Management accounting and R&D cooperation: The case of standards for the calculation of cost-of-ownership in the semiconductor industry

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Abstract

Based on a field study of the semiconductor industry, we consider the role of standards for the calculation of total cost-of-ownership that underpin R&D processes. Drawing on Robson’s theory of accounting calculations as mobile, combinable, and stable inscriptions that expedite long-distance control, we examine how the standards helped to mobilize, combine, and stabilize these industry-wide calculations. The findings also suggest the standards enabled the calculations to become malleable: companies could significantly modify calculations by inserting private data, adjusting the manufacturing setting and products reflected in calculations, switching between default values and proprietary data, or using parts of the standards selectively. The combination of stability and malleability, because of the existence of standards for the calculation, strengthened the capacity of cost-of-ownership calculations to be a mediating instrument that impacted the investment decisions of integrated circuit (IC) manufactures and semiconductor equipment companies. The study demonstrates how standards created commonality and at the same time enhanced flexibility and thereby the influence of accounting.

Keywords: cost-of-ownership; interorganizational management accounting; semiconductor industry; management accounting standards; product development; R&D

1 Introduction

Sharing information on technology, operational processes, and costs with other companies is relevant in the context of R&D cooperation and supply chain management (Agndal and Nilsson, 2009; Anderson, Glenn and Sedatole, 2000; Caglio and Ditillo, 2008; Carr and Ng, 1995; Cooper and Slagmulder, 2004; Håkansson and Lind, 2004; Kulp, 2002; Munday, 1992). One particularly interesting setting for studying such cooperation and the role of interorganizational management accounting is the semiconductor industry. Miller and O’Leary (2007) and Miller, Moll, and O’Leary (2012) focused on this particular industry, and they investigated various kinds of mediating instruments that help firms in aligning their investment decisions with investments made by other firms and agencies in the same or related industries. These mediating instruments also comprise cost-of-ownership calculations. Our intention is to provide more depth to those findings by addressing the role of standards to strengthen the mediating capacity of cost-of-ownership calculations. “Standards” refers to a defined, "official," but voluntary method for the calculation of cost-of-ownership of semiconductor manufacturing equipment, described in publicly available documents (SEMI 2012a, 2012b). We want to develop the ideas of Miller and O'Leary (2007) and Miller, Moll, and O'Leary (2012) further, by investigating how the mediating capacity of cost-of-ownership calculations is influenced and reinforced by the existence of these standards for the calculation of cost-of-ownership.

Understanding the mediating capacity of cost-of-ownership calculations is important, because these guide large investment decisions in R&D and capital equipment (Miller and O'Leary, 2007). The context of the semiconductor industry is important here: investments in R&D and in manufacturing equipment are enormous; the lead time for developing future technologies is very long and it is difficult to predict the outcome; moreover, many different parties are involved in creating markets and shaping technological progress. Miller and O'Leary (2007) analyzed cost-of-ownership calculations as one of the mediating instruments in this industry. Cost-of-ownership includes depreciation of the expensive capital equipment and various kinds of recurring costs, such as for tools and auxiliary materials. These calculations are used as an indicator of the attractiveness of a candidate technology and of a specific supplier offering. Only looking at the initial investments is not enough, because operational costs are also considerable, and there are interdependencies between investment costs and throughput, yield, uptime and other variables that also affect the economics of the technology. These cost-of-ownership calculations represent a form of interorganizational management accounting (Caglio and Ditillo, 2008, 2012; Fayard et al., 2012): It is the integrated circuit manufacturer who will incur the cost-of-ownership, but equipment suppliers and other firms and agencies also provide some of the data and use the results. Therefore,

> "calculations of cost-of-ownership are utilized extensively throughout the semiconductor and related industries. They are intended to compare two or more systems or technologies by relating the capital costs and operating expenses associated with each one to measures of output and operational effectiveness" (Miller and O'Leary 2007, p. 727).

Why would we expect *standards* to be important for the mediating capacity of cost-of-ownership calculations—a facet Miller and O'Leary (2007) do not consider? Organizational structures and practices in the semiconductor industry are highly networked and hybrid, and standards are generally more important as the organization of an industry is more networked and hybrid (Schilling and Steensma, 2001; Sahayn, Steensma and Schilling, 2007). Standards in the semiconductor are developed and revised through an industry organization focused just on that: SEMI (Semiconductor Equipment and Materials International) is a global industry association that provides a forum for collaboration and standard setting. These are mainly technical standards (such as for production processes, testing, or wafer size), but some standards are called "equipment metrics" and concern topics such as cost-of-ownership. In fact, the semiconductor industry seems to be the only case of having cost accounting standards for the calculation of cost-of-ownership that are voluntary, publicly available, and widely used (Geißdörfer, 2008). Thus, the networked semiconductor industry represents a setting in which standards are likely to be important, it provides an intriguing and rare example of management accounting standards, and these are left unexplored by Miller & O'Leary (2007), although the role of cost-of-ownership calculations as such has shown to be important.

This leads to the research questions for the present study: In what way does the existence of standards for the calculation of cost-of-ownership enhance the capacity of these calculations to be a mediating instrument? This does not address the accuracy or comprehensiveness of standards, but how standards help making these calculations "work," in the sense of influencing what is happening in organizations, or more specifically, in directing semiconductor companies' investment decisions.

Robson (1992) provides a powerful way for analyzing the role of standards. For the present study, drawing on Robson's (1992) notions of mobility, stability and combinability helped to develop a more nuanced understanding of the mediating capacity of cost-of-ownership calculations in the semiconductor industry. We distinguish between different situations in which cost-of-ownership calculations were mobile in the semiconductor industry. We investigate what combinability of these calculations meant in these situations. We also analyze how the existence of standards for the calculation of cost-of-ownership helped stabilizing these mobile and combinable calculations. Beyond this, we investigate how standards made the calculations of cost-of-ownership *malleable*, which went beyond aggregating, disaggregating, and rearranging numbers (i.e., combinability) and concerned more fundamental changes to the calculations, such as inserting proprietary data or changing the calculation methods. We find that standards made the meaning of the input data and calculation methods enough commonly understood, so that users could make such significant changes. The standards contributed both to the commonality of accounting calculations as well as to their flexibility. The study provides a more nuanced understanding of how accounting can be both—common and flexible—because of the existence of standards.

This is an empirical study based various kinds of data. We consulted research papers and other publicly available documents. We have spoken with many experts on cost-of-ownership in the semiconductor industry, and several of them have been involved in these developments since more than 20 years. We also obtained documents and an example calculation based on software that incorporates the cost-of-ownership standard. Furthermore, we have created a spreadsheet-based model of cost-of-ownership calculations to verify our detailed understanding of the standards for the calculation of cost-of-ownership.

The remainder of this paper is structured as follows. A literature review follows in Section 2, including a description of the standards for the calculation of cost-of-ownership. Details on the research method are provided in Section 3. Section 4 presents research findings on the use of cost-of-ownership calculations in public and in private contexts. In Section 5, we discuss how the standards contributed to the capacity of cost-of-ownership calculations to be a mediating instrument, because these also enabled calculations to be malleable. Section 6 concludes the paper.

2 Literature review

We will quite extensively summarize Miller and O’Leary (2007) in Section 2.1, who analyzed cost-of-ownership calculations as a mediating instrument for coordinating investments across companies in that industry. Documents on the standards for the calculation are reviewed in Section 2.2. The framework of Robson (1992) will be used in this paper to analyze the role of these standards for cost-of-ownership calculations (Section 2.3).

2.1 Accounting as a mediating instrument in the semiconductor industry

Miller and O’Leary (2007, p. 702) use the term “mediating instruments” to refer to “those practices that frame the capital spending decisions of individual firms and agencies, and that help to align them with investments made by other firms and agencies in the same or related industries.” This helps to better understand how investment processes are managed not only within organizations, but also among groups of organizations. When organizational structures and practices become more networked and hybrid, there is a need to better understand how accounting practices may play a role in the cooperation and sharing of expertise among firms.

> “Even competing firms engage in continuous and frequent information exchange on a much larger scale than commonly acknowledged. … Much of this information is accounting-based, albeit modified to deal with the often localized nature of the information transfers” (Miller, Kurunmäki and O’Leary, 2008, p. 962-963).

Miller and O'Leary (2007) focus on integrated circuits (IC), and seen more widely, semiconductors also include flat-panel displays and photovoltaics. R&D requires huge investments, very long lead times, and many different parties are involved: firms that develop and manufacture final products (e.g., computers, phones, cameras), components (e.g., microprocessors, memory—such as Intel, Samsung, Texas Instruments, Toshiba, and NXP), equipment and subsystems (e.g., lithographic equipment, lenses and lasers—firms such as ASML, Canon, Nikon and Applied Materials), but also universities, government agencies, national laboratories, and science foundations. Research cooperation and knowledge sharing is partly organized through SEMATECH (Browning et al., 1995; Carayannis and Alexander, 2004; Link and Finan, 1997; Müller-Seitz, 2012).

Miller and O'Leary (2007) analyze *Moore's Law*, *technology roadmaps*, and *cost-of-ownership calculations* as mediating instruments in this industry. These help to resolve choices for alternative technologies and set benchmarks for cost reduction targets to safeguard the profitability of different parties.

Moore's Law describes an ongoing growth in the number of components per IC, as a result of miniaturization, and this leads to a reduction of the cost per component. Moore's Law predicts a doubling of the number of electronic elements per IC every two years.[1] This principle has become the fundamental expectation for technological progress and cost reduction of the entire IC industry. To some extent, this can be realized by continuous improvement of a particular technology. In parallel, development of an entirely new generation of equipment is necessary. For example, Miller and O'Leary (2007) describe how optical lithography, which involves beaming light through an "image" and lenses in order to project the pattern of the IC on the silicon wafer, was reaching its limits. Adherence to Moore's Law would at some point require making the project lines so small, that the wavelength of light could not project them anymore. Fundamentally new technology had to be developed, starting many years in advance of optical lithography becoming inadequate.

Technology roadmaps describe the required performance and technical standards of several steps in the production process of ICs for the next 15 years in detail. The roadmap

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[1] For example, see Intel, *Moore's Law Inspires Intel Innovation*, http://www.intel.com/content/www/us/en/silicon-innovations/moores-law-technology.html (accessed 24 October 2012). The 2010 update to the roadmap has growth slowing at the end of 2013, after which the number doubles only every three years. See Wikipedia, *Moore's law*, http://en.wikipedia.org/wiki/Moore%27s_law (accessed 24 October 2012), and the International Technology Roadmap for Semiconductors, *2010 Overall Roadmap Technology Characteristics (ORTC) Tables*, http://www.itrs.net/Links/2010ITRS/2010Update/ToPost/2010Tables_ORTC_ITRS.xls, for example on the worksheet *Notes for ORTC-2A* (accessed 24 October 2012).

coordinates by making sure that the overall expected technical progress according to Moore's Law is achieved, and it also coordinates by detailing what different technologies need to accomplish. For example, the roadmap lays out the number of electronic elements per chip (in billions of transistors), and the size of lines. For new technology generations, the roadmap also shows which choices for alternative new technologies are still open. Roadmaps bundle knowledge and facilitate decision making in the industry. They help companies to understand which choices are likely be become dominant, so they can make more informed choices about R&D and equipment investments. The roadmap documents are produced and published by an organization called "International Technology Roadmap for Semiconductors" (ITRS) (www.itrs.net), which is sponsored by the five large semiconductor industry associations in the world.[2] Meetings organized by ITRS have the aim to identify barriers for achieving technological progress as defined on the industry roadmap. Information sharing in these meetings is subject to rules about what may be discussed and exchanged as to not violate antitrust legislation (Miller, Moll and O'Leary, 2012). Figure 1 provides an overview of some of the actors in the semiconductor industry.

(Insert Figure 1 around here.)

Cost-of-ownership calculations are a key element for making technology decisions. Apart from the technology question "will it work?" there is the question of whether a particular new technology will be acceptable from a cost point-of-view. Calculations of cost-of-ownership are used to compare the economic attractiveness of technologies and supplier offerings. These results are compared to overall expectations for cost reduction, based on the roadmap, and competing offerings are compared against each other. Cost-of-ownership can be defined as

> "the total lifetime cost associated with acquisition, installation, and operation of fabrication equipment,"[3] or as the "full cost of embedding, operating, and decommissioning in a factory environment equipment needed to accommodate the required volume of units actually processed through the equipment" (SEMI, 2012a, p. 4).

Miller and O'Leary (2007) describe that in the 1990s several alternative technologies to follow-up optical lithography were considered on the technology roadmap (X-ray, electron-beam, and extreme ultraviolet). Immersion lithography entered on the roadmap in 2003,

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[2] The European Semiconductor Industry Association (ESIA), the Japan Electronics and Information Technology Industries Association (JEITA), the Korean Semiconductor Industry Association (KSIA), the Taiwan Semiconductor Industry Association (TSIA), and the United States Semiconductor Industry Association (SIA).

[3] See SEMATECH, *SEMATECH Dictionary of Semiconductor Terms,* http://www.sematech.org/publications/dictionary/con_to_cz.htm (accessed on 29 August 2012).

which would make smaller lines possible with optical lithography than ever imagined, and so it could extend the life of optical lithography as a suitable technology for pattering ICs. Around 2004, the fundamental technical problems of extreme ultraviolet (EUV) were considered solvable and cost-of-ownership comparisons between EUV and immersion lithography became relevant. Miller and O'Leary (2007) describe a study by Silverman (2005) evaluating these alternative technologies based on cost-of-ownership, and which estimated that the cost-of-ownership of both technologies would be quite similar.

In sum, Miller and O'Leary (2007) and Miller, Moll, and O'Leary (2012) investigated cost-of-ownership and other mediating instruments in the semiconductor industry. Underexposed in these studies, though, is the role of standards for the calculation of cost-of-ownership, although standards are likely to be important in such as networked and hybrid sector (Schilling and Steensma, 2001). We want to nuance their observations, which leads to the research question introduced above: In what way does the existence of standards for the calculation of cost-of-ownership enhance the capacity of these calculations to be a mediating instrument?

2.2 Standards for the calculation of cost-of-ownership

We firstly describe the SEMI E35 standard that defines the calculation method of cost-of-ownership, and then the SEMI E10 standard, which defines operational parameters that are key inputs to the calculation according to the E35 standard. We need a few pages for providing enough background information and to illuminate the following aspects, which will be important for the analysis: Each calculation of a cost-of-ownership result requires a lot of data for describing the manufacturing situation. This makes data collection (and exchange) an important issue, but it also means that each calculation reflects only a very particular setting. The calculations are complex, and therefore the interpretation requires a detailed explanation of how it has been conducted. The standards provide such an explanation. The relevant standards E10 and E35 address different aspects, whereby E10 provides data on utilization as key input for the costing calculations according to E35. The standard contains default values.

SEMI E35, guide to calculate cost-of-ownership metrics

The standard SEMI E35-0312 can be purchased for US$100 from SEMI (www.semi.org). The document is called a "guide" and its purpose is "to provide standard metrics for evaluating unit production cost effectiveness of manufacturing equipment in the semiconductor related industries" (SEMI, 2012a, p. 1). The guide is applicable to any type of equipment for processing semiconductor units, such as IC wafers and devices.

The often-mentioned “basic equation” for cost-of-ownership in semiconductors proposed by Carnes and Su (1991) and Dance, DiFloria and Jimenez (1996) provides an intuitive introduction to the general idea:

$$COO = \frac{CF + CV + CY}{TPT * Y * U}$$

COO is the cost-of-ownership, *CF* is the total fixed cost, *CV* the total variable cost, and *CY* the total cost due to yield loss. In the denominator, *TPT* stands for throughput, *Y* is composite yield, and *U* is utilization of equipment. By multiplying throughput with utilization, we get the total amount of produced units, which is reduced to the total amount of *good* units by the multiplication with the yield figure.

SEMI E35 splits the cost-of-ownership into the cost of equipment ownership (*CEO*) and the cost of yield loss (*CYL*) (SEMI, 2012a). *CEO* is a factor in cost-of-ownership that includes all costs not associated with yield loss. *CYL* is based on the idea that a unit lost at the end of a given manufacturing process step represents the loss of the cost of the starting unit and the manufacturing costs to that point. The basic equation can be rewritten by splitting the nominator into two parts, which are described below.

$$COO = \frac{CF + CV}{TPT * Y * U} + \frac{CY}{TPT * Y * U} \triangleq CEO + CYL$$

Cost of equipment ownership: 20 cost elements

CEO represents the fixed and variable cost in relation to the good amount of units produced, and the *CEO* equation is formulated as follows (SEMI, 2012a):[4]

$$CEO = \frac{(FC + RC) * ER}{TPT * Y * U} = \frac{(\sum_{ij} F_{ij} + \sum_{km} R_{km}) * ER}{TPT * Y * U}$$

The fixed costs per unit of equipment (*FC*) and the recurring costs per unit of equipment (*RC*) are multiplied with the amount of equipment required (*ER*), since the fixed costs and recurring costs are measured per piece of equipment. The indices “*i*” and “*j*” for the fixed costs refer to a table in the standard that defines cost categories *i* and within those the cost elements *j*. These include the cost categories equipment (with 5 cost elements, such as installation) and facilities. Similarly, the indices “*k*” and “*m*” for the recurring costs refer to a table that defines cost categories *k* and within those cost elements *m*. These include consumables (with 5 cost elements, e.g., utilities), maintenance (with 4 cost elements, such as spare parts), and labor (with 4 cost elements, for example, engineering).

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[4] In the standard document SEMI E35, the term “*GUE* per year” is used. *GUE* stands for “good unit equivalents”, and *GUE per year* is equal to *TPT* × *U* × *Y*. In the equation, “Recurring costs” are what the basic formula considers “variable costs”.

The definitions of these cost categories and cost elements include many specific issues. For example, differences between the costs of consumable parts, spare parts, and repair parts are defined within the recurring costs. Also, the definitions avoid double counting, such as counting a part that has been purchased initially together with equipment acquisition cost later again as a spare part. Furthermore, for each cost element, the document includes a description of the method for measuring the particular cost element.[5]

The E35 guide also includes "default values" such as for the cost of space in a wafer fab. These values can be used if actual data are not available.

Cost of yield loss: three cost elements

The cost of yield loss (*CYL*) expresses the costs incurred by yield losses (*CY*) per good unit ($TPT \times U \times Y$). This represents that a unit lost at the end of a particular manufacturing process step causes a cost equal to the cost of the starting unit plus the manufacturing cost of the step at which it was lost. This requires knowledge of the accumulated manufacturing costs before the unit is lost. So, if a unit is damaged during this process step, the cost of yield loss incurred includes the cost-of-ownership of the equipment in this process step. This means that the cost-of-ownership of a piece of equipment is an input value for the cost of yield loss, and thereby also input for the calculation of the cost-of-ownership. This circular relation is solved by performing iterations to approach the cost-of-ownership value.

The cost of yield loss equation is further specified into 3 cost elements: equipment yield loss, defect limited yield loss, and parametric limited yield loss. Measuring these various yield losses requires further assumptions, input values, and measurement models.

The SEMI E35 does not include all elements for the cost-of-ownership calculations. Several of the input parameters and calculations are defined in other SEMI standards, particularly in the SEMI E10 standard. Those standardized parameters and calculations are also needed for other purposes, such as for exchanging technical data among different machines connected in a production line.

SEMI E10, reliability, availability, maintainability, and utilization

The SEMI E10 standard is called "Specification for definition and measurement of equipment reliability, availability, and maintainability (RAM) and utilization". We used the

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[5] For example, for the cost element Labor within the cost category of Maintenance, the method is formulated as follows (SEMI, 2012a, p. 14): "Calculate the number of maintenance labor hours required for scheduled and unscheduled downtime based on using SEMI E10 metric inputs. Multiply the actual burdened costs for labor-hours of effort multiplied by the number of hours for each equipment purchaser's personnel type. Equipment user may need to adjust actual hours required due to warranty and service contract coverage. Note that operation labor hours are not included in this category."

SEMI E10-0312 version, available through www.semi.org at a price of US$ 200. This standard provides the detailed explanation of the definitions and calculations that underlie *total utilization* and *operational uptime*, which are key parameters in the cost-of-ownership calculation. Furthermore, the E10 standard includes the definition and calculation of the costs of consumable material, nonconsumable parts, and maintenance, which are also part of the cost-of-ownership calculation. The importance of standardization for effective information exchange is mentioned in this standard:

> "This Document establishes a common basis for communication between users and suppliers of semiconductor manufacturing equipment by providing a standardized methodology for measuring reliability, availability, and maintainability (RAM) and utilization performance of equipment in a manufacturing environment." (SEMI, 2012b, p. 1).

The core of the SEMI E10 standard is the definition of various operating states of equipment that cover all equipment conditions and periods of time:

1. Non-scheduled state: time when the equipment system is not scheduled to be utilized in production (for example, holidays out of the production schedule).
2. Unscheduled downtime state: time when the equipment system has experienced a failure until equipment is restored to a condition where it may perform its intended function (for example, replacing a broken component).
3. Scheduled downtime state: time when the equipment system is not available to perform its intended function due to planned downtime events (for example a setup activity for converting the equipment to another process).
4. Engineering state: time when the equipment system is in a condition to perform its intended function, but it is operated to conduct engineering experiments.
5. Standby state: the time other than nonscheduled time, when the equipment system is in a condition to perform its intended function and consumable materials and facilities are available, but the equipment system is not operated (e.g., no operator is available).
6. Productive state: the time in which the equipment system is performing its intended function.[6]

The operating states 2-6 are called *operations time*, consisting of *downtime* (2 and 3) and *uptime* (4-6). Semiconductor manufacturing equipment registers the operation states,

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[6] Just to illustrate the level of detail required for defining these states, note that the standard describes, for example, that "times for heating, cooling, purging, pump down, cleaning, etc., that are specified as part of production recipes shall be specifically included in productive time. However, similar times that are not specified as part of production recipes shall be specifically excluded from productive time" (SEMI, 2012b, p. 8)

either automatically, or the operator needs to enter information about equipment status that cannot be monitored automatically.[7]

Transitions between different states define events. For example, a *downtime event* is a state transition event either into a scheduled downtime state from a state other than a scheduled downtime state, or into an unscheduled downtime state from a state other than an unscheduled downtime state. The latter is also called a *failure*, and failures are further classified into six different types of failures.

Twenty-six performance measures for reliability, availability, and maintainability (RAM) and utilization are defined based on the states and the events. For example, *mean uptime between failures* (MTBF_u) is uptime ÷ number of failures during uptime; and *total utilization* is productive time ÷ total time.

The SEMI standards for cost-of-ownership calculations are incorporated in the commercially available software sold by WWK, called TWO COOL. This software has been purchased by about 3000 companies in the semiconductor industry.[8]

2.3 Mobility, stability, and combinability of calculations.

Robson (1992) provides a compelling way to analyze how standards impacted the capacity of cost-of-ownership calculations to be a mediating instrument. We will draw on Robson's (1992) notions on accounting numbers as "inscriptions" and the mobility, stability and combinability of these. Inscriptions "refer to the various techniques of 'marking' an object or event that is to be known—writing, recording, drawing, tabulating" (p. 689). Such "technologies for *inscribing* the world" (p. 689, emphasis in original) lead to information and knowledge. In other words, information and knowledge is usually obtained from inscriptions rather than through direct interaction with the original objects and events. "It is arguably the case that most of our knowledge does not come to us directly from our own experience of the world: books, newspapers, etc., all supply our 'information'" (p. 689).

Accounting numbers are analyzed by Robson (1992) as inscriptions, which are explained not in terms of how accurately they correspond to the original objects or events (i.e., represent reality), but in terms of their impact on the world. Inscriptions can travel

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[7] Furthermore, the guideline describes several activities included in each state, and both the scheduled downtime state and the unscheduled downtime state are formally broken down into eight more detailed substates each. For example, two substates of scheduled downtime are *preventative maintenance* (which consists of the time for preventative action, equipment test, and verification run as specified by the supplier) and *maintenance delay, supplier* (which is the time during which the equipment cannot perform its intended function because it is waiting for supplier personnel, supplier-controlled parts, supplier-controlled consumable materials, or supplier-controlled information such as test results).

[8] Interview notes 2012-06-01 J

between a context of action and an actor who is remote from that context and who wants to influence it. Accounting numbers as inscriptions can influence action at a distance, such as headquarters of a company prescribing certain types of reporting from divisions to represent local activities, formulating targets in terms of those reported numbers, which may lead to taking actions (e.g., replacing local management). Robson (1992) discusses several powerful characteristics of accounting numbers that enhance their capacity to influence action at a distance: mobility, stability and combinability. These characteristics of accounting numbers allow them the impact action at distance, almost independent from their representational qualities. We will discuss these characteristics in more detail below when analyzing the findings.

In the semiconductor industry, numbers, graphs, tables, and explanatory text that compose a cost-ownership calculation can be seen as inscriptions of the processes, products, and costs of IC manufacturers. These inscriptions influence investment decisions across the boundaries of individual organizations, such as IC manufacturing companies' investment decisions regarding capital equipment, and equipment suppliers' investment decisions on R&D projects (Miller and O'Leary, 2007). We will draw on Robson's theory to analyze our research question introduced in the previous section on how the existence of standards for the calculation of cost-of-ownership in the semiconductor industry has strengthened the capacity of such calculations to be a mediating instrument.

3 Research method

This empirical study is based several kinds of data. We used information that is publicly available as papers published in academic and professional journals, internet pages, and documents that can be downloaded for free (such as several SEMATECH reports and presentations) or at a moderate price (such as SEMI standard documents). These sources are included in the list of references at the end of this paper, and internet pages are referred to in footnotes.

Furthermore, we consulted 17 different experts on standards for the calculation of cost-of-ownership in the semiconductor industry, who work or have worked at industry organizations (SEMI, SEMATECH, ITRS), software companies (WWK, IC Knowledge), semiconductor equipment companies (ASML, Centrotherm, RENA), IC manufacturing companies (Texas Instruments, Infineon, NXP, Intel, AMD, Global Foundries, and others), engineering consulting firms, and other companies in the semiconductor industry, such as material suppliers. Many of them had been involved in standard setting for cost-of-ownership calculations and conducting cost-of-ownership analyses for at least ten years, and sometimes even twenty or thirty years.[9] From April 2012 to June 2014 we exchanged numerous emails with these people. Forty-one emails contained specific data used for this study, such as detailed explanations of particular events that occurred in the history of developing the SEMI standard, or descriptions of cost-of-ownership information exchanges between companies and its use within companies. We also conducted twelve interviews (in person, over the telephone, or via Skype) and received several documents that are not publicly available.[10]

Thirdly, we created a spreadsheet-based model of comprehensive cost-of-ownership calculations to verify our detailed understanding of the standards. We used a particular set of input values obtained from the cost-of-ownership software and services firm WWK, as well as the cost-of-ownership results generated by their software that is in accordance with the standards. Thus, in the process of studying the standards and programming our model, we could compare those cost-of-ownership results. We consulted experts in this process, and our experience with reconstructing the results and creating a consistent model was not only helpful for verifying our comprehension of the standards, but also insightful towards the complexities of these cost-of-ownership calculations and the many different ways in which these could potentially be developed. We also visited a university cleanroom to better understand semiconductor manufacturing processes.

Analysis of the data was focused on the main themes of the study: use of the standard and the reasons for the development and existence of it. At a general level, these themes were clear from the beginning of the study. We knew from prior literature about the role of cost-of-ownership in the semiconductor industry, we know from other sources about the existence of a detailed, influential standard for these calculations, and we believed that the role of this standard for the capacity of cost-of-ownership calculations to be a mediating instrument was not yet well understood. So, we set out to better understand why it existed and how it was used. The qualitative data analysis was a process of connecting the different pieces of information we had obtained, as well as discovering gaps and inconsistencies, which sparked new questions about the themes that were guiding the research. These led to revisiting our

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[9] For example, one of these experts received the SEMI International Standards Excellence Award in July 2014. As co-chair of the North America Metrics Technical Committee Chapter since 1996, he has participated in the improvement and development of several key equipment maintenance standards and multiple cost-of-ownership metrics. See: SEMI, *Standards Industry Leaders Honored at SEMICON West 2014*, http://www.semi.org/en/node/50446 (accessed 18 July 2014). More information on the background of each of these experts is provided in an appendix.

[10] Wright, Williams & Kelly, 2011. *A Guide to Using Two Cool*; Wright, Williams & Kelly, 2004. *Rapid Implementation of Cost of Ownership Using TWO COOL*; an ASML presentation on cost targets in logic markets.

data, collecting new information by asking follow-up questions to interviewees with whom we already were in contact and by asking them to provide further contacts that enabled us to expand the circle of experts we talked to. This also led to triangulating the information obtained from experts with publicly available information. For example, an interviewee talked about an earlier initiative by the associations SEMI and VDMA for establishing a cost-of-ownership standard in the photovoltaic industry, as well as his personal involvement in this initiative, and we subsequently also found information about this initiative in publicly available sources.

As the story unfolded, the themes and questions become more nuanced and specific. For example, when looking at examples of the use of the standards, it became clear that in some situations standards were used extensively, but in other situations they somehow played not such an important role. How did these situations differ? Why was the role of the standard dissimilar? We found that we had to differentiate between use of the standard in public calculations, private calculations used within companies, and situations in which suppliers and buyers of equipment exchanged information. It also became clear that we had to more clearly differentiate between two interwoven standards (E10 and E35).

Not only did the themes and questions become more refined and specific, but we also started to organize the data more closely connected to Robson's (1992) framework. We discovered more and more indications of how the data could be understood through that theoretical lens. This prompted us to revisit the data, conduct follow up research with the experts, and to restructure and rewrite the paper.

4. Mobility, stability, and combinability of cost-of-ownership calculations, and the role of industry standards

In this section we describe our findings on how cost-of-ownership calculations in the semiconductor industry were used in public and in private calculations. Sections 4.1-4.3 focus on public cost-of-ownership calculations constructed by different organizations that jointly defined the context, provided information for the calculation, and used the results internally. We analyze an example of such a joint, public calculation, using empirical data from several papers published in a science and engineering journal (Hazelton et al., 2008a, 2008b; Wüest et al., 2008a),[11] a presentation (Wüest et al., 2008b),[12] and interviews with one

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[11] This example concerns EUV, as does the example reported in Silverman (2005) described in Miller and O'Leary (2007). However, Silverman (2005) does not provide a calculation, but a high-level estimation of broad categories of costs—"quantitative comments" as they are called in the paper (p. 4). Miller, Moll and O'Leary (2012) briefly refer to Wüest et al. (2008a), but the example is analyzed in far more detail in the present paper.

of the researchers and authors of these papers and presentation.[13] Section 4.4 addresses calculations used in commercial settings, where IC companies select equipment and provide feedback. This is based on interview data. Table 1 provides an overview of Section 4.

(Insert Table 1 around here.)

4.1 Mobility of joint, public cost-of-ownership calculations

Mobility was an important characteristic of the joint, public cost-of-ownership calculations referred to above. Mobility refers to the capacity of numbers to move from the setting of the actor and back. Accounting allows people to assess activities they cannot otherwise see, and it enables people to act. Early accounting allowed investors to influence their foreign trade activities, because the physical reports with accounting numbers were literally brought back from other countries, and they represented, for example, labor, inventories and flows of good and cash. The written numbers were independent from the language: "'1' is '1' in Italian, French, German and English, unlike 'uno', 'un', 'ein' or 'one'" (Robson, 1992, p. 694). Accounting makes the organization visible for shareholders, analysts, banks, suppliers, tax inspectors, and consumers, who can then take action, for example, by selling or buying shares, voting the directors out, formulating wage claims, switching to other suppliers, etc. "Few activities of this type are practically accomplishable by personal inspection of the organization" (p. 695).

Cost-of-ownership calculations are inscriptions of the processes and products of IC manufacturers. We will analyze that mobility of these inscriptions; first, by describing how it allowed different organizations to be involved in defining the context and contributing information for the calculation. Different parties provided different pieces of the puzzle of the cost of ownership calculation. Second, mobility of the inscriptions made it possible that such organizations took the joint, public calculation and modified it, making it an internal, private calculation. This mobility "in two directions" helped to make cost-of-ownership a powerful inscription that was used to evaluate candidate technologies and to inform and coordinate investment decisions in R&D efforts and capital equipment.

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[12] Hazelton et al. (2008a) reports a comparison of the technology at the time (45 nm half-pitch) with four new technologies at a half-pitch of 32 nm and five new technologies at an even smaller half-pitch of 22 nm. It includes a sensitivity analysis of the effect of throughput and uptime on the cost-of-ownership of EUV, and it looks at the cost impact of larger (450 mm) wafers. Hazelton et al. (2008b) reports on cost-of-ownership results for partly other technologies, also at a half-pitch of 32 and 22 nm. The paper looks in more detail at the cost of the reticle, which is a main cost component of the total lithography cost-of-ownership. Wüest et al. (2008a) is close to Hazelton et al. (2008a) and includes alternatives based on upgrading installed equipment. Wüest et al. (2008b) is close to Hazelton et al. (2008a) and addresses the cost of EUV technology in more detail.

[13] Interview notes files 2013-6-18 W and 2012-10-18 W

Mobility: data and expertise moving from organizations to a joint, public calculation

To begin with, mobility meant that companies and other organizations contributed their expertise, provided data on the many input parameters, and were involved in choosing the technical setting (products and manufacturing processes) that would be modelled in these joint and public calculations of cost-of-ownership.

The involvement of quite a few different parties in this joint, public cost-of-ownership calculation is clearly illustrated by the fact that the acknowledgements section in Hazelton et al. (2008a) mentions 17 people from 9 different organizations: the IC manufacturing companies AMD, Freescale, Intel, and Toshiba; the semiconductor equipment companies TEL and Nikon; the semiconductor material supplier Rohm and Haas; the French research-and-technology organization CEA-LETI Minatec; and SEMATECH. Similarly, for another example Seidel (2007) acknowledges 18 people from 8 different organizations: the supplier to IC manufacturing companies Pall; the IC manufacturing companies Freescale, TI, AMD, IBM; the reticle company Photronics; the research-and-technology organization ATDF, and SEMATECH and ISMI (which is a subsidiary of SEMATECH).

Furthermore, an illustrative remark in Hazelton et al. (2008a, p. 3) indicates that many different parties were involved in producing these joint, public cost-of-ownership calculations:

> “In follow-up conversations with many device manufacturers, unrealistic mask costs were identified as a possible issue with our COO conclusions. A second set of mask costs was introduced based on the general opinions of several device manufacturers.”

This demonstrates how selecting input parameters was not just a strict technical affair done by one organization, such as SEMATECH, that would be simply conducting a cost-of-ownership calculation and publishing it. Instead, it was a collective process of defining what needed to be compared and gathering the relevant information for the analysis.

Mobility: results moved back to be modified within those organizations

Mobility also meant that companies could take these joint, public calculations and modify these to construct new, private calculations that were more relevant for them. The joint, public cost-of-ownership calculations moved between the public and private domain to be used within an organization. However, as we will explain below, this was not a matter of simply using those given calculations, but these were adapted to become private calculations.

Companies modified these calculations with *private data* they would consider more relevant. Public data to estimate the cost-of-ownership of a new technology were early estimates, and there was a lot of uncertainty around the public, joint calculations for the new technology introduced above. Amongst our interviewees the widespread viewpoint seemed to be that, to some extent, "nobody" possessed very accurate data for new technologies. As the interviewed author put it:

> "Because it was new technology, you don't have any data to compare technologies and to make calculations." [14]

Even if a company would have internal estimates it considered of reasonable quality, they were often unwilling to contribute their confidential estimates to the joint calculation. The same interviewee explained:

> "At SEMATECH, you don't have the full insight; companies have their own data on yields, uptime, etc. They will not tell it. At the company I work now, we also keep that secret." "Yield is the big secret."

He initially also wondered what the worth of these COO calculations would be

> "when it's not very exact. But companies told us they found it useful as a guideline: 'We have an idea and we can take it further.'"

Firms not only put in private data when modifying public calculations for their internal use, but also modified these calculations to make the *manufacturing situation* that was being modeled more relevant for their own context. To understand why this happened, it is relevant to appreciate that joint, public calculations of the cost-of-ownership of new technology necessarily concerned a very specific situation in terms of manufacturing technology, process flow, type of layer, and type of device. The example introduced above was defined in terms of the following aspects:

- Half-pitch node is the central variable reflecting miniaturization through technological progress, and these steps are derived from the semiconductor roadmaps.[15] In these examples, half-pitch nodes of 45 nm, 32 nm, and 22 nm were investigated.
- Candidate technologies, so alternative ways of achieving the next half-pitch node. For example, Hazelton et al. (2008a) looked at EUV and at various optical technologies for "double patterning" whereby the pattern is split into two separate pieces that are exposed separately on a single layer of a wafer. Figure 2 shows the candidate

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[14] Interview notes files 2013-06-18 W and 2012-10-18 W

[15] Half-pitch refers to the distance between the lines on a chip, expressed in nanometers (nm), which is one-billionth of a meter (10^{-9}), or one-millionth of a millimeter. Half-pitch is the usual measure for the ongoing miniaturization, and a particular half-pitch is also called a "technology node".

technologies and process flows as an illustration. However, specific IC manufacturers may have different process flows, which they typically do not want to reveal in detail.

(Insert Figure 2 around here.)

- Type of layer and type of IC. A chip consists of several layers and the design of these layers depends on the type of chip (for example, logic versus memory ICs). The costs of one layer were estimated. “The total layer cost including lithography, deposition, etching, and other process steps was calculated for each of the technology options” (Hazelton et al., 2008a, p. 2). Also, the costs of an entire DRAM device were calculated, with contained five critical layers, seven middle layers, and 22 rough layers at the 32 nm half-pitch and eight critical layers, eight middle layers, and 19 rough layers for the 22 nm half-pitch (Hazelton et al., 2008a, p. 7).
- Unit of analysis. The cost-of-ownership can be expressed in different ways, such as the cost per wafer, cost per die, or cost per function. In Hazelton et al. (2008a) the cost per *wafer* is used when looking at one layer, the cost per *function* is used when looking at the DRAM device, and the cost per *die* is used for investigating the cost impact of moving to larger, 450 mm wafers. It would become unnecessarily technical to explain why these different units of analysis are used, but it illustrates further *choices* that have to be made for a particular cost-of-ownership calculation.
- Assumptions, because so much is uncertain. In this example, it is stated:

> “In comparing the different technologies, the following was assumed:
> 1. All technologies are equally reliable. 2. All technologies support equal yield.
> These assumptions may not be realistic, but there is currently no quantitative basis to justify other assumptions” (Hazelton et al., 2008a, p. 3).

All these choices may not be representative of what a particular company would be interested in. It would not be practically possible to model all possible situations in a joint effort. But in addition, and more crucially, companies often did not want to disclose the precise manufacturing situation that would be most relevant for them. Such information was also sensitive. As an expert involved in cost-of-ownership analyses and selection of equipment and materials in a major IC manufacturing company explained:

> “While much of the data input for these models is public knowledge (depreciation rate, etc.) other data, such as the price [our company] pays for the equipment and materials, is confidential. Other data is even more sensitive, such as the impact of the product or material of die yield and wafers yield. The structure of the COO model may be product specific as well. For example, in high performance logic

> there are many interconnect layers (10+) so companies … are very sensitive to the back end of the process.” [16]

And so, the calculations also had to be mobile in the sense that individual companies could take a joint, public calculation and, in turn, modify it by adjusting the modelling choices: inserting their confidential data on costs, throughput, yield, and other parameters for the calculation. Hence, mobility also meant that the joint, public calculation moved back to the contributors and would be turned into a private calculation.

4.2 Combinability of joint, public cost-of-ownership calculations

Combinability of the joint, public cost-of-ownership calculation was another key characteristic. Combinability means that the accounting numbers can be aggregated, tabulated, and recombined by the actor “in order to establish new relationships, and calculate ‘norms’ through which to compare the settings to be influenced in accordance with his or her specific objectives, aims or ideals” (Robson, 1992, p. 697). Combinability means that disparate concepts are blended, because these are assumed to have identical qualities and, thus, can be represented as numbers that can be treated with mathematical operations. Accounting performs a monetary quantification as the ultimate treatment to make comparing apples to oranges possible—“enabling the combination of things that are different” (p. 699). Combinability, furthermore, means that the aggregate, blended results can be compared to each other and to norms or targets.

> “Financial and investment analysts, for example, combine and compare company financial data with the ‘averages’ and ‘variance distributions’ for similar organisations or industrial sectors, as well as compute past and project future financial trends for the company” (p. 699). Similarly, “tax inspectors recalculate the tax payable and compare with the company’s past tax payments and those of similar organisations” (p. 700).

The ability to aggregate, reorganize, and disaggregate accounting numbers, and to juxtapose these to other numbers from the past, trends, or comparable entities, creates possibilities for not only informing, but also influencing actors.

> “The combinability of company accounts provides the possibility that new relations amongst the wealth of inscriptions collected from afar can be established to inform new motives for acting at a distance” (p. 700).

Semiconductor manufacturing processes are complex and involve many different inputs and interactions between the costs of initial investments (such as for manufacturing

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[16] Interview notes 2012-09-11 S and emails file 2013-07-04 C

equipment, spare parts, training, and cleanroom space), recurring costs (such as for reticles, auxiliary materials, operators) and operational parameters (such as yield, uptime, and throughput). Cost-of-ownership is an *encompassing measure* that incorporates possible offsetting effects of technology decisions and operational decisions (Miller and O'Leary, 2007). The cost-of-ownership calculation makes it possible to *aggregate* many different aspects into an overall number, which can be *compared to targets* that are based on Moore's Law and technology roadmaps.

Combinability: comparisons of joint and public calculations to industry-wide targets

Joint and public cost-of-ownership calculations in the semiconductor industry, as described in the example above, led to an overall cost-of-ownership outcome for which clear targets existed that are specified in the roadmaps. Joint and public cost-of-ownership calculations reemphasize the mediating role of Moore's Law, because the whole point of the calculation was to verify that overall cost reduction targets according to Moore's Law were still feasible. For comparing candidate technologies, a

> "requirement is that the technology should enable the cost reduction trend predicted by Moore's Law. In simple terms, this trend says the cost per device function (e.g., bit of memory or processing capability), should go down by half every 2 years. As the cost of the leading edge lithography technology for the 32 nm and 22 nm half-pitch nodes is forecasted to increase dramatically, the cost per function must be considered to understand whether this increase in cost represents an end to the economic scaling of Moore's Law" (Hazelton et al., 2008a, p. 1).

And so, the main conclusion of the paper is stated in relation to expectations for cost reduction according to Moore's Law, which is visualized in Figure 3.

> "The total lithography cost was calculated for all layers of 45 nm, 32 nm, and 22 nm DRAM devices. These results show that the 32 nm lithography costs are slightly higher than the Moore's Law trend, but EUVL at 22 nm is in line with the trend. This suggests lithography will continue to be affordable under many scenarios" (Hazelton et al., 2008a, p. 9).

(Insert Figure 3 around here.)

Combinability: comparisons of private calculations to industry-wide and internal targets

When companies used the joint, public calculations and created private adjustments of these calculations, combinability also referred to aggregation and comparison to targets. Companies could compare the outcomes of their private calculations to targets for continuous reduction of cost-of-ownership based on the roadmap and to more specific targets they may have formulated for themselves. For example, a major equipment manufacturer performed its own studies of cost-of-ownership while developing a new lithographic technology. It needed to understand if cost-of-ownership expectations of customers, namely the IC companies, were satisfied for this new equipment technology, and it wanted to guide its R&D efforts to achieve the required cost-of-ownership levels. The equipment manufacturer considered the standardized definitions of input parameters important to make sure that their private analyses were consistent with how their customers also analyzed the new technology's cost-of-ownership. The director of strategic marketing of an equipment company explained the role of cost-of-ownership modelling at his company:

> "Roadmaps are very important, they drive the whole industry. ... Moore's law, every two years there are twice as many transistors on a wafer. Costs do increase, but not as much, so on balance it's more economical. … Wafers per hour is the central parameter, and we model a few steps around it, such as deposition, litho, and etching. For example, we model alternative patterning steps for simulating COO, and then it's a tradeoff between the costs of these steps. Five of the 100 steps really determine it, so it's not too detailed. It's also garbage in, garbage out—for new technologies a lot is unknown. And customers really don't tell us everything, so modelling is difficult, for example the number of layers of a particular device." In such models for evaluating the cost-of-ownership of technologies, "there are lots of parties, many factors, and everything is dynamic. … We base our assumptions on reports and models that are available, contacts with other companies, and we coordinate with customers. But you cannot incorporate too many parameters and the info is not very accurate. It's still very exploratory." So, the outcomes of the models "don't mean that much. The assumptions, that's what's all it about. But having the same definitions is important. … We follow the standards for the parameters." [17]

4.3 Stability: standards helped stabilizing the mobile and combinable calculations

The complexities of the cost-of-ownership calculation, as laid out in Section 2, caused ample possibilities for inconsistencies and misunderstanding when different parties were providing input to a joint cost-of-ownership calculation or were internally modifying the results. That is why the SEMI E35 and E10 standards played a stabilizing role.

Stability means that the accounting numbers are recognizable to their users: "stability of the relation between the inscription and the context to which it refers" (Robson, 1992, p. 695). Rules and conventions can create such stability. For example, written texts follow certain conventions of grammar, spelling, and spatial distribution. Accounting also follows conventions, such as conventions that are more generally applied to numbers and texts (e.g., indexing, use of Arabic numbers) and ones that are more specific to accounting (e.g., double entry bookkeeping, international accounting standards).

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[17] Interview notes 2012-09-11 S

The role of the SEMI standards is rather implicitly described in the joint, public cost-of-ownership calculation introduced above. “Lithography costs were calculated using a simplified version of the SEMATECH cost of ownership model” (Hazelton et al., 2008a, p. 2). The cost-of-ownership formula used was given in a presentation (Wüest et al., 2008b), but more details of the calculation model were not provided in the various papers. The researcher and author we interviewed who had been involved in these calculations, explained that the employed SEMATECH models were aligned with the SEMI standards.

> “We based a lot on Phil Seidel’s work. … We used the SEMI standard, for example for the cost of floor space and for uptime, … We used definitions of the parameters according to the standard.” [18]

To better understand how these “SEMATECH models” incorporated the SEMI standards for the calculation of cost-of-ownership some more background on the development of these standards is required. SEMATECH developed a cost-of-ownership model starting in the late 1980s, and it was made available first to SEMATECH and SEMI/SEMATECH members, and later to the entire industry (Lafrance and Westrate, 1993). In the mid-1990s, this model was no longer supported by SEMATECH but handed over to the software firm WWK for software development and support, which led to the commercially available TWO COOL software. Parallel to that, standard development and publication was transferred to SEMI, which led to the SEMI E35 and E10 standards.[19] As a senior industry analyst involved in performing cost-of-ownership calculations at SEMATECH explained:

> “Today, SEMATECH uses the software from WWK for COO modeling. It is much easier to standardize across the company with a commercial software product which is supported and updated on an ongoing basis.” [20]

However, until several years ago, further developed versions of SEMATECH’s original spreadsheet model were still being used within SEMATECH for cost-of-ownership studies, such as for the analyses reported in Muzio (2000), Seidel (2007), Hazelton et al. (2008a, 2008b), and Wüest et al. (2008a, 2008b). One of the people heavily involved at SEMATECH in developing the cost-of-ownership models and applying these for new technology evaluations, explained that Phil Seidel

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[18] Interview notes files 2012-10-18 W and 2013-06-18 W

[19] Websites: SEMATECH, *SEMATECH History*, http://sematech.org/corporate/history.htm (accessed 28 August 2012 and 24 June 2013), SEMI, *About SEMI*, http://semi.org/en/about (accessed 30 August 2012), Scace, R., *Thirty-five years of semi standards!* SEMI, http://semi.org/en/Standards/P043719 (accessed 30 August 2012). Emails files 2012-08-29 B, 2012-08-29 J, 2013-06-06 B, 2014-06-17a B, 2014-06-17a J

[20] Emails file 2012-10-29 L

> "kept developing that effort through the mid-2000s. … The real issue with COO is that everyone understands how the calculation works."[21]

He could confirm that at least until 2010, these SEMATECH models were aligned with the SEMI standards.

The SEMI standards helped *stabilizing* the mobile and combinable cost-of-ownership calculations, firstly, because putting together the inputs from different organizations was facilitated by using the standards. They created stability, in the sense that these different organizations—commercial companies (such as suppliers, equipment companies, and IC manufacturers) and research organizations (such as SEMATECH, universities, government labs)—knew how to change their internal, private information into commonly understood information that could be incorporated into the joint, public calculation. For example, a senior director who was also a costing and metrics expert at an IC company explained that

> "[our company] as a whole participates in those, for example, in research projects with imec or other European-funded research projects to work together on particular topics. In the past when [our company] was still developing DRAM and highly integrated logic ICs, we did joint development with partners such as IBM and Toshiba. Of course, those were joint developments. There we have used the COO models of SEMATECH."[22]

Secondly, the standards helped stabilizing the cost-of-ownership calculations by enabling different companies to modify these public calculations for internal, private use. As mentioned above, the analyzed joint, public cost-of-ownership calculations included considerable uncertainty and were inevitably made for a very specific situation in terms of process flow, layer, and device. Companies could take the public calculations and modify them to construct new, private calculations that were more relevant for them. They could internally adjust them for their manufacturing setting and products, and also update them with private data—perhaps later in time when data they considered more accurate became available.[23] Stability implied that companies knew how they could be substituting elements of a joint, public calculation with private information (regarding data, devices, and manufacturing processes). The use of the SEMI standards for joint, public calculation was helping to make this possible. Therefore, users of the calculations found it important that the public and more "general" calculations were transparent and being conducted according to the industry standards.[24]

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[21] Emails file 2013-04-28 T

[22] Interview notes 2014-04-10b A

[23] Interview notes files 2012-10-18 W and 2013-06-18 W

[24] Interview notes 2013-06-18 W

Another example of how cost-of-ownership calculations were stabilized when moving between the public to the private domain is found in an earlier SEMATECH report on the results of lithography cost-of-ownership calculations for competing technologies (Muzio, 2000). It is stated that

> “several simplifying assumptions must be made, along with a large number of controversial parameter estimates”, and therefore “International SEMATECH uses a periodic formal review process in which all of the COO assumptions are reviewed, documented, and published on a public website (http://www.sematech.org/public/ resources/coo/index.htm). This makes it possible for individual users to review the analysis and understand what modifications are necessary to apply the International SEMATECH “generic” analysis to a specific case” (Muzio, 2000, p. 1).[25]

4.4 Mobility, combinability and stability of commercial cost-of-ownership calculations

Besides in a public setting, cost-of-ownership calculations played a role in commercial relationships between organizations, such as when investing in new equipment and selecting a supplier, investing in equipment upgrades, or measuring supplier performance. We will investigate mobility and combinability in this setting and how standards helped to stabilize the mobile and combinable cost-of-ownership calculations.

Mobility of cost-of-ownership information meant that suppliers provided information (and contractual guarantees) to IC companies about the performance of their equipment, and IC companies provided information about the actual performance, such as throughput, capital costs, and consumable costs and usage.[26] *Combinability* was not related to overall roadmap targets, in contrast to the case of joint, public calculations discussed above. It meant that cost-of-ownership estimates for different kinds of equipment being compared for offer-selection purposes or for post-installation review purposes, when the actual outcomes were compared to the promises and guarantees.

The standard created *stability* of these mobile and combinable calculations, because it enabled the information to be produced by one organization and used by another one. When asked whether the SEMI COO standard is recognizable in this exchange process, one expert who had observed many situations in which companies exchanged information explained:

> “Typically, that is the case. It may be referred to as SEMI COO, or SEMATECH, or WWK. But, a high percentage of companies in the IC industry understand there is a standard and abide by most of its requirements; those that don’t usually find some level of rejection.” He also explained that exchanging TWO COOL files “was typical of TI and IBM. Since they already had TWO COOL, they

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[25] This website is no longer available.

[26] Emails file 2013-06-13 J

> suggested to suppliers that using the TWO COOL data format was an easy way to exchange data. However, this is not necessarily the most common way to exchange data. It would be more common for data to be exchanged via spreadsheets.” [27]

Mobility, combinability and stability of commercial cost-of-ownership calculations can be illustrated with the following example presented by an expert in the industry, who had worked many years as the cost-of-ownership specialist at a major IC company. He explained they asked for data from equipment manufacturers and other suppliers in accordance with the E10, E35 and other SEMI standards for decisions about investing in new equipment, modifying processes, or comparing different materials.

> “Usually, I was involved with exchanging data with just equipment suppliers. COO was one of the six major decision factors in the equipment selection process during procurement. The group I was in was responsible for evaluating the alternate equipment suppliers and their specific equipment for next generation technology nodes and negotiating with them to become the required supplier/equipment for all future purchases to support that node. As part of that process, we would often share their equipment performance data, including the COO analysis summary report results using the E35 default values. We generally would not share the specific materials (e.g., gas or chemical) specific unit costs as this was considered very confidential. … I believe that there were some suppliers who would provide us with their TWO COOL COO input database files so we could verify their analyses and to use as a starting point for our internal COO analyses.” [28]

Note his comments about default values, which we will discuss below. If an equipment supplier would be disproportionate regarding the cost-of-ownership value of its equipment, the IC company gave feedback on their relative position and discussed possibilities to improve their offer:

> “If they were out of line from a COO point of view relative to their competitors, we would give them a relative idea of how they stood and negotiate with them to find ways to reduce it to make them more competitive (e.g., lower equipment purchase price, cost of supplier-provided technical support, extended warranties).”

He believed an equipment supplier would internally use the data it received from IC manufacturers

> “in their COO analyses to determine the priorities of their equipment and process development/improvement projects much as the users [i.e., IC companies] do for their own internal projects. To improve effectiveness in selecting what projects of

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[27] Emails file 2013-06-13 J

[28] Emails file 2013-06-06 B

> the many potential projects that can be done but are not, due to limited resources, COO is one of the factors that needs to be considered."

A contrast: commercial cost-of-ownership calculations in the photovoltaic industry

The use of standards in these commercial settings can be contrasted with a related industry, namely photovoltaic, where standards for the calculation of cost-of-ownership are not as common as in IC manufacturing. As a result, commercial calculations require a detailed specification of data for every new request for quotation.[29] For example, an engineering-consulting firm had compared different turn-key offers for a factory producing photovoltaic cells and solar modules. The managing director of this firm explained that in this industry, there is not a standard to get comparable input data and calculation results:

> "We had requested cost-of-ownership data from several suppliers. And then you obtain a very different calculation from each supplier. The most foolish thing to do would be to just compare the final results of each—then the one who has cheated most ends first. We advise to look in detail into these calculations, and then it becomes apparent that the suppliers have used different definitions and calculation schemes. It's not so easy to find this out, because you don't get the spreadsheet files, but just pdf documents, without the underlying formulas".[30]

SEMI had started to promote the use of the E10 and E35 standards for cost-of-ownership calculations in photovoltaics (Raithel et al., 2014).[31] Reflecting on this, a SEMI director commented:

> "The PV cost of ownership project that we did, I think, was a good reminder to the semiconductor industry how successful these documents are, right, that they're accepted and they're used. And what a challenge it was to get these in place. Cause, like you say, for PV there's no apples to apples comparisons with these numbers. Everyone is using a different metric to claim that they have a lower cost of ownership, but there's no way to compare them, unless you do a lot of work on your own and really dig down into the equations they are using." [32]

In sum, the data in Section 4.4 clearly point to a role for standards in cost-of-ownership calculations in a commercial context, to make sure that supplier data and customer data are comparable. The standards for the calculation of cost-of-ownership enabled the existence of different versions of cost-of-ownership calculations, which would be similar and commonly understood in exchanges, but which could be dissimilar as long as they remained only internally used and were not exchanged.

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[29] Interview notes 2014-04-15 R

[30] Interview notes 2014-04-17 H

[31] Interview notes 2014-04-17 H and 2014-07-17 A.

[32] Interview notes 2014-07-17 A

5 Discussion: Standards enabled "malleability" of cost-of-ownership calculations

The findings described in Section 4 provided further insights into the nature of mobility, combinability, and stability of cost-of-ownership calculations. These characteristics helped to understand how such calculations influenced "at a distance" the investment decisions of IC manufacturers and equipment suppliers in capital equipment and R&D. The existence of standards for the calculation of cost-of-ownership helped stabilizing these mobile and combinable cost-of-ownership calculations, and thereby the standards enhanced the capacity of those calculations to be a mediating instrument in the semiconductor industry.

However, the role of standards went further. In this section, we will discuss that the existence of standards for the calculation of cost-of-ownership enabled the calculations to be *malleable*. Malleability refers to the possibility to modify significant elements of the calculation, without the accounting numbers losing the ability to be mobile, combinable, and stable. Such modifications related to the input data used for the calculation, the manufacturing processes and products that were being modelled, as well as the way final results (e.g., throughput or costs) were being calculated. Thus, these changes went "beyond" aggregating, tabulating, and recombining calculations, as captured by the attribute of combinability—malleability refers to more drastic alterations. Our key point is that malleability was made possible by the existence of standards for the cost-of-ownership calculation. Standards created enough of a *common basis*, so various actors could contribute data to joint calculations, take data and calculations from others, and compare outcomes to targets. Yet, the same basic common understanding of these numbers and calculation methods created *flexibility*: standards enabled exchanging, changing, comparing, and again exchanging the adjusted calculations and data. The malleability of cost-of-ownership calculations, made possible by the existence of standards, made them even more suitable as a mediating instrument for influencing and coordinating investment decisions of various companies in the semiconductor industry. In this section, we will discuss why malleability was important for the mediating capacity of cost-of-ownership calculations and how standards supported this malleability. A summary is included in Table 1.

Previous studies investigating management accounting calculations' ability to influence action at a distance looked at, for example, the role of consultants, universities and other experts (Jones and Dugdale, 2002; Näsi and Rohde, 2007; Qu and Cooper, 2011) and at rhetorical and visual aspects of management accounting (Busco and Quattrone, 2014; Jordan et al. 2013; Quattrone, 2009). A central idea is that management accounting concepts are pliable and flexible, and that makes them influential (Briers and Chua, 2001; Busco and

Quattrone, 2014; Dechow & Mourtisen, 2005; Emsley, 2008; Sandhu, Baxter & Emsley, 2008). Plasticity in this literature is closely related to the notion of boundary objects (e.g., Star & Griesmer, 1989; Nicolini, Menges and Swan, 2012). These are flexible because they can have different meanings in various groups and organizations, and at the same time, their structure is common to all these groups and organizations so that they recognizable to them and can serve as a means of translation. For example, Locke and Lowe (2012, page 118) analyzed the role of flowcharts as boundary objects and found these are

> "weakly structured in common use" but become more specific and idiosyncratic as they are constructed by an individual in a specific context. "Flowcharts are an example of an abstract visualization, a boundary object that is highly malleable. The chart while appearing to be a highly specific tool is nevertheless open to considerable flexibility."

In architecture, as another example (Yaneva, 2005, page 872), scale models together with a number of more schematic presentations of the building such as diagrams, sketches and technical drawings, do not have to purpose to merely

> "visualize invisible substances. Instead, their purpose is to gather a number of things—human and non-human actors, and their concerns, requirements and disputes—and to 'accommodate' them into objects that can be subjected to design experiments. By making models architects invent objects, which have the properties of being composite and mutable." Models can be considered as "compositions of things that are manipulated in the scaling process, and whose transformations cumulatively lead to the building."

The flexibility of accounting—the possibility that accounting can mean something different for different people—enables accounting to have an impact across organizational boundaries (such as different functional areas, different business units, or local versus central organizational units) and across interorganizational boundaries. A "common" idea about a management accounting concept, such balanced scorecards, customer profitability, or quality costs, is often vague and flexible enough to have the potential to be many things to different actors. This can make it acceptable to those actors and, thereby, influential in shaping organizational practices. It other words, at some general and more abstract level, people can talk about and agree on an accounting concept, and because of the flexibility of that concept, people can also develop more detailed ideas for their own domains (Quattrone et al., 2012). For example, Emsley (2008) describes how quality costing was introduced in an organization and then developed into two rather different outcomes, even though the intention was to implement the concept similarly.

> "For example, different actors might all agree that the boundary object that is Juran's cost of quality consists of certain core characteristics such as prevention, appraisal and failure costs. However, scratch beneath the surface and these hard characteristics become plastic as actors have different interpretations about what each of these costs precisely means (such as what costs to include as failure costs and how to calculate them). To move forward, actors translate these differences by deconstructing each of these costs into their component parts whereby the assumptions underpinning them are scrutinised and debated" (p. 379).

For example, Briers and Chua (2001) demonstrated how the actual development of accounting was ongoing and driven largely by interests and coincidental circumstances. Accounting information may temporally settle down on something that works for the different actors involved, but this situation cannot be explained by "rational" contingency factors, and further changes may be triggered by all kinds of events. Briers and Chua (2001) describe a striking contrast between the way particular management accounting information was developed and how it was later presented. The development of information on cost and profitability in the steel company they studied took many years, failed several times, included the creation and shutting down of various costing models, and involved many compromises regarding scope and data. However, the final costing system was presented to outsiders (such as in practitioners' publications) as a straightforward, rational and unproblematic account of developing a better costing system: an exemplar case presented as leading practice. Accounting was not "better" in the sense of providing more accurate information, but accounting was successful when it could be used to hold together different interests, to accommodate different interpretations about facts, and to suggest different ideas about information needed. Actors adopted particular accounting information as long as it represented also their interests, interpretations, and ideas. It was the ambiguousness and flexibility that made accounting concepts accepted and influential.

The importance of such flexibility, or malleability, of cost-of-ownership calculations was apparent in the findings presented above in several ways. It occurred when companies were adjusting joint, public calculations. These companies could replace public data with company-specific and confidential data, and they would alter the manufacturing setting (layers, composition of the IC, process flows), thereby changing the joint, public calculation and turning it the calculation into an internal, private calculation. In commercial calculations, companies could also exchange some information, but keep other information confidential and combine exchanged data with internal data. One of the experts involved in cost-of-ownership in the industry since decades explained:

> "The biggest issue is that [equipment manufacturers] don't have the data on how the factory will use their equipment or materials. So, initially, they have to make generic models and then try to work with the IC manufacturer to refine the model to be more reflective of the actual use. In most cases, this doesn't happen and the IC manufacturer uses the data provided by the supplier in their own models and may not share the actual results." The equipment manufacturer would then internally "get materials data from applications engineering, reliability data from the service group, or if this is a completely new tool, you might have to get estimated data from development engineering."[33]

Industry standards for the calculation of cost-of-ownership enabled malleability, because these made it possible to change input data, scope, and methods for conducting the calculations, made it possible to aggregate, disaggregate, resort, and compare outcomes. Because standards defined the "mechanics" of the joint, public calculation and created comprehensibility, these also allowed users to significantly adapt these calculations.

Some specific features of these standards provide a further understanding of how these helped to make the calculations malleable. As we will discuss in more detail below, the default values as part of the standard was also an element that supported malleability. These made it possible to change between public, general default values and internal, specific numbers. Furthermore, the two-part structure of the standard (E10 and E35) made it possible to choose between applying the standards fully or just partially, whereby partially can be only the E10 standard, or even only that part of the E10 standard that defines machine states and events (so not the performance measures, e.g., uptime and MTBF, based on these). This way, companies could limit data exchange and use different methods for the calculation of internal performance measures or costs. At the same time, standards create enough commonality for exchanging calculations, discussing these, perhaps disagreeing, and finding solutions.

The role of default values

The E35 guide includes "example values", such as the cost of space in a wafer fab. Separately for 150 mm, 200 mm and 300 mm wafers, 34 default values are provided in the standard document (SEMI 2012a). Although these values have not been changed for many years[34], they still played an important role, because the default values reduced the need for data sharing in commercial calculations. As described in the example in Section 4 above, the IC manufacturer could exchange cost-of-ownership calculations with suppliers that contained actual data on the performance and costs of the suppliers' equipment, because those were relevant for the issue that they were discussing. Yet, other data the IC company did not want

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[33] Emails file 2013-06-13 J

[34] Emails file 2013-06-06 B

share, could be replaced by the standard's default values. Both the supplier and IC manufacturer could analyze the calculations and communicate about these. The expert at the IC company emphasized:

> "We mitigated a lot of this issue by including the example default values. My experience is that using the default values and the real [company] values very rarely affected the COO enough to alter any decisions being made. … We had the E35 defaults saved for import into the COO model for sharing with suppliers as well as the updated [company]-specific values we maintained for more accurate values for internal use only." [35]

So, default values made it possible to change between public, general default values and internal, specific numbers, thereby enhancing the malleability of the calculations.

Nuanced roles of the E10 and E35 standards in commercial calculations

However, not always was the entire standard used when companies exchanged data for quotations and contracts. Some interviews pointed to a differentiated role for the E35 and E10 standards, and to differentiated roles of the elements within the E10 standard (the machine states and events versus the performance measures derived from these). These are subtle elements of the standard that are important to understand how the existence of the standards helped to create malleability.

A corporate director of an equipment manufacturer explained that measurement of machine states was crucially dependent on the E10 standard, also for technical reasons: different pieces of equipment in a production system (called "tools" in the semiconductor industry) send data about their machine states to the technical control system of a factory.

> "All these SEMI standards are, of course, included in our machines. For all productivity issues, these SEMI standards are largely included, simply also to connect the machine to the customer's host system. … The SEMI states are included in the machine software."

Similarly, these machine states were a basis when the supplier and customers exchanged requests for quotation and contracts, which always included performance measures based on machine states (such as the mean uptime between failures, mean time to repair, or the operational uptime). Customers sometimes referred to the E10 standard for particular performance measures, or they provided their own definitions of these.

> "If [the customer] wants to have productivity, he should define for us exactly, what he means by productivity. For example, there is a customer who says

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[35] Emails file 2013-06-06 B. Another expert was also very clear when asked about information that is not shared: "Anything to do with yield." Emails file 2013-06-13 J.

> productivity for me is also when the machine is standing there ready to produce. And another customer says productivity applies when the machine is producing. So you have these differences. For example, let's take [IC company]. I think they define productivity also when the machine is standing there ready to produce. It's basically switched off, but it has a high uptime. And for example [another IC company] there's only productivity when it's producing."[36]

This had consequences for what needed to be described in requests for quotation and contracts:

> "Throughput is in any case covered, because it's included in the specifications, and uptime, mean time to repair, and mean time between failures are also determined in the contract. … [Customers] describe what kind of uptime they have, and either they define it precisely again, or we ask 'how do you exactly understand uptime?' As I just explained, the issue of available time, and so forth. For our specifications, we ask precisely how the customer understands it. … That is also exactly described in the contract."[37]

And also if the customer's definitions of the performance measures deviated from the definitions that are included in the E10 standard, the machine states and events—the "raw data" for the calculation of such customer-defined metrics—were always according to the E10 standard.

A senior director and costing and metrics expert at an IC company also commented specifically on the role of the E10 standard, when he explained that the IC company, where he worked at, followed the E10 definitions of the performance measures. Usage of the E10 standard was mandatory for all its wafer fabs, and the company also used the standard for benchmarking with other companies:

> "The E10 standard plays a very different role [than E35]. … For example, when the issue is to define an input parameter for a calculation that purchasing makes when buying machines—we mentioned uptime a moment ago—when this should be guaranteed, there we surely go back to the SEMI standard. Another example is benchmarks. We exchange particular parameters with other firms. It's also internally simply an advantage to be able to go back to a standard that must be applied in all our factories, because every factory thinks it somehow has a special wish. Then it's very good if you can refer to a standard. The SEMI E10 standard is very interesting for us and is also "law", but the E35 standard does not play a role for us."[38]

While the E10 standard was crucial for information exchange in these commercial settings, the role of the E35 standard was different. The same senior director described that his company did not exchange cost-of-ownership calculations with suppliers. He felt that

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[36] Interview notes 2014-04-10a L
[37] Interview notes 2014-04-10a L
[38] Interview notes 2014-04-10b A

providing too much transparency about its cost calculations towards equipment suppliers was not in its company’s best interest. For comparing alternative tools for investment decisions, the company had developed its own cost-of-ownership spreadsheet model, originally based on the SEMATECH costing model, including fixed costs and variable costs, years of operation, utilization, and yield. However, this was not shared with suppliers and did not have to be compliant with the current standard.

> “Very interesting that you mention this, because here we are, of course, not interested in standards. We make our calculation to assess equipment alternatives. We have no interest in sharing this with equipment suppliers. They only want to prove that their tool is the best one, and we want to avoid that discussion. … We provide an input template to suppliers, according to the SEMI E10 standard, on which they enter their data, and we process these inputs further.”[39]

The company calculated the various performance metrics, such as uptime, according to the E10 standardized definitions.[40]

These examples provide a nuanced understanding of how specific elements of the standards, namely the default values and the relationship between the E10 and E35 standards, helped to make the calculations more malleable. Overall, the existence of a standard for the calculation of cost-of-ownership not only provided commonality for different companies involved in producing and using these calculations, but also these also provided the basis for companies changing these calculations. Through this combination, the existence of standards supported the malleability of cost-of-ownership calculations in this industry.

6 Conclusions

We have investigated interorganizational management accounting calculations that influence investment decisions involving different firms in an innovation network. Previous studies by Miller and O’Leary (2007) and Miller, Moll, and O’Leary (2012) have pointed to the role of cost-of-ownership calculations as a mediating instrument for R&D investments and capital equipment investments in the semiconductor industry. We provide more depth to that observation by showing how this mediating capacity depended on the existence of an industry standard for the calculation of cost-of-ownership.

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[39] Interview notes 2014-04-10b A

[40] Another reason why this IC company had not adopted the E35 standard was that product costing was done less detailed than that standard, which is focused on a single process step. It easily had 100s of tools in a wafer fab, and 1000s of different products (“recipes”) each going through 100s of steps. To manage this complexity, it had developed a modular costing system, consisting of the standard cost for each process step of about 150 to 200 more general recipes. It took the most appropriate cost modules to calculate the standard cost of the actual manufacturing plan. Interview notes 2014-04-10b A

Drawing on Robson's framework, we investigated how combinability not only meant that cost-of-ownership calculations possessed the ability to aggregate many different manufacturing costs and other relevant inputs into an overall cost number; it also meant that these aggregate numbers could be compared to cost-of-ownership targets based on the technology roadmap, another mediating instrument discussed Miller and O'Leary (2007) and Miller, Moll, and O'Leary (2012). The calculations had to be mobile, because the semiconductor industry has many highly specialized companies and other organizations, which together determine the economics of a new technology. Moreover, many different actors would be looking at, contributing to, and modifying the calculations. This went "beyond" the calculations being combinable—as in aggregating, disaggrating, reordering—and it concerned making more drastic changes to the calculations. Users could be changing a joint, public calculation by incorporating their own manufacturing processes and products (ICs) and other private information they had not contributed to the public calculation. In this context, the existence of standards for the calculation of cost-of-ownership provided a combination of homogeneity and heterogeneity: They stabilized the combinable and mobile calculations by providing enough of a common understanding such that the calculations would still be interpretable by different actors. However, the same common understanding also enabled malleability of the calculations. By knowing how it worked (the input data, the formulas for the calculation), it could be changed.

Some specific elements of the standards were important here. The standards included different parts, and some companies exchanged complete cost-of-ownership calculations based on the E35 standard—sometimes even with WWK software files. Others exchanged only data on availability and utilization based on the E10 standard, but performed cost calculations internally. It was even possible to merely exchange data on machine states and events according to that specific part of the E10 standard, and perform company-specific calculations (different from those in the E10 standard) on performance measures, such as availability and utilization. Furthermore, the default values in the standard enabled replacing confidential data with "neutral" default values when exchanging calculations.

This study contributes to the literature on how accounting can influence action across boundaries. Our findings suggest that the existence of industry standards may enhance the malleability of mobile, combinable and stable calculations. These standards contributed both to the commonality of accounting calculations as well as to their flexibility. The study provides a more nuanced understanding of how accounting can be both—common and flexible—because of the existence of standards.

A limitation of the present study is that we had to rely on interviews and publicly available data, although this provided the opportunity to engage with a larger number of different organizations than possible in a longitudinal case study. Future research could investigate the mediating role in the semiconductor industry in even greater detail. A longitudinal case study would be great for collecting more granular data on specific investment decisions, the cost-of-ownership calculations and other information that are “on the table” when these decisions are discussed, the data that are received from and provided to other organizations, and the modifications that are made.

Another limitation of the present study is that it focused on only one industry, albeit an intriguing one. The semiconductor industry seems to be one of the very few cases of a voluntary, publicly available and widely used standard for the calculation of interorganizational management accounting calculations (Geißdörfer, 2008). Future research could also compare and contrast the practices in the semiconductor industry to industry standards for interorganizational management accounting (or lack thereof) in other industries. For example, the Gartner cost-of-ownership model is established in information technology, but it is a commercial service from the firm Gartner (McKeen and Smith, 2010; Mieritz and Kirwin, 2005). Its methodology is partially disclosed only to clients, and any purchased analyses and calculation methods are strictly for internal noncommercial use by the licensed Gartner client.

To conclude, this study has focused on detailed management accounting practices that are specific to the semiconductor industry. The findings provide a deeper understanding of that industry, by analyzing the role of standards through the lens of mobility, combinability, stability and malleability of calculations. The study also helps to understand how standards helped to create calculations that are more common and, at the same time, more flexible.

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Table 1. Standards stabilized cost-of-ownership calculations and increased their malleability in the semiconductor industry

	Mobility	**Combinability**	**Stability**	**Malleability**
	The capacity of accounting numbers to move from the setting of the actor and back.	Accounting numbers can be aggregated, tabulated, and recombined in order to establish new relationships, and calculate ‘norms’ through which to compare the settings to be influenced.	Accounting numbers are recognizable to their users, due to stability of the relation between the inscription and the context to which it refers.	Significant elements of the calculation (data, scope, method) can be modified, without the accounting numbers losing the ability to be mobile, combinable, and stable.
	Section 4.1	***Section 4.2***	***Section 4.3***	***Section 5***
Joint, public cost-of-ownership calculations	Companies and other organizations *contributed* their expertise and data to the calculation.	Various aspects of equipment performance were *aggregated* into an overall cost-of-ownership number, which were *compared* to public roadmap-based targets.	Companies and other organizations knew how to make their internal information fit and become *commonly understandable* input to the joint, public calculation.	An individual company could *rework* a joint, public calculation by inserting its own input data, manufacturing process steps, kinds of layers, and types of IC in order to make the modified, private calculation more relevant for them.
Private adjustments of public calculations	Companies and other organizations could *take* the calculation, and remake it into a private calculation.	Overall cost-of-ownership numbers were *compared* to targets which companies set for themselves, and which were derived from the industry roadmap.	These organizations understood *how* the calculation had been conducted, enabling them to substitute elements of the joint, public calculation with private information.	
		Section 4.4		
Commercial calculations	Equipment suppliers *provided* information about the performance of their offerings. IC manufacturing companies *reported* information about actual performance.	IC manufacturing companies *compared* different offerings on certain *overall* performance metrics (for selection). Subsequently, the actual performance was *compared* to promises and guarantees.	Performance data could be *interpreted* in the same way by both parties, without having to agree on definitions each time. E10 seems to be more pervasive than E35.	Companies could *replace* confidential numbers with default values when exchanging calculation. They could *limit* data exchanges to machine states and events (E10). Each company could use *different methods* for the calculation of internal performance measures or costs.

Figure 1. Map of various organizations in the semiconductor industry

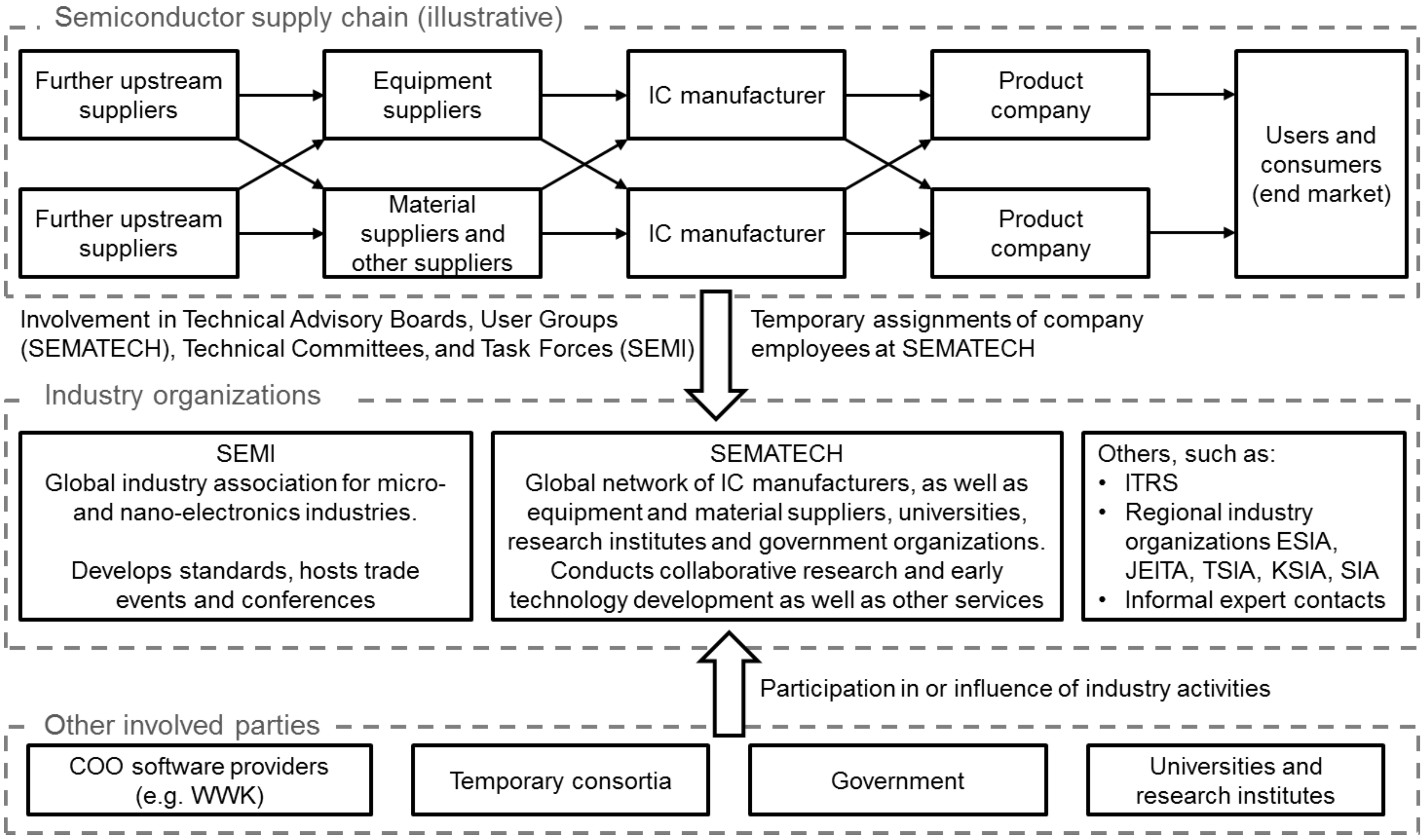


Figure 2. Candidate technologies and process flows (Source: Hazelton, 2008a, p. 2)

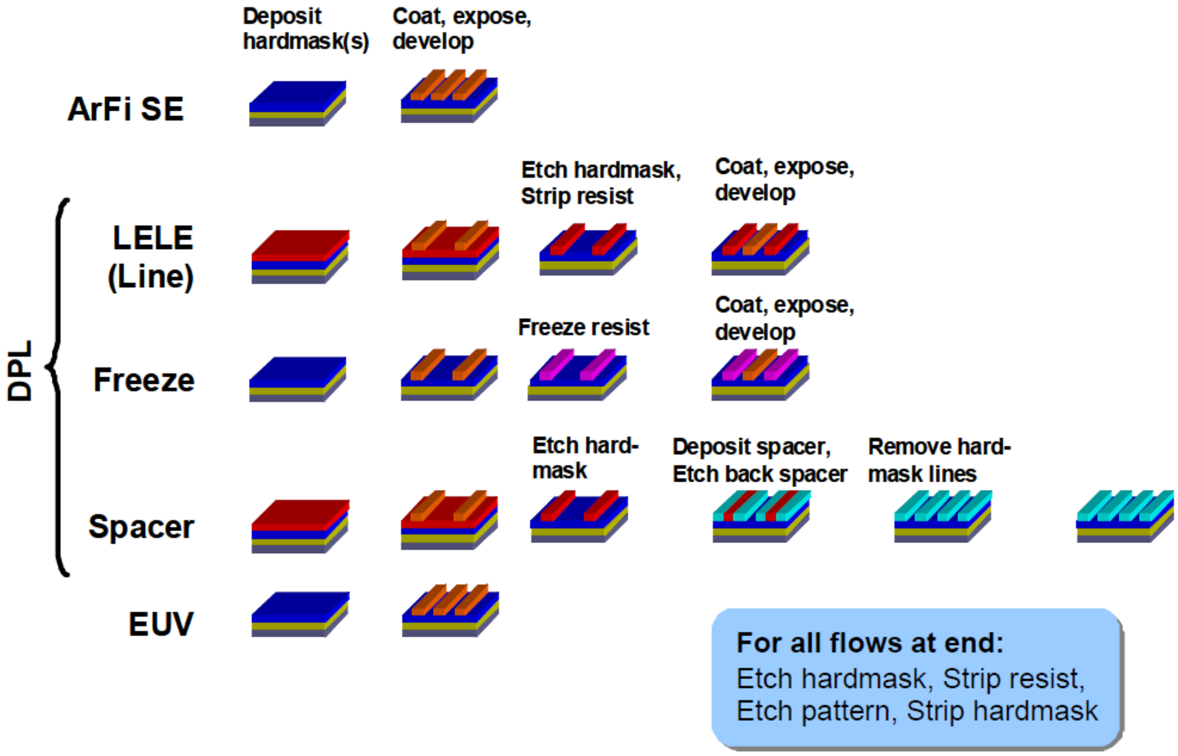
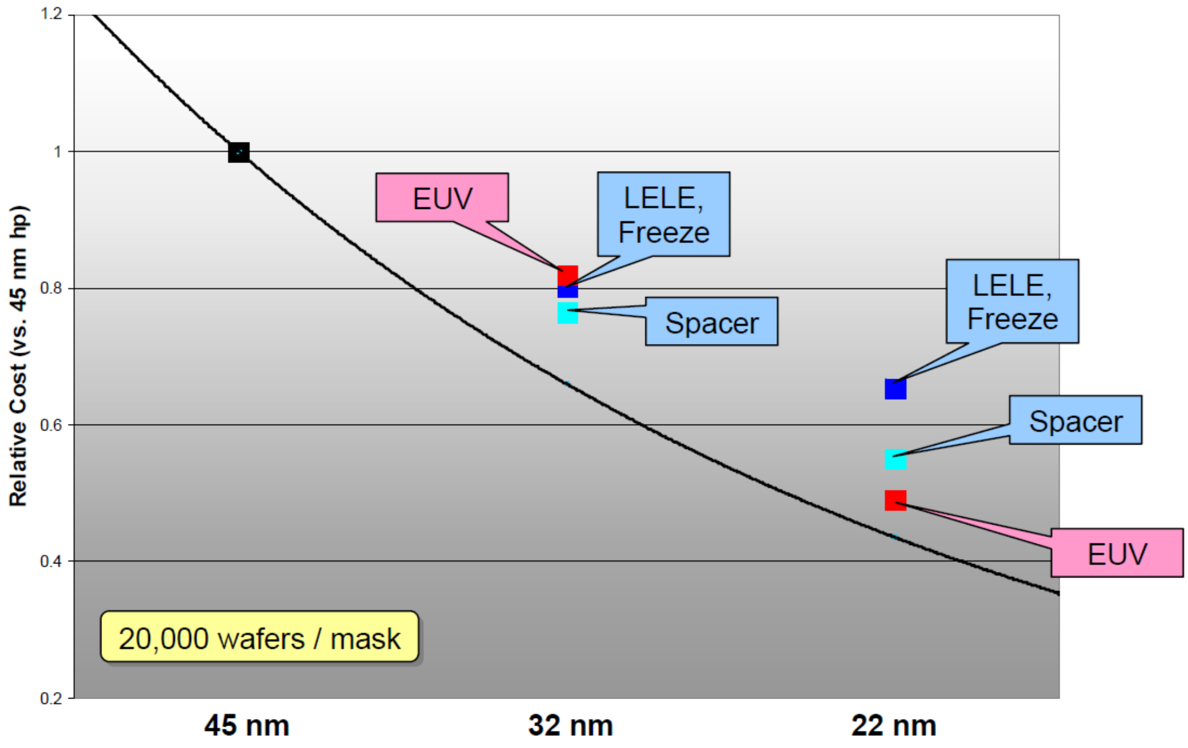


Figure 3. Total lithography cost per function for future technologies, DRAM device, 20,000 wafers / mask (Source: Hazelton, 2008a, p. 7)



APPENDIX: Experts interviewed in meetings, calls, and via email

1. Consultant with over 30 years of experience in the semiconductor industry. He was at Texas Instruments between 1978 and 2007, where he worked as project manager and was responsible for cost-of-ownership modeling. Co-chair of the SEMI NA Metrics Technical Committee since 1996.
2. Co-Founder and chairman of the software firm WWK (Wright Williams & Kelly) since 1991. He began cost-of-ownership modeling work in 1986 when he developed Ultratech Stepper’s initial COO software. He is closely involved with SEMI’s standard-setting activities.
3. Managing director of SEMI’s Berlin office and the Director for PV Europe.
4. Director of the Trybula Foundation and at the University of Texas at Austin and Texas State University at San Marcos. IEEE Fellow and SPIE Fellow, SEMATECH Senior Fellow from 1993-2006, and he was involved in the ITRS Roadmap.
5. Senior Industry Analyst at SEMATECH specialized in economic modeling. Before he worked at the semiconductor companies Global Foundries and AMD.
6. President and owner of software firm IC Knowledge, with over 30 years of experience in the semiconductor industry.
7. Professional in strategic marketing at ASML, with 25 years of experience in the semiconductor industry at SenzAir, ST Ericsson, NXP, Philips Semiconductors, and IC Sensors.
8. Director of strategic marketing at ASML with 30 years of experience in the semiconductor industry.
9. Key account manager at the semiconductor company Sensirion, and before that was project leader and member of the technical staff at SEMATECH in 2006-2010.
10. Scientist and manager at a German material supplier to semiconductor companies Siltronic, Wacker Helitronic; he has been involved in SEMI technical standardization activities since 1991.
11. Professor in nanofabrication, and before that he spent 16 years at Intel in manufacturing processes and technology.
12. Senior director strategic production planning at a large semiconductor company and work experience in the semiconductors since 1996.
13. Corporate director R&D and technology at a manufacturer of equipment for thermal processing and coating for photovoltaic and semiconductor industries.
14. Director of marketing at an engineering firm for photovoltaic manufacturing equipment lines, and previous experience at an equipment manufacturer and at a large semiconductor company.
15. Managing director of an engineering firm for photovoltaic manufacturing equipment lines.
16. Vice president of technology at WWK. Before he was a senior member of the technical staff at SEMATECH responsible for cost modeling, and a staff engineer with American Microsystems. His career has focused on yield modeling, manufacturing capacity simulation and cost modeling.
17. Director at SEMI headquarters.