loops can also be thought of as crossovers). Consider a crossovers cell, shown in Figure 3, which is defined

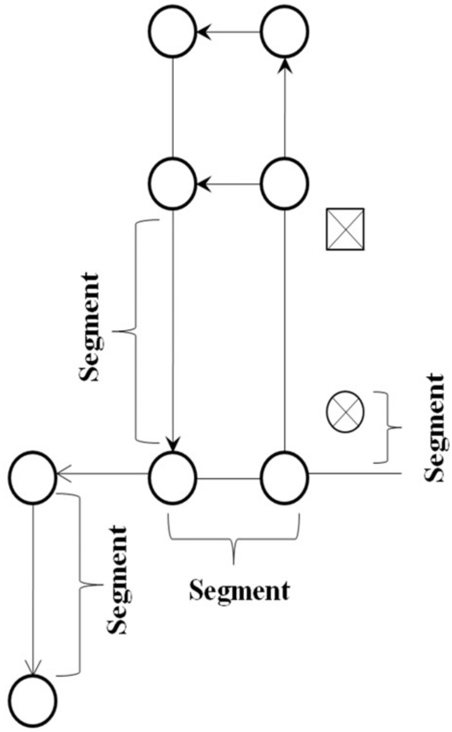

Figure 2. Conveyor segments.

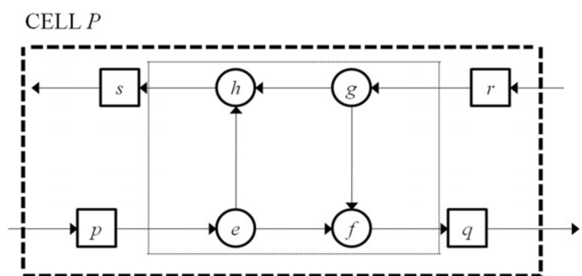

Figure 3. Cell p consists of two crossovers in opposite directions.

by the four turntables (labelled e, f, h, g), two crossovers and four intersection points (labelled p, q, r, and s). For the interbay system, the four intersections represent the four bays surrounding the cell of crossovers as shown in Figure 4. The decision to include crossovers eh and gf are made independently. For an interbay system with N bays there will be a maximum of $M-1$ cells as shown in Figure 4. Further define the set of all bays as A and the set of all cells as B.

For an intrabay system, the four intersections represent the four stations surrounding the single crossover in each bay. For example, in an intrabay system, r, s, p, and q, would represent the output station of buffer 1, the input station of buffer 2, the output station of buffer 3, and the input station of buffer 4, respectively, as illustrated in Figure 5.

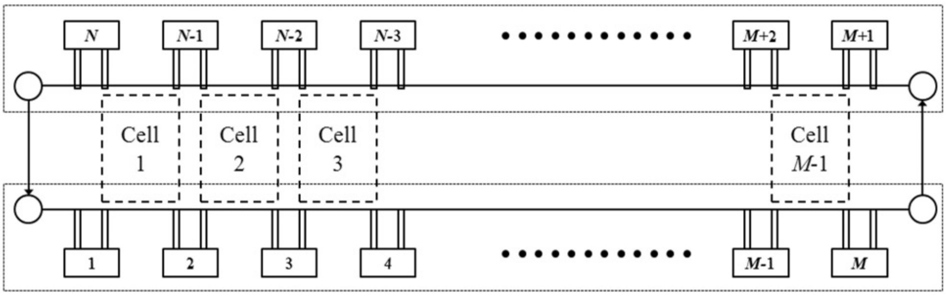

Figure 4. Cells in the system.

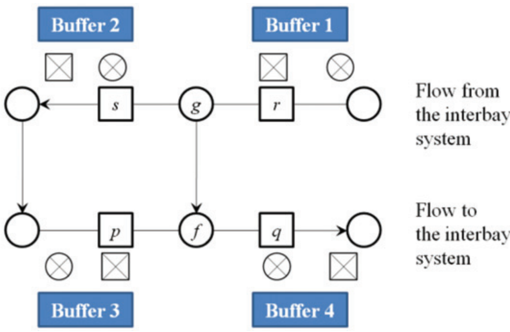

Figure 5. A cell in an intrabay system consists of one shortcut.

The following additional assumptions were made to derive the analytical model for analysing the accumulating work-in-process due to the turntables in Nazzal *et al.* (2010):

- Crossovers are analysed independently from each other, i.e., queueing effects at a crossover do not impact the arrival process of loads to downstream crossovers, nor do they impact the service process of the upstream turntables.
- Loads arrive to each crossover following a Poisson process.
- Turning time of loads is deterministic and identical for all turntables.

See Nazzal *et al.* (2010) for a further discussion of each of these assumptions.

4.2.1 *Analysis of the upstream turntable in a crossover (turntable g or e)*

Arrival rates of lots to crossovers, λ_{eh} and λ_{gf}, shown below, were estimated in Nazzal *et al.* (2010) as the average number of lots per unit time that will require travel on, respectively, crossovers eh and gf to take the shortest distance path from their origin to their destination. Define α_{ij} as the average rate of lots travelling from bay i to bay j, bay $N+1$ is bay 1, and define $U_{gf}\,(U_{eh})$ as the set of crossovers upstream of crossovers $gf\,(eh)$ and in the same direction. y_{kl} is defined as an indicator variable that crossover kl is installed ($y_{kl}=1$), or not ($y_{kl}=0$). For the interbay system, λ_{eh} and λ_{gf} can be estimated from:

$$\lambda_{eh} = \sum_{i=s+1}^{p} \sum_{j=s}^{i-1} \alpha_{ij} - \sum_{kl \in U_{eh}} \lambda_{kl} y_{kl} \tag{1}$$

$$\lambda_{gf} = \sum_{i=q+1}^{r} \sum_{j=q}^{i-1} \alpha_{ij} - \sum_{kl \in U_{eh}} \lambda_{kl} y_{kl}. \tag{2}$$

Equations (1) and (2) are executed sequentially; Equation (1) should be executed starting at cell 1 followed by cell 2 and so forth up to cell $M-1$. Equation (2) should be executed in the opposite direction; starting at cell $M-1$ and moving backwards down to cell 1.

For the intrabay systems, there is only one crossover in each bay, crossover *eh*, as illustrated in Figures 1 and 2. λ_{eh} is simply the rate of loads that will be dropped off at buffer 4, or loads originating from buffer 1 and will not subsequently visit tools in buffers 2 or 3.

The average WIP at turntables *e* and *g* was estimated via an M/D/l queue with arrival rate $\lambda_{pe} = \lambda_{eh} + \lambda_{ef}$ and $\lambda_{rg} = \lambda_{gf} + \lambda_{gh}$, respectively. The expected service time is t for a turning load and 0 for a passing load; where t is the time required by the turntable to rotate the load 90°, wait for the load to be moved off the turntable, and turn back 90° to its original position. By the Pollaczek-Khintchine formula, the expected WIP, L_e and L_g, due to turntables *e,* and *g*, respectively, are:

$$L_e = \frac{\lambda_{pe}\lambda_{eh}t^2}{2(1-\lambda_{eh}t)} + \lambda_{eh}t \tag{3}$$

$$L_g = \frac{\lambda_{rg}\lambda_{gf}t^2}{2\left(1-\lambda_{gf}t\right)} + \lambda_{gf}t. \tag{4}$$

4.2.2 *Analysis of the downstream turntable (h or f)*

The mean arrival rates of loads to segments between interbay crossovers within a cell λ_{ef} and λ_{gh} are estimated as the average number of lots per time that will travel from bays s, $s+1, \ldots, p$ to bays q, $q+1, \ldots, r$, plus – if the prior shortcut was not installed – the lots that would have travelled on the prior crossover. These are stated as:

$$\lambda_{ef} = \sum_{i=s}^{p} \sum_{j=q}^{r} \alpha_{ij} + \lambda_{gf}\left(1 - y_{gf}\right) \tag{5}$$

$$\lambda_{gh} = \sum_{i=q}^{r} \sum_{j=s}^{p} \alpha_{ij} + \lambda_{eh}(1 - y_{eh}). \tag{6}$$

For the intrabay systems, crossover *eh* carries the loads that will be dropped off at buffer 4, or loads originating from buffer 1 and will not subsequently visit tools in buffers 2 or 3, and therefore, λ_{ef} is simply the arrival rate of loads to the tools served by buffers 2, and 3.

Lots travelling on segments *ef* and *gh* are passing lots that will be delayed by the lots coming from crossovers *gf* and *eh*, respectively. Because the turning time of all turntables is deterministic, the minimum inter-arrival time to turntables *f* and *h* from the crossover (by the turning lots) is *t,* the turning delay. Therefore, the passing lots on segments *ef* and *gh* will wait between 0 and *t* depending on the probability of finding the turntable occupied by a turning lot (utilisation of the turntable) and the remaining turning time for the lot

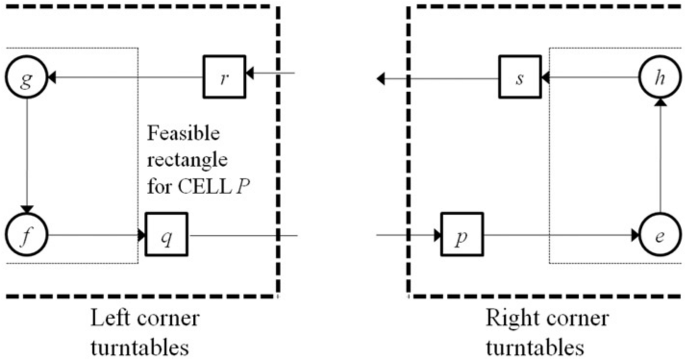

Figure 6. Illustration of corner turntables.

blocking their path. Defining C_s^2 as the coefficient of variation of turning time, the average remaining service time, $E(t_r)$, of a turning lot as seen by a randomly arriving passing lot is $E(t_r) = (t)(C_s^2 + 1)/2$. Since turning times are deterministic, $C_s^2 = 0$ and thus, $E(t_r) = t/2$. The expected service (busy) time of turntables f and h, is the proportion of loads that turn multiplied by the turning time. Therefore, the expected WIP due to turntables f and h is:

$$L_f = \frac{\lambda_{gf}^2 t^2}{2} + \lambda_{gf} t \tag{7}$$

$$L_h = \frac{\lambda_{eh}^2 t^2}{2} + \lambda_{eh} t. \tag{8}$$

Analysis of the turntables located at the corners of a conveyor loop are a special case of Equations (3), (4), (7), and (8) with, $\lambda_{ef} = \lambda_{gh} = 0$, as shown in Figure 6.

4.2.3 *Analysis of the entrance and exit turntables into and out of each bay*

When a load enters or exits an intrabay system, turntables must be activated to make the 90° turn into the bay. Analysis of accumulating WIP due to these turntables is based on the same queueing formulae utilised in the previous sections. The entrance turntable, turntable s or q in Figure 3, is analysed as M/D/1 queueing systems with two types of arrivals. The expected service time is t for a turning load and 0 for a passing load. Define λ_s as the rate of loads arriving to turntable s, and λ_i as the rate of loads visiting bay I, then by the Pollaczek-Khintchine formula, the expected WIP L_s due to turntable s is:

$$L_s = \frac{\lambda_s \lambda_i t^2}{2(1 - \lambda_i t)} + \lambda_i t. \tag{9}$$

Similarly, the exit turntable, turntable r or p in Figure 3 is analysed as M/D/1 queueing systems with two types of arrivals. Further, define λ_r as the rate of all loads arriving at turntable r, and λ_i is the rate of loads visiting bay I, then similarly by the Pollaczek-Khintchine formula, the expected WIP L_r due to turntable r is:

$$L_r = \frac{\lambda_r \lambda_i t^2}{2(1 - \lambda_i t)} + \lambda_i t. \tag{10}$$

The equivalent equations for the expected delays due to turntables can be calculated by applying Little's law to the formulae above. For more details on the derivation of Equations (1)–(8) and the equations for expected delays due to turntables the reader is referred to Nazzal *et al*. (2010).

4.3 *Phase III – estimating total expected WIP*

Nazzal *et al*. (2010) estimate the expected WIP on the conveyor as:

$$\begin{aligned} \mathrm{WIP_{conv}} = {} & \underbrace{\sum_{i\in S} w_i q_i}_{\text{travelling WIP}} + \underbrace{\sum_{\forall (e,h)\in M} (L_e + L_h)\, y_{eh}}_{\substack{\text{accumulated WIP due to}\\ \text{turntables } e \text{ and } h \text{ in each cell}\\ \text{on the interbay including corners}}} + \underbrace{\sum_{\forall (g,f)\in M} \left(L_g + L_f\right) y_{gf}}_{\substack{\text{accumulated WIP due to}\\ \text{turntables } g \text{ and } f \text{ in each cell}\\ \text{on the interbay including corners}}} \\ & + \underbrace{\sum_{\forall (e,h)\in N} (L_e + L_h)\, y_{eh}}_{\substack{\text{accumulated WIP due to}\\ \text{turntables } e \text{ and } h \text{ in each bay}\\ \text{including corner turntables}}} + \underbrace{\sum_{\forall (s,r)\in N} (L_s + L_r)}_{\substack{\text{accumulated WIP due to}\\ \text{entrance and exit turntables}\\ \text{for each bay}}} . \end{aligned} \tag{11}$$

The first term is the travelling WIP on every segment i in the conveyor. S is the set of segments in the conveyor network, summing all the estimated WIP travelling on each window w_i. The second and third terms are the accumulating WIP due to the crossovers in each cell on the interbay system including the corner turntables. The fourth term is the accumulating WIP due to the crossovers in each intrabay system including the corner turntables. The fifth term is the accumulating WIP due to the entrance and exit turntables for each bay. The detailed expressions for the WIP are given in Equations (3), (4), (7), (8), (9), and (10). The term y_i is the indicator (0,1) variable activated if crossover i is installed. The third term is the expected WIP accumulating due to the crossover in each of the N bays.

4.4 *Model validation*

A simulation model of a virtual fab developed by International SEMATECH was used in Nazzal *et al*. (2010) for validating the analytical model. A numerical study was conducted to evaluate the analytical model over a wide range of operating scenarios. The authors investigated the impact of the following factors: structure of the from-to matrix, coefficient of variation of move requests arrival process, the volume of move requests, and the speed of the conveyor and turntable delay. Validation was performed for the average delays at each turntable and for the overall work-in-process on the conveyor given in Equation (9). The relative error in estimating the turntable delays under extreme experimental conditions averaged less than 8% and the relative error in estimating the expected work-in-process on the conveyor was less than 7%. Details of the validation numerical study can be found in Nazzal *et al*. (2010).

5. Optimising crossovers

The use of crossovers in a conveyor-based material handling system will reduce the wafer lot's travel time. Ultimately, their application will contribute towards reducing WIP and cycle time, as well as increasing equipment utilisations. However, these benefits must be traded off against the costs associated with constructing and maintaining the crossovers. Thus, the objective of the crossover placement problem could be expressed as minimising the weighted sum of the WIP cost and crossover costs. The weights indicate the ratio of the cost of the crossover relative to a unit of WIP. This ratio can vary widely depending on the particular fab configuration. For instance, the unit cost of WIP, measured in FOUPs, would be lower in a fab operating under a 12-wafer-lot policy than under a 25-wafer-lot policy. Thus, in this paper, a variety of different values are investigated to characterise the robustness of the proposed methods to changes in this weight. One could find the optimal set of crossovers to be installed by evaluating all possible combinations of crossovers with the model from Nazzal *et al.* (2010). For the problem under study, this implies to consider 2^n combinations, where n is the number of potential locations for crossovers. Clearly, exhaustive enumeration becomes computationally expensive for large instances of the problem. To address this issue, several heuristics are proposed in the next sections.

5.1 *Local improvement heuristic*

The first proposed heuristic is a *local improvement heuristic*. This heuristic takes into consideration the symmetrical configuration of the fab's spine layout. The reader should note that most interbay systems are designed to partition the fab into two equal parts. For instance, the layout shown in Figure 1 contains six bays; three bays are located in the upper part of the layout and the same number of bays is located in the bottom. The local improvement heuristic selects and evaluates the most promising combinations of crossovers based on achieving a relative balance of flow from each side of the spine. If the balance of material moving from any given bay to any other given bay is relatively equal for all bays, this minimises congestion within a material handling system. However, in semiconductor manufacturing, a perfect balance is not feasible because process routes are very long including hundreds of steps and processing equipment are grouped in bays in order to maximise equipment utilisation and minimise maintenance costs.

The local improvement algorithm is applied for all values $k = 1, \dots, n$ where n is the number of potential locations for crossovers and k is the number of crossovers that are installed, thus this aspect is an exhaustive search. For a value of k in a specific iteration:

Step 1: Given k crossovers, $k/2$ crossovers will go from the bottom of the spine to the top and the remainder from the top to the bottom of the spine. When k is odd, we round up k/2, denoted by $\lceil k/2 \rceil$. Define $n_{\text{down}} = \lceil k/2 \rceil$ as the number of crossovers that will connect the top to the bottom of the spine (i.e., crossovers in a downward direction). The remaining $n_{\text{up}} = k - n_{\text{down}}$ crossovers will connect the bottom to the top of the spine (i.e., crossovers in an upward direction).

Step 2: Using Equation (11), evaluate all possible combinations of the n_{down} crossovers and select the best location for these crossovers.

Step 3: Given the optimal location of the downward crossovers, find the optimal location of the n_{up} upward crossovers through exhaustive search.

Step 4: Begin an upward search by redefining $n_{\text{down}} = n_{\text{down}} + 1$, the number of crossovers from the bottom is $k - n_{\text{down}}$ because the value of k is constant for the iteration.

Repeat Steps 3–4 until the solution resulting from increasing n_{down} does not yield an improvement.

Step 5: Begin a downward search with $n_{\text{up}} = k - \lceil k/2 \rceil$. Repeat Steps 2, 3, and 5 until the solution resulting from increasing n_{up} does not yield an improvement.

5.2 *A modified ranking heuristic*

This greedy heuristic is modified from the heuristic algorithm in Johnson *et al.* (2009) for determining the set of crossovers to include in the layout:

Step 1: Start with a conveyor system without any crossovers.

Step 2: Using Equation (11), evaluate the effects of adding each crossover independently. Rank the crossovers according to their impact identifying the best crossover to add to the system. The ranking of crossovers is determined as the relative improvement in WIP comparing a layout with no crossovers to a layout with only the crossover under consideration being included.

Step 3: Identify the highest ranked remaining crossover. If the marginal impact of adding the crossover exceeds the cost of constructing such a crossover, go to Step 4; otherwise STOP as the heuristic procedure has terminated.

Step 4: The heuristic recommends adding this crossover. Eliminate the crossover from the ranking and return to Step 2.

The modified ranking heuristic recalculates the ranking list after the selection of each crossover, whereas Johnson *et al.*'s heuristic uses one ranking list. The modified ranking heuristic outperforms Johnson *et al.*'s heuristic; however, requires a longer calculation time.

5.3 *Genetic algorithm-based heuristic*

The genetic algorithm (GA) is a metaheuristic based on the mechanics of natural selection and natural genetics (Goldberg 1989). GAs were developed by John Holland and his colleagues in the 1970s. In a GA, the solution space must be encoded to a binary representation. A set of candidate solutions is generated and variants are developed using various standard operators (e.g., selection, mating, mutation). The quality of a solution is obtained by evaluating the fitness function.

In the context of our problem, the solution space is encoded to represent all the possible crossover locations. A value of '1' signifies that the crossover exists, while a value of '0' implies that the crossover does not exist. The search space is all possible combinations of layouts (2^n). The fitness of a candidate solution can be obtained using the analytical model described in Equation (11).

The GA scheme used to search different machine configurations is similar to the one presented in Heragu (1997) and is described as follows:

Step 0: Select the maximum number of individuals in the population P and the maximum number of generations G. *G*enerate P solutions for the first generation's population randomly, and represent each solution as a string. Set generation counter $N_{\text{gen}} = 1$.

Step 1: Determine the fitness of each solution in the current generation's population and record the string that has the best fitness.

Step 2: Generate solutions for the next generation's population as follows:

(1) Retain 0.2 P of the solutions with the best fitness in the previous population (selection);
(2) Generate 0.75 P solutions via crossover;
(3) Select 0.05 P solutions from the previous population randomly and mutate them.

Step 3: Update $N\text{gen} = N\text{gen} + 1$. If $N\text{gen} \leq G$, go to Step 1. Otherwise, STOP.

The mating operator used in Step 2.2 was a single point crossover. On the other hand, the mutation operator used in Step 2.3 was to toggle one of the bits. After exhaustive experimentation it was concluded that for the crossover location problems, P should to be set to 100, while G should be set to 25.

6. Application of the analysis to a semiconductor wafer fab

6.1 *SEMATECH layout*

A virtual fab model developed by International SEMATECH (SEMATECH, 2002) is used to compare the proposed heuristics. This model is a representation of a 300 mm wafer fab. The product family modelled is SEMATECH's 300 mm aluminium process flow for 180 nm technology, consisting of six metal layers and 21 masks. The release rate is 20,000 wafers per month (wpm). The processing route consists of approximately 316 processing steps. In addition, there are 60 different workstations and about 300 tools. A lot can hold 25 wafers. The SEMATECH model has 24 bays arranged using a spine layout configuration similar to the layout previously shown in Figure 1. Bays are connected by a unified conveyor system. Four virtual bay buffers are located in each of the 24 bays, as shown in Figure 1. Each buffer has an input and an output port, and is capable of storing wafers for up to six tools within the same bay.

Details concerning the processing steps are implicitly represented by the number of move requests received by the conveyor system (i.e., from-to matrices). We use both the stated parameters for the SEMATECH model and modified some parameters to perform our study under different types of operating scenarios. The utilisation of the bottleneck tool in the fab is set to 97% by changing the release rate of the wafer lots. The factors modified in this study include the move request rates (factor 1) and the ratio of the conveyor speed to the turntable speed (Factor 2).

The description for each factor is summarised as follows:

- Factor 1: *expected rate of move requests.*
  This factor indicates the structure of moves requests matrix between each pair of bays. Three different from-to matrices are considered (i.e., A, B, C). Scenario A has the same from-to matrix as SEMATECH process flow, scenario B is similar to scenario A with heavier traffic requiring longer travel distances, and scenario C is an extreme scenario where the move requests are uniformly distributed among all stockers (i.e., every stocker sends the same number of lots to every other stocker).

- Factor 2: *conveyor speed/turntable rotation time*.
  This factor is a combination of two conveyor settings; the conveyor speed and turntable turning time. Two cases are considered, fast and slow. For the slow case, the conveyor speed is 0.305 ft/s and the turntable cycle time is 7 seconds. For the fast case, the conveyor speed is 1.0 ft/s and the turntable cycle time is 5 seconds.

6.2 *Comparison of methods*

We implemented all proposed solution methodologies using Visual Basic for Applications (VBA) and Microsoft Excel 2007. The program runs on Microsoft Windows 7 (64 bits, 6 GB memory, Dual-core 2.50 Ghz). The experiments compare four algorithms: exhaustive enumeration, local improvement heuristic, ranking algorithm (Johnson *et al*. 2009), and the GA-based heuristic. All six combinations of the two factors described above are evaluated. Several different values were considered for the cost weight defined as the ratio of the cost of a crossover to the cost of one lot of wafers: 0.001, 0.01, 0.75, 1, 10, and 100. Figure 1 in the Appendix shows the optimal cost as a function of the number of crossovers (optimally placed) for each cost weight. This figure is one way to characterise the shape of the cost curve.

The various algorithms are compared on the basis of four measures:

(1) A proxy for cost calculated as: number of crossovers $*$ weight $+$ average WIP of best solution.
(2) An optimality gap of the solution compared to the optimal solution: $\%opt_{\mathrm{best}}$.
(3) The run time in seconds to obtain the solution: $run\ time_{\mathrm{best}}$.
(4) Given the stochastic nature of a GA, five runs were conducted and average results are reported as: Z_{ave}, $\%opt_{\mathrm{ave}}$, and $run\ time_{\mathrm{ave}}$.

6.3 *Results*

6.3.1 *Interbay system crossovers design*

We present all of the experimental results in Tables I–VI and Figures I–IV in the Appendix. Both the local improvement heuristic and the GA-based heuristic perform well consistently. The ranking heuristic performance deteriorates when the cost related to the crossover is large relative to the cost of WIP. Table 1 presents one instance of the results. Figure 7 illustrates the optimal location of the crossover; each square represents a potential crossover location: a black-filled square indicates that a crossover should be installed.

The solution shown in Figure 7 provides several useful insights. First, as the conveyor rotates in a counter clockwise direction, most downward crossovers are located on the left-hand side of the layout, and in contrast, most upward crossovers are located on the right-hand side of the layout. When the turntables speed and the conveyor speed are slower, crossovers are more valuable. Thus solutions under the slow setting typically have more crossovers. Furthermore, the number of downward crossovers is almost equal to the number of upward crossovers. This balance allows the local improvement heuristic to be effective. Figures I–IV summarise the results when the weight is varied between

Table 1. Results of scenario A, fast conveyor setting, and weight of 1.00 in the objective.

Weight 1	Z_{best}	$\%opt_{\text{best}}$	Z_{ave}	$\%opt_{\text{ave}}$	*Run* $time_{\text{best}}$	*Run* $time_{\text{ave}}$	#crossovers
Exhaustive enumeration	48.41	–	–	–	15494	–	7
Modified ranking heuristic	48.41	0.00%	–	–	8	–	7
Local improvement heuristic	48.41	0.00%	–	–	100	–	7
GA-based heuristic	48.41	0.00%	48.44	0.05%	62	62	7

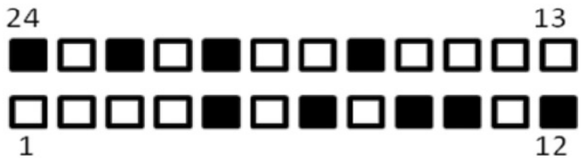

Figure 7. Optimal locations of the crossovers (denoted as a black-filled box) for scenario A, fast conveyor setting, and weight of 1.00.

0.001 and 100. When the weight is 0.001 all crossovers are included. Whereas, when the weight is 100 none of the crossovers is included[1]. For values in-between the extremes, the algorithms determine the number of crossovers and their locations:

- **Computational performance**. The exhaustive enumeration method requires between 15,248 and 15,780 seconds to solve. The ranking algorithm can shorten the computational time, but the solution quality is poor relative to the other methods. The two remaining heuristics experience similar computational times, in the order of 60–101 seconds.
- **Solution quality**. The exhaustive enumeration method is always optimal by definition. The ranking algorithm produces good results in scenarios A and C; however, for the heavy traffic scenario (i.e., scenario B) the performance is highly variable. The local improvement heuristic produces solutions within 0.0–9.0% optimality gap (mostly 0.0, only three instances show 0.1%, 0.3% and 9.0% opt gap in scenario B). The GA-based heuristic produces good solutions over all scenarios with a 0.0–1.0% opt gap.

The local improvement heuristic is more likely to identify the optimal solution; however, the GA-based heuristic has a similar average performance with a lower variation than the local search heuristic. Based on the experimental results either of these methods is appropriate for locating crossovers in a conveyor-based semiconductor wafer fab. The proposed local search heuristic is expected to deteriorate as the number of potential crossovers increases. However, additional divisions of the material handling system can be used to partially address this issue. The problem size studied is representative of a typical scenario in a semiconductor wafer fab. As wafer fabs continue to grow in size and complexity, the value of heuristic for design purposes will become even more valuable. In the material handling design process, typically the designer will go through a significant number of alternative designs, thus methods that allow the designer to estimate important characteristics reasonably accurately and fast are desirable.

Table 2. Results of locating intrabay crossovers.

	Weight	0.001	0.01	0.75	1	10	100
Fast	Scenario A	all	all	Bays 22, 5	none	none	none
converyor	Scenario B	all	all	Bays 24, 22, 5	none	none	none
setting	Scenario C	all	all	none	none	none	none
Slow	Scenario A	all	all	Bays 1, 22, 21, 5	Bays 22, 21, 5	none	none
converyor	Scenario B	all	all	Bays 1, 24, 22, 5	Bays 24, 22, 5	none	none
setting	Scenario C	all	all	none	none	none	none

6.3.2 *Locating crossovers in the intrabay systems*

Based on the discussion of locating crossovers in the intrabay system in Sections 4.2.1 and 4.2.2, we evaluate the benefit of a crossover using the same set of weights that was used for the interbay system: 0.001, 0.01, 0.75, 1, 10, and 100. The results in Table 2 present the bays where a crossover should be located for each weight value and each layout scenario at each speed setting.

The results for locating the crossovers in each of the 24 bays indicate that, as expected, the reduction in the work-in-process as a result of adding a crossover are lower at faster conveyor settings than at the slower settings.

7. Conclusion and future research

This study presented a local search heuristic and a genetic algorithm-based heuristic for identifying the locations for a set of crossovers in a closed-loop conveyor-based AMHS in semiconductor wafer fabrication facilities. The local search heuristic takes advantage of the typical layout used in semiconductor wafer fabs to find the optimal solution to the crossover placement problem. A wide variety of scenarios were investigated to demonstrate that the proposed local search heuristic and an adapted genetic algorithm can produce optimal or near optimal crossover locations in terms of balancing costs and WIP on the conveyor and delays caused by turntables.

Further research could investigate the utility of these heuristics integrated with the analytical model to generate a robust design of the conveyor network. Specifically, the selection of crossover locations allows the AMHS network to be designed to address trades-offs between construction costs and WIP costs while being specific to conveyors. This contribution builds to the goal of being able to design a network for a conveyor-based AMHS that is optimal among a wide variety of potential layouts, thus allowing a fair comparison against the vehicle-based material handling networks which also have been optimised over a large set of potential layouts.

Note

1. Crossovers 12 and 24 are included in all solutions because they are necessary to form the loop.

References

Agrawal, G. and Heragu, S., 2006. A survey of automated material handling systems in 300 mm SemiconductorFabs. *IEEE Transactions on Semiconductor Manufacturing*, 19, 112–120.

Arzt, T. and Bulcke, F., 1999. A new low cost approach in 200 mm and 300 mm AMHS. *Semiconductor Fabtech, Edition*, 10, 19–26.

Bass, E. and Wright, R., 2008. Modeling semiconductor factories for equipment and cycle time reduction opportunities. *Future Fab International*, 24, 50–55.

Bozer, Y.A. and Hsieh, Y-J., 2005. Throughput performance analysis and machine layout for discrete-space closed-loop conveyors. *IIE Transactions*, 37 (1), 77–89.

Brown, C. and Linden, G., 2009. *Chips and change: how crisis reshapes the semiconductor industry*. Cambridge, MA: MIT Press.

Goldberg, D.E., 1989. *Genetic algorithms in search, optimization and machine learning*. Reading, MA: Addison-Wesley.

Heragu, S., 1997. *Facilities design*. 1st ed. Boston, MA: PWS.

Johnson, A.L., *et al*., 2009. A greedy heuristic for locating crossovers in conveyor-based AMHS. *In*: M.D. Rossetti, *et al*., eds. *Proceedings of the 2009 winter simulation conference*, 13–16 December, 1667–1676.

Johnson, C., 2001. Automated reticle delivery in a 300 mm fab. *Semiconductor International*, 24 (6), 99–106.

Marshall, L., Rust, K., and Schmidt, K., 2007. 30 mm prime gaps that need to be addressed to boost productivity. In: *Proceedings of the international symposium on semiconductor manufacturing (ISSM 2007)*, 15–17 October, Santa Clara, CA, 1–4.

Meller, R.D., 1997. The multi-bay manufacturing facility layout problem. *International Journal of Production Research*, 35 (5), 1229–1237.

Myers, S., 2007. The 450 mm debate. *Semiconductor International*, 30 (2), 61–63.

Nazzal, D. and El-Nashar, A., 2007. Survey of research in modeling conveyor-based automated material handling systems in wafer fabs. *In*: *Proceedings of the 2007 winter simulation conference*, Washington DC: IEEE Press, 1781–1788.

Nazzal, D., *et al*., 2010. An analytical model for conveyor-based material handling system with crossovers in semiconductor wafer fabs. *IEEE Transactions on Semiconductor Manufacturing*, 23 (3), 468–476.

Peters, B.A. and Yang, T., 1997. Integrated facility layout and material handling system design in semiconductor fabrication facilities. *IEEE Transactions on Semiconductor Manufacturing*, 10 (3), 360–369.

Pettinato, J.S. and Pillai, D., 2005. Technology decisions to minimize 450 mm wafer size transition risk. *IEEE Transactions on Semiconductor Manufacturing*, 18 (4), 501–509.

Pillai, D., 2006. The future of semiconductor manufacturing. *IEEE Robotics and Automation Magazine*, 13 (4), 16–24.

SEMATECH, 2002. Fab simulation modeling software [online]. Available from: http://ismi.sematech.org/modeling/simulation/index.htm#models [Accessed 18 March 2010].

SEMATECH, 2009. *Unified 450 mm/NGF guidelines* [online]. Available from: http://ismi.sematech.org/research/450/docs/450_NGF Factory Vision and Unified Guidelines.pdf [Accessed 18 March 2010].

Ting, J.H. and Tanchoco, J.M., 2000. Unidirectional circular layout for overhead material handling systems. *International Journal of Production Research*, 38 (16), 3913–3936.

Ting, J.H. and Tanchoco, J.M., 2001. Optimal bidirectional spine layout for overhead material handling systems. *IEEE Transactions on Semiconductor Manufacturing*, 14 (1), 57–64.

Uzsoy, R., Lee, C.Y., and Martinvega, L.A., 1992. A review of production planning and scheduling models in the semiconductor industry part 1: system characteristics, performance evaluation and production planning. *IIE Transactions*, 24 (4), 47–60.

Yang, T. and Peters, B.A., 1997. A spine layout design method for semiconductor fabrication facilities containing automated material-handling systems. *International Journal of Operations and Production Management*, 17 (5), 490–501.

Yang, T., Rajasekharan, M., and Peters, B.A., 1999. Semiconductor fabrication facility design using a hybrid search methodology. *Computers and Industrial Engineering*, 36 (3), 565–583.

Appendix

Table AI. Results for low conveyor speed and scenario A.

	Z_{best}	$\%opt_{best}$	Z_{ave}	$\%opt_{ave}$	*Run* $time_{best}$	*Run* $time_{ave}$	#crossovers
Weight 0.001							
Exhaustive enumeration	96.07	–	–	–	15396	–	20
Modified ranking heuristic	96.07	0.00%	–	–	15	–	20
Local improvement heuristic	96.07	0.00%	–	–	95	–	20
GA-based heuristic	96.07	0.00%	96.07	0.00%	61	62	20
Weight 0.01							
Exhaustive enumeration	96.25	–	–	–	15396	–	20
Modified ranking heuristic	96.25	0.00%	–	–	15	–	20
Local improvement heuristic	96.25	0.00%	–	–	95	–	20
GA-based heuristic	96.25	0.00%	96.25	0.00%	59	59	20
Weight 0.75							
Exhaustive enumeration	108.85	–	–	–	15396	–	15
Modified ranking heuristic	108.85	0.00%		–	13	–	15
Local improvement heuristic	108.85	0.00%		–	95	–	15
GA-based heuristic	108.85	0.00%	108.95	0.09%	60	60	15
Weight 1							
Exhaustive enumeration	112.50	–	–	–	15396	–	14
Modified ranking heuristic	112.50	0.00%	–	–	13		14
Local improvement heuristic	112.50	0.00%	–	–	95	–	14
GA-based heuristic	112.50	0.00%	112.50	0.00%	60	60	14
Weight 10							
Exhaustive enumeration	166.04	–	–	–	15396	–	3
Modified ranking heuristic	167.80	1.06%	–	–	5	–	3
Local improvement heuristic	166.04	0.00%	–	–	95	–	3
GA-based heuristic	166.04	0.00%	166.39	0.21%	60	60	3
Weight 100							
Exhaustive enumeration	259.61	–	–	–	15396	–	0
Modified ranking heuristic	259.61	0.00%	–	–	2	–	0
Local improvement heuristic	259.61	0.00%			95	–	0
GA-based heuristic	259.61	0.00%	259.61	0.00%	59	59	0

Table AII. Results for high conveyor speed and scenario A.

	Z_{best}	$\%opt_{best}$	Z_{ave}	$\%opt_{ave}$	*Run* $time_{best}$	*Run* $time_{ave}$	#crossovers
Weight 0.001							
Exhaustive enumeration	36.37	–	–	–	15494	–	20
Modified ranking heuristic	36.37	0.00%	–	–	15	–	20
Local improvement heuristic	36.37	0.00%	–	–	100	–	20
GA-based heuristic	36.37	0.00%	36.37	0.00%	60	61	20
Weight 0.01							
Exhaustive enumeration	36.55	–	–	–	15494	–	19
Modified ranking heuristic	36.55	0.00%	–	–	14	–	19
Local improvement heuristic	36.55	0.00%	–	–	100	–	19
GA-based heuristic	36.55	0.00%	36.55	0.00%	61	61	19
Weight 0.75							
Exhaustive enumeration	46.49	–	–	–	15494	–	9
Modified ranking heuristic	46.49	0.00%	–	–	10	–	9
Local improvement heuristic	46.49	0.00%	–	–	100	–	9
GA-based heuristic	46.49	0.00%	46.50	0.02%	61	62	9
Weight 1							
Exhaustive enumeration	48.41		–	–	15494	–	7
Modified ranking heuristic	48.41	0.00%	–	–	8	–	7
Local improvement heuristic	48.41	0.00%	–	–	100	–	7
GA-based heuristic	48.41	0.00%	48.44	0.05%	62	62	7
Weight 10							
Exhaustive enumeration	72.90	–	–	–	15494	–	2
Modified ranking heuristic	72.90	0.00%	–	–	4	–	2
Local improvement heuristic	72.90	0.00%	–	–	100	–	2
GA-based heuristic	72.90	0.00%	73.32	0.58%	61	61	2
Weight 100							
Exhaustive enumeration	120.30	–	–	–	15494	–	0
Modified ranking heuristic	120.30	0.00%	–	–	2	–	0
Local improvement heuristic	120.30	0.00%	–	–	100	–	0
GA-based heuristic	120.30	0.00%	120.30	0.00%	61	61	0

Table AIII. Results for low conveyor speed and scenario B.

	Z_{best}	$\%opt_{\text{best}}$	Z_{ave}	$\%opt_{\text{ave}}$	*Run* $time_{\text{best}}$	*Run* $time_{\text{ave}}$	#crossovers
Weight 0.001							
Exhaustive enumeration	96.68	–	–	–	15258	–	20
Modified ranking heuristic	96.68	0.00%	–	–	15	–	21
Local improvement heuristic	96.68	0.00%	–	–	85	–	20
GA-based heuristic	96.68	0.00%	96.68	0.00%	62	62	20
Weight 0.01							
Exhaustive enumeration	96.86	–	–	–	15258	–	20
Modified ranking heuristic	96.87	0.01%		–	15	–	21
Local improvement heuristic	96.86	0.00%	–	–	85	–	20
GA-based heuristic	96.86	0.00%	96.86	0.00%	62	62	20
Weight 0.75							
Exhaustive enumeration	109.52	–	–	–	15258	–	16
Modified ranking heuristic	110.83	1.19%	–	–	14	–	18
Our heuristic	109.65	0.12%	–	–	85	–	17
Modified GA	109.52	0.00%	109.96	0.41%	63	62	16
Weight 1							
Exhaustive enumeration	113.52	–	–	–	15258	–	16
Modified ranking heuristic	115.33	1.59%	–	–	14	–	18
Local improvement heuristic	113.81	0.26%	–	–	85	–	15
GA-based heuristic	113.52	0.00%	113.52	0.00%	63	63	16
Weight 10							
Exhaustive enumeration	170.69			–	15258	–	4
Modified ranking heuristic	195.59	14.59%		–	8	–	6
Local improvement heuristic	170.69	0.00%	–	–	85	–	4
GA-based heuristic	170.69	0.00%	170.69	0.00%	63	63	4
Weight 100							
Exhaustive enumeration	351.32	–	–	–	15258	–	2
Modified ranking heuristic	597.96	70.20%		–	6	–	4
Local improvement heuristic	351.32	0.00%		–	85	–	2
GA-based heuristic	351.32	0.00%	354.73	0.97%	63	63	2

Table AIV. Results for high conveyor speed and scenario B.

	Z_{best}	$\%opt_{\text{best}}$	Z_{ave}	$\%opt_{\text{ave}}$	*Run* $time_{\text{best}}$	*Run* $time_{\text{ave}}$	#crossovers
Weight 0.001							
Exhaustive enumeration	37.29	–	–	–	15780	–	20
Modified ranking heuristic	37.29	0.00%	–	–	15	–	21
Local improvement heuristic	37.29	0.00%	–	–	101	–	20
GA-based heuristic	37.29	0.00%	37.29	0.00%	60	60	20
Weight 0.01							
Exhaustive enumeration	37.46	–	–	–	15780	–	19
Modified ranking heuristic	37.47	0.03%	–	–	15	–	20
Local improvement heuristic	37.46	0.00%	–	–	101	–	19
GA-based heuristic	37.46	0.00%	37.46	0.00%	60	60	19
Weight 0.75							
Exhaustive enumeration	47.57	–	–	–	15780	–	9
Modified ranking heuristic	49.38	3.81%	–	–	12	–	12
Local improvement heuristic	47.57	0.00%	–		101	–	9
GA-based heuristic	47.57	0.00%	47.69	0.26%	61	61	9
Weight 1							
Exhaustive enumeration	49.75		–	–	15780	–	7
Modified ranking heuristic	52.01	4.54%	–	–	11	–	10
Local improvement heuristic	49.75	0.00%	–	–	101	–	7
GA-based heuristic	49.77	0.03%	49.87	0.24%	61	61	8
Weight 10							
Exhaustive enumeration	74.60	–	–	–	15780	–	2
Modified ranking heuristic	102.71	37.69%	–	–	7	–	5
Local improvement heuristic	81.30	8.98%	–	–	101	–	3
GA-based heuristic	74.60	0.00%	74.96	0.48%	60	61	2
Weight 100							
Exhaustive enumeration	254.60	–	–	–	15780	–	2
Modified ranking heuristic	478.71	88.02%	–	–	6	–	4
Local improvement heuristic	254.60	0.00%	–	–	101	–	9
GA-based heuristic	254.60	0.00%	255.96	0.53%	61	61	2

Table AV. Results for low conveyor speed and scenario C.

	Z_{best}	$\%opt_{best}$	Z_{ave}	$\%opt_{ave}$	*Run* $time_{best}$	*Run* $time_{ave}$	#crossovers
Weight 0.001							
Exhaustive enumeration	94.12	–	–	–	15446	–	22
Modified ranking heuristic	94.12	0.00%	–	–	15	–	22
Local improvement heuristic	94.12	0.00%	–	–	94	–	22
GA-based heuristic	94.12	0.00%	94.12	0.00%	62	62	22
Weight 0.01							
Exhaustive enumeration	94.32	–	–	–	15446	–	22
Modified ranking heuristic	94.32	0.00%	–	–	15	–	22
Local improvement heuristic	94.32	0.00%	–	–	94	–	22
GA-based heuristic	94.32	0.00%	94.32	0.00%	62	62	22
Weight 0.75							
Exhaustive enumeration	108.40	–	–	–	15446	–	18
Modified ranking heuristic	108.40	0.00%	–	–	14	–	18
Local improvement heuristic	108.40	0.00%			94	–	18
GA-based heuristic	108.40	0.00%	108.48	0.07%	62	61	18
Weight 1							
Exhaustive enumeration	112.52	–	–	–	15446	–	16
Modified ranking heuristic	112.52	0.00%	–	–	14	–	16
Local improvement heuristic	112.52	0.00%	–	–	94	–	16
GA-based heuristic	112.52	0.00%	112.66	0.12%	60	60	16
Weight 10							
Exhaustive enumeration	169.50	–	–	–	15446	–	4
Modified ranking heuristic	170.94	0.85%	–	–	4		2
Local improvement heuristic	169.50	0.00%	–	–	94	–	4
GA-based heuristic	169.94	0.26%	170.32	0.48%	60	60	4
Weight 100							
Exhaustive enumeration	237.92	–	–	–	15446	–	0
Modified ranking heuristic	237.92	0.00%	–	–	2	–	0
Local improvement heuristic	237.92	0.00%	–	–	94	–	0
GA-based heuristic	237.92	0.00%	237.92	0.00%	60	60	0

Table AVI. Results for high conveyor speed and scenario C.

	Z_{best}	$\%opt_{best}$	Z_{ave}	$\%opt_{ave}$	*Run time*$_{best}$	*Run time*$_{ave}$	#crossovers
Weight 0.001							
Exhaustive enumeration	35.50	–	–	–	15732	–	22
Modified ranking heuristic	35.50	0.00%	–	–	15	–	22
Local improvement heuristic	35.50	0.00%	–	–	92	–	22
GA–based heuristic	35.50	0.00%	35.50	0.00%	62	62	22
Weight 0.01							
Exhaustive enumeration	35.70	–	–	–	15732	–	22
Modified ranking heuristic	35.70	0.00%	–	–	15	–	22
Local improvement heuristic	35.70	0.00%	–	–	92	–	22
GA-based heuristic	35.70	0.00%	35.70	0.00%	62	62	22
Weight 0.75							
Exhaustive enumeration	46.45	–	–	–	15732	–	8
Modified ranking heuristic	46.61	0.35%	–	–	9	–	8
Local improvement heuristic	46.45	0.00%	–	–	92	–	8
GA-based heuristic	46.45	0.00%	46.51	0.13%	63	63	8
Weight 1							
Exhaustive enumeration	48.45	–	–	–	15732	–	8
Modified ranking heuristic	48.49	0.10%	–	–	9	–	7
Local improvement heuristic	48.45	0.00%	–	–	92	–	8
GA-based heuristic	48.45	0.00%	48.64	0.40%	63	63	8
Weight 10							
Exhaustive enumeration	72.98	–	–	–	15732	–	2
Modified ranking heuristic	72.98	0.00%	–	–	4	–	2
Local improvement heuristic	72.98	0.00%	–	–	92	–	2
GA-based heuristic	72.98	0.00%	73.29	0.41%	63	63	2
Weight 100							
Exhaustive enumeration	100.12	–	–	–	15732	–	0
Modified ranking heuristic	100.12	0.00%	–	–	2	–	0
Local improvement heuristic	100.12	0.00%	–	–	92	–	0
GA-based heuristic	100.12	0.00%	100.12	0.00%	63	63	0

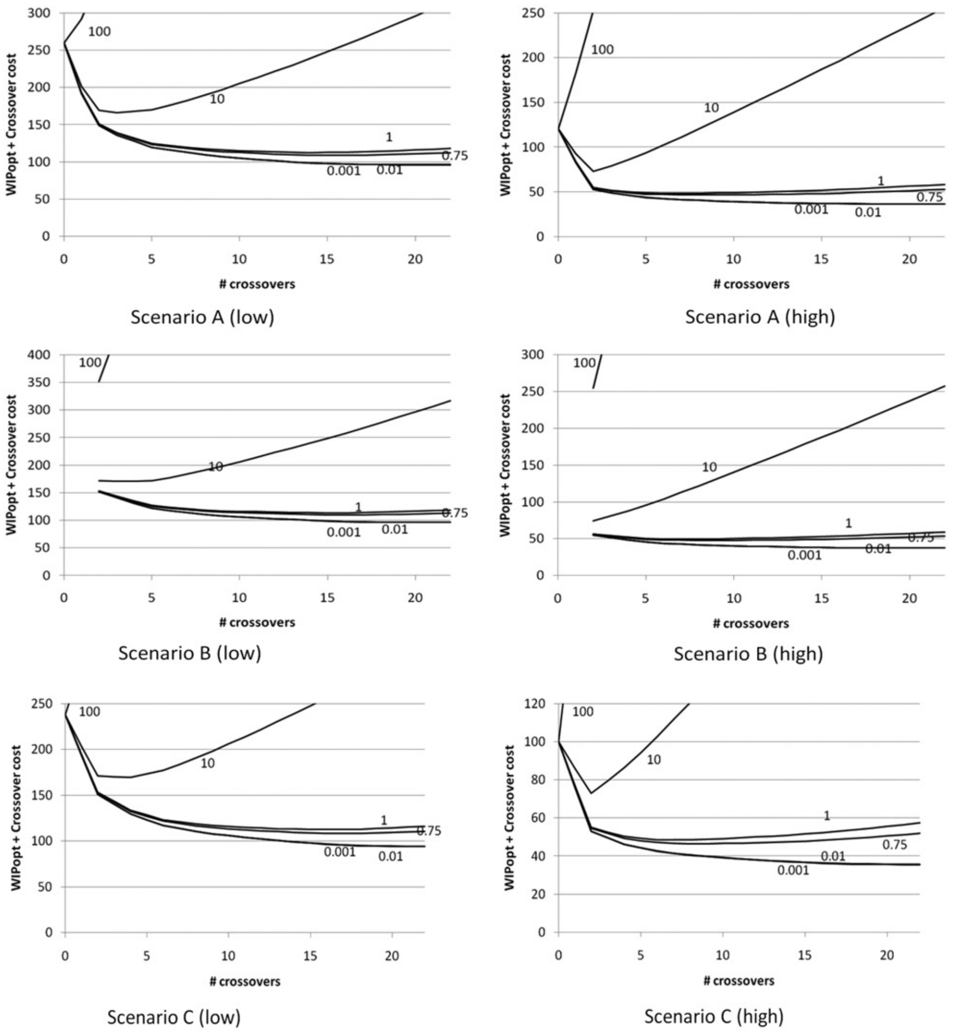

Figure AI. Objective function value calculated via exhaustive enumeration for varying number of crossovers included in the layout (lines are labelled with the weight used in the objective function).

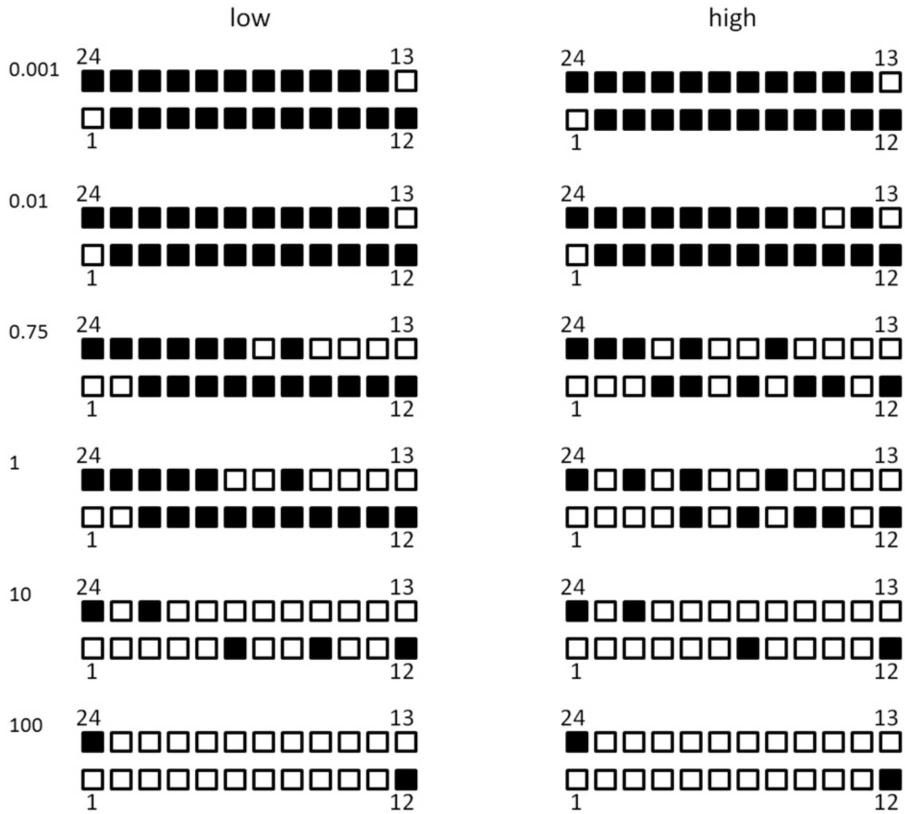

Figure AII. The best crossover layout identified via the exhaustive enumeration for scenario A for both low and high conveyor speeds varying the value of the weight in the objective function.

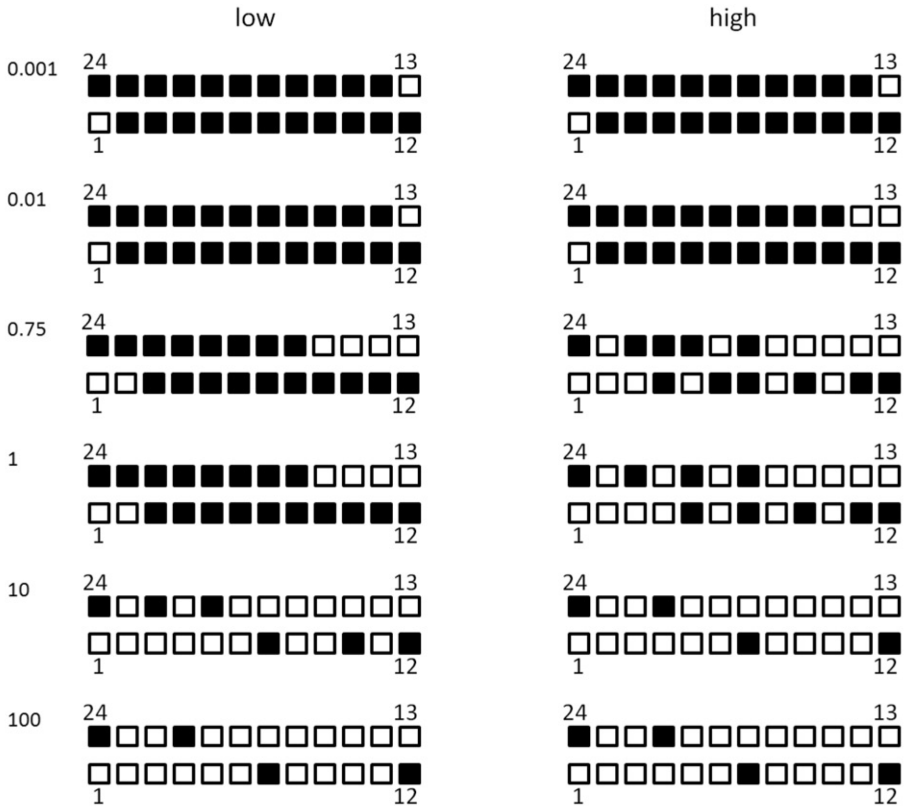

Figure AIII. The best crossover layout identified via the exhaustive enumeration for scenario B for both low and high conveyor speeds varying the value of the weight in the objective function.

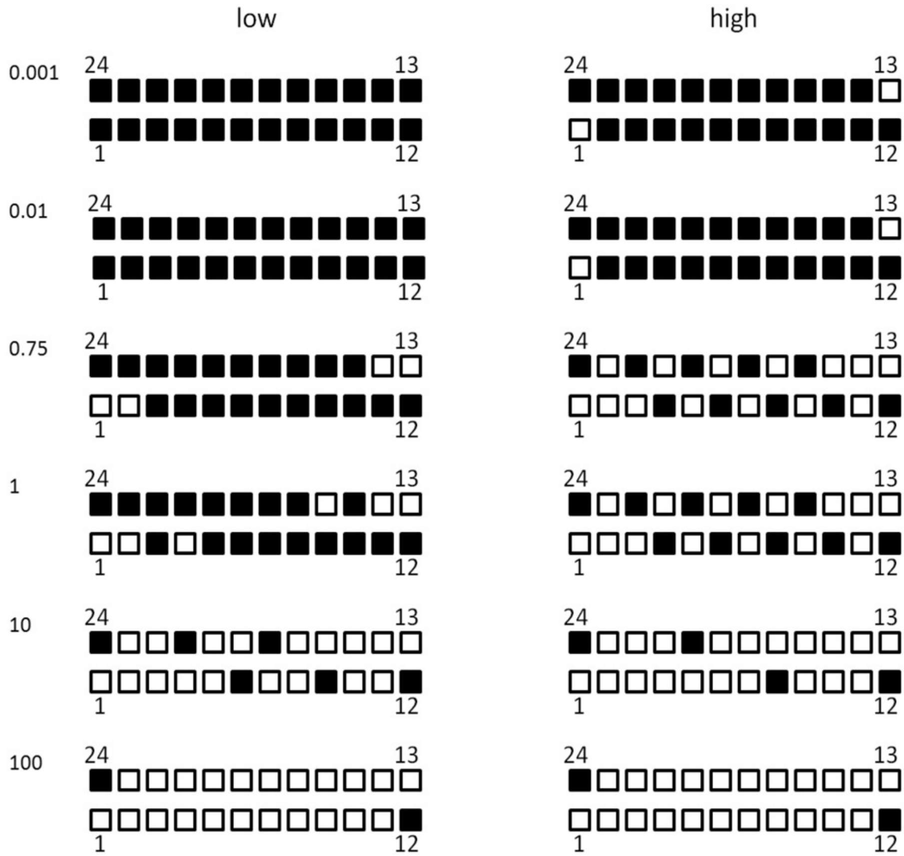

Figure AIV. The best crossover layout identified via the exhaustive enumeration for scenario C for both low and high conveyor speeds varying the value of the weight in the objective function.