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MULTI-RESOLUTION MODELING METHOD FOR AUTOMATED MATERIAL HANDLING SYSTEMS IN SEMICONDUCTOR FABS

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ABSTRACT

This paper presents a novel modeling framework for semiconductor fabrication facilities (FABs) that integrates production and material handling systems. Because the productivity of semiconductor FABs is significantly influenced by their material-handling systems, existing research has focused on optimizing operational logic considering both aspects. However, the scale and complexity of modern FABs make implementation of fully integrated models challenging, resulting in slow simulation speeds for long periods. To address this issue, we propose a multi-resolution modeling framework that creates material-handling system models at two distinct resolution levels, enabling fast, fully integrated FAB models while accounting for material-handling effects. Experimental results demonstrated accelerated simulation completion compared to single-resolution models while maintaining consistent results. The proposed method provides a practical approach for semiconductor FABs to investigate long-term phenomena and urgent decision-making problems while considering both production and material-handling systems.

1 INTRODUCTION

A semiconductor fabrication facility (FAB) is one of the most complex manufacturing systems owing to various product types, numerous production steps, re-entrant flows, batch processing, and queue time constraints (Mönch et al. 2013). To study long-term phenomena and support decision-making in this domain, discrete event simulation is used (Fowler et al. 2015). Other manufacturing systems frequently employ fully integrated simulation models, which incorporate both in-process logistics and production models, while semiconductor FABs typically model production and material-handling systems separately because of their immense complexity and scale, with typically over 1000 facilities and 2000 pieces of logistics equipment in a FAB.

Because the performance of a material-handling system is closely related to the productivity of semiconductor FABs (Sun et al. 2005; Gaxiola et al. 2013), concurrently simulating production and material-handling systems is crucial for obtaining realistic simulation results. However, fully integrated models for semiconductor FABs increase computational costs (Jimenez et al. 2005), leading to the requirement of a considerable amount of time to explore long-term phenomena. Furthermore, they are less suitable for addressing decision-making problems that demand rapid responses.

To address these limitations, this study introduces a novel multi-resolution modeling (MRM) method for an automated material-handling system (AMHS) in semiconductor FABs. The proposed method models AMHS at two different resolutions: entity and unit levels. The entity-level models reflect the operation of overhead hoist transports (OHTs) in semiconductor FABs. By contrast, the unit-level model is designed as a statistical model, initialized with transport logs from the entity-level models. By employing this framework, capturing variability in the AMHS of semiconductor FABs by using entity-level models and expediting simulation experiments while maintaining consistency with the unit-level model is possible.

The rest of this paper is organized as follows. Section 2 includes a literature review on MRM and simulation research on semiconductor FABs. Section 3 introduces the MRM framework for the AMHS in semiconductor FABs. Section 4 presents the simulation results. Finally, Section 5 provides the conclusion.

2 PROBLEM DESCRIPTION

2.1 Multi-resolution Modeling

In simulation models, "resolution" refers to the level of detail used to represent a system (Rabelo et al. 2015). MRM involves developing single or consistent sets of models with multiple resolutions for the target system (Davis and Bigelow 1998). It has proven effective in addressing complex problems in large-scale systems, such as defense modeling and simulation (Lee et al. 2020). Moreover, it has been applied to various fields, including the development of distributed modeling and simulation frameworks for enhancing sustainability in smart supply chains and manufacturing facilities as well as the creation of multi-resolution train operation models to improve train control system platforms (Li et al. 2018; Gorecki et al. 2020).

Furthermore, high-resolution models (HRMs) require more data space and computation time but yield highly accurate simulation results. Conversely, low-resolution models (LRMs) need less data space and computation time but offer low accuracy. Because changing resolutions according to the operational purposes of models is crucial in MRM, numerous studies have been conducted on developing resolution-conversion approaches. This study employs the aggregation/disaggregation (A/D) approach, which changes model resolution under specific conditions. Aggregation refers to merging multiple HRMs into one LRM, while disaggregation means dividing one LRM into multiple HRMs. In this study, the HRM—referred to as "entity-level models" —simulates the dynamic of OHTs in FABs. Simultaneously, the LRM—called the "unit-level model" —calculates the delivery time for each transport request. Aggregation proceeds when a sufficient level of logs is collected from the entity-level models.

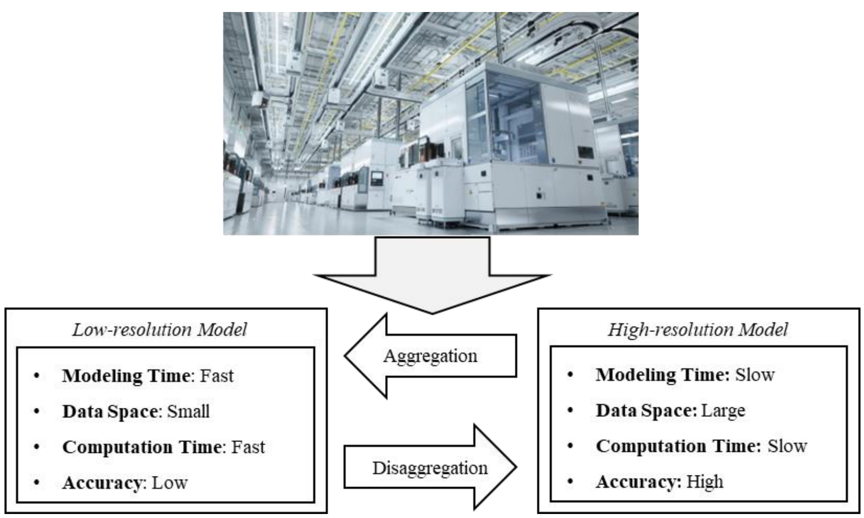

Figure 1: Multi-resolution modeling.

2.2 Fully Integrated Simulation Modeling for Semiconductor FABs

The considerable impact of AMHS on production systems in semiconductor FABs has driven numerous studies to integrate production and AMHS for efficient operations, with a primary focus on developing scheduling algorithms that improve productivity by considering AMHS. Sun et al. (2005) proposed a dispatching rule integrating lot dispatching and AMHS control. Drießel and Mönch (2012) suggested an extended shifting bottleneck heuristic for job-shop systems. Further, Karimi et al. (2017) developed an efficient scheduling algorithm incorporating transport times, and Ham et al. (2020) proposed an algorithm combining production and material handling in semiconductor photolithography processes.

Additionally, research on the operational aspects of AMHS in semiconductor FABs aims to enhance efficiency by considering productivity factors. For example, Huang and Lin (2016) proposed a predictive OHT dispatching method using equipment delivery information in diffusion areas, and Wan and Shin (2021) presented an efficient predictive OHT dispatching method in environments where delivery request arrivals can be predicted.

To effectively combine production and AMHS aspects, developing a fully integrated FAB model is essential. Dejong and Wu (2002) integrated AMHS and FAB capacity models to evaluate the impact of priority lots on other lots. Jimenez et al. (2005) created integrated models by combining less detailed AMHS representation with capacity models and investigated the prediction of capacity loss. Kong (2007) proposed a two-step simulation structure in which AMHS simulation optimizes in-process logistics using outputs from production models.

However, a challenge in developing fully integrated models for semiconductor FABs is the slow speed of simulation models, which leads to long periods for obtaining experimental results. To address this issue, this study proposes an efficient method for creating a fully integrated model by employing MRM to construct AMHS models.

3 MULTI-RESOLUTION MODELING FRAMEWORK

3.1 MRM Framework for Semiconductor FAB Simulation

The framework of the proposed methodology is shown in Figure 2. The semiconductor production system models are modeled in a single resolution to evaluate the performance of dispatching algorithms. There are models of tool groups, production facilities, products, and manufacturing execution system (MES). The MES model requests delivery between stations and the OHT control system (OCS) model on the AMHS side. Please note that one of the key components of a semiconductor FAB's AMHS, the storage part (Track buffers and stockers), is implemented at a single resolution.

The AMHS system models are modeled at two resolution levels: entity and unit. Here, the entity-level model of AMHS contains multiple individual OHT models and the OHT track layout that incorporates intrabays and interbays. Within entity-level models, observing the effect of delays and bottlenecks of OHTs is possible. By contrast, the unit-level model is developed as a statistical model based on transportation logs from the entity-level model. Thus, when a transport request is generated, the unit-level model returns traveling times on the basis of starting and ending position information.

The simulation starts with the unit-level model, which calculates transportation time using the Manhattan distance method. Upon completion of the warm-up period, this simulation switches to the entity-level models. At this stage, it starts collecting logs, ensuring the transport request volume is sufficient to accurately reflect the system’s congestion. The unit-level model is initialized when a certain number of logs are collected. By using the aggregated model (unit-level model) for the remaining period of the simulation experiment allows for a swift completion.

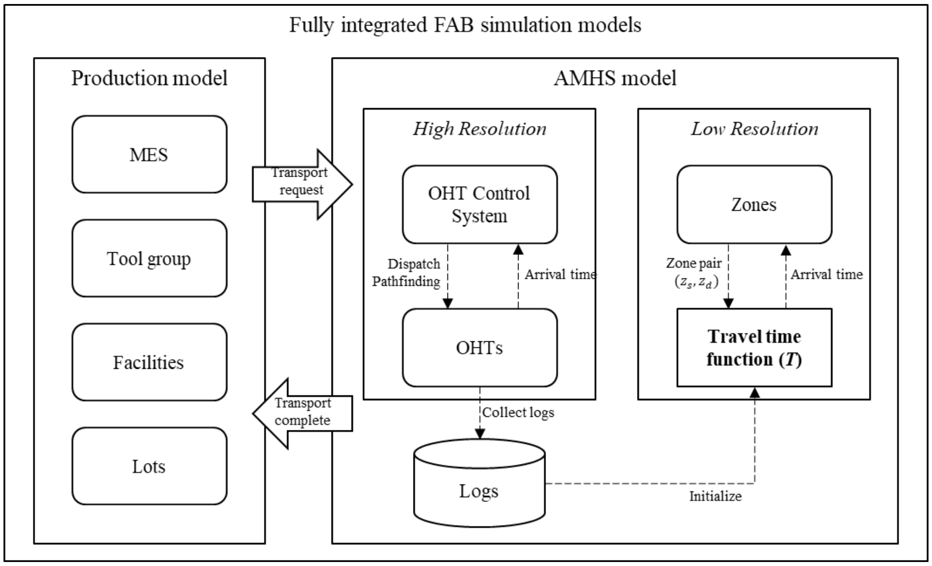

Figure 2: Multi-resolution modeling framework for AMHS in semiconductor FABs.

3.2 Entity-level Modeling for AMHS

In semiconductor FABs, wafers are placed in carriers called front opening unified pods (FOUPs) and transported between stations by OHTs. OHTs travel unidirectionally along track networks (Figure 3) and encounter various delay situations (Figure 4). Delay situations can be categorized into two types: (1) delays resulting from loading and unloading tasks performed by vehicles ahead (Figure 4(a)); and (2) bottlenecks caused by collision prevention controls at merging and branching points (Figure 4(b)). These delay situations contribute to larger bottlenecks in the OHT layout network, resulting in variance in OHT deliveries.

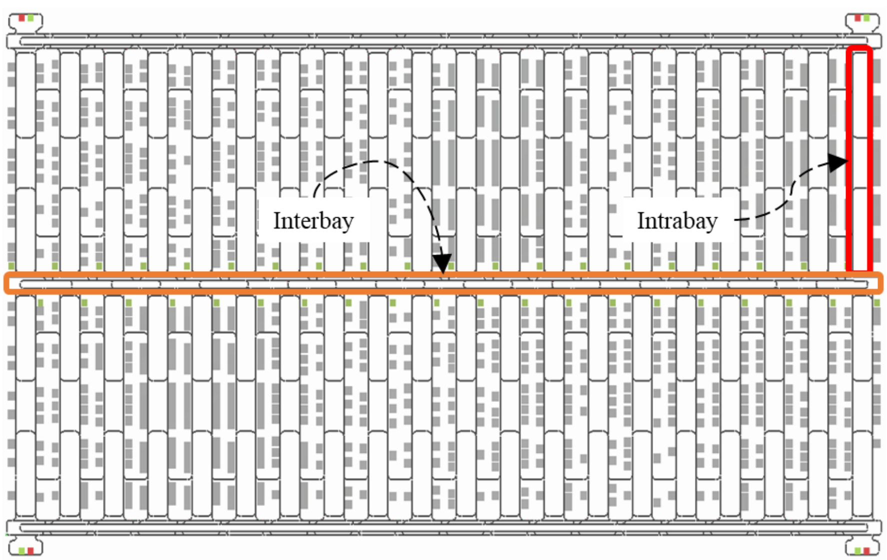

Figure 3: OHT network example.

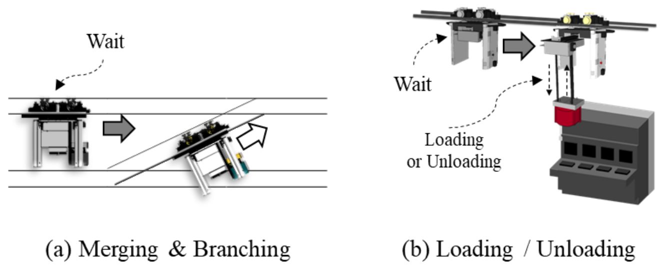

Figure 4 OHT traffic delay situations.

In this study, an entity-level model was used to simulate OHT dynamics, such as acceleration and deceleration. When each entity-level model completes a journey from one location to another, it records a log containing departure location, destination, and delivery time information. Although two different logs have the same start and destination locations, delivery times can be varied because of traffic situations in the OHT track network. Accordingly, the impact of delay situations on OHTs is reflected in the transport logs.

For the entity-level models, a controller model, which serves as OCS in real FABs, is required. This model is responsible for tasks such as dispatching (assigning transport requests to suitable vehicles), pathfinding (determining the optimal path for an OHT to travel), and idle vehicle management (deciding the waiting locations for idle OHTs awaiting their next jobs). The implemented entity-level models are shown in Figure 5. Each vehicle is represented by a triangle shape and is assigned different colors according to its status (Idle: Green; Pre-Drive/Main-Drive: Blue; and Loading/Unloading: Yellow).

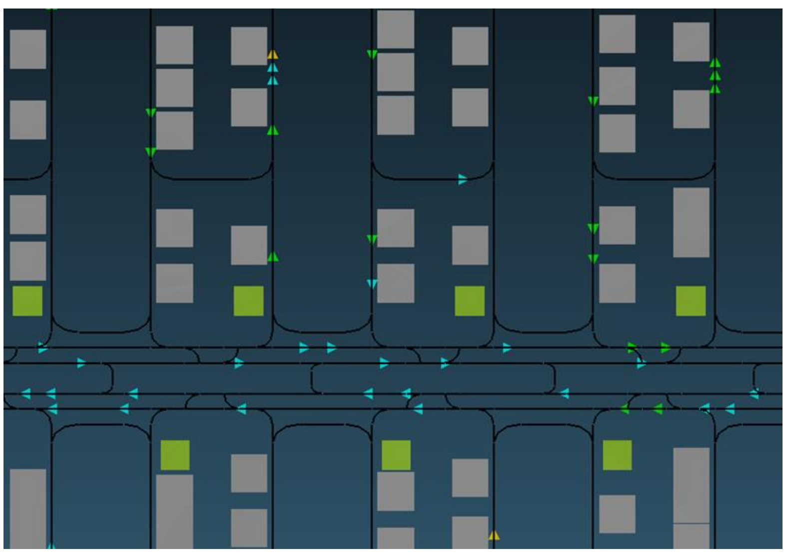

Figure 5: Implemented entity-level AMHS models.

3.3 Unit-level Modeling for AMHS

This paper proposes a unit-level model that represents the OHT track layout as a grid (Figure 6) without modeling individual OHTs. Each cell in the grid is referred to as a zone, and the set of zones for a single OHT track layout is denoted as Z. A zone pair (z_s, z_d) is utilized for a delivery request if z_s is the zone containing the departure station and z_d is the zone containing the destination station. The unit-level model utilizes a traveling time function $T: Z \times Z \to \mathbb{R}$ for all zone pairs in the grid. The model provides the delivery time for a transport request as the time taken for transport from the departure zone (z_s) to the destination zone (z_d).

Each travel time function is formulated as a normal distribution with the collected logs from the entity-level models. L denotes the set of collected logs, and L_{sd} represents the set of logs for a zone pair (z_s, z_d). The target logs L_{sd} are extracted from L using Algorithm1. A normal distribution is modeled by calculating the mean and variance of the extracted logs, forming a delivery time interval from z_s to z_d. This process integrates the delay information collected by individual entity-level models during delivery.

Algorithm 1 Extract Log EL(List<Log> L, Zone z_s, Zone z_d)

Input: All logs from the entity-level models L, Departure zone z_s, Destination zone z_d
Output: Target Log list L_{sd}

$L' = \{\}$; /* Initialize log list */
foreach l **in** L **do**
    SZ = GetZone(l.Start);
    EZ = GetZone(l.Destination);
    if SZ = z_s&& EZ = z_d **then**
        L'.Add(l);
    end if
next
return L';

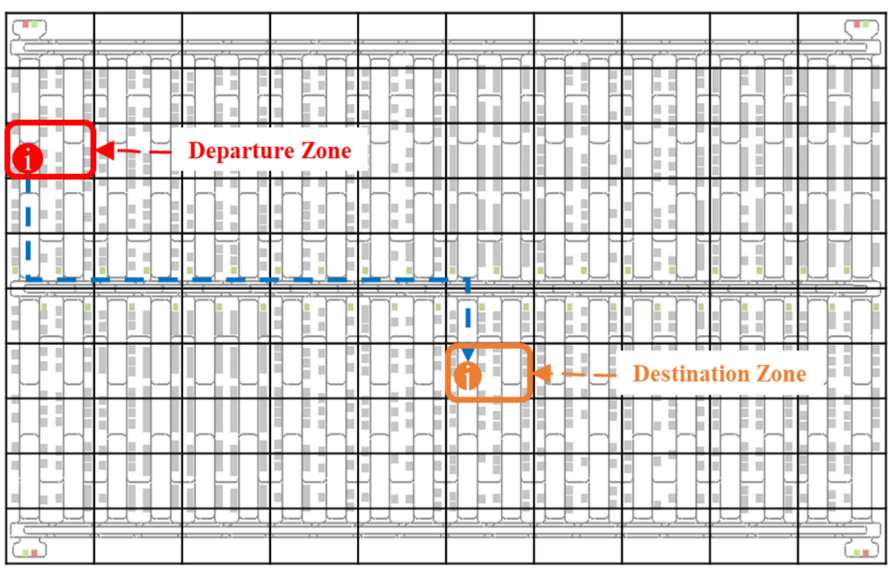

Figure 6: Grid concept of the unit-level model.

To develop the unit-level model, the grid resolution must be established first. In this study, we opted for grids of sizes 30×30 and 20×20. As the grid resolution increases, the model reflects the logistical variability in the existing system more precisely. However, this also significantly increases computational load during the initialization of the unit-level model. Furthermore, the number of logs for each zone pair decreases as the grid resolution increases, which reduces the explanatory power of the model. Therefore, selecting an appropriate level of resolution that balances accuracy and computational efficiency is essential.

Even with a sufficient number of collected logs and an appropriately set grid resolution, missing values may still exist because in a typical job-shop production system such as a semiconductor FAB, transport requests are generated on the basis of the production routes of products. However, if there are insufficient logs for a zone pair (z_s, z_d), the normal distribution modeled from L_{sd} lacks explanatory power.

This study proposes a simple imputation method to restrict the abovementioned limitations as follows: (1) Determine the minimum threshold number of logs to guarantee sufficient explanatory power of the model. (2) For all zone pairs, logs (L_{sd}) are extracted from L to create the target traveling time function. If the number of logs (L_{sd}) exceeds the threshold, generate a model for the zone pair (z_s, z_d). (3) If the number of logs (L_{sd}) is below the threshold, the explanatory power of the model is weak; in this case, combine logs with neighboring zones of z_d. Collect logs from neighboring zones that are one step away. If the combined log count still does not surpass the threshold, incrementally increase the step and continue merging logs, as shown in Figure 7. The algorithm for collecting logs from neighboring zones is outlined as Algorithm 2.

Algorithm 2 Collect Neighbor Log *CNL*(List<Log> *L*, Zone z, Integer *dist*)

Input: All logs from the entity-level models *L*, destination zone *z*, step distance *dist*
Output: Log

L' = {}; /* Initialize target log list */
for $x = z.x - dist$ **to** $z.x + dist$ **do**
  for $y = z.y - dist$ **to** $z.y + dist$ **do**
    L_{sxy} = *EL*(*L*, z_s, z_{xy});
    L'.Merge(L_{sxy});
  next
next
return L'

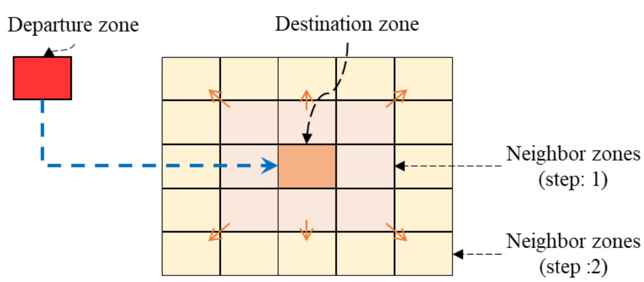

Figure 7: Log-combining procedure.

Using the algorithms proposed above, sufficient logs are collected to achieve high explanatory power for all zone pairs in the OHT track layout. The traveling time function for all zone pairs is formulated without missing values by utilizing the algorithms proposed herein. Algorithm 3 shows the overall initialization procedure for the unit-level model.

Algorithm 3 Initialize Unit Model *Init*(List<Log> *L*, List<Zone> *Z*, Integer *limit*)

Input: All logs from the entity-level models *L*, All zones in a FAB *Z*, Minimum threshold *threshold*

foreach z_s **in** *Z* **do**
  foreach z_d **in** *Z* **do**
    L_{sd} = *EL*(*L*, z_s, z_d);
    dist = 1;
    while $|L_{sd}|$ < *threshold* **then** **/*** Insufficient number of logs */
      L_{sd} = *CNL*(*L*, z_d, dist);
      dist += 1;

```
        next
        T(s, d) = NormalDist(L_sd);
    next
next
```

4 SIMULATION EXPERIMENTS

4.1 Simulation Model

In this study, we conducted simulation experiments using two testbeds: SMT2020 and SMAT2022. SMT2020 is a simulation testbed for semiconductor FABs that reflects the scale and complexity of modern FABs as presented by Kopp et al. (2020). Moreover, it focuses solely on the production systems found in modern FABs, featuring eleven process types, including eight types of production steps and three types of metrology steps. There are 105 tool groups for the 11 process types and around 1000 facilities. The system comprises 10 product types and 5 priority levels, with predefined process routes for each product.

For AMHS models, we used the SMAT 2022 model introduced by Lee et al. (2022). This dataset incorporates AMHS models for SMT2020, comprising 500 OHT vehicles. The track layout for the OHT system incorporates 40 intrabays and 3 interbays. Additionally, storage systems for holding lots in waiting are included. In this study, we implemented production models for dataset 4 (LV/HM_E) of SMT2020 and SMAT2022 at a single resolution and two resolutions, respectively (entity and unit levels).

For production, the lot dispatching for production equipment used the logic specified by toolgroup in SMT2020. In AMHS, the dispatching rules for the entity-level models (OHT models) were the Shortest Vehicle First (Job-initiated) and Nearest Job First (Vehicle-initiated). Vehicle routing was determined using the Dijkstra algorithm.

4.2 Design of Experiments

The goal of the simulation experiment was to study the efficiency of the proposed MRM. We expected that the proposed models to maintain high consistency with high simulation speed. The experimental design is summarized in Table 1.

Table 1: Comparison between samples.

Factor	Level	Count
Production model	1	1
AMHS model	Entity-level, Entity + Unit (20×20), Entity + Unit (30×30),	3
# of independent simulation replications		5
total # of simulation runs		15

In this study, the models were evaluated in two aspects: simulation speed and consistency. First, we compared the simulation speeds of AMHS models, and the times required by them to initialize unit-level model. Two metrics were used to evaluate simulation speed aspect.

- Simulation Speed (simulation sec/sec): the number of simulated seconds elapsed per real-time computational second on the computer.
- Initialization time (sec): the average time of the Entity-level model to initialize using the OHT log data.

The second aspect of evaluation was consistency. Because testbeds, which are not actual production systems, were selected as the target system for modeling in this study (SMT2020 + SMAT2022), the fidelity of each model could not be evaluated. Therefore, the performance of the MRM models was assessed by comparing the consistency of the experimental results obtained from only the entity-level AMHS, which is the high-resolution model. Three metrics were used to evaluate the consistency of our framework.

- Throughput (TH): the number of completed lots within the simulation horizon.
- Average cycle time (ACT): the average cycle time (in days) of products to finish the production process.
- Percentage of on-time lots (%ONTIME): the percentage of on-time lots.

A simulation horizon of two year was applied in all experiments, where a warm-up phase of one year was excluded from the statistics and log collection period for the MRM models. Simulations were conducted in the following computer environment: CPU: i9-12900k; RAM: 32GB DDR5; and GPU: RTX 3080Ti. The experiments were performed using the commercial simulation engine PINOKIO 1.0, developed by Carlo in the Republic of Korea.

4.3 Simulation Results

The detailed simulation results for the different AMHS models are presented in Table 2. These results show that the average simulation with the entity-level model took 62.5 hours for a one-year simulation. By contrast, it took only 3.36 hours with the proposed MRM framework simulation models. There were few differences between MRM models because the mechanisms to calculate the traveling time for each transport task are the same; the only difference was initialization time. The scheme with the 30×30 unit-level model required 12% more time for initialization, as it had more detailed transport models than the scheme with the 20×20 unit-level model.

The detailed simulation results, which focus on simulation speed, are presented in Table 2. These findings demonstrate that the average simulation speed achieved with our proposed MRM framework simulation models is 18 times faster than simulation conducted exclusively with entity-level models. The initialization time slightly increases as the resolution of the unit-level model increases.

Table 2: Simulation results with only entity-level simulation models.

Scheme	Average Simulation Speed (simulation sec/sec)	Initialization Time (sec)
Entity-level only	141.47	-
Entity + Unit [20×20]	2570.14	10
Entity + Unit [30×30]	2652.12	26

The results indicated that both MRM schemes (20×20 and 30×30) maintained consistent outcomes even though they completed simulations 18 times faster than the scheme using only the entity-level models. Among the MRM schemes, the one with a higher-resolution unit-level model (Entity + Unit [30×30]) demonstrated greater consistency with the entity-level model results compared to the lower-resolution model (Entity + Unit [20×20]). Our analysis suggests that the higher scheme reflects the entity-level delivery situation more accurately.

Table 3: Simulation results.

Scheme	Lot type	TH	ACT (days)	%ONTIME
Entity-level Only	PRL	20080	37.73	93.15
	PHL	538	26.30	58.92
	ERL	3271	44.71	100
	EHL	826	31.21	65.73
Entity + Unit [20×20]	PRL	20044	37.77	85.94
	PHL	540	26.37	55.92
	ERL	3276	44.85	99.38
	EHL	827	31.44	63.60
Entity + Unit [30×30]	PRL	20029	37.90	89.91
	PHL	539	26.24	56.40
	ERL	3261	44.95	99.78
	EHL	823	31.36	64.27

Experiment results indicate that ACT values tend to increase when employing our MRM framework. This situation arises primarily due to the outliers in the transport logs with the entity-level models. These outliers inflate the average and standard deviation of the unit-level model's normal distributions, resulting in a slight increase in ACT values. This problem can be resolved by excluding certain outlier logs during the initialization stage of the unit-level model.

5 CONCLUSIONS

This paper presents a novel MRM framework for AMHS in semiconductor FABs that balances fidelity and computational efficiency. The performance evaluation showed that the proposed MRM framework maintained acceptable fidelity while reducing simulation time, providing significant benefits for decision makers within semiconductor FABs. The framework enables analysis of variations in the production system performance dictated by the operational logic of the AMHS. However, while the framework boasts quicker simulation capabilities compared to conventional integrated simulation models, its speed is slower relative to that of production simulation models. Hence, in scenarios where the influence of logistics does not substantially impact the experimental results, the use of an entity-level model may be unnecessary. In such instances, the unit-level model can be initialized and employed exclusively with the OHT Logs obtained from the initial experiment.

Regarding future research, we aim to extend our methodology to multi-FAB environments. Recently, many practitioners in semiconductor manufacturing companies have shown interest in the operation of connected multi-FABs, which facilitate FOUP deliveries between different FABs to improve process equipment utilization. Although this approach effectively enhances FAB performance, modeling multi-FABs increases the difficulty of simulation modeling. To the best of our knowledge, simulation studies on connected FABs have not been conducted owing to their high complexity and large scale. Therefore, our future research will apply the proposed MRM framework to connected multi-FAB environments to expand its applicability and utility in semiconductor FAB operations.

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