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How an industry standard may enhance the mediating capacity of calculations: Cost of ownership in the semiconductor industry

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ABSTRACT

Drawing on a field study of the semiconductor industry, we look at a standard for interorganizational management accounting—more specifically, for cost of ownership (COO) in the semiconductor industry. These COO calculations are inscriptions that make the costs of manufacturing processes and products of integrated circuit manufacturers visible to other organizations in the industry. COO calculations mediate between these organizations by guiding their R & D and capital equipment investment decisions. We consider how the standard that defines the method for calculating COO enhanced the mediating capacity of COO calculations. Drawing on Robson's (1992) notions of mobility, stability, and combinability, we find that the standard provided a common understanding when COO calculations were exchanged and compared to targets. At the same time, the standard provided adaptability that was needed for COO calculations to be mediating instruments. Adaptability meant that companies could significantly modify calculations by inserting private data and adjusting the manufacturing setting and products. Further, companies could switch between default values of the standard and their own proprietary data, and they could use the standard to a greater or lesser extent by selectively applying different parts of the standard. The standard enabled different versions of COO calculations to coexist, which would be similar and commonly understood in exchanges but for internal use, different versions could be calculated and used.

1. Introduction

Sharing information on technology, operational processes, and costs with other companies is relevant in the context of research and development (R & D) cooperation and supply chain management (Agndal and Nilsson, 2009; Anderson et al., 2000; Caglio and Ditillo, 2008; Carr and Ng, 1995; Cooper and Slagmulder, 2004; Håkansson and Lind, 2004; Kulp, 2002; Munday, 1992). A particularly interesting setting for studying such cooperation and the role of interorganizational management accounting is the semiconductor industry. Prior research that focused on this industry has investigated various kinds of mediating instruments that help firms align their investment decisions with investments made by other firms and agencies in the same or related industries (Miller and O'Leary, 2007; Miller et al., 2012). These mediating instruments also comprise calculations of cost of ownership (COO), which include depreciation of the expensive capital equipment and various kinds of recurring costs, such as for tools, operators, and auxiliary materials.

Understanding the mediating capacity of COO calculations is important, because these calculations guide large investment decisions in R & D and capital equipment (Miller and O'Leary, 2007). Our intention is to provide more depth to those findings by examining the role of a costing standard in strengthening the mediating capacity of COO calculations. "Standard" in our research refers to a defined, official, but voluntary method for calculating COO of semiconductor manufacturing equipment, which is described in two publicly available documents published by the industry association Semiconductor Equipment and Materials International (SEMI) (SEMI 2012a,b). This standard incorporates definitions of input parameters and steps in the calculation method.[1] In particular, we want to further develop the ideas of Miller and O'Leary (2007) and Miller et al. (2012), because although they addressed how COO helps to mediate between different organizations, they did not investigate how the presence of the standard for the calculation method mattered for that mediating capacity. We investigate

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[1] "Standard" can be a confusing term. It is a defined *method* for calculating COO. In contrast, we use "calculation" to refer to a set of *numbers* showing a COO result, which may or may not have been conducted according to the method defined in the standard. "Standard" does not refer to quantitative benchmarks or norms, which actually do play an important role in this industry, but for those we use "targets."

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how the standard for the calculation of COO influences and reinforces the mediating capacity of COO calculations.

The context of the semiconductor industry is important for COO calculations acting as mediating instruments. Investments in R & D and manufacturing equipment are enormous, and lead times for developing future technologies are very long and the outcomes are difficult to predict. Moreover, many parties are involved in creating markets and shaping technological progress. COO calculations are used as an indicator of the attractiveness of a candidate technology and of a specific supplier offering. Looking only at the initial investments would not be enough, because operational costs are also considerable; moreover, interdependencies between investments, operational costs, throughput, yield, uptime, and other variables also affect the economics of the technology. These COO calculations represent a form of inter-organizational management accounting (Caglio and Ditillo, 2008, 2012; Fayard et al., 2012). While the integrated circuit manufacturer incurs the COO, equipment suppliers and other firms and agencies 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 a *standard* to be important for the mediating capacity of COO calculations—an aspect Miller and O'Leary (2007) do not pay much attention to? Imagine two parties negotiating about particular capital equipment investments and thereby also exchanging COO calculations. They could probably define a calculation method to be used in that particular context. The role of an international, institutionalized standard would not be apparent. A standardized method for calculating COO could also be initiated by a large customer firm enforcing this on its suppliers (Dekker 2003; Schulze et al., 2012). However, Miller and O'Leary (2007) provide a deep understanding of how in the semiconductor industry many different organizations (such as semiconductor companies and suppliers for production equipment, subsystems, and materials) need to work together for creating new technology and markets. COO mediates when these organizations make decisions on investments in R & D and capital equipment. A standardized method for calculating COO becomes relevant in that highly networked and hybrid context. Standards are generally of greater importance when an industry is more networked and hybrid (Schilling and Steensma, 2001; Sahayn et al., 2007). We will also see, however, that the role of the COO standard is quite nuanced and not equally important in all exchanges.

Standards in the semiconductor industry are developed and revised through SEMI, which is focused solely on that activity. It provides a forum for collaboration and standard setting, mainly of technical standards (such as for production processes, testing, or wafer size) but also of some standards called "equipment metrics" that relate to topics such as COO. In fact, the semiconductor industry seems to be alone in having a cost accounting standard for the calculation of COO that is voluntary, publicly available, and widely used (Geißdörfer, 2008). Thus, in the networked semiconductor industry standards are likely to be important, and that industry provides an intriguing and rare example of a management accounting standard that is unexplored by Miller and O'Leary (2007).

This background leads to the research question for the present study: In what way does the existence of a standard for the calculation of COO enhance the capacity of these calculations to be a mediating instrument? This research does not address the accuracy or comprehensiveness of the standard, but focuses on how the standard helps to make these calculations "work," in the sense of influencing what is happening in organizations, or more specifically, in directing semiconductor companies' investment decisions.

The main contribution of the present study is to show that the standard supported the mediating capacity of COO calculations because it provided adaptability to those calculations. We analyze COO calculations as inscriptions of the manufacturing processes and products of integrated circuit manufacturers, through which these products and processes are made visible to other organizations in the industry. Drawing on Robson's (1992) notions of mobility, stability, and combinability of inscriptions, we find that the standard provided a common understanding adequate to make the numbers understandable to different users. This understanding increased the possibility to meaningfully aggregate, disaggregate, and recombine the calculations and compare these to norms. Moreover, information could more easily be exchanged when organizations were contributing to calculations and spreading the results. However, we find that the standard also enhanced the meditating capacity of COO calculations in a more intriguing and paradoxical way, namely by providing adaptability. By having a common *method*, users could make significant changes to the actual *calculations* and thereby adapt these to their own needs and situation. These changes concerned quite fundamental modifications to the calculations, such as inserting proprietary data or changing the manufacturing processes. Users could also switch between their own data and default values that are defined in one of the documents describing the standard. Furthermore, the standard could be used in different ways: from completely (including the encompassing COO metric), to only partially regarding particular performance metrics (such as uptime, utilization, or mean time between failures), or to even only for the definition of the basic data on machine states as input for performance metrics. The standard provided adaptability that allowed the calculations to be mediating instruments, because different users had different requirements. In other words, the standard codified the *method* for calculating COO and at the same time provided the groundwork that allowed users to flexibly adapt specific *calculations* to make them more relevant mediating instruments.

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

The remainder of this paper is structured as follows. A literature review follows in Section 2. Details on the empirical research method appear in Section 3. The findings and analysis are in Section 4, which includes a description of the standard for the calculation of COO, examples of use of the standard, and analyses of how the standard contributed to the mediating capacity of the calculations. In Section 5 we discuss these findings and analyses, and Section 6 concludes the paper.

2. Literature review

We quite extensively summarize prior work analyzing COO calculations as a mediating instrument for coordinating investments across companies in the semiconductor industry (Miller and O'Leary, 2007). We also briefly mention other research in accounting that has investigated mediating instruments in other industries. Furthermore, we review the framework of Robson (1992), which we use to analyze the role of the standard for the COO calculation method. To get a first idea of how we will look at COO calculations that mediate between very diverse areas, consider the following example from Latour (1987). When Thomas Edison was looking for a way to create an affordable electrical lamp, he considered that the cost for consumers needed to be equal to that of gas lighting. He collected information about market prices for various materials for the filament, and he was bound by the laws of physics behind electrical resistance and the generation of electrical light. All these very diverse considerations were related to each other and these relationships could be represented by equations. Edison concluded that the economics required him to aim for a high-resistance lamp and that therefore he needed to find an affordable material for the filament that provided enough durability for that technological choice.

> This example shows … how foreign domains [physics, economics, technology] can be combined and brought to bear on one another once they have a common form of calculation (Latour, 1987, p. 240).

2.1. Accounting as a mediating instrument in the semiconductor industry

The term "mediating instruments" refers 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" (Miller and O'Leary 2007, p. 702). When organizational structures and practices become more networked and hybrid, a need arises to better understand how accounting practices may affect firms' cooperation and sharing of expertise.

> 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 et al., 2008, pp. 962–963).

Other studies have also analyzed accounting calculations as mediating instruments. Christner and Strömsten (2015) examined how various kinds of calculations (concerning market share and financial results, internal rate of return, and discounted cash flows) mediated between academic company founders, venture capitalists, professional managers, and analysts. They investigated how these calculations affected key choices about technology development, the product and its target market, and the organization of product development activities. Jeacle and Carter (2012) investigated how accounting practices such as sales budgets, sales and inventory reports, and garment cost cards linked creative and commercial concerns in the retail fashion industry, analyzing how these practices influenced design decisions and inventory management. In another creative industry of television series production, Maier (2017), showed how budgets and the calculative practices that extend from them mediate between the creative aspirations of the scripts and the financial realities of the project. Carlsson-Wall and Kraus (2015) showed how, rather than accounting calculations, a nonfinancial method (called the technology maturity staircase) mediated between the R & D department, top management, national funding agencies, and a key outside academic. Jordan et al. (2013) analyzed how risk maps mediated between project members from different organizations in the oil and gas industry. These risk maps mediated by providing a signal of project members' confidence and commitment, stimulating identification with the project, and settling different interests. However, the role of *standards* has hardly been investigated in relation to accounting as a mediating instrument.

Miller and O'Leary (2007) study the semiconductor industry,[2] where R & D and capital equipment require huge investments, technology development has very long and unpredictable lead times, and many different parties are involved in R & D and production.[3] Fig. 1 provides an overview of some of the actors. Miller and O'Leary (2007) analyze Moore's Law, technology roadmaps, and COO calculations as instruments, which mediate between the many parties that are making investment decisions: R & D investments for the development of new technologies to enable longer-term technological progress as foreseen on the technology roadmap, R & D investments for further improvements of technologies already in use, and integrated circuit (IC) companies' investments in manufacturing equipment based on new or current technology. The mediating instruments 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 integrated circuit as a result of miniaturization, which 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.[4] This principle has become the fundamental expectation for technological progress and cost reduction across the entire IC industry. To some extent, the predicted doubling can be realized by investing in the continuous improvement of a particular technology. In parallel, investing in the 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 to project the pattern of the IC onto the silicon wafer, was reaching its limits. Adherence to Moore's Law would at some point require making the project lines so fine that the wavelength of light could no longer project them. Investments in fundamentally new technology had to be started many years in advance of optical lithography becoming inadequate.

Technology roadmaps detail the overall expected technical progress according to Moore's Law toward many detailed specifications for ICs and the production process of ICs for the next 15 years. For example, the roadmap lays out the number of electronic elements per chip (in billions of transistors) and the size of lines. The roadmap also shows which choices for alternative new technologies are still open. Roadmaps help companies understand which choices are likely to 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 five large semiconductor industry associations.[5]

COO calculations are a third mediating instrument discussed by Miller and O'Leary (2007). Apart from the technology question of "will it work?" there is the question of whether a particular new technology or a specific supplier offering is acceptable in terms of cost. COO results for candidate technologies are compared to overall expectations for cost reduction based on the roadmap. COO results for alternative supplier offerings are also compared to each other. COO can be defined as the "total lifetime cost associated with acquisition, installation, and operation of fabrication equipment"[6] ; 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).

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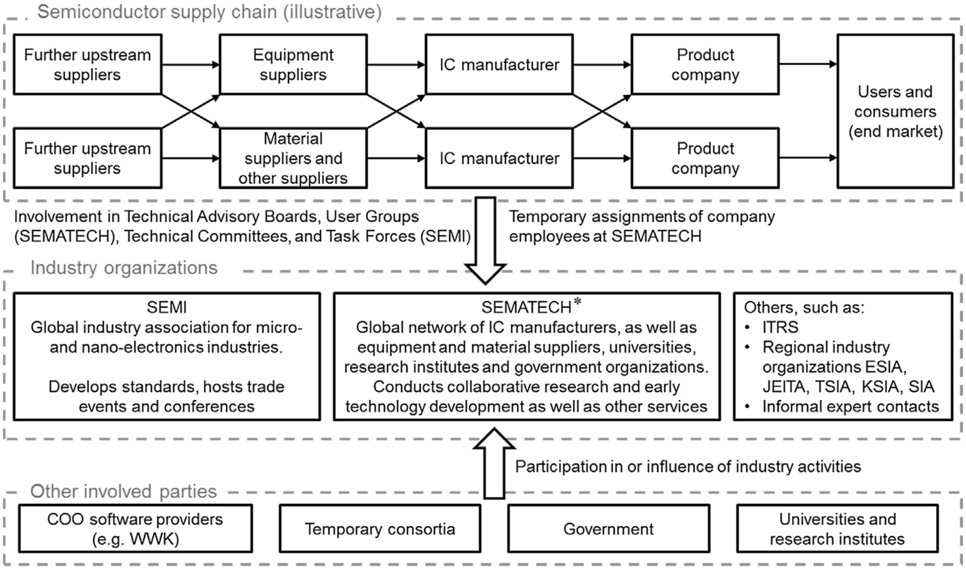
[2] Miller and O'Leary (2007) and our study both focus on integrated circuits, and more widely semiconductors also include flat-panel displays and photovoltaics.

[3] Companies for final products such as computers, phones, and cameras and components for these products such as microprocessors and memory include Intel, Samsung, Texas Instruments, Toshiba, and NXP. Those for production equipment, subsystems, and materials such as lithographic equipment, lenses, lasers, and silicon wafers include firms such as ASML, Canon, Nikon, Applied Materials, and Wacker. Also included are universities, government agencies, national laboratories, and science foundations. Research cooperation and knowledge sharing are partly organized through SEMATECH (Browning et al., 1995; Carayannis and Alexander, 2004; Link and Finan, 1997; Müller-Seitz, 2012), network organizations (such as SEMI and ITRS), and regional industry organizations.

[4] 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 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 examples of the worksheet Notes for ORTC-2A (Accessed 24, October 2012).

[5] 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).

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



*SEMATECH has not existed since 2015 when it merged with SUNY Polytechnic Institute.

Fig. 1. Map of various organizations in the semiconductor industry.

For example, in the 1990s, several alternative technologies to follow-up optical lithography were considered (X-ray, electron-beam, and extreme ultraviolet) and in 2003 immersion lithography, which could extend the life of optical lithography, entered the roadmap. Around 2004, the fundamental technical problems of extreme ultraviolet (EUV) were considered solvable and COO comparisons between EUV and immersion lithography became relevant. Miller and O'Leary (2007) describe a study by Silverman (2005) that evaluated these alternative technologies with respect to COO and suggested that the COO of both technologies would be quite similar.

In sum, Miller and O'Leary (2007) and Miller et al. (2012) investigated COO and other mediating instruments in the semiconductor industry, although these studies, as well as other studies on mediating instruments and accounting, did not consider the role of the standard. However, standards are likely to be important in such a networked and hybrid industry (Schilling and Steensma, 2001). We seek to refine Miller, O'Leary, and Moll's observations by pursuing the research question introduced above: In what way does the existence of the standard for the calculation of COO enhance the capacity of these calculations to be a mediating instrument? For this refinement, we will draw on the idea of mediating instruments and their mediating capacity. However, we understand mediating capacity in broader terms. While Miller and O'Leary (2007) focused on capital spending decisions for R & D investments made by various organizations for developing candidate technologies, we extend the concept of mediating capacity to commercial calculations for capital spending decisions of individual firms (i.e., equipment purchasing).

2.2. *Mobility, stability, and combinability of calculations*

Accounting numbers can be seen as inscriptions, and these "refer to the various techniques of 'marking' an object or event that is to be known—writing, recording, drawing, tabulating" (Robson, 1992, p. 689). Such "technologies for *inscribing* the world" (p. 689, emphasis in original) lead to information and knowledge. In other words, information and knowledge are 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" (Robson, 1992, p. 689).

Accounting numbers as inscriptions 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 between a context of action and an actor who is remote from that context but wants to influence it. Accounting inscriptions can influence action at a distance, such as the headquarters of a company prescribing certain types of reporting from divisions to represent local activities and formulating targets in terms of those reported numbers, which may lead to taking action (e.g., replacing local management).

In the semiconductor industry, numbers, graphs, tables, and explanatory text that make up COO calculations can be seen as inscriptions of the processes, products, and costs of IC manufacturers to make these visible to other organizations in the industry. 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).

Robson (1992) discusses several powerful characteristics of accounting numbers that enhance their capacity to influence action at a distance: mobility, stability, and combinability. *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 brought back from other countries and they represented, for example, labor, inventories, and flows of goods 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, and so on. "Few activities of this type are practically accomplishable by personal inspection of the organization" (Robson, 1992, p. 695).

Combinability means that the accounting numbers can be aggregated, tabulated, and recombined by the actor "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 can be 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" (Robson, 1992, 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. . [Similarly,] tax inspectors recalculate the tax payable and compare with the company's past tax payments and those of similar organisations (Robson, 1992, pp. 699–700).

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 (Robson, 1992, p. 700).

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 those that are more generally applied to numbers and texts (e.g., indexing, use of Arabic numbers) as well as those that are more specific to accounting (e.g., double-entry bookkeeping, international accounting standards).

Mobility, combinability, and stability as qualities of inscriptions go hand in hand. Drawing on Robson's theory, we examine how the *standard* for the calculation of COO supported the mediating capacity of such calculations, because the standard enhanced the stability, mobility, and combinability of such calculations in the semiconductor industry. We also address the fact that combinability was not equally important in all contexts, which will help to understand variation in the use of the standard.

3. Research method

For our research, we used publicly available information, such 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 the two SEMI documents describing the standard).

In addition, we consulted 17 experts on the standard for the calculation of COO in the semiconductor industry. These experts 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 COO calculations and had been conducting COO analyses for at least 10 years, and in some cases even 20 or 30 years.[7] From April 2012 to July 2017, we exchanged numerous emails with these people. Forty-one of these messages 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 COO exchanges between companies and its use within companies. We also conducted 13 interviews (in person, over the telephone, or via Skype) and received several documents that are not publicly available.[8]

Further, we created a spreadsheet-based model of COO calculations to verify our detailed understanding of the standard. With this model we reconstructed the COO result we had obtained from the COO software and services firm WWK, which had been generated by the firm's software that is in accordance with the standard. This experience with creating a model and reconstructing the result also revealed the complexities of these COO calculations and the many ways in which these could potentially be conducted. We also visited a university cleanroom to better understand semiconductor manufacturing processes.

Analysis of the data focused on the main themes of the study, which at a general level were clear from the study's beginning. We knew from prior literature about the role of COO in the semiconductor industry. We also knew from other sources about the existence of a detailed, influential standard for these calculations, and we believed that this standard's role in providing the capability of COO calculations to be a mediating instrument was not yet well understood. Therefore, we set out to better understand why the standard 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 questions led to revisiting our data, collecting new information through follow-up questions to interviewees with whom we were already in contact, and asking these interviewees to provide further contacts that enabled us to expand the circle of experts we talked to. This approach 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 COO standard in the photovoltaic industry, as well as his personal involvement in this initiative, and we subsequently found information about this initiative in publicly available sources.

As the story unfolded, the themes and questions became more nuanced and specific. For example, analysis of examples of the use of the standard made clear that in some situations the standard was employed extensively, but in other situations it played a much less 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 joint, public calculations, private calculations used within companies, and situations in which suppliers and buyers of equipment exchanged information. We also saw that we had to more clearly differentiate between two parts of the standard as described in two documents (E10 and E35).

Through this process, the themes and questions became more refined and specific, and we started to organize the data more closely according to Robson's (1992) framework. We increasingly discovered how the data could be understood through that theoretical lens, prompting us to revisit the data and to conduct follow-up research with the experts.

4. Use of a standard for COO calculations in the semiconductor industry

In this section, we first summarize some SEMI documents that describe the COO standard (Section 4.1). We present our findings on the

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[7] For example, one of these experts received the SEMI International Standards Excellence Award in July 2014. Since 1996, he has participated in the improvement and development of several equipment maintenance standards and COO 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 expert is provided in the Appendix A.

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

use of this standard in particular calculations, whereby we distinguish between joint, public calculations (Section 4.2), and commercial calculations (Section 4.3). We then analyze how the standard fostered stability, mobility, and combinability of COO calculations, whereby the use of the standard varied and was more extensive in joint, public calculations than in commercial calculations (Section 4.4.1). Finally, we analyze how the standard enhanced the adaptability of COO calculations (Section 4.4.2), which we identify as another quality that was crucial for their mediating capacity.

4.1. Standard for the calculation of COO

The standard consists of two parts. We will first describe the SEMI E35 document, which defines the method for calculating COO, and then describe the SEMI E10 document, which defines operational parameters that are key inputs for the method in the E35 part of the standard.[9] We need a few pages to provide adequate background information and illuminate several aspects that will be important for the analysis. Each calculation of a COO result requires considerable data, making the collection and exchanges of data and calculations an important issue. In addition, each calculation reflects a specific setting. The calculations are complex, and therefore their interpretation requires a detailed explanation of how they have been conducted. Also important is that the standard contains default values.

As mentioned in the introduction, the industry organization SEMI provides a forum for standard-setting. The procedures (SEMI, 2013a,b) are the same for technical standards (the majority of the SEMI standards) and for COO. A revision is triggered if the responsible Technical Committee of SEMI identifies technical issues, or if the latest publication process was more than five years ago. The revision is assigned to a Task Force, which is responsible for reviewing and updating the standard documents with experts from the industry. The task force puts out a call for participation, such as for the 2011 revision of the E35 document (McLeod, n.d.). A task force consists of experts from SEMI member companies.

The task force discusses the technical issues, develops a proposal for the revision of a standard, and presents this to the technical committee. If the technical committee agrees with the task force's recommendations, it puts the new standard document out for voting by SEMI's member companies. Voters rejecting the proposal must write an explanation of their objection. These objections are crucial in the process of approving a standard, because a single important objection against a proposal raised by one expert can be an overriding argument. The technical committee can decide (requiring 2/3's of the votes) that an objection is considered not related or not persuasive. However, the procedure emphasizes that every effort should be made to negotiate a consensus between the reject voter and members of the technical committee. Thus, the SEMI revision procedures are based on technical discussions aimed at persuasion with technical arguments, and are finalized by voting.

The SEMI standard for COO calculations is incorporated in the commercially available software TWO COOL, which is sold by WWK. This software has been purchased by about 3000 companies in the semiconductor industry.[10]

4.1.1. SEMI E35: a method for calculating COO

The SEMI E35-0312 document can be purchased for US$100 from SEMI (www.semi.org). The document's 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 method is applicable to any type of equipment for processing semiconductor units, such as IC wafers and devices. The E35 document also includes "default values," such as for the cost of space in a wafer fab. These values can be used if parties do not want to exchange actual data, and the role of the default values will be important in Section 4.3.1.

The often-mentioned "basic equation" for COO in semiconductors provides an intuitive introduction to the general idea (Carnes and Su, 1991; Dance et al., 1996):

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

where CF is the total fixed cost, CV the total variable cost, and CY the total cost due to yield loss. In the denominator, multiplying TPT (throughput) and U (utilization of equipment) gives the total amount of produced units produced, and multiplication with Y (yield) reduces that to the total amount of *good* units produced.

The SEMI E35 document splits the COO into the cost of equipment ownership (CEO) and the cost of yield loss (CYL) (SEMI, 2012a). The basic equation can be rewritten by splitting the numerator into two parts:

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

4.1.2. Cost of equipment ownership: 20 cost elements

CEO represents the fixed and variable cost in relation to the number of good units produced, and the *CEO* equation is formulated as follows (SEMI, 2012a)[11]:

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

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 document that defines cost categories *i* and within those the cost elements *j*. These include the cost categories equipment (five 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 categories the cost elements *m*. These include consumables (five cost elements, such as utilities), maintenance (with four cost elements, such as spare parts), and labor (with four cost elements, such as engineering).

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 to avoid counting a part initially purchased in equipment acquisition again as a spare part. Furthermore, for each cost element, the document includes a description of the method for measuring the particular cost element.[12]

4.1.3. Cost of yield loss: three cost elements

The cost of yield loss (*CYL*) 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. *CYL* requires knowledge of the accumulated manufacturing costs

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[9] We also refer to these documents as the "E35 part of the standard" and "E10 part of the standard."

[10] Interview notes 2012-06–01 J

[11] In the SEMI E35 document, the term "*GUE* per year" is used. *GUE* stands for "good unit equivalents," and *GUE* per year is equal to $TPT \times U \times Y$. In the equation, "recurring costs" are what the basic formula considers "variable costs."

[12] 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."

before the unit is lost. Therefore, if a unit is damaged during this process step, the cost of yield loss incurred includes the COO of the equipment in this process step. Thus the COO of a piece of equipment is input for the cost of yield loss, and thereby also an input for the COO calculation. This circular relationship is solved by performing iterations to approach the COO result.

The *CYL* equation is further specified into three 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 document does not include all elements for the COO calculations. Several of the input parameters and calculations are defined in other SEMI documents, particularly in the SEMI E10 document. Those parameters and calculations are also needed for other purposes, such as for exchanging technical data among different machines connected in a production line.

4.1.4. SEMI E10: reliability, availability, maintainability, and utilization

The SEMI E10 document is titled "Specification for definition and measurement of equipment reliability, availability, and maintainability (RAM) and utilization." We used the SEMI E10-0312 version, available through www.semi.org at a price of US$200. It provides a detailed explanation of the definitions and calculations that underlie *total utilization* and *operational uptime*, which are key parameters in the COO calculation. Furthermore, E10 includes the definition and calculation of the costs of consumable material, non-consumable parts, and maintenance, which are also part of the COO calculation. The importance of standardization for effective information exchange is mentioned in this document:

> 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 document 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 used 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 owing 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 is operated to conduct engineering experiments.
5. Standby state: time other than non-scheduled 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 in operation (e.g., no operator is available).
6. Productive state: time in which the equipment system is performing its intended function.[13] Operating states 2–6 are called *operations time*, consisting of *downtime* (2–3) and *uptime* (4–6).[14]

Transitions between different states define events. For example, a *downtime event* is a transition into a scheduled or unscheduled downtime state. The latter is also called a *failure*, which is further classified into six different types of failures. Twenty-six performance measures for reliability, availability, maintainability, and utilization are defined on the basis of these states, events, and failures. For example, *mean uptime between failures* ($MTBF_u$) is uptime divided by the number of failures during uptime; *total utilization* is productive time divided by total time.

4.2. Use of the standard in a joint, public calculation

We present our findings for the use of the standard in joint, public calculations. Some of the evidence is based on an example of a joint, public COO calculation that has been published in a science and engineering journal (Hazelton et al., 2008a,b; Hazelton et al., 2008a,b; Wüest et al., 2008a)[15] and is available as a presentation (Wüest et al., 2008b).[16] We also conducted interviews with one of the authors to obtain more background information. The papers and presentation do not explain the standard, but they present a COO calculation that is based on the standard. Furthermore, we present additional evidence based on interviews with COO experts about the mediating role of such joint, public calculations and the role of the standard.

4.2.1. An example of a joint, public calculation

The calculation was constructed by a large number of different organizations. The acknowledgements section in Hazelton et al. (2008a) mentions 17 people from nine 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.[17] Furthermore, a remark in Hazelton et al. (2008a, p. 3) indicates that many parties were involved in producing this joint, public COO calculation:

> 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.

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[13] To illustrate the level of detail required for defining these states, note that the E10 document describes 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).

[14] Furthermore, the E10 document 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 sub-states each. For example, two sub-states 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).

[15] 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 (p. 4). Miller et al. (2012) briefly refer to Wüest et al. (2008a), but the example is analyzed in far more detail in the present paper.

[16] Hazelton et al. (2008a) report 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 COO of EUV, and it looks at the cost impact of larger (450 mm) wafers. Hazelton et al. (2008b) report on COO results for some 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 COO. The paper by Wüest et al. (2008a) is close to Hazelton et al. (2008a) and includes alternatives based on upgrading installed equipment. The paper by Wüest et al. (2008b) is close to Hazelton et al. (2008a) and addresses the cost of EUV technology in more detail.

[17] Similarly, for another example Seidel (2007) acknowledges 18 people from eight 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).

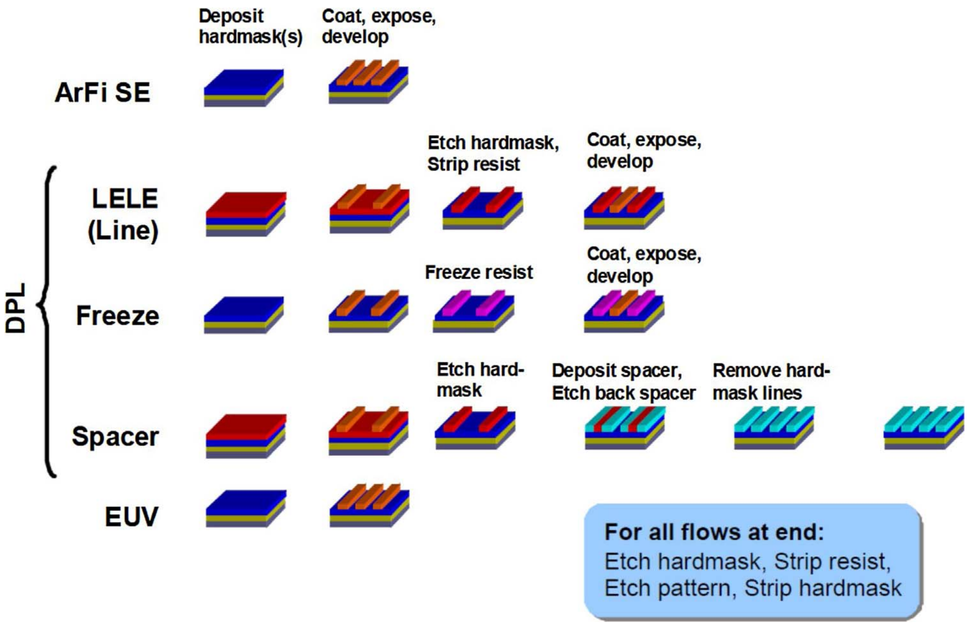

Fig. 2. Candidate technologies and process flows (Source: Hazelton, 2008a, p. 2).

The calculation concerned a very specific technological setting. This aspect is crucial in our later analysis of the importance of the adaptability of the calculations. This calculation was defined in terms of the following aspects:

1. Half-pitch node, which is the central parameter reflecting miniaturization through technological progress. These steps are derived from the semiconductor roadmaps.[18]
2. Candidate technologies, which are 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. Fig. 2 shows the candidate technologies and process flows as an illustration.

- 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, "including lithography, deposition, etching, and other process steps [that were] calculated for each of the technology options" (Hazelton et al., 2008a, p. 2). Also, the costs were calculated for an entire DRAM device, which contained 69 layers (Hazelton et al., 2008a).
- Unit of analysis. COO 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 this description illustrates further *choices* that have to be made for a particular COO 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).

Selection of this specific setting for the analysis was not merely a strict technical affair done by one organization such as SEMATECH. The parties mentioned earlier were involved in defining what needed to be compared and gathering the relevant information for the analysis.

Use of the SEMI standard is implicitly described in these calculations. "Lithography costs were calculated using a simplified version of the SEMATECH cost of ownership model" (Hazelton et al., 2008a, p. 2). The COO formula used was given in a presentation (Wüest et al., 2008b), but details of the calculation model were not provided in the various papers. The author we interviewed explained that the employed SEMATECH models were aligned with the COO standard:

> 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.[19]

As another example of the use of the COO standard for joint, public calculations, a senior director who was also a costing and metrics expert at an IC company related to us:

> [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.[20]

A better understanding of how the SEMATECH models are related to the COO standard as described in the SEMI documents requires more background on the history of the standard. In the late 1980s, SEMATECH developed a COO model and made it available first to SEMATECH and SEMI/SEMATECH members and later to the entire industry (Lafrance and Westrate, 1993). In the mid-1990s, SEMATECH no longer supported this model but handed it over to the software firm WWK for software development and support, which led to the commercially available TWO COOL software. At the same time, standard development and publication were transferred to SEMI, which led to

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[18] 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."

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

[20] Interview notes 2014-04-10b A.

the SEMI E35 and E10 documents.[21] Thus, the SEMATECH model became the basis for the COO standard as described in the SEMI documents and the software developed by WWK. As a senior industry analyst involved in performing COO 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.[22]

However, until a few years ago, further developed versions of SEMATECH's original spreadsheet model were still being used within SEMATECH for COO studies (e.g., Muzio, 2000; Seidel, 2007; Hazelton et al., 2008a,b; Wüest et al., 2008a,b). One interviewee who was heavily involved at SEMATECH in developing the COO models and applying these for new technology evaluations explained that an expert at SEMATECH

> kept developing that effort through the mid-2000s. . The real issue with COO is that everyone understands how the calculation works.[23]

He could confirm that at least until 2010, these SEMATECH models were aligned with the COO standard as described in the SEMI documents.

The joint, public calculation introduced at the beginning of this section led to an overall COO result that was in line with targets specified on the roadmap. The point of the calculation was to verify that overall cost-reduction targets according to Moore's Law were still feasible. In 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).

Thus, the main conclusion of the paper is stated in relation to expectations for cost reduction according to Moore's Law, which is depicted in Fig. 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).

4.2.2. *Modifying joint, public calculations for internal use*

Companies in turn adapted such joint, public calculations for several reasons. First, companies modified these calculations with *private data* they considered to be more relevant. The data used to estimate the COO of a new technology consisted of early estimates, and considerable uncertainty existed with respect to the joint, public calculations for the COO of the new technology. Among our interviewees, the widespread perception seemed to be that "nobody" possessed very accurate data for new technologies. As put by the author we interviewed, who had been involved in the joint, public calculation presented above:

> Because it was new technology, you don't have any data to compare technologies and to make calculations.[24]

Even if a company had internal estimates it considered to be of reasonable quality, it was often unwilling to contribute all its confidential estimates to the joint calculation. Companies sometimes provided actual numbers, but also other data if actual numbers were considered too sensitive. 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 [where] 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."

In a follow-up interview, he described this as follows:

> The IC companies know their processes the best and we would never know that. They could look at the calculations and see if it fits with what they have. . We put in standard numbers on purpose and explained what we did. These are the results, and if you don't like the results, fine, than you can just plug in your own numbers and see what happens. . We put the equation in [our papers]. If anybody felt something was wrong or had a different view, they could themselves recreate our model and then tweak the numbers for their own purposes.[25]

Second, firms not only put in private data when modifying joint, 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. As described above, joint, public calculations of the COO of new technology necessarily concern a very specific situation in terms of manufacturing technology, process flow, type of layer, and type of device. However, these choices may not reflect what a particular company would be interested in. Modeling all potential situations in a joint effort would be practically impossible. More crucially, companies often did not want to disclose the precise manufacturing situation that would be most relevant for them, as such information was also sensitive.[26] As an expert involved in COO 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.[27]

Thus, individual companies could take a joint, public calculation and modify it by replacing some of the data with company-specific confidential data (such as on costs, throughput, or yield) and altering the manufacturing setting (layers, composition of the IC, process flows). They would thereby change the joint, public calculation and turn it into an internal, private calculation, creating mobility in two directions when it moved back to the contributors.

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[21] 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.

[22] Emails file 2012-10–29 L.

[23] Emails file 2013-04–28 T.

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

[25] Interview notes file 2017-07–19 W.

[26] Interview notes 2012-09-11 S.

[27] Emails file 2013-07-04C.

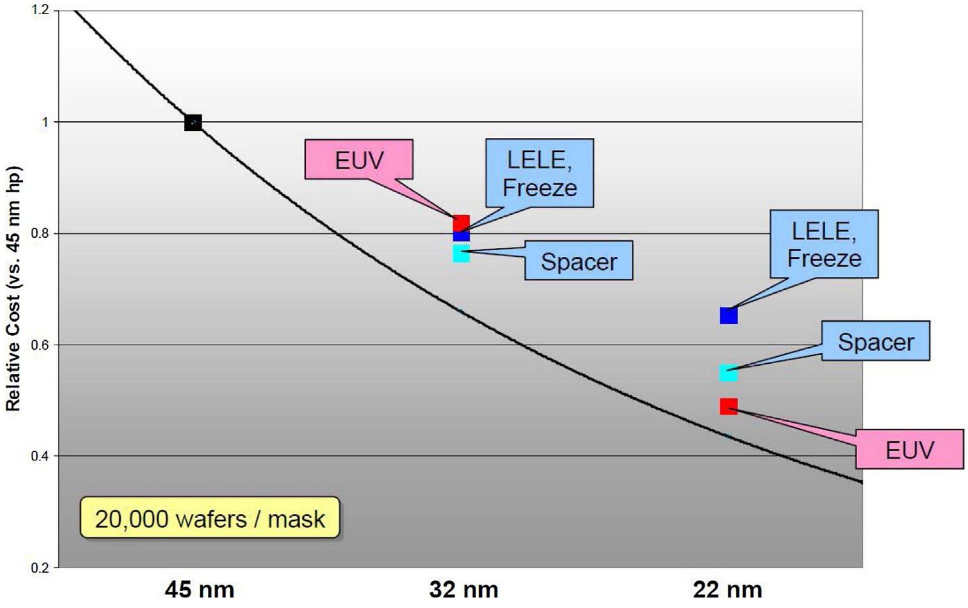

Fig. 3. Total lithography cost per function for future technologies, DRAM device, 20,000 wafers/mask (Source: Hazelton, 2008a, p. 7).

4.3. *Use of the standard in commercial calculations*

COO calculations also played a role in commercial relationships between equipment suppliers and IC manufacturers. In this section, we present and analyze our findings that are based on interviews with experts, who talked about the mediating role of commercial calculations and the role of the COO standard in such settings from the perspectives of IC companies and equipment suppliers.

4.3.1. *The COO standard and its default values in commercial calculations*

Commercial calculations refer here to calculations that are exchanged between different parties and that play a role in commercial relationships around equipment investments. For example: IC manufacturers selected a supplier for investments in new equipment, decided on equipment upgrades, or measured supplier performance. Suppliers provided information (and contractual guarantees) to the IC manufacturers about the performance of their equipment. IC manufacturers in turn provided feedback about the actual performance, such as throughput, capital costs, and consumable costs and usage.[28] In this section, we will first present a COO expert's insights, then look at commercial calculations and information exchanges from the perspective of an IC company (that expert also talks about the importance of default values), and finally consider an equipment company's point of view.

According to a COO expert who had observed many situations in which commercial calculations were exchanged:

> The request for data is almost always driven by the customer. . The IC manufacturer has a request for quote which specifies that COO data must be provided (TI, IBM). It can also be used by the supplier as a sales and marketing tool to help sell upgrades to existing equipment.[29]

However, what information companies wanted to exchange was subject to serious limitations, as well as uncertainty about data:

> 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.

When asked what kinds of data are not exchanged, he commented: "Anything to do with yield." Companies exchanged some information but kept other things confidential, and each party blended exchanged data with its own private internal data. For example, the equipment manufacturer would 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.

When asked whether the COO standard is recognizable in the exchange process for commercial calculations, he 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.

He also explained that exchanging TWO COOL files

> was typical of TI and IBM. Since they already had TWO COOL, they 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.

The use of the standard for commercial COO calculations can also be illustrated with the following example offered by another expert, who had worked for many years as the COO specialist at a major *IC company*. He explained that the company 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,

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[28] Emails file 2013-06–13 J.

[29] Emails file 2013-06–13 J.

> 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.[30]

Note his comment about the E35 *default values*. The E35 document includes "example values," such as the cost of space in a wafer fab. For each wafer size of 150, 200, and 300 mm, 34 default values are provided (SEMI 2012a). This expert explained that although these values have not been changed for many years, they still played an important role, because the default values reduced the need for data sharing in commercial calculations. The IC manufacturer could exchange with suppliers COO calculations that contained actual data on the performance and costs of the suppliers' equipment, because those were relevant for the issue they were discussing. Other data the IC company did not want to share could be replaced by these default values. Both the supplier and the IC manufacturer could analyze the calculations and communicate about these. This 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.

If the COO result of the equipment of an equipment supplier was disproportionate, the IC company gave feedback on its relative position and discussed possibilities to improve its 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).

This expert believed equipment suppliers would internally use the data they 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 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.

On the other side, for an *equipment manufacturer*, the use of the standard was important to be able take the perspective of the IC companies when estimating COO. For example, a major equipment manufacturer performed its own COO studies while developing a new lithographic technology. It needed to understand whether COO expectations of customers, namely the IC companies, were satisfied by this new equipment technology, and it wanted to guide its R & D efforts to achieve the required COO levels. The equipment manufacturer considered the standard's definitions of input parameters to be important in ensuring that the firm's private analyses were consistent with how its customers also analyzed the new technology's COO. The director of strategic marketing of an equipment company explained the role of COO modeling 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 modeling is difficult, for example the number of layers of a particular device. [In such models for evaluating the COO 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. [Therefore, the results of the models] don't mean that much. The assumptions, that's what it's all about. But having the same definitions is important. . We follow the standards for the parameters.[31]

4.3.2. *Partial use of the standard in commercial calculations*

However, not always the *entire* standard was used when companies exchanged data for quotations and contracts. Some interviews pointed to a differentiated role for the E35 and E10 parts of the standard, and to differentiated roles of the elements within E10 (the machine states and events versus the performance measures derived from these). We first present the view of an expert working in an equipment company and then present the perspective of an expert from an IC company.

A corporate director of an *equipment manufacturer* explained that measurement of machine states depended crucially on the E10 part of the standard also for technical reasons: different pieces of equipment in a production system 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.[32]

Similarly, these machine states provided a basis for the supplier and customers to exchange requests for quotations and contracts, which always included performance measures based on machine states (such as the mean uptime between failures, the mean time to repair, or the operational uptime). Customers sometimes referred to the E10 part of the standard for particular performance measures or 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 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 for [another IC company] there's only productivity when it's producing.

This state of affairs 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?"

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[30] Emails file 2013-06-06 B.

[31] Interview notes 2012-09–11 S.

[32] Interview notes 2014-04-10a L.

> 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.

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

Another senior director and costing and metrics expert at an *IC company* also commented specifically on the role of the E10 part of the standard. He explained that the IC company where he worked followed the E10 definitions of the performance measures. Use of the E10 part of the 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 the E35 standard]. . 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.[33]

While the E10 part of the standard was crucial for information exchange in these commercial settings, the role of the E35 part of the standard was different. The same senior director stated that his company did not exchange COO calculations with suppliers. He felt that providing equipment suppliers with too much transparency about cost calculations was not in his company's best interest. To compare alternative machines for investment decisions, the company had developed its own COO spreadsheet model, originally based on the SEMATECH costing model, including fixed costs and variable costs, years of operation, utilization, and yield. However, this information was not shared with suppliers and did not have to be compliant with the 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.

He also explained that his company calculated the various performance metrics, such as uptime, according to the definitions in the E10 part of the standard.

These various examples provide a more fine-grained understanding of how specific elements of the standard (the default values and the relationship between the E10 and E35 parts) allowed a differentiated use of the standard for commercial calculations.

4.4. Analysis of the role of the standard for the mediating capacity of calculations

We saw variations in the use of the standard, with the clearest role for the entire standard for the COO calculation method in joint, public calculations and a nuanced role in commercial calculations. Using the framework of Robson (1992), we analyze what this variation in the extent to which the standard was used, meant for the mediating capacity of the calculations. We also analyze how the standard made the calculations adaptable, which was another important quality for the mediating role of COO.

4.4.1. Mediation and the combinability, mobility, and stability of calculations

Cost of ownership as an encompassing performance metric could mediate between technologies, investments, and the concerns of various companies. This was the focus of joint, public calculations we described in Section 4.2. The mediation involved IC companies that would be investing in and using manufacturing equipment based on a particular new technology. The companies had concerns about increased capital equipment investments for the new technology and whether these investments were justified by the improved performance and reduction of the costs per unit with the new technology. Mediation also involved equipment manufacturers that needed to develop the new technology. They had concerns about the required R & D investments, their strategic choices for which candidate technologies to continue to pursue in R & D and which to abandon, the profitability of the equipment they would offer based on the new technology, and how they could consider the perspective of potential customers when evaluating the performance and cost of their new technology.

In this context, combinability was crucial for the mediating capacity of joint public calculations of the COO of new technologies. The calculations needed to be able to address the overall effect and economic tradeoffs of a candidate technology. In general, combinability refers to the capacity of numbers to be aggregated, recombined, and compared to norms. Semiconductor manufacturing processes are complex, COO calculations require many types of inputs and involve interactions between the costs of initial investments (such as for manufacturing 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 as an encompassing measure made possible the aggregation of dissimilar aspects into an overall number inscribing a new technology, which could be compared to targets that were based on Moore's Law and technology roadmaps (Miller and O'Leary, 2007).

This mediating role also required mobility, which in general refers to the capacity of numbers to move from the setting of the actor and back, allowing actors to assess activities they cannot otherwise see, and it enables them to act. In our study, companies and other organizations contributed their expertise to a joint, public calculation, provided input data, and shaped the choice of the technical setting (products and manufacturing processes) that would be modeled in these COO calculations. We also saw above that companies took the results of joint, public calculations and modified these based on internal, private data (mobility in the other direction).

However, combinability and mobility of COO calculations depended on stability of the calculations. Stability refers to the capacity of numbers to be recognizable to their users and to constancy in the relation between the inscription and the context to which it refers. In joint, public calculations, the complexities of COO caused ample possibilities for inconsistencies and misunderstanding when different parties were providing input into such a calculation. However, because of the standard, these various organizations—commercial companies (such as suppliers, equipment companies, and IC manufacturers) and research organizations (such as SEMATECH, universities, government labs)—knew how to make their internal, private information fit and become commonly understood input to the joint, public calculation. Similarly, because of the standard these parties knew how they could modify the joint, public calculation on the basis of internal, private data. Thus, the entire standard (the E35 and E10 parts together) improved the mediating capacity of these calculations by enhancing their stability, mobility, and combinability.

However, we saw a lesser role for combinability and, therefore, for

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[33] Interview notes 2014-04-10b A.

the *entire* COO standard in commercial calculations presented in Section 4.3. Mediation involved a particular IC company that specified various attributes of the manufacturing equipment or upgrades it wanted to buy, equipment suppliers that specified how their equipment would perform, and the IC company that later measured actual performance and provided feedback. In this context, combinability was less important. An IC company could make its own economic tradeoffs related to various internal concerns (such as initial investments, recurring costs, utilization, uptime, mean time between failures). An IC company and equipment supplier could talk about the various, separate attributes of the equipment when negotiating about the conditions of the investment. Such separate and detailed numbers and calculations could mediate in these one-on-one commercial negotiations and no single encompassing measure was necessary to bring everything together. For this reason, COO as such was not always of critical importance and the standard for the COO calculation method (the E35 part of the standard) did not have such a universal role, as we have seen in Section 4.3.

Nevertheless, mobility and stability remained crucial for mediation in this setting, which helps to explain why the E10 part of the standard still had an important role. The two-part structure of the standard (E10 and E35) made possible a choice between applying the standard fully or partially. As we have seen from the examples laid out in the interviews, some companies exchanged complete COO calculations based on the E35 part of the standard, while others exchanged performance metrics such as uptime and MTBF on the basis of the E10 part of the standard but performed cost calculations internally. Companies also merely exchanged data on machine states and events according to that specific part of the E10 part of the standard but performed company-specific calculations (different from those in the E10 part of the standard) on performance measures (such as uptime and MTBF). Thus, the basic data on machines states, events, etc. really required an international, institutionalized standard. However, for the performance metrics and COO, different versions could exist in different commercial exchanges, and that is why we observed variation in the use of the standard for commercial calculations.

The comparison of commercial calculations and joint, public calculations sheds further light on the role of the standard for the calculation method to enhance the mediating capacity of COO calculations. Without the standard, in principle, a COO calculation may have some mediating capacity in a commercial setting involving two or a few parties for a particular investment. A COO calculation could offer combinability by bringing together many different aspects; as a compact calculation that can be exchanged it could also provide mobility; moreover, stability may be achieved if each time the COO calculation would come with a sufficiently detailed explanation of how a particular calculation has been constructed. But, it is hard to imagine how this would work in the context of evaluating candidate technologies through joint, public calculations. Many different parties are involved, and the results are taken and modified again by a large number of organizations. These calculations are no “islands” that each time can be done based on differently defined input data and according to a different calculation method. There are too many connections to information from different sources, other internal and public calculations, subsequent changes of the calculation, connections to projected cost reductions on the roadmap, the need for actors to put themselves in the shoes of another party, and so on. Organizational structures and practices are highly networked and hybrid in the semiconductor industry (Miller and O’Leary, 2007). A large number of diverse organizations need to work together in many different networks to create new technology and markets, and they need to coordinate their investments in R & D and capital equipment. The international and institutionalized COO standard provided a stable backbone that could mediate between the concerns of these organizations.

4.4.2. Mediation, adaptability of COO calculation, and the role of the standard

However, to understand the mediating capacity and the role of the standard, we also need to look beyond combinability, mobility, and stability. As described above, actors who contributed to a joint, public calculation also took the results back and modified them to create different internal calculations. They could incorporate information about the input data used for the calculation, the manufacturing processes and the products, and the way the final results (e.g., throughput, or costs) were being calculated, as well as other private information they had not contributed to the joint, public calculation. Making such changes was important for calculations to mediate between a general technology, the internal manufacturing context of a specific IC company, and the R & D activities of equipment suppliers, because these calculations needed to provide an adequate common understanding but also remain adjustable to the specific situation. Different versions of COO calculations coexisted, which would be similar and commonly understood in exchanges, but for internal use, a different version could be calculated and used. Thus, the mediating capacity of COO calculations required the possibility to modify significant elements of the calculation, without the accounting numbers losing the ability to be mobile, combinable, and sTable Such *adaptability* was enabled by the standard. The standard for the calculation of COO made the concept quite rigid, but at the same time enabled the individual calculations to be adaptable. By knowing how the calculations had been produced and worked in terms of the input data and the formulas for the calculation, organizations could adapt these calculations to their specific requirements.

Adaptability also meant that organizations could choose to use the standard to a greater or lesser extent. When combinability in joint, public calculations was important for mediation, the entire standard for the calculation of COO played an important role to create stability, mobility, and combinability. But in commercial settings, companies could also specify and measure various separate performance metrics without aggregating these into a COO metric. That is why the E10 part of the standard was still important to facilitate the exchange of those separate metrics, but the standard for the COO metric (as defined in the E35 document) was not required for mediation. The two-part structure of the standard enabled this adaptability. Moreover, the default values in the standard created adaptability that supported the mediating capacity of the calculations, because the default values in the standard enabled replacement of confidential data with “neutral” default values when exchanging calculations in commercial settings. Default values therefore made possible clearly defined placeholders to change between default values (which are generally known, because they are part of the standard) and company-internal numbers. This also enhanced the mobility of calculations as users were less reluctant to share them.

5. Discussion

Our results suggest that the standard enhanced the meditating capacity of COO calculations, not only because it supported their combinability, mobility, and stability but also because it allowed for adaptability of those calculations. In this section, we discuss adaptability in a broader research context by comparing it to pliable concepts and by considering commercial COO calculations in another industry.

5.1. A comparison: adaptability of calculations and pliability of concepts

Adaptability of individual *calculations* was made possible by the presence of the standard that codified the *method* for calculating COO. This adaptability of calculations supported the mediating capacity of COO, which could be surprising in the light of several previous studies that have investigated the ability of accounting to influence action at a distance. These studies found that management accounting concepts are often pliable rather than rigid, which is what makes them influential

(Briers and Chua, 2001; Busco and Quattrone, 2015; Dechow and Mouritsen, 2005; Emsley, 2008; Sandhu et al., 2008; Qu and Cooper, 2011). Accounting concepts are pliable in that 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, making them recognizable and able to serve as a means of translation. Examples are balanced scorecards, customer profitability, and quality costs, which have the potential to be many things to different actors. At some general and more abstract level, people can talk about and agree on such an accounting concept, and because that concept is pliable, people can also develop more detailed and diverse ideas for their own domains (Quattrone et al., 2012; Briers and Chua, 2001). For instance, 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 (Emsley, 2008, p. 379).

Similarly, Briers and Chua (2001) demonstrated how, in the steel company they studied, the actual development of accounting was ongoing and driven largely by interests and coincidental circumstances. Accounting information survived as long as it worked for the different actors involved, because 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 also represented their interests, interpretations, and ideas. It was the accounting concepts' pliability that made the concepts acceptable and influential. The idea of pliable accounting concepts is closely related to the notion of boundary objects (e.g., Star and Griesemer, 1989; Nicolini et al., 2012; Locke and Lowe, 2012).[34]

However in our findings, COO was not very pliable, as it was codified as a calculation method in documents that have become stable over many years. Revisions were typically limited to specific technical matters.[35] In light of the semiconductor industry's strong interdependencies, the whole point was to have a common understanding when information was exchanged (e.g., various actors contributed data to joint calculations, took data and calculations from others, and compared results to targets), and this understanding was achieved through stable concepts and methods. The standard provided stability to COO calculations and enhanced their mobility and combinability. Quattrone (2009) also stressed the point that accounting tools can offer a stable method which can be used with different contents—"a performable space, an archetype, a frame, which could then be filled by those who were going to use the method" (p. 109). Similarly, in the study of Huikku et al. (2017) the IAS 36 standard for the valuation of goodwill provided a stable backbone for the structure of the calculation (such as the goodwill impairment calculation), and it was less important that the calculation method would be very pliable.

> The mathematics of calculation – how to make the world visible – is a minor concern because it has already been defined by regulation. IAS 36 develops a delimitation – a template of a financial model – which is not easily given up as it is mandated. The drift noted for example by Quattrone and Hopper (2001, 2005), requires that accounting is understood as malleable, seems not to be as urgent in the case of goodwill accounting where the delimitation is clearer. (Huikku et al., 2017, p. 77).[36]

Still, as we have seen in Section 4, some form of flexibility was needed for COO calculations to be mediating instruments. Various organizations wanted to use the information differently, depending on the situation (e.g., public versus private calculations). But rather than through pliable *concepts*, flexibility was achieved by making the *calculations* themselves adaptable, without losing the ability to be mobile, combinable, and stable. This way, the standard made it possible that the same calculation method could be used for serving different purposes. The calculations could be adjusted to fit various private, commercial contexts; they could be tailored for use internally within one organization (i.e., an IC company) regarding its own processes, products and costs; they could also be adopted by an organization (i.e., an equipment supplier) for simulating someone else's processes, products and costs; and they could be deployed in joint, public contexts. The standard enabled different versions of COO calculations to coexist, which would be similar and commonly understood in exchanges but which could be dissimilar as long as they were used only internally and were not exchanged.

5.2. A contrast: commercial COO calculations in the photovoltaic industry

The use of the standard in these commercial settings can be contrasted with the related photovoltaic (PV) industry, where a standard for the calculation of COO is not as common as in IC manufacturing. In the absence of a standard, commercial COO calculations require a detailed specification of data for every new request for quotation.[37] As an example, an engineering consulting firm had compared different turnkey offers for a factory producing photovoltaic cells and solar modules. The managing director of this firm explained that in this industry, no standard existed 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

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[34] As a non-accounting example of boundary objects, imagine people from a real estate company, civil servants of a municipality, and representatives of nearby residents discussing a new property development project. They use wooden scale models to discuss the size and position of the new buildings. They will have different considerations, such as: creating buildings with sizes and shapes that maximize profitability (real estate company), complying with zoning regulations and making the buildings fit their surroundings (municipality), and avoiding that the buildings obstruct views and take away too much sunlight (nearby residents). Suppose the scale models, as boundary objects, help these actors to reach agreement on the shape and position of the new buildings. Yet, many other aspects are still open and, for now, each party can have their own ideas about, for example, the material and colors of the façade. The boundary object can create some common understanding but simultaneously mean different things to different people, so commonality is only temporary. Boundary objects may also allow to continue working together *without* even temporary, limited consensus. For example, because the process of talking with the help of boundary objects makes that the actors start to have more sympathy for the others' points of view, or because as long as they talk around boundary objects, each actor can create more hope with the group they represent of reaching agreement in the future.

[35] For instance, the revision in 2011 involved correction of an error identified in a product yield equation. This concerned removing the "×(1–Rework)" term, because the effect of rework rate is already accounted for in defining the volume requirement (Emails file 2013-06-06 B).

[36] The vast literature on financial reporting standards mainly looks at standard-setting processes. Robson and Young (2009) provide a review, in particular of studies that considered social, political, and institutional dimensions of standard-setting. Examples are Richardson (2009, 2011), Pelger (2016) and Kettunen (2017). However, our study is not about standard-setting; it does not investigate, for example, how the standard has been developed, who was involved, or which factors could explain the existence of the standard.

[37] Interview notes 2014-04-15 R.

> 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.[38]

SEMI has started to promote the use of E10 and E35 for COO calculations in photovoltaics (Raithel et al., 2014).[39] Reflecting on this practice, 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. Because, 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.[40]

While this example may raise other questions, such as why the standard might not exist in PV semiconductors as it does in the IC semiconductors, we have introduced it here to demonstrate that absence of a standard makes creating the stability, mobility, and combinability of *commercial calculations* more difficult—not impossible. This example shows that COO calculations can also mediate without international, institutionalized standards, if parties agree a convention for every instance. But, this is less practical. That is also consistent with the varied use of the standard in commercial calculations in the semiconductor industry.

We found no evidence in the PV industry of *joint, public calculations* to evaluate candidate technologies—calculations that would mediated between concerns around long-term technology developments in relation to a roadmap. The more stringent need for an institutionalized, international standard for conducting joint, public calculations was not apparent.

The difference between these two industries regarding the presence or absence of a standard is consistent with differences in how commercial calculations were conducted, with differences in producing stability, mobility, and combinability of such calculations, and with differences in the role of joint, public calculations. Thus, this example provides an illustration of using counterfactual conditions in qualitative research, which "has the potential to add to the clarity and strength of the arguments developed" (Lukka, 2014, p. 565).

6. Conclusions

We have investigated interorganizational management accounting calculations that influence investment decisions involving several firms in an innovation network. Previous studies have pointed to the role of COO calculations as a mediating instrument for R & D investments and capital equipment investments in the semiconductor industry (Miller and O'Leary, 2007; Miller et al., 2012). 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 COO. This study contributes notably to the literature on how accounting can influence action across boundaries. First, our findings suggest that an industry standard may support the mediating capacity of calculations by enhancing their mobility, combinability, and stability. Second, such a standard also may also create adaptability of the calculations, which we identified as another crucial property for their mediating capacity.

Regarding the first contribution, COO calculations are inscriptions of the manufacturing processes and products of IC manufacturers, through which these products and processes are made visible to other organizations in the industry. COO calculations mediated between these organizations by guiding their investment decisions regarding R & D and capital equipment. The joint, public calculation portrayed the cost of a new technology that was on the horizon (or better, on the roadmap) by bringing together information from many different parties, and this action affected future R & D developments. For example, the "verdict" of the joint, public COO calculation on EUV justified retaining this alternative technology on the semiconductor industry roadmap and suggested it was more likely to become a reality through further investments in R & D and capital equipment. The standard supported a process where different parties provided various pieces of the COO puzzle. In private commercial calculations, the standard also allowed the equipment company to calculate the COO in a way it considered consistent with how its customers would calculate it. The company could use insights derived from the calculation to adjust its R & D investments—in particular if its estimated COO would not be in line with customers' expectations, which it could know from the roadmap targets. Cost of ownership also connected parties such as equipment suppliers and IC manufacturers in commercial negotiations and allowed subsequent feedback.

Regarding the second contribution, the standard created adaptability that supported COO calculations as mediating instruments. They could be modified so they would be more suitable for an organization's internal purposes. On the one hand, the standard codified the calculation method and made the concept rigid. On the other hand, the standard also made the calculations themselves adaptable. The standard made it possible to change input data, change manufacturing setting, use the standard's default values instead of private data, change the methods for calculating performance measures, and apply the standard more or less extensively. This adaptability provided a remarkable contrast to earlier studies in accounting that have investigated how accounting concepts gain more influence when they are pliable. However, in the hybrid industry that we have investigated, the concepts as well as the method for calculating COO needed to be stable so they could be commonly understood in order to mediate. Some form of flexibility was still required, because companies had different requirements (such as their own products and processes) and wanted to shield private information. Flexibility was provided by adaptability of the calculations, and the standard allowed the needed adaptability of the mediating calculations. As a result, the mediating capacity of COO calculations was enhanced, as companies could adapt a calculation to their specific requirements, draw conclusions, and then approach the other players in a commercial or public setting for negotiations or discussion based on their findings.

A limitation of the present study is that we had to rely on interviews and publicly available data, although this approach provided the opportunity to engage with a larger number of organizations than would have been 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 ideal for collecting more granular data on specific investment decisions, the COO calculations, and other kinds of information that are on the table when these decisions are discussed, as well as 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 offer 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). This study presents an example of how focusing on a specific industry can provide strengths, because factors that operate in a particular industry can shape distinctive accounting practices that are carried out at the organizational level and that are typical for that industry (Messner, 2016). Future research within this sector of could investigate a different but closely related question, namely which factors could explain *why* the standard exists in this sector. That research could also be expanded to compare and contrast the presence of the standard in the IC

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[38] Interview notes 2014-04–17H.

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

[40] Interview notes 2014-07–17 A.

semiconductor industry to standards for interorganizational management accounting in other industries. Looking more at the photovoltaic part of the semiconductor industry would be interesting. Another example of a subject for investigation in future research is the Gartner COO model, which is established in information technology but is a commercial service from the research and advisory firm of Gartner, Inc. (McKeen and Smith, 2010; Mieritz and Kirwin, 2005). Its method is partially disclosed only to clients, and any purchased analyses and methods are strictly for internal noncommercial use by the licensed Gartner client. Finally, future research could investigate adaptability of calculations in relation to standards for financial reporting. The "management approach" in some IFRSs requires companies to also disclose information if that is reported internally (Wagenhofer, 2016; Weißenberger and Angelkort, 2011). This implies that similar calculations are supposed to serve different internal and external purposes. It would be interesting to investigate if and how financial reporting standards enhance adaptability of calculations for such different purposes.

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 the standard through the lens of mobility, combinability, stability, and adaptability of calculations. The study analyzes how the standard codified the calculation method, yet at the same time made the specific calculations adaptable, thereby enhancing their mediating capacity.

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Appendix A. Experts Interviewed in Meetings and Calls and via Email

Experts Interviewed in Meetings and 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 COO modeling. He has been 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 COO 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. He was an IEEE Fellow and SPIE Fellow and SEMATECH Senior Fellow from 1993 to 2006, and he was involved in the ITRS Roadmap.
5. Senior Industry Analyst at SEMATECH specializing in economic modeling. He previously 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, who previously was project leader and member of the technical staff at SEMATECH from 2006 to 2010.
10. Scientist and manager at a German material supplier to semiconductor companies Siltronic and Wacker Helitronic. He has been involved in SEMI technical standardization activities since 1991.
11. Professor in nanofabrication, who previously spent 16 years at Intel in manufacturing processes and technology.
12. Senior director of strategic production planning at a large semiconductor company with work experience in the semiconductors since 1996.
13. Corporate director of 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, with 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, who previously was a senior member of the technical staff at SEMATECH responsible for cost modeling, and was a staff engineer with American Microsystems. His career has focused on yield modeling, manufacturing capacity simulation, and cost modeling.
17. Director at SEMI headquarters.

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