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ASIC Commercialization Analysis: Technology Portfolios and the Innovative Performance of ASIC Firms during Technology Evolution

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Abstract

We examine the relationship between application-specific integrated circuit (ASIC) firms' technology portfolios and their innovative performance. This relationship is complex, and we hypothesize that it changes according to the stage of ASIC technology evolution. We test our hypotheses using a longitudinal dataset of 67 firms from the ASIC industry over the period 1986–2003. We find that ASIC technology evolution negatively moderates the effects of the size and diversity of the internal technology portfolio on ASIC firms' innovative performance. This implies that, in earlier phases of ASIC technology evolution, successful ASIC firms developed large and diverse portfolios to cope with technological uncertainty. During later phases of ASIC technology evolution, they tend to have relatively smaller and less diverse portfolios, and they focus on unique, protectable, and exploitable advantages.

Keywords: ASIC industry, technology portfolio, technology diversity, innovation strategy, technology evolution, innovative performance

1. Introduction

We examine the relationship between the size and diversity of ASIC firms' technology portfolios and their innovative performance as ASIC technology evolves.

For many technology-based firms, in-house developed technology is crucial for the creation of innovations and for capturing innovation returns [1–3]. In-house technology development

enables firms to increase the complexity of their innovations, so it becomes difficult for competitors to imitate them [4]. It also enables firms to maintain secrecy and, in that way, to establish a lead time [5]. Especially, technology that is classified as "distinctive competencies" [6] and that forms the core of the firm's technological capabilities will mostly be developed in-house because of these reasons. In-house technology development also creates absorptive capacity, i.e., the knowledge that enables firms to better understand, source, and use external technology [5, 7, 8].

In this chapter, we focus on the effects of the size and diversity of the in-house ASIC technology portfolio on ASIC firms' innovative performance. The size of the portfolio reflects the firms' total efforts to develop ASIC technology in-house. The diversity of the portfolio reflects how firms' development efforts are spread over various ASIC sub-technologies.

The relationship between the size and diversity of firms' internal technology portfolios and their innovative performance is complex, and the results of the previous research have been conflicting. We contribute to this research by investigating the moderating effect of technology evolution. As a moderator, we use Abernathy and Utterback's concept of technology evolution of an industry [9]. They distinguish three evolutionary phases: the fluid phase, the transitional phase, and the specific phase. Currently, ASIC technology is in the specific phase, according to patent counts, and this is also indicated by the industry's technology trends. The exact evolutionary phase may differ per ASIC sub-technology: gate array technology is at the end of its evolution, standard cell technology is in the late specific phase, and PLD technology is also in the specific phase. A competing technology such as FPGA is earlier in the specific phase. Emerging technologies, whether they are labeled as ASIC or as competing with ASIC, are in the fluid phase.

In the early, fluid phase of technology evolution, technological uncertainty is high, and firms need to keep various development options open to cope with that uncertainty. They need to develop large and diverse technology portfolios that are useful for various technology development scenarios. In the later, specific phase of technology evolution, after a "dominant design" has been established [10], technological uncertainty is much lower. This means that there is less need for large and diverse technology portfolios. This enables firms to focus on those technologies they can best exploit.

Managers of technology-based firms need to know whether and when during the evolution of a technology, investments in large or diverse technology portfolios contribute to their firms' innovative performance. Building and maintaining such technology portfolios require large and risky resource investments, and it is therefore important to ensure the returns to these investments.

To study the effects of portfolio size and diversity on innovative performance during technology evolution, we developed a longitudinal dataset of 67 firms from the ASIC industry over the period 1986–2003. Our results support the moderating effect of technology evolution on the relationship between technology portfolio size and diversity and firms' innovative performance. Our findings contribute to a better understanding of the complexity of these relationships.

The practical implication is that ASIC firms need to adjust their technology sourcing strategy according to the phase of ASIC technology evolution. In earlier stages of technology evolution,

investing in a relatively large and diverse technology portfolio seems to be a better approach to improve innovative performance. In later stages, focusing on a relatively smaller and specialized technology portfolio seems to improve innovative performance. ASIC firms that focus on multiple technology areas need to balance their technology portfolios across the areas: focusing for the late-evolution technologies and investing and diversifying for early-evolution technologies.

2. ASIC industry and technology

The ASIC industry is a part of the semiconductor industry that can be characterized as an independent market for design modules [11] that has been a driving force behind major technological breakthroughs in the semiconductor industry [12]. The history of this industry is well known: the inventions of the point contact transistor (by John Bardeen and Walter Brattain in 1947) and the junction transistor (by William Shockley in 1948) in the Bell Labs provided, together with the diffusion-oxide masking photo process (1954), the integrated circuit (1958), and planar technology (1959), and the foundations for the development of the global semiconductor industry [11, 13]. By 1961, it had developed into a worldwide billion-dollar industry [13]. Although the development of ASIC technology began at the end of the 1960s [14], it became popular in the 1980s [15]. In the 1980s it became possible to combine standard integrated circuits (ICs) into custom ICs that were tailored to particular systems or applications or Application-Specific Integrated Circuits (ASICs) [16].

The successful development of ASICs requires the knowledge and competencies of different types of firms [17]. As a result, it is an industry characterized by newcomers, strategic alliances, and mergers and acquisitions [17]. The dynamic patterns and the need for different knowledge and competencies make it an attractive industry for our type of research. The major firms currently active in the ASIC industry are Texas Instruments, Infineon Technologies, STMicroelectronics, Renesas Electronics, Analog Devices (which acquired Linear Technology in 2017), Maxim Integrated Products, NXP Semiconductors, ON Semiconductor, Qualcomm, and Intel [18]. All these major players are active in multiple segments of the semiconductor industry, ASIC being one of them.

Analogous to most semiconductor firms, ASIC firms initially worked according to the integrated device manufacturer (IDM) business model. They vertically integrated every aspect of chip production, from design to manufacturing, packaging, and testing [19]. In 1984, Xilinx was the first firm adopting a "fabless" business model, focusing on the design of ASICs, and outsourcing its manufacturing to other "IDM" firms [19]. Soon after, in 1987, TSMC adopted a pure foundry business model, focusing on the manufacturing [20]. During the 1980s, most firms still used the IDM model. By now, most semiconductor firms use the fabless model, although a few major ones, such as Intel and STMicroelectronics, still use the IDM model, still accounting for about 55% of the market [21].

The industry reports generally define three ASIC subsegments:

- Full-custom design: a circuit that is customized on all mask layers and is sold to one customer.

- Semi-custom design: a circuit that has one or more customized mask layers, but does not have all mask layers customized and is sold to one customer. This segment includes gate array and standard cell technologies [22], although standard cell is sometimes placed separately in between full-custom and semi-custom designs.

- Programmable logic devices (PLD): a circuit with fuse that may be programmed (customized) and, in some cases, reprogrammed by the user. This segment includes CPLD, SPLD, and PAL technologies. FPGA technologies have in the past been regarded as a special kind of PLD but are now generally considered as a technology that competes with ASIC (see, e.g., [23]).

The three categories contain different devices with the same system functionalities that can be programmed at different moments in the development process; by the vendor (for standard cell, gate array), by the designer, prior to assembly (for full custom); or by the user (for PLD). Programmable logic devices offer the cheapest solution for low volumes. If volumes are higher and exceed a few thousand units, gate arrays offer the best solution. Full-custom devices are the best choice when production volumes exceed hundreds of thousands.

For the total ASIC industry, we can define the various phases of technology evolution based on our data. Based on the technological developments of all firms together, starting with the first patents developed in the ASIC industry, we can put the *fluid phase* before 1991, the *transitional phase* between 1992 and 1997, and the *specific phase* after 1998. This is an industry-level metric, which is in line with the framework of Abernathy and Utterback [9] and Utterback [24]. **Figure 1** shows the evolution of the number of firms in the industry. Although this data runs only until 2003, we can clearly see a reduction in the number of firms, indicating a mature market.

Looking at the ASIC subsegments, we start with gate array technology, which existed in some form since the mid-1960s but did not capture a sizable share until around 1983 [15]. By the 2010s this technology was hardly applied anymore [25]. In the mid-1980s, the standard cell was implemented. The first type of programmable logic device was invented in the 1970s [26], but the technology became more popular in the 1980s, and the PLD submarket became one of the fastest-growing sectors in the semiconductor industry. **Figures 2** and **3** show the units
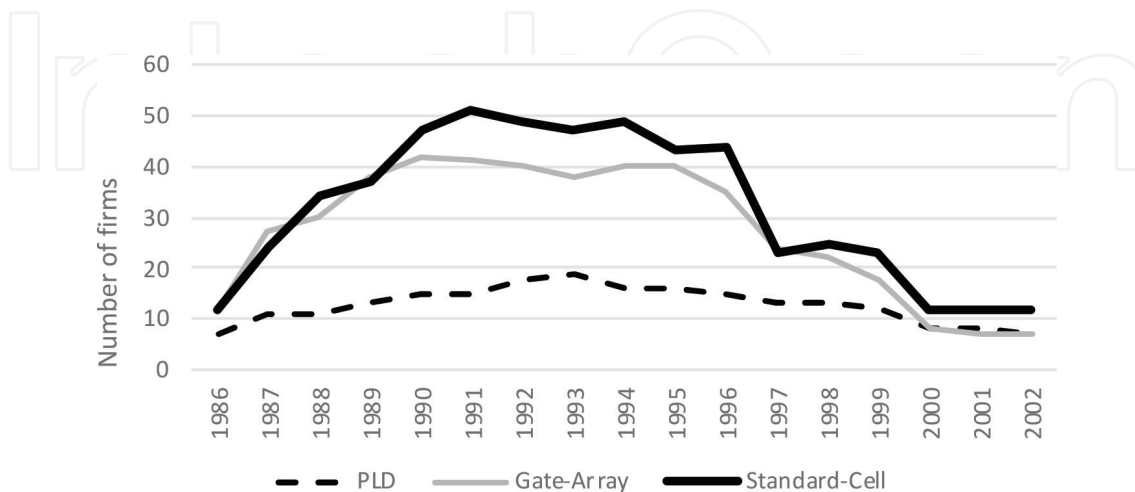
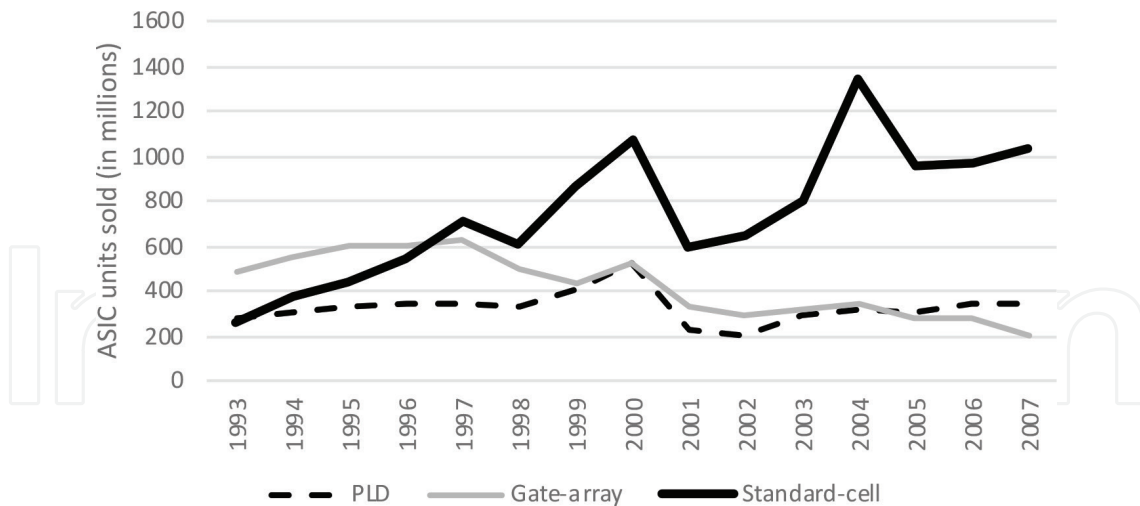

Figure 1. Number of ASIC firms.

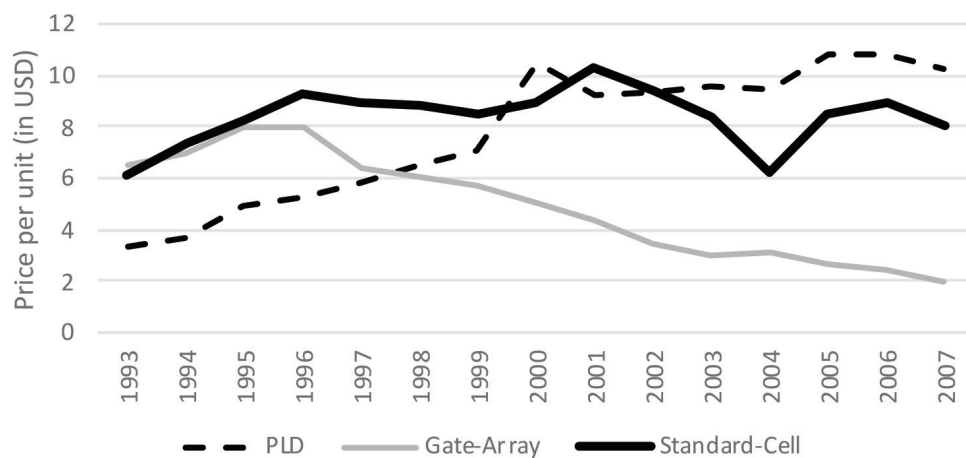**Figure 2.** ASIC units sold (in millions).

Figure 3. Price per unit (in USD).

sold and the prices per subsegment. These figures clearly indicate that the gate array technology evolution preceded the standard cell and PLD technologies in time.

We identify four major technology trends in the ASIC industry (see also [27, 28]). The first trend is the continuation of Moore's law through increasingly smaller DRAM pitch scales, increasing numbers of mask layers, and multi-patterning in lithography [29]. This trend is commonly referred to as "more Moore" [27, 28]. It entails strongly increasing cost of development of ASICs. As a consequence, minimum efficient design scale (numbers of ASICs sold per design) increases, and only few large design firms (fabless or IDM) are able to continue profitable operations, an indication of a mature technological field [9]. This development also fits the trend of firms concentrating on core competencies by adopting a fabless business model.

The second trend is increased efficiency in manufacturing due to wafer-size increases. The share of 300 mm wafers is still increasing [30], and efforts were made to increase wafer sizes from 300 to 450 mm [29]), although the consortium of firms involved abandoned its efforts at

the end of 2016 [31]. This trend is mainly production process innovation, which like "more Moore" requires large investments in manufacturing facilities [29]. This, too, is a logical development in a mature technological field, and it fits in the trend of firms focusing on core competencies by adopting a foundry business model. Here, too, relatively few firms will be able to profitably carry out such investments because the minimum efficient scale of manufacturing ASICs increases.

These first two technology trends fit with market demand trends of ASICs as commodities for high-volume applications, such as Internet of Things, which require a lot of ASICs but not necessarily require leading-edge technology. Other markets with such demand are virtual and augmented reality, automotive electronics, smartphones, personal computing, and wearable electronics [32].

The third trend is added functionality, resulting in increasingly complex products for advanced applications such as machine learning or blockchain mining. This trend is commonly referred to as "more than Moore" [27, 28]. Examples of products are "software-defined hardware" or combinations of ASICs and general-purpose chips on a single-circuit board, like "domain-specific system-on-chip" [33] or "system-in-package" designs [27, 28]. This trend, too, indicates a relatively mature technological field with a focus on specific, albeit high-end, applications. This trend is accompanied by a shift from technology push-based roadmapping, to a more interactive approach in which multiple stakeholders are involved in defining future developments [27].

As a note on trends one till three: a mature technological field does not mean that technology does not develop or improve anymore. The technology still develops, e.g., in speed, power consumption, cost reductions, and performance for specific applications, but it develops in a relatively predictable direction and with a relatively predictable speed. This does not mean that such technology development becomes easier for firms: while the purely technological risks and uncertainties may be lower than before, the resource investments and the business risks are considerable, as are the business opportunities. In business terms, the industry moved from exploring new technologies to exploiting existing technologies.

The fourth trend, perhaps more accurately a collection of trends, is the emergence of new technologies such as quantum computing or nano-carbon technology [28]. This trend deals with completely new technological fields, and it is not always immediately clear whether these are still related to "ASIC" or the emergence of a completely new industry. Such uncertainty is a characteristic of the fluid phase of technology evolution [9]. This could be referred to as "beyond Moore."

3. Theory

Technological knowledge is a resource that helps create innovation by enabling firms to add value to incoming factors of production [34]. Here, we look at the size and the diversity of firms' technology portfolios. We would normally expect a positive effect of the *size of the technology portfolio* on innovative performance, because:

1. Technological knowledge embedded in patents is often converted into innovative products that contribute to firm performance (see, e.g., [35]). Given a certain efficiency of this function, more input (patents) will result in higher performance.

2. Knowledge as a resource is indivisible and self-generating, which cause it to have strong static and dynamic economies of scale in its application [3]. Indivisibility [36] means that a certain critical mass of technological knowledge is needed before it can be productively applied. Therefore, more technological knowledge can be expected to create higher innovative performance after this critical mass is reached. Self-generating ability [37] means that new relevant knowledge may emerge from the technology development process as additional output besides the normal output of (new) goods and services. The accumulated knowledge then becomes a basis for subsequent technological developments [7].

3. A larger technology portfolio allows for more recombination of knowledge (e.g., [38]). The possible number of combinations of knowledge exponentially grows with the size of the portfolio.

However, the relationship between technology portfolio size and innovative performance is more complex than expected. Lin et al. [39] find nonsignificant effects of technology portfolio (technology stock) on firm performance metrics. Artz et al. [40] show that, while the direct effects of R&D input to patent output (invention) and of patent input to product announcement output (innovation) are positive as expected, the indirect effect of R&D input on product announcement output is unexpectedly U-shaped and the indirect effect of patent input on firm performance is even negative.

The choice between a diverse and a focused knowledge base is one of the fundamental choices in a firm's knowledge strategies [1]. We would normally expect a positive effect of *technology diversity* on innovative performance because:

1. A diverse technology portfolio may generate economies of scope, or "synergies," meaning that it is more efficient to develop (related) technologies together than independently [3, 41].

2. Combining various technologies may generate "causal ambiguity," meaning that competitors are unable to determine the source of a firm's competitive advantage and therefore may have difficulty imitating it [4].

3. If we see innovation as a process of "recombinant search" for new combinations, a more diverse portfolio may result in many more possible combinations [38, 42].

However, this relationship, too, is more complex than expected. More diversity leads to increased coordination cost, which may partly or wholly offset the benefits, dependent on the strength of the firm's "integrative capabilities" [3]. Distributed technological capabilities may limit the firm's focus to develop strong core capabilities [43, 44]. The recombinant search advantage of a diverse portfolio depends on the degree of interdependency between components and on the size of the search space. Fleming and Sorenson [38] show that when interdependency is too high or too low, and when the search space is too large, recombinant

search will become progressively less efficient. Building on this literature, Leten et al. [44] and Huang and Chen [45] argue that the relationship between diversity and innovative performance is complex and nonlinear. Lin [46] finds a nonsignificant relationship and suggests that diversity may interact with other variables.

A possible explanation for these complex results is that there is another variable that moderates the relationships between the size and diversity of a technology portfolio and innovative performance. We propose that technology evolution of an industry [9] is such a variable and that we may (partially) explain the complexities by including it in our model. We use Utterback's model [24] for our definition of technology evolution. This is a refined and validated version of the original Abernathy and Utterback model [9]. It specifies three phases in technology evolution: the fluid phase, the transitional phase, and the specific phase.

During the *fluid phase* of technology evolution, technological uncertainty is high. Technology solutions are not readily available, and technology development investments are explorative and focused on product innovation [9]. In this phase, firms in high-tech industries require technological scientific knowledge, i.e., knowledge gained through fundamental scientific research [47]. As a result of the uncertainty, firms do not know exactly which technological knowledge, i.e., which patents or combinations of patents, will improve their innovative performance.

They need to keep many options open and need to explore multiple different technological trajectories. To gain innovative performance in the early phases of technology evolution, firms need a large and diverse technology portfolio. A diverse technological knowledge base allows a firm to adapt [2] to turbulent environments and to develop a higher number of technologies. It also reduces the danger of a lock-in into dead-end technologies [48], and it hedges against the risks of developing the wrong technology [49]. As a result, diversification is positively associated with innovative performance. As technological scientific knowledge solutions are not readily available internally or externally, they need to be developed, adding to the portfolio size. Often, because of indivisibilities, various sub-technologies have to be developed simultaneously to create feasible technology solutions. When firms plan to source knowledge externally, they first need to develop a stock of knowledge internally that will enable them to scan and absorb external knowledge [7, 50]. During technology development, an increase in the number of components results in an exponentially larger number of possible combinations [38]. Grant [2] argues that different types of specialized knowledge are complements rather than substitutes, meaning that they are most useful when combined, or that there are economies of scope. A diverse technological knowledge base is required to be creative [47] and to create cross-fertilization between technological areas, which increases innovative performance [48]. Incidentally, this kind of cross-fertilization resembles the layout of the Bell Labs Murray Hill building in which the transistor was invented by design enabling—almost forcing—close contacts between researchers from different technological disciplines [51].

In the *transitional phase* of technology evolution, technological uncertainty decreases. Firms have had the chance to learn and acquire knowledge in the previous phase. Technological solutions are available, and technology development investments become more exploitative. In this phase, technology requirements shift toward application-related knowledge [47] and toward

knowledge of process rather than product innovations. More certainty means that it is no longer necessary to explore many technological trajectories. In this phase, it is necessary to have a technology portfolio that is close to the dominant design. Therefore, in the transitional phase, firms require a smaller technology portfolio to gain innovative performance. To appropriate returns on technological knowledge, this knowledge should be unique to the firm, focused on the uniqueness of the portfolio not on portfolio size. When a firm needs technological knowledge outside of its own area of competence, there is a good chance that such knowledge is available with other firms and can be externally sourced. This also reduces the need to maintain large portfolios, provided the firm built up sufficient absorptive capacity in the fluid phase. Limiting the numbers of technologies generates cost advantages and thereby increases performance. Focusing the technology portfolio on the dominant design enables the firm to generate innovations that the market accepts, thereby increasing innovative performance. Having a unique technology portfolio close to its core competencies allows the firm to appropriate returns from the technology, which also leads to higher innovative performance. Since technology-related uncertainty is lower in this phase, firms can specialize rather than diversify their technological knowledge base, focusing on a narrow technological area [39] related to the dominant design. This creates important financial savings, which may be invested to improve the technological core, and in turn enables firms to outperform their rivals and maintain their technological leadership [39]. As much of the required technological scientific knowledge is available in this phase, either inside or outside of the firm's boundaries, the necessity to develop the scope of this knowledge is much lower. In this phase, it is more important to find the right applications for the knowledge that has been developed. Instead of being flexible and keeping all options open, firms should focus on their key technologies and core competencies [52]. This means increased specialization, leading to efficiency gains in knowledge acquisition and storage [34]. This applies especially when knowledge is specific to products or dominant designs because it is less subject to economies of scope than nonspecific knowledge [34]. During the transition phase, the cost aspect becomes more important, and it is too expensive to maintain a broad technological diversification.

In the *specific phase* of technology evolution, technological uncertainty is low, and most relevant technological knowledge is readily available. In this phase, firms need a small core technology portfolio to gain innovative performance. The dominant design is firmly established, and it is clear which technological knowledge is relevant. Since the technologies and products commoditize, cost savings are important, and maintaining a smaller portfolio will increase performance. During this phase, market-related rather than technology-related knowledge is required, and a large technological knowledge base is no longer necessary. As firms in this phase focus on exploiting existing knowledge, the uniqueness and protection of knowledge are even more important than in the transition phase. As it is not necessary to develop new technological knowledge, the economies of scope of a diverse portfolio no longer apply. It therefore makes sense to limit the technology portfolio to save resources. Any necessary related technological knowledge that is not available internally could easily be externally sourced. Saved resources can be invested in understanding the market and exploiting the firm's core technologies better.

In summary, we reason that during the fluid phase, firms need to develop large and diverse technology portfolios to cope with uncertainty and to keep development options open. In

later phases, after a dominant design appears and technological uncertainty is lower, firms will benefit more from smaller, specialized portfolios that can be more easily protected and exploited. Based on this reasoning, we formulate the following hypotheses:

> **H1**: *Firms with a large technology portfolio in earlier phases of technology evolution will achieve higher innovative performance than firms with a large technology portfolio in later phases.*

> **H2**: *Firms with a diverse technology portfolio in earlier phases of technology evolution will achieve higher innovative performance than firms with a diverse technology portfolio in later phases.*

4. Data and methods

We test our hypotheses in the ASIC industry because it is knowledge-intensive, technology-intensive, and dynamic [11]. This makes it possible to measure the impact of the size and diversity of the internal technology portfolio on the innovative performance of ASIC firms during the phases of ASIC technology evolution.

We constructed a panel dataset that includes data from 300 ASIC firms and selected all 67 ASIC firms with innovative performance from this dataset for the period 1986–2003, using the Integrated Circuit Engineering ASIC-Outlook industry reports (1986–1999) and the Integrated Circuit Engineering status reports (1980–1999) until 1999. For the period between 2000 and 2003, we used the IC Insights reports [53], Compustat, product guides, Gartner reports, and data of the World Semiconductor Trade Statistics Corporation. We selected these firms based on the available data from the Integrated Circuit Engineering Corporation and IC Insights Company.

To measure our dependent variable, innovative performance, we collected data on the number of ASIC patents during 1986–2003 at t = i (where i = 1986, 1987, … 2003). **Figure 4** shows an example of a firm's innovative performance over time.

We measured the first independent variable, the size of a firm's technology portfolio, by collecting data on the number of successful ASIC patent applications measured at t = i minus 5 (where i = 1986, 1987, … 2003). We added all submarket-related patents per segment (PLD + gate array + standard cell) in 5 years prior to the year of observation. Henderson and Cockburn [54] recommend this moving window of 5 years, arguing that prior technologies can be expected to contribute to the development of new technologies. **Figure 5** shows an example of a firm's technology portfolio size over time.

We measured the second independent variable, the diversity of a firm's technology portfolio, by collecting data on the types of ASIC patents (PLD, gate array, standard cell) and by adding up all three submarket-related patents that a firm received during 5 years prior to the year of observation. This diversity is based on three types of technologies (PLD, gate array, standard cell) that the portfolios may contain in each year, which means that the value of this variable varies between 0 and 3: 0 if a firm has zero technologies in a year, 1 if a firm has one ASIC technology in its portfolios, etc. **Figure 6** shows an example of a firm's technology portfolio diversity over time.
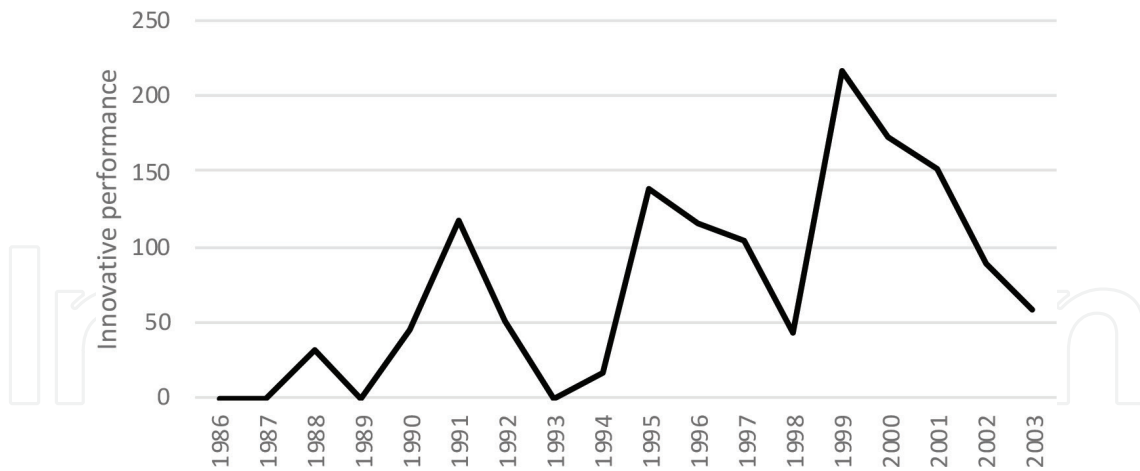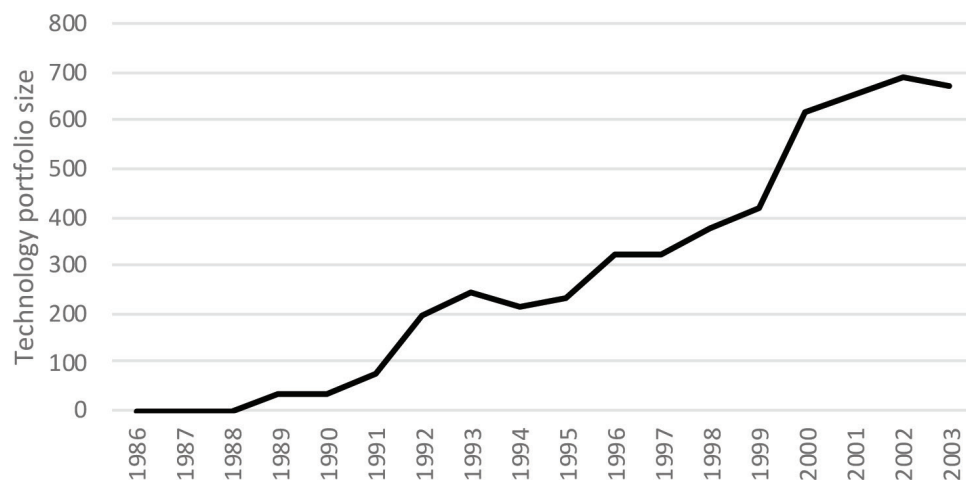
Figure 4. Example innovative performance.

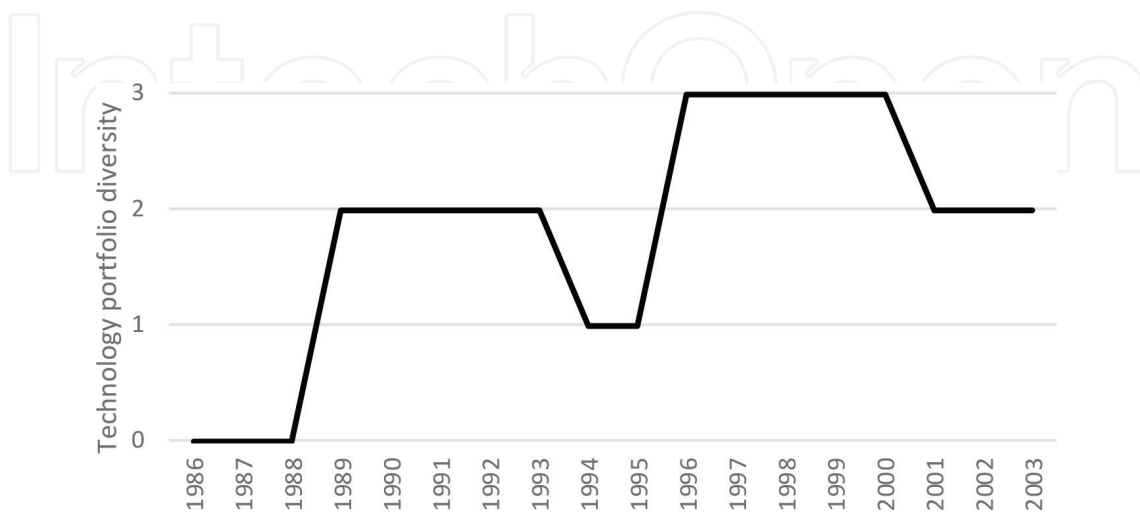**Figure 5.** Example technology portfolio size.

Figure 6. Example technology portfolio diversity.

We measured the moderating variable, technology evolution, based on its three phases: the fluid phase between 1986 and 1991, the transitional phase between 1992 and 1997, and the specific phase between 1998 and 2003. We use an industry-level metric, which is in line with the framework of Abernathy and Utterback [9] and Utterback [24]. It is based on the technological developments of all firms together, starting with the first patents developed in the ASIC industry. The metric is the same across the three subsegments, PLD, gate array, and standard cell.

We computed the interaction effect of technology portfolio size and technology evolution phase and the interaction effect of the technology portfolio diversity and technology evolution phase by multiplying the independent variables involved in the interaction. To enhance interpretability and eliminate nonessential multicollinearity, we standardized the independent variables in the interaction terms prior to computing those interaction terms [55]. We standardized the variables by first subtracting the overall mean from the value for each case, resulting in a mean of zero. We then divided the difference between the individual's score and the mean by the standard deviation, which results in a standard deviation of one.

We include five control variables. We measured the size of a firm's strategic alliance network as the number of cooperative relationships between firms: a firm's degree centrality [56]. We calculated this for each year using UCINET software. We use cooperation between firms over the last 5 years prior to the year of observation. We measured firm size as the natural log of the number of employees. Because larger firms are more dominant and have more financial

Variable	Time	Description	Mean	SD	Min.	Max.
Innovative performance	$t = i$	Number of ASIC patents per year	151	409	0	4764
Technology portfolio size	$t = i - 5$	Number of successful patent applications	590	1592	0	19,454
Technology portfolio diversity	$t = i - 5$	Zero, one, two, or three types of ASIC patents (PLD, gate array, standard cell) in the technology portfolio	1.35	1.24	0	3
Technology evolution	$t = i$	0 = fluid phase, 1 = transitional phase, 2 = specific phase	0.94	0.81	0	2
Alliance network size	$t = i - 5$	Normalized degree centrality	0.80	0.84	0	5.3
Firm size	$t = i$	Natural log of the number of employees	8.81	2.77	2.30	13.00
R&D/sales ratio	$t = i$	Percentage of sales invested in research and development	13%	15%	0%	300%
Asia region	$t = i$	Dummy variable denoting that the headquarters are located in Asia (default = America)	0.25	0.43	0	1
Europe region	$t = i$	Dummy variable denoting that the headquarters are located in Europe (default = America)	0.18	0.38	0	1

Table 1. Overview of the variables.

	Innovative performance	Technology portfolio size	Technology portfolio diversity	Technology evolution phase	Alliance network size	Firm size	R&D/ sales ratio	Asia region	Europe region
Innovative performance	1.00								
Technology portfolio size	0.81	1.00							
Technology portfolio diversity	0.32	0.37	1.00						
Technology evolution	0.20	0.31	0.32	1.00					
Alliance network size	0.22	0.26	0.46	0.28	1.00				
Firm size	−0.00	0.03	0.42	−0.02	0.27	1.00			
R&D/sales ratio	−0.01	−0.00	−0.11	0.03	−0.07	−0.43	1.00		
Asia region	−0.06	0.04	0.27	0.05	−0.19	0.35	−0.27	1.00	
Europe region	−0.14	−0.14	−0.09	−0.03	0.17	0.31	−0.05	−0.25	1.00

Table 2. Correlations.

means and resources to invest in R&D than smaller firms, they may have a higher innovation output compared to smaller firms due to economies of scale. We used a natural log because the number of employees is not normally distributed and the order of magnitude of the firm matters rather than its exact size. We used a firm's R&D expenses as a percentage of total sales, to check for the firm's propensity to invest in R&D. We also controlled for region indicating whether the firm's headquarters are located in America, in Asia, or in Europe.

Table 1 gives an overview of the variables. The firm-level data show a high average R&D intensity of 13% and a high average of 590 ASIC patents in the firms' portfolio, which indicate that the ASIC industry is knowledge-intensive and technology-intensive.

To test the hypotheses, we composed a longitudinal panel dataset. We conducted Hausman tests to decide whether to use fixed or random effect models. The panel analyses with the dependent count variable innovative performance are based on weighted patents. The mean and variance of the count distribution of these weighted patents are unequal, which means over-dispersion of the data, resulting in the need for a negative binomial regression [57].

Table 2 shows the correlation matrix. Based on the robustness of the test results (pair-wise exclusion of the variables with high correlations), no variables need to be excluded to avoid multicollinearity. Based on the results of the Hausman test, we selected fixed effects models for testing both hypotheses.

5. Results

To check our hypotheses, we test three models, the results of which are presented in **Table 3**. Model 1 is the baseline model that tests the direct effects of technology portfolio size and technology portfolio diversity on innovative performance. The model indicates positive and significant effects of portfolio size and portfolio diversity on a firm's innovative performance.

Model 2 tests how the technology evolution stage influences the relationship between technology portfolio *size* and innovative performance. It does so by including the interaction term of technology portfolio size and the phase of technology evolution. The estimates show that technology evolution negatively moderates the relationship between the size of the technology portfolio and the firm's innovative performance. It means that in later phases of the technology evolution, firms with smaller portfolios perform better. This supports Hypothesis 1.

Model 3 tests how the technology evolution stage influences the relationship between technology portfolio *diversity* and innovative performance. It does so by including the interaction term of technology portfolio diversity and the phase of technology evolution. The estimates show that technology evolution negatively moderates the relationship between the diversity of the technology portfolio and the firm's innovative performance. It means that in later phases of the technology evolution, firms with less diverse portfolios perform better. This supports Hypothesis 2.

All models indicate that larger firms and firms with larger networks have higher innovative performance, which is in line with findings of Gopalakrishnan and Bierly [58]. Larger firms

	Model 1 (main effects)	Model 2 (portfolio size and technology evolution)	Model 3 (portfolio diversity and technology evolution)
	Fixed effects♯♯	Fixed effects♯♯	Fixed effects♯♯
Technology portfolio size	0.000107*** (0.000)	0.000368*** (0.000)	0.000127*** (0.000)
Technology portfolio diversity	0.726*** (0.109)	0.586*** (0.110)	0.675*** (0.107)
Technology evolution phase	0.0403 (0.055)	−0.0056 (0.054)	0.274*** (0.071)
Technology portfolio size x technology evolution phase ♯		−0.357*** (0.036)	
Technology portfolio diversity x technology evolution phase ♯			−0.276*** (0.054)
Alliance network size	0.356*** (0.055)	0.350*** (0.054)	0.358*** (0.055)
Firm size	0.146*** (0.032)	0.164*** (0.032)	0.183*** (0.034)
R&D/sales ratio	−0.0162 (0.411)	0.065 (0.416)	0.0646 (0.408)
Asia region	0.772*** (0.147)	0.788*** (0.149)	0.763*** (0.147)
Europe region	−0.625*** (0.195)	−0.619*** (0.198)	−0.768*** (0.197)
Constant	−3.315*** (0.311)	−3.435*** (0.314)	−3.776*** (0.334)
Number of observations	807	807	807
Number of firms	59	59	59

Standard errors in parentheses. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

♯To calculate the interaction terms, we standardized the variables. For the main effects, the variables are not standardized.

♯♯The values of the Hausman test are for Model 1 Prob > χ^2 = 0.0042, for Model 2 Prob > χ^2 = 0.0001, and for Model 3 Prob > χ^2 = 0.0000. Since the tests are significant ($p < 0.05$), the null hypothesis is rejected, and the fixed effects model is most appropriate.

Table 3. Results.

have larger knowledge bases, and firms with larger networks are able to attract more external knowledge, which can be complementary to internally developed technology. Given the positive and significant main effects, the effects of these two control variables are not surprising.

The models also show that R&D investments, measured as the R&D/sales ratio, have nonsignificant effects on innovative performance. While this may seem surprising, there are various possible explanations. First, in our data, R&D investment is measured for all the firm's technologies, not specifically for the ASIC technologies. Many of the firms in our dataset also develop non-ASIC technologies, so that only a part of their R&D investment is related to ASIC development. Second, the effects of R&D on performance have sometimes been found to be nonsignificant or curvilinear (e.g., [40]), and these effects are not captured in our model.

Related to this, R&D spending is regarded as an input to the development of a technology portfolio and may therefore be subject to the efficiency of the "invention production function" that is not captured in our model.

Finally, the models show that relatively more innovative firms were located in Asia and relatively fewer in Europe between 1986 and 2003. Explanations for this are that more ASIC-developing firms are based in Asia and fewer in Europe to begin with and that during this period some European firms exited the sector, whereas in Asia new players entered.

6. Discussion

The main effect of *portfolio size* is positive and significant in base Model 1 and remains so when we include the moderating effect of technology evolution in Model 2. Thus, firms with a larger portfolio show a better innovative performance, regardless of the phase of technology evolution. This is in line with earlier findings of Ernst [35], Fleming and Sorenson [38], and Granstrand [3].

We find that technology evolution negatively and significantly moderates the relationship between technology portfolio size and innovative performance. This is a possible explanation for the previous conflicting results of Lin et al. [39] and Artz et al. [32]. Our results indicate that it is more beneficial for a firm to have a relatively large portfolio in an earlier phase of technology evolution and to reduce the size of its portfolio in later phases. To put it differently, in the earlier phases, firms are more focused on production of knowledge from R&D, whereas in later phases, they are more focused on production of innovation from knowledge. Conducting cross-sectional research in an earlier phase would result in underestimating the production of innovations from R&D, while doing so in a later phase would result in overestimating the production of innovations from R&D.

If we return to the characteristics of technological knowledge as we mentioned before, namely, economies of scale [3], indivisibilities [36], and self-generative abilities [37], firms likely need to accumulate a certain critical mass of technological knowledge in earlier phases before such knowledge becomes productive and leads to innovative performance. Conversely, in later phases, when such critical mass has been reached, it should be easier to achieve innovative performance, and expanding the technology portfolio is unnecessary.

Our findings for the *portfolio diversity* are similar to those for portfolio size. Here, too, the main effect of portfolio diversity on innovative performance is positive for base Model 1 and for Model 3 that includes the moderating effect of technology evolution. This is in line with earlier findings of Granstrand [3] and Breschi et al. [59] that a diverse portfolio is associated with innovativeness.

We find that technology evolution negatively and significantly moderates the relationship between technology portfolio diversity and innovative performance. This finding complements existing explanations of the complexity of the relationship between technology

portfolio diversity and innovative performance. Our research indicates that it is beneficial for a firm to have a relatively diverse portfolio in earlier phases of technology evolution and to reduce portfolio diversity in later phases.

It is widely recognized that this relationship is complex. Granstrand [3] argued that the coordination and integration costs of multidisciplinary R&D become higher with increased diversification. Research by Leten et al. [44] and Huang and Chen [45] confirms this argument. They found an inverted U-shaped effect of technological diversification on technological performance. While technological diversification enables combination and recombination, (too) high levels of diversification provide only marginal benefits due to high coordination and integration costs.

Our findings complement this explanation by arguing that more coordination efforts are needed in the earlier phases of technology evolution when technologies are unknown and that less coordination efforts are needed later when the relevant technologies are much better known. Therefore, we suggest that the inverted U-shape will have steeper slopes during earlier phases of technology evolution, when there are both high benefits from technology diversity and high costs of technology diversification. The inverted U-shape will have gentler slopes in later phases, when the benefits from technology diversity are less and the cost of technology diversification is lower.

Whether the firm can gain net benefits from the balance between technology diversity and coordination costs depends on the integrative capabilities of both technologists and managers [3]. If the firm possesses the capabilities to integrate diverse technologies, this is associated with causal ambiguity and sustainable competitive advantage [4].

7. Conclusions

The relationships between the size and diversity of firms' internal technology portfolios and their innovative performance are complex. We contribute to the literature by introducing technology evolution as a moderating variable of the relationship between internal technology sourcing and innovative performance. Our results support these moderating effects. The findings from our study contribute to explaining the complexity of the relationships between technology portfolio size and diversity and innovative performance by offering a possible explanation for conflicting empirical findings (technology portfolio size) and by offering an explanation that complements earlier findings (technology portfolio diversity).

Our findings suggest that during earlier phases of ASIC technology evolution, ASIC firms need broad technological portfolios and technological capabilities to keep their options open to adapt [2], to avoid lock-in [48], and to avoid investing in the wrong technology [49]. Such a broad portfolio requires strong integrative capabilities to profit from technology diversity. As such in earlier phases, causal ambiguity is created, making the firm's innovation difficult to imitate. During later phases of ASIC technology evolution, ASIC firms need to focus on

their core technologies and their core capabilities [52], in which the causal ambiguity has been embedded. In these phases, the role of integrative capabilities would be less pronounced.

For managers in the ASIC industry, our results imply that they need to invest in a large and diverse technology portfolio in the early phase of technology evolution and need to maintain relatively smaller and less diverse technology portfolios later on, to optimize their firm's innovative performance. Having a large and diverse ASIC portfolio in early phases of technology evolution gives the firm the flexibility to keep all options open during uncertain periods, while a smaller and specialized portfolio contributes to a focus on the core competencies in more certain periods. In the fluid phase, ASIC firms need to explore the technology space by developing a large and diverse technological knowledge portfolio. In the transitional phase, they need to reduce the size and diversity of their technological knowledge base and focus on their own unique knowledge contribution within the dominant design, applying knowledge from their core technological base. In the specific phase, they need to concentrate on a small, focused, unique, protectable, and exploitable technological knowledge base.

ASIC technology is currently in the specific phase, and it therefore may make most sense for ASIC firms to focus on such a small, focused, unique, protectable, and exploitable technological knowledge base. As we argued in our discussion of the trends in the ASIC industry, they can do this by focusing on cost reduction and large-scale production of commodity products to earn back the ever-larger design and production investments or by focusing on providing added functionality solutions for specific high-end applications. Of course, while doing so, they need to separately manage their portfolios regarding emerging technologies. If they want to play an active role in such emerging technologies, they will need to develop large and diverse portfolios again to deal with the uncertainties that such technologies bring.

The research described in this chapter has several limitations, which can provide directions for future research. First, we tested the effects of the size and diversity of the technology portfolio separately. We recognize that the combination of both effects may have an impact on innovative performance as well. Lin et al. [39] suggest that firms with smaller knowledge stocks should concentrate on a specific technological field and that the size of the knowledge stock may moderate the relationship between diversification and performance. This implies that, for individual firms, there may be different roads to success: either building large and diversified technology portfolios (e.g., Intel or Texas Instruments) or developing small and focused technology portfolios (e.g., SK Hynix). Future research could investigate the implications of technology evolution for both these roads, e.g., by case study analyses. Second, we did not specifically include the interactions between internal and external sourcing through the innovation network. The past research indicates complementarities between internal and external technology sourcing (e.g., [8, 50]). This implies that firms could, for example, combine internally focused portfolios with external cooperation to ensure the necessary diversity. Further research could extend out model to include such effects. Finally, we did not include the effects of mergers, acquisitions, buyouts, and spin-offs as vehicles to manage and build technology portfolios. This, too, could be addressed by future research using case study analyses.

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