HIGH FIDELITY SIMULATION MODELS FOR EQUIPMENT PERFORMANCE PREDICTION IN SEMICONDUCTOR INDUSTRY

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To my beloved wife and children

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ABSTRACT

Semiconductor manufacturing is a high-technology industry which is capital intensive and operationally complex with its process technology refreshed every two years. Precision in capacity planning is critical to ensure the right amount of capital equipment is purchased to match the demand while meeting aggressive cost and operational targets. The key input parameter for capacity calculations is the equipment output rate. As equipment get more complex, its output rate become difficult to predict using spreadsheets, thus the need for detailed dynamic equipment simulation models. However, literature on how to build detailed equipment simulation models for real-world is scarce. Practitioners do not share their experience openly due to proprietary reasons. This dissertation investigates the complexity of semiconductor manufacturing which makes its capacity planning difficult. The techniques to build, verify and validate high fidelity equipment simulation models were developed. The models are then used to augment capacity planning and productivity improvement decision making. Case studies are conducted using the models to improve capacity forecast planning accuracy for capital purchase decisions which resulted in million dollars capital avoidance, test equipment productivity improvement ideas and decide which ones have benefits to pursue, and determine the effect of different operator manning ratios for manufacturing execution decisions. The results show that raw model accuracy can be up to 99% using the methods described here. For manufacturing execution, model accuracy can be up to 95% due to variability in human performance, but good enough to provide insights on manning ratio strategies. The case studies demonstrate how the results directly contribute to company performance in terms of capital efficiency, capital expenditure avoidance, and waste reduction. It enables optimal equipment configuration decisions to be made upfront during technology development. It also earns credibility and senior management confidence in using such simulation models for decision making.

ABSTRAK

Pembuatan semikonduktor merupakan industri teknologi tinggi berintensif modal, tahap pengendalian yang kompleks serta mengalami pembaharuan teknologi proses setiap dwitahunan. Ketepatan perancangan kapasiti adalah penting untuk memastikan modal peralatan dibeli dapat dipadankan dengan permintaan serta sasaran kos dan operasi yang agresif tercapai. Parameter utama untuk pengiraan kapasiti ialah kadar keluaran peralatan. Peralatan yang semakin kompleks merumitkan penggunaan lembaran hamparan untuk meramal kadar keluaran. Justeru, model simulasi peralatan yang dinamik dan terperinci diperlukan. Sorotan kajian mengenai proses pembinaan model simulasi peralatan dunia nyata secara terperinci sukar didapati. Pengalaman pengamal-pengamal bidang berkaitan tidak dikongsi secara terbuka atas alasan harta milik intelektual. Disertasi ini mengkaji kerumitan yang dialami oleh pembuatan semikonduktor sehingga menyukarkan aktiviti perancangan kapasiti. Model simulasi peralatan fideliti tinggi dibina, ditentusah dan digunakan sebagai alat bantu di dalam membuat keputusan berkaitan peningkatan serta pembaikan perancangan kapasiti dan produktiviti. Penggunaan model simulasi di dalam beberapa kajian kes bertujuan untuk meningkatkan ketepatan ramalan keputusan kapasiti pembelian modal, menilai kebernasan idea-idea untuk meningkatkan produktiviti peralatan serta menentukan kesan nisbah pengendalian operator yang berbeza ke atas perlaksanaan keputusan berkaitan pembuatan. Keputusan menunjukkan ketepatan model asas sehingga 99% dengan menggunakan kaedah yang diterangkan di sini. Bagi pelakuan pembuatan, walaupun keragaman prestasi manusia menjadikan ketepatan model mencapai 95%, ia masih memadai untuk memberi gambaran awal kesan strategi nisbah pengendalian operator. Keputusan yang diperolehi daripada kajian kes menunjukkan kesan langsung ke atas prestasi syarikat dari aspek kecekapan modal, pengurangan perbelanjaan modal dan pembaziran. Segala keputusan yang melibatkan konfigurasi peralatan secara optimum boleh dibuat di sepanjang waktu teknologi dibangunkan. Hasil daripada model simulasi yang berkaitan turut berupaya meningkatkan kebolehpercayaan dan keyakinan pihak pengurusan atasan di dalam pembuatan keputusan.

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LIST OF ABBREVIATIONS

3D	-	Three-dimensional
A/T	-	Semiconductor Assembly and Test
AMHS	-	Automated material handling system
CAL	-	Chip Attach Line
DES	-	Discrete event simulation
DO	-	Direct observation
DRAM	-	Dynamic random-access memory
Fab	-	Semiconductor wafer fabrication plant
FC-BGA	-	Flip Chip Ball Grid Array
FFSM	-	Full factory simulation modeling
FOUP	-	Front Opening Unified Pod
HFSM	-	High fidelity simulation model(s)
HFSME	-	High fidelity simulation model(s)/modeling of equipment
HLA	-	High Level Architecture
HVM	-	High volume manufacturing
IC	-	Integrated circuits
IE	-	Industrial Engineer
ISMI	-	International Manufacturing Initiative
JEDEC	-	Joint Electron Devices Engineering Council
LAL	-	Lid Attach Line
MASM	-	Modeling and Analysis of Semiconductor Manufacturing Laboratory
MHS	-	Material handling system

MILP	-	Mixed integer linear programming
MNC	-	Multinational companies
PCB	-	Printed circuit board
P&P	-	Pick-and-place (referring to robotics system end effector)
PR	-	Photoresist
Prep	-	Preparation (used in Wafer and Die Preparation)
SEC	-	Samsung Electronics Corp.
SEMATECH	-	Semiconductor Manufacturing Technology
SEMI	-	Semiconductor Equipment and Materials International
SME	-	Small and medium enterprise
SMT	-	Surface Mount Technology
TD	-	Technology Development
TPM	-	Total Productive Maintenance
UPH	-	Unit(s) per hour
USA	-	United States of America
UV	-	Ultra-violet
VT	-	Validation Tester
WinterSim	-	Winter Simulation Conference

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CHAPTER 1

INTRODUCTION

1.1 Prologue

This research focuses on high fidelity simulation modeling of equipment (HFSME) in semiconductor manufacturing. The aim is to develop and apply HFSME methodology that can be used to accurately predict complex equipment capability, augmenting capacity planning and productivity improvement decisions in achieving capital equipment and operational efficiencies.

1.2 Research Background

Simulation is the imitation of the operation of real-world process or system over time [1] on a computer so that it can be used to study and predict the system when variables are changed. Simulation is a powerful tool for analysis of new system designs, retrofits to existing systems, and proposed changes to operating rules [2]. Some of the specific issues that simulation is used to address in manufacturing include determining the required quantity of equipment and personnel, performance evaluation such as throughput and bottleneck analyses, and evaluation of operational procedures such as production scheduling, inventory policies, control strategies, and reliability analysis [3].

In manufacturing and service industries, it is important to ensure that the capacity needed to setup manufacturing or services matches the demand. Unused excess capacity will lead to wasted equipment utilization while on the other hand

capacity shortage will lead to inability to meet demand, thus causing opportunity lost and factory congestion. Therefore, it is very important to have precise capacity model to determine the right amount of capacity required to support demand, especially for operations which require huge capital investment.

There are various methods to perform capacity planning depending on the operational complexity. For operations without much complexity, the easiest form of capacity planning can be done with spreadsheet models. For highly complex operations, capacity planning requires combination of discrete event simulation (DES) modeling, mathematical optimization, and data integration with enterprise systems. This is true for the industry of interest in this research – the highly complex semiconductor industry where silicon is used to fabricate the ubiquitous integrated circuits (IC) used in computers, communication devices, and electronics appliances.

Semiconductor manufacturing can be divided into wafer fabrication (fab), sort, die preparation (prep), assembly and test (A/T), the last two involving assembling dies into various package types and testing them. The cost of setting up a wafer fab with the latest technology is about 4 to 5 billion dollars [4,5], for plant, capital equipment cost, and collaterals. Despite the high cost, the technology can only last a few years as the number of transistors doubles approximately every two years based on Moore's law [6]. In other words, factory with newer process technology is required every two years. Thus, it is very important to determine the right amount of capital investment which will pay back within two years before the technology becomes obsolete.

Due to very high capital cost to setup wafer fab, simulation is widely used for strategic and operational decision making. Simulation is one of the major quantitative techniques used to understand a system, predict its capability, quantify improvement ideas, and provide valuable insights on where to focus and whether it makes sense to pursue the idea and understanding the trade-off. There was less focus for A/T since traditionally it costs about 10% of wafer fab. However, the cost to build and start an A/T factory has gone up as well, for example, it costs a billion dollar for Intel's latest A/T factory in Vietnam [7]. More than two third of the cost is capital expenditure for equipment. The complexity of A/T has increased due to miniaturization of die and packaging, thus requiring more mechanization and

automation instead of just relying on cheap operators for manual assembly. Having large A/T factories instead of many small factories helps improve efficiency.

The capital equipment purchased will be used to manufacture various types of products. Due to high complexity of the equipment, each product has its own robot speed, process recipe, form factor, and media density parameters. The equipment capability expressed in units per hour (UPH) will be product-specific. If spreadsheet model is used, its accuracy can only be determined after every different combination of input parameters is validated during initial production runs. This is a very tedious process since validation needs to be performed for all products. It cannot be done for new products which are still under development. If simulation model is used, it must be able to mimick the complexity of the equipment faithfully for all possible combinations of input parameters, hence the need for a very detailed and accurate equipment simulation model. The detailed simulation model needs be validated for existing products so that it can be used to predict equipment capability of existing and future products. Otherwise the simulation model will not be able to augment capacity modeling in increasing its accuracy.

This research is about real-world application of how HFSME was successfully developed and used to augment enterprise capacity planning system and productivity decisions, enabling precise capacity planning of A/T factories resulting in millions of dollars savings achieved through capital equipment avoidance. The simulation team has developed and applied state-of-the art techniques for detailed and faithful modeling of highly complex equipment. The methods developed here can be generalized and applied to many other industries using moderate to highly complex equipment.

1.3 Research Problem

There are many research and publications on using factory simulations and mathematical models for semiconductor manufacturing capacity planning. These will be described in Chapter 2. Unfortunately, there was not much focus on how to get accurate input data into the capacity models such as equipment processing time

or UPH. The equipment UPH must be understood well and accurately quantified for various run conditions before it can be used as input to the capacity models, regardless of how novel the methods used in the capacity modeling. Otherwise, the capacity calculations will be inaccurate, resulting in coarse estimates and leading to risky decision making.

Detailed equipment simulation modeling can be used to generate various UPH responses for various equipment run conditions. However, publications on detailed equipment modeling are scarce compared to full factory simulation modeling (FFSM). Most of the publications on equipment modeling come from industry practitioners but the modeling methods applied were shared at high level only. For academic research on wafer fab, there are various data provided by industry such as the Intel Five-Machine Six Step Mini-Fab [8] and other datasets made available by Modeling and Analysis of Semiconductor Manufacturing Laboratory (MASM Lab) of Arizona State University [9]. The Semiconductor Manufacturing Technology (SEMATECH) International Manufacturing Initiative (ISMI) provides sample working models for wafer fab FFSM using AutoSched AP (ASAP) and automated material handling system (AMHS) using AutoMod [10], both software from Applied Materials. However, there is no sample model for any semiconductor equipment modeling.

The literatures reviewed show that the application of DES in A/T is not as widespread and common as in wafer fab. Based on proceedings from Winter Simulation Conference (WinterSim) from 2001 to 2012 where most of the semiconductor manufacturing simulation practices are shared, the number of papers presented on A/T or back-end manufacturing of semiconductor is less than 10% of papers presented on wafer fab. Given that there are many semiconductor A/T factories operating in Malaysia, the number of papers from Malaysia is negligible compared to United States of America (USA), Singapore, Korea, and Taiwan. There are only a handful of papers from Malaysia as summarized in Table 2.1. “Malaysia” keyword search in WinterSim archive from 1968 to 2012 returns 25 hits from 11 articles, most of them referring to authors who originated from Malaysia and doing research in other countries.

Table 2.1 WinterSim papers from A/T in Malaysia

Year	Authors	Topic
2001	McAllister, Altuntas, Frank (Penn State U), Potoradi (Infineon) [11]	Infineon Melaka A/T factory modeling of scheduled maintenance strategy
2001	Rosen, Geist, Finke, Nanda, Barton (Penn State U) [12]	Infineon Melaka A/T factory burn-in process modeling using graphical methods
2002	Potoradi, Boon (Infineon), Mason (UoA), Fowler, Pfund (ASU) [13]	Infineon Melaka A/T factory simulation-based scheduling for lot release planning
2007	Ong (Intel) [14]	Intel Malaysia A/T factory establishing man-machine ratio using simulation

Most of the technology companies headquartered in California, USA have its presence in Malaysia, especially Penang, which is dubbed as the silicon valley of Asia. This research will not try to study the reasons why there are only a few publications on simulation modeling from Malaysia indicating lack of simulation modeling practices in semiconductor factories based in Malaysia. For some companies, simulation analyses are performed by centralized team located at the company's headquarter outside of Malaysia. The Malaysia factory team will take the recommendation from simulation analysis and implement the idea, but will not have the knowledge and skills on how to perform simulation modeling and analysis.

Finally, this research is also trying to address the lack of knowledge sharing on how to develop and apply very detailed DES models for semiconductor manufacturing equipment, not just for A/T, but for wafer fab equipment modeling as well. There are experts in equipment modeling in various companies, but the knowledge and methods may be treated as company's intellectual property (IP), thus the lack of knowledge sharing. When a new engineer is hired into simulation organization, even after attending basic and advanced simulation classes, the new engineer needs to be trained and coached internally before the person can do the job. Without proper coaching, the reference for examples of equipment models is from AutoMod demonstration models. Unfortunately, only 1 out of the 16 demonstration models has the fidelity that is required. However, it was developed using the old

AutoMod version requiring low-level C programming. Without the proper documented methodology, standardizing modeling technique will be a challenge for in-house simulation team and create issues with model reusability and sustaining. Each simulation engineer will end up developing own approach in modeling instead of adopting a standardized method. As described by Shannon [15], the process of conducting a simulation study requires both art and science. Simulation modeling is an art that requires specialized training and therefore the practitioners' skill levels vary widely.

1.4 Research Justification

It was described earlier that semiconductor manufacturing is highly capital intensive costing up to a billion dollar for A/T and four to five billion dollars for wafer fab plants. Since equipment output rate is the key input parameter to capacity planning system when making strategic and tactical decisions, it is necessary to ensure the values are accurate. The use of HFSME makes this possible to achieve. The methods developed in this research can be generalized for other similar industries such as electrical and electronic products manufacturing.

Electrical and electronic products continue to be Malaysia's largest export. Based on Ministry of International Trade and Industry statistics [16], the export of electrical and electronic products is 34.4% of total export, far exceeding the other major categories such as palm oil (9.3%), liquid natural gas (LNG, 7.2%), and chemicals and chemical product (6.8%). Manufacturing sector generates employment for 1 million people. Manufacturing sector also created business opportunities for small and medium enterprise (SME) in supporting the ecosystem such as building construction and maintenance, precision tooling, equipment supply and maintenance, transportation, and human resource training and development. Some of the mature SME ended up supporting and exporting their products to the multinational companies (MNC) worldwide. Without manufacturing sector's presence, the SME will not be able to learn and grow to the current level.

Penang has the highest foreign direct investment in 2010 and 2011, mainly driven by investment of high technology companies. However, investors also consider other emerging markets such as Vietnam and Indonesia as their cost of manufacturing is lower with abundance of cheap operator. Due to that, it's important for Malaysia to strive productivity improvement to remain competitive despite the cost disadvantage.

Simulation is one of the key scientific methods to improve manufacturing's productivity. If the application of simulation is more widespread in manufacturing and service sectors, more productivity and efficiency can be achieved. This will help Malaysia to remain competitive with the use of knowledge workers and using science in improving operations of manufacturing and services.

There are many simulation practitioners around the world, including for semiconductor industry. The simulation consultants who present tutorials during simulation conferences share generalized techniques for modeling to cater for broad range of audience, mainly academic researchers and students. Also, their motive of sharing is to market their product superiority. The simulation practitioners who work in semiconductor manufacturing companies and its related ecosystem such as equipment suppliers have expertise in simulation modeling but are not sharing the experience, most likely due to confidentiality and IP. Thus, if someone tries to look for "a guide for dummies" how to develop and apply detailed equipment simulation models, there is none available. Even the practitioner's handbook by Chung [17] covers only the basic modeling techniques.

1.5 Research Objectives

The research aim is to develop and apply HFSME methodology to accurately predict complex equipment capability, augmenting capacity planning and productivity improvement decisions in achieving capital equipment and operational efficiencies. The research objectives of the dissertation are as follow:

a) Develop HFSME methodology for use in predicting complex equipment capability accurately.

b) Demonstrate HFSME to augment A/T capacity planning system and show how it solves the inaccuracy problem when calculating equipment capability using spreadsheet models.

c) Demonstrate HFSME for use in equipment productivity improvement decision making, which include quantifying the impact of improvement ideas and recommending which ideas to pursue.

d) Develop methodology to extend HFSME so that operational considerations such as equipment interrupts and operator interactions can be comprehended faithfully. Demonstrate the extended HFSME methodology for use in manufacturing planning and execution decision making.

1.6 Research Scope

The scope of research is for semiconductor manufacturing, specifically A/T. It covers from technology development (TD) to high volume manufacturing (HVM). It will be shown that the objectives can be achieved through case studies of real-world industry problems and how the HFSME results directly contribute to the company's performance by eliminating the need to purchase additional capital equipment costing millions of dollars. The scope also includes developing the guidelines on how to apply HFSME in real world.

1.7 Organization of the Dissertation

This dissertation is organized as follows and summarized in Figure 2.1. Chapter 2 provides an overview of semiconductor manufacturing process flows and a background of different types of simulation used in semiconductor manufacturing. Literature reviews are done mainly in this chapter and supplemented in subsequent

chapters. Chapter 3 briefly summarizes the problem statement from literature reviews and outlines the research methodology. Chapter 4 describes how detailed equipment simulation models are developed and used to answer various questions on equipment capability, an extension of a conference proceeding paper jointly written by the simulation team [18]. It includes a detailed guide of how a detailed equipment simulation model for a generic linked-equipment is developed. Chapter 5 provides a few case studies on how HFSME are developed and used to drive capital reduction and productivity decisions. Chapter 6 describes how HFSME is extended to include equipment downtime and operator interactions, followed by case studies of its usage in manufacturing execution decisions. Chapter 7 concludes the research and suggests future research areas.

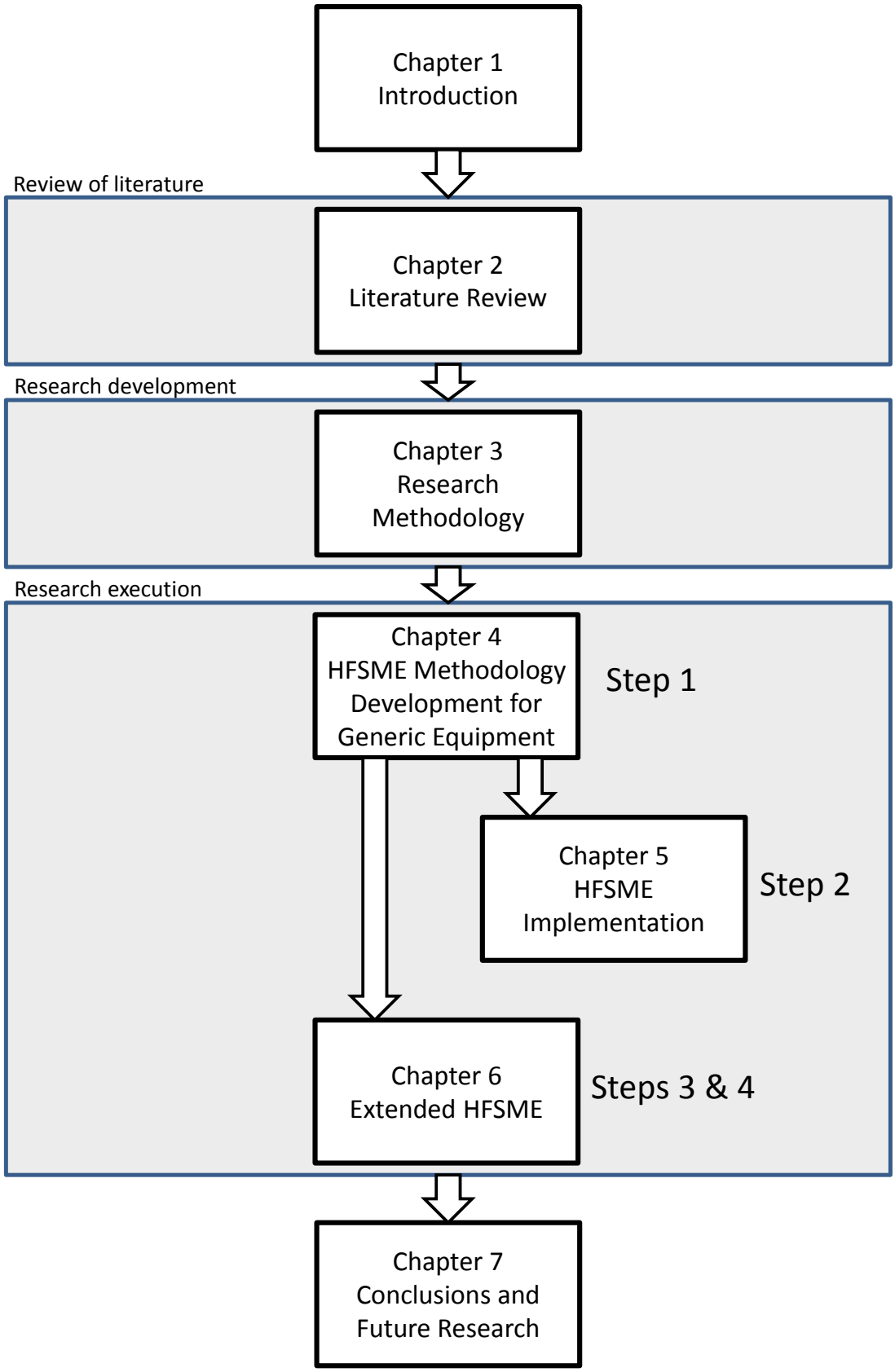

Figure 2.1 Dissertation structure

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