Journal of the Operational Research Society (2005) 56, 1141–1150
www.palgrave-journals.com/jors

A system dynamics model of the semiconductor industry development in Taiwan

JH Chen* and TS Jan

National Chiao-Tung University, Hsinchu, Taiwan

Taiwan has become the fourth largest semiconductor manufacturer worldwide within only 25 years. Taiwan's success in developing its semiconductor industry has been widely recognized. Building a semiconductor industry in a developing country is costly, risky, and requires long-term accumulations of capital, technology, human resources, and production capacity. The development process depends on environmental interactions, which should be studied in an integrated and holistic manner. Using system dynamics methodology, this study analyses the development experience of the Taiwanese semiconductor industry, in order to provide better insight into the long-term industrial development process. The study also simulates the proposed model in one historical setting and two future scenarios. Implications for the development of the semiconductor industry in Taiwan and other Asian countries are discussed.
Journal of the Operational Research Society (2005) **56,** 1141–1150. doi:10.1057/palgrave.jors.2601958
Published online 23 February 2005

Keywords: semiconductor industry; development; developing country; system dynamics

Introduction

Taiwan has become the fourth largest semiconductor manufacturer worldwide within only 25 years, with its foundry, Integrated Circuits (IC) design, and Dynamic Random Access Memory (DRAM) industries ranked first, second, and fourth in the world, respectively. In 2003, the revenue of the Taiwanese semiconductor industry exceeded US$23 billion. Many Taiwanese semiconductor companies have become internationally influential. For instance, the Taiwan Semiconductor Manufacturing Corp. (TSMC) and the United Microelectronics Corp. (UMC) are the most competitive wafer foundry companies in the world, and together they control over 70% of the international foundry market. Additionally, TSMC has been one of the top 10 semiconductor manufacturing companies in the world since 2001.[1]

The success of semiconductor industry development in Taiwan has been widely recognized and discussed. The so-called flying-geese theory asserts that industrial development migrated from the United States to Japan in the 1980s, and then moved on to the 'small tigers' of East Asia (Korea, Taiwan, and Singapore) in the 1990s. However, this theory does not explain the different development paths that the newly industrialized countries (NICs) pursued in order to catch up with industry leaders.[2] Nor can the flying-geese theory explain the lack of semiconductor industry development in other potential countries, such as Hong Kong and India.[3,4] Some researchers have discussed the development stage of the Taiwanese semiconductor industry. Mathews[5] described the development of Taiwan's semiconductor industry in a four-phase development model, and emphasized the importance of local government and public research institutes in the leveraging process of resource and technology. Similarly, Chang and Tsai[6] divided Taiwan's development process into five stages and characterized the impacts of industrial consortia. Various other studies have also noted the importance of the government and public research institutes in the development of the Taiwanese semiconductor industry.[7–9] Although stage models are useful to describe the importance of the government, public research institutes, and their strategies in different periods, those models do not comprehensively describe the dynamic interactions between the industry and its socioconomic environment. Consequently, previous studies have not revealed the underlying structure of Taiwan's successful development experience. In fact, building a semiconductor industry in a developing country is costly, risky, and requires long-term accumulations of capital, technology, human resources, and production capacity. The development process should be studied in an integrated and holistic manner, both in terms of its resource accumulation structure and its environmental interactions.

System dynamics (SD)[10–12] has been used in various industrial researches to explore system structures and to improve the policymaking process.[13–17] This methodology suggests that a system's behaviour is caused by that system's structure, which could be interpreted by feedback loops, stocks and flows, time delays, and non-linearity.[18] For the

*Correspondence: JH Chen, Department of Management Science, National Chiao-Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan
E-mail: jc@iim.nctu.edu.tw

long-term industrial development in a developing country, the underlying structure could evolve according to internal and external changes in the environment.[19] SD is a useful methodology that not only advances understanding of the dynamic industrial development process, but also helps governmental and industry policymaking.

This study uses SD to identify the development structure of Taiwan's semiconductor industry. First, we analysed the characteristics of the semiconductor industry and its interaction with Taiwan's socioconomic environment, deriving a qualitative model according to the identified structure. Second, we derived and simulated a quantitative model in a historical setting. Third, we simulated the model in two possible scenarios to test their impacts. Finally, we discuss the simulation results and their implications for the development of semiconductor industry in Taiwan, as well as other NICs.

General characteristics of the semiconductor industry

The development of the semiconductor industry depends, in general, on the accumulation of capital, human resources, technology, and production capacity, along with their interaction with the environment. The key characteristics of the industry are as follows:

It is capital intensive

A 12-in wafer plant costs nearly US$3 billion, where machines and equipment represent over 80% of the cost. These facilities will be outdated within 5–7 years due to rapid technology advancement. Consequently, a vast and constant capital investment is crucial to maintain a semiconductor manufacturing facility.

It is technology intensive

Modern IC production process requires the integration of technologies in electronics, optics, chemistry, precision machinery, and materials science. A typical IC fabrication process involves over 300 procedures, through which millions of transistors are fabricated in class-1 clean rooms, where the maximum allowable airborne particles (as small as 0.1 micron) are restricted to no more than 35 per cubic foot. Moore's Law[20] demonstrates the rapid speed of development in semiconductor technology. Owing to the high technology and rapidly changing nature of the industry, therefore, heavy investment and research and development (R&D) efforts are required to improve technology levels.

It requires high-level human resources

A wafer plant requires about 10 000 employees to operate, of which 60% are engineers. Engineers in a wafer plant frequently must regularly problem-solve in order to maintain production stability and efficiency.[21] An engineer's ability to manage the fabrication process grows with time and experience.[22]

Modelling

The development of semiconductor industry depends on the accumulation of development resources. For a latecomer like Taiwan, the government and leading multinational companies are also important in the development process. We analysed the development structure according to Taiwan's government policies, its accumulation structure of manpower and capital, and their interactions with local and international environment, as described below.

Government policies

Since 1976, the Taiwanese government has developed several policies to nurture the semiconductor industry. First, the government established public research institutes to upgrade industry technology and accumulate initial R&D capacity. The public research institutes acquired technology from national R&D projects or from foreign sources, and then delivered it to the private sector though technology transfer or spin-offs. Second, the government established a science park with tax subsidies to support the industry's development. The success of the HsinChu Science Park in high-technology (high-tech) industry development has become a model emulated by other developing countries.[23] Third, the government assisted the spin-off companies in raising initial funds from public and private investors.

The Industrial Technology Research Institute (ITRI), founded in 1973, is the most influential public R&D institute on the industrial development in Taiwan. Notably, the Electronics Research and Service Organization (ERSO), established within the ITRI in 1974, was the pioneer in introducing semiconductor technology to Taiwan. The government implemented the Electronic Industry Development Project (EIDP, 1976–83), through which ERSO acquired Taiwan's initial 7-μm process technology from RCA in 1976. The EIDP wound up and resulted in the spin-off of several initial semiconductor companies in Taiwan, including UMC and some IC design companies. The government continued to fuel the industry via the VLSI and ULSI project, and both of these eventually spun off into TSMC and Vanguard, respectively.[24]

Because the new spin-offs were not competitive initially, the government reinforced the capital flow by persuading domestic companies focused on traditional industry to invest in the semiconductor industry. However, this approach had no significant effect. The government then adopted another strategy, by forming public–private joint ventures with leading multinational corporations (MNCs), such as Philips, to leverage their technology and subsequent product orders.

Figure 1 illustrates the interaction among government policies and the initial accumulation of manpower, capital, and machine flows stated above.

Accumulation of manpower flow

Human resources are the foundation of semiconductor industry development. The human resources in Taiwan come from three major pools: local education institutes, public R&D institutes, and overseas students. The structure of the manpower flow for the Taiwanese semiconductor industry is explained below.

Education-emphasized tradition

Chinese emphasize education, and typically hope their children to receive as high an education as possible.[25] Going abroad to pursue an advanced education is a common practice in Taiwan. The number of Taiwanese students in the United States has grown steadily since the 1960s. Between 1983 and 1987, Taiwan ranked higher than any other country in the enrolment of international students in the United States.[26] In 1990, for example, 33 530 Taiwanese students enrolled in US universities; three-quarters of them were graduate students, mostly in science and engineering.

Many Taiwanese students stayed in the United States after graduation. They acquired the latest technology skills and industrial connections while in the United States, and thus became potential human resources for Taiwan. Taiwan's development opportunities lured many of them home, in hopes of building new careers. Approximately 19 000 technicians returned to Taiwan from the United States between 1980 and 1988, and many of them have contributed significantly to the Taiwanese semiconductor industry. For instance, Dr Morris Chang left his position as vice president of Texas Instruments to establish TSMC in Taiwan. Dr Miin Wu returned to Taiwan after many years of serving in high-level positions at Intel and VLSI to become a cofounder of Macronix, the largest flash memory manufacturer in Taiwan.

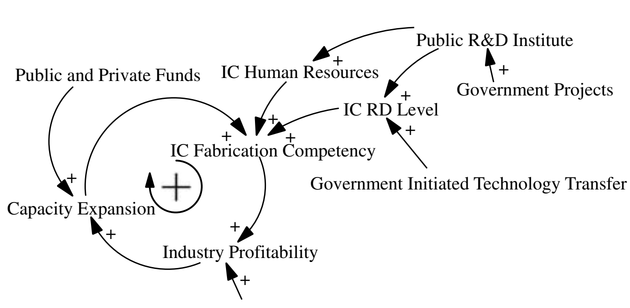

Figure 1 Government–industry interaction loop.

Social inclination for engineering and science

Electronics, information technology, and engineering have long been the most favoured fields in higher education in Taiwan. Top students have flooded these fields, striving to become engineers. In 1990, Taiwan had 37 247 students enrolled in engineering-related university departments, and over 135 000 students enrolled in technician-related college departments.

Impact of public R&D institutes

During the initial development of the semiconductor industry, public R&D institutes in Taiwan served as human resource reservoirs. The institutes retained and incubated superior R&D personnel who eventually diffused into the industry.

During Taiwan's early industrialization, the compensation and working environment in these public institutes exceeded the industry standard. The institutes attracted outstanding graduates who then contributed to government-supported research projects. As industrial development progressed, many of these graduates left to seek new opportunities in the private sector. The diffusion of professionals from ITRI contributed significantly to the development of Taiwan's industry technology and to its R&D. Over 12 000 personnel left ITRI by 1999, approximately 86% of them to enter private companies or start their own businesses.[27] Many top management members of major Taiwanese semiconductor companies, like TSMC, UMC, Windbond, Macronix, and Mosel-Vitelic, had worked in ITRI.

Employee profit-sharing system

An employee profit-sharing system prevails in the Taiwanese high-tech industry.[28] The system differs slightly from employee stock options. Specifically, companies issue new stocks as stock dividends to their owners from retained earnings, but reserve a certain proportion of these new stocks to distribute to employees. As calculated on the face value of the stock, the proportion distributed to employees generally ranges from 5 to 25% of annual profits. For a company with a high stock price, the market value of employee-shared stock can average as much as US$60 000 per employee annually.

Figure 2 illustrates the structure of the accumulation of human resources. Students who graduate from relevant departments may choose to go abroad, enter public research institutes, or launch a career in industry. The level of excess compensation from the employee profit-sharing system influences graduates' decisions as they select different career paths. These human resources may then absorb the latest technology and marketing information and gradually become important IC R&D and manufacturing personnel. Manpower accumulation is essential to R&D and

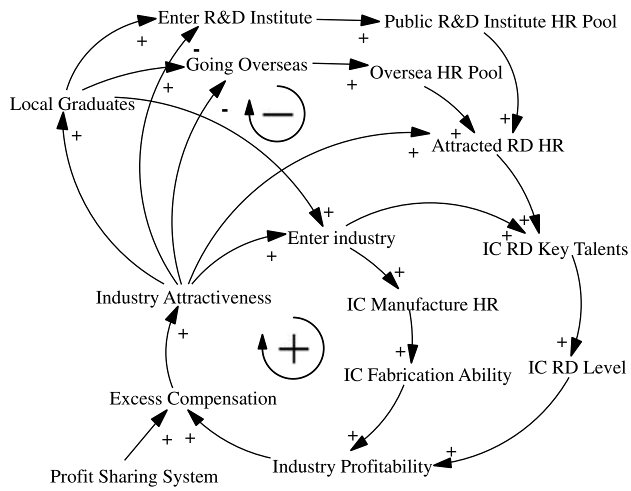

Figure 2 Human resource and excess compensation loop.

manufacturing competency, and thus influences industry profitability.

Accumulation of capital flow

Generally, semiconductor companies source their capital from either capital markets or corporate profits. Taiwanese capital markets have two characteristics that support the development of the semiconductor industry.

First, Taiwan has accumulated large amounts of capital due to its rapid industrialization and long-lasting international trade surplus. The per capita income in Taiwan grew from US$360 in 1970 to over US$12 000 in 2000. By the end of 2000, Taiwan's foreign exchange reserves approached US$133 billion. The savings rate in Taiwan has exceeded 20% since the 1970s, and climbed as high as 33% in 1986 and 1987.[29] Moreover, Taiwan's stock market is extraordinarily liquid, with an annual turnover rate over 250% and daily trading volume reaching as high as US$10.2 billion.[30] Consequently, as soon as an industry is perceived to have good prospects, raising funds from the capital market by issuing stock or company bonds becomes relatively easy.

Second, Taiwanese stock investors favour the distribution of stock dividends more than cash dividends, and consider it as an indicator of future company growth. Therefore, Taiwanese companies are more likely to retain their cash by distributing stock dividends to their stockholders and reinvesting the capital in capacity expansion or further technology upgrades.

Interaction of capital, production capacity, and international cooperation

Developing countries frequently acquire new technology through licensing, joint ventures, or strategic alliances with foreign leading companies. Capital and production capability are important for latecomers to the semiconductor industry, so that they may attract cooperative ventures from leading multinationals.[31] In Taiwan's early development stage, the private sector relied on public research institutes to obtain foreign technologies. Later, as industry development progressed, firms were more capable of negotiating directly with foreign companies. The collaborative activities between Taiwanese semiconductor companies and leading multinationals increased rapidly in the 1990 s. For instance, TSMC dedicated its highly efficient production capacity to its major customers in exchange for their licenses on advanced technologies, and most Taiwanese DRAM manufacturers were founded by joint ventures with foreign DRAM industry players.

Besides production capacity and process technology, production management is also important for IC fabrication. The ability to control and manage production depends on accumulated experience. Wafer plants with many experienced personnel are more likely to have efficient and stable production processes.[32] However, expanded production capacity generates more vacancies that must be filled by new employees, which in turn dilutes the proportion of experienced personnel. The dilution effect of capacity expansion reduces average management effectiveness and, thereby, fabrication competency.

Figure 3 shows a feedback loop representing the above relationships. IC fabrication and R&D competency determine industry profitability, and hence affect capital flow from capital market and corporate profits. Firms can reinvest capital into new capacity or R&D activities. The money-to-capacity relationships integrate into two positive feedback loops. Firms with more developmental resources are more likely to attract international cooperation and thus acquire advanced technologies. But, with the expansion of production capacity, new employees dilute the average human resource quality, and create a balancing loop.

Quantitative model

To build the quantitative model, we constructed an influence diagram (see Figure 4) based on the relationships described above. The quantitative model includes six level variables. Coyle's concepts of Inventory-and-Order-Based Production Control System[33] and the example of the Skill pool model[34] provide some information about how to model industrial practices and the accumulation of human experiences. Moreover, on building the quantitative model, it is important to formulate properly the non-linear relationships between model variables. In this model, variables of IC Manufacturing Competency, R&D Level, and Excess Compensation are sufficiently important that additional efforts should be spent to handle them as described below.

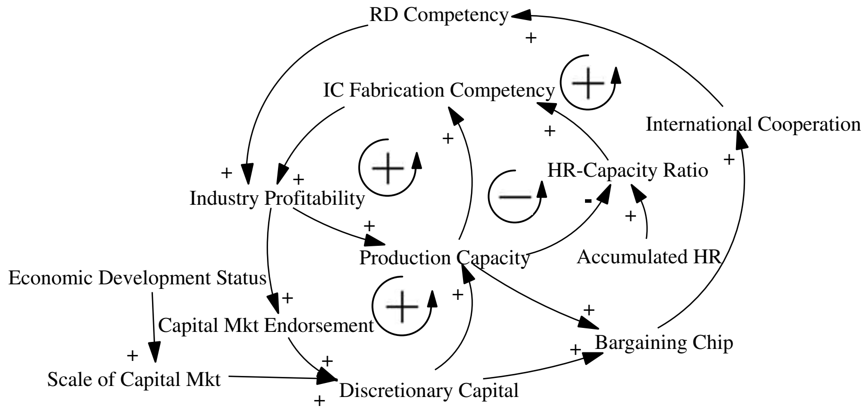

Figure 3 Interactions of loops.

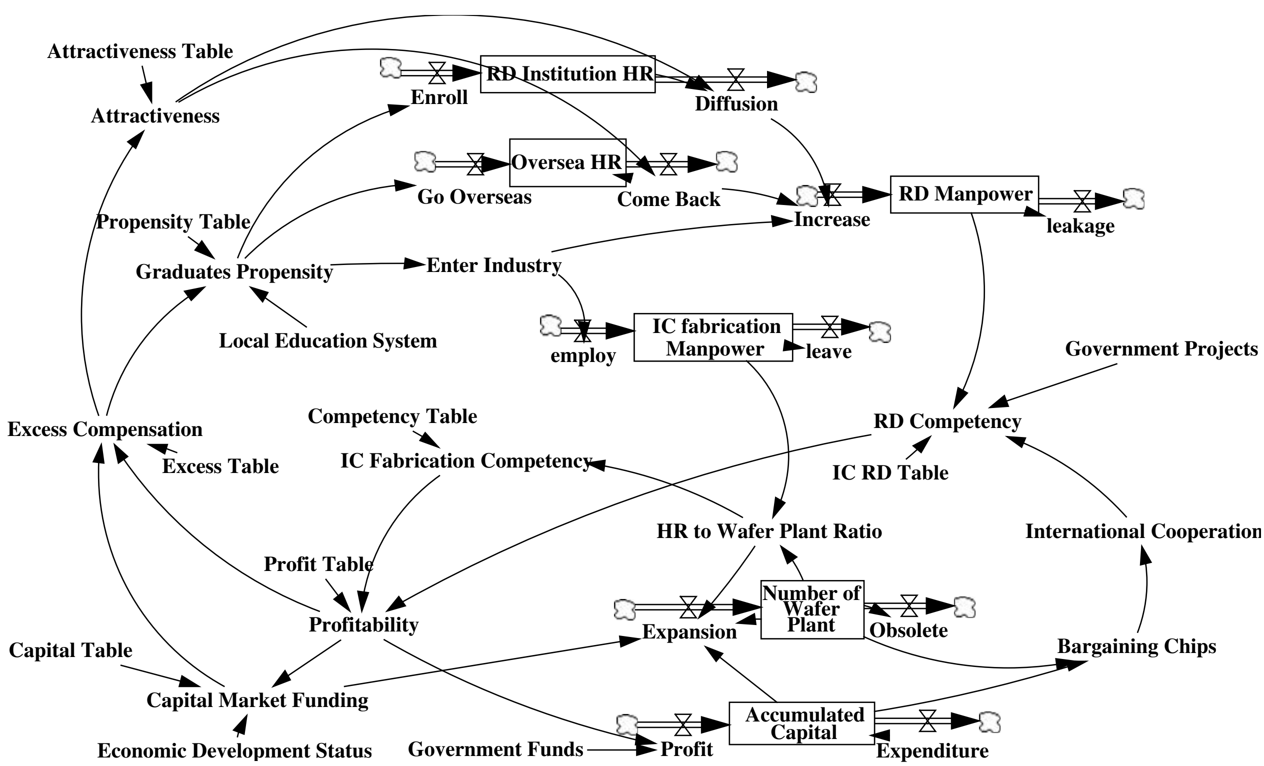

Figure 4 Integrated flow diagram of the model (by Vensim software).

IC fabrication competency

This variable is measured by the average die yield of wafer fabrication. Die yield represents the percentage of usable dies in a wafer, and here is expressed as a value between zero and one. This study assumes that die yield is positively related to the number of experienced engineers in a plant.

To achieve higher data reliability,[35] the authors contacted several industrial professionals, and interviewed a senior vice president of TSMC to determine the company's manpower situation. The interview confirmed our finding that engineer experience is essential for die yield improvement, and a newly recruited engineer can become experienced in roughly 2 years of work and a veteran engineer after about 5 years. Assuming that the manpower situation across the industry is similar to TSMCs, we can estimate the required number of experienced engineers per plant to maintain an efficient fabrication process. For example, TSMC had a die yield of over 95% in mature production lines, and an average yield of around 90% in 2000. Meanwhile, TSMC had about 5700 engineers, seven 8-in wafer plants, and two under-construction 12-in wafer plants, which represent an average of over 600 experienced engineers per plant. The non-linear relationship between experienced engineers per plant and die yield is

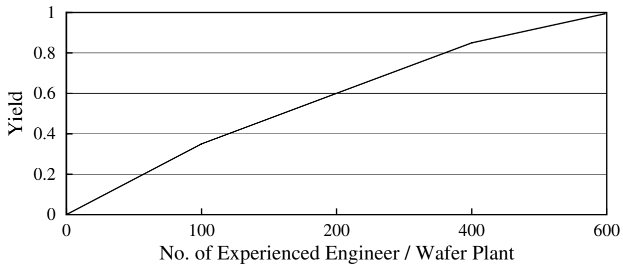

Figure 5 Relationship between die yield and number of experienced engineers/wafer plant.

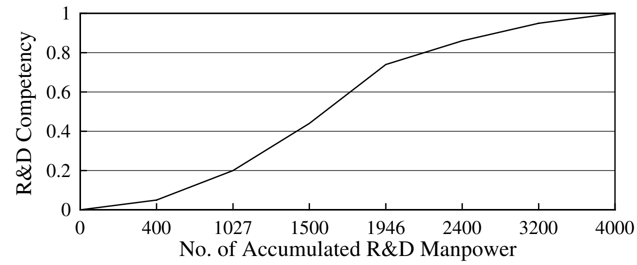

Figure 6 Relationship between R&D manpower and R&D competency.

formulated in Figure 5. Only a few experienced engineers are required to achieve a basic die yield, but higher production efficiency calls for greater expertise. When the yield reaches 80%, more even more problem-solving expertise is required. Consequently, the relation between the two variables is a concave upward curve.

R&D competency of process technology

This variable is defined as the level of IC technology relative to the state-of-the-art, measured by the intensity of IC fabrication process. The variable takes a value between zero and one, where zero represents rudimentary technology and one represents the state-of-the-art.

Process technology can be enhanced through R&D investments or technology transfer. Due to the speed of technological advancement, process technology requires more R&D effort to achieve and sustain higher competency levels. The variable is therefore estimated based on R&D manpower accumulated in this industry. Taking TSMC again as an example, the company finished developing the 0.13-μm logic process in 2000, and unveiled its full 0.09-μm technology in 2002. Both of these achievements were completed ahead of the schedule of the International Technology Roadmap for Semiconductors. Meanwhile, the R&D work force at TSMC numbered around 400 in 2001 and between 600 and 700 in 2002.

As IC fabrication involves technologies from many scientific fields, increased R&D manpower is associated with increasing rate of return. However, as R&D competency increases, leading edge problems become correspondingly complex and difficult. The relationship is a typical learning curve.[36] According to the estimates made for the overall industry based on the TSMC case, the table function of R&D competency and manpower is established as displayed in Figure 6.

Excess compensation

This variable is defined as the average market value per employee of stock distributions. For simplicity, this study assumes that the proportion of profit allocated for employee sharing is constant over time, and the stock price is

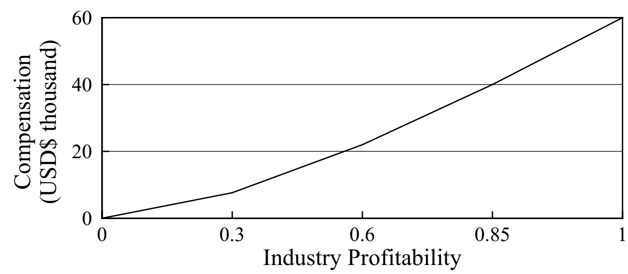

Figure 7 Relationship between industry profitability and excess compensation/employee.

determined by industry profitability. Therefore, the stock price and the level of profit determine the market value of employee-shared stocks. As the stock price reflects investors' sentiment toward a given industry, profitable industries will have a higher price/earnings ratio and, thus, non-linearly higher stock price. In addition, the more profit an industry earns, the more stocks to be distributed. This study formulated the relationship between excess compensation and industry profitability as a concave upward curve in Figure 7.

Take the actual data as examples, the net income of TSMC was US$1.93 billion in 2000 (return on equity (ROE) 0.25), and US$136 million was allocated from revenue and issued to employees as new stock. The market value of this stock was approximately US$900 million, averaged to US$60 000 per employee. In the same year, the net income of UMC was US$1.5 billion (ROE 0.21), and its stock price was only 70% of TSMCs. If the two companies allocated the same proportion of revenue for profit-sharing, the average market value of excess compensation per employee in UMC was only 74% of that in TSMC. Generally, unprofitable companies issue little or no stock to employees.

Results and discussion

The validity of an SD model lies in the usefulness of and users' confidence in the model,[37] which can be evaluated from model structure, model behaviour, and policy implications.[38] This study identified the development structure of Taiwan's semiconductor industry and derived the model based on historical facts, industrial practices, and mental data from industry professionals. The simulation results of the quantitative model under the historical setting, as illustrated in Figures 8 and 9, are compared and discussed according to the industry's historical behaviour. Based on the results, we simulated the model in two possible scenarios to test their respective implications.

Simulation results

The historical setting was formulated under the assumption of unlimited development resources and market demands. Figure 8 illustrates the comparison of some simulation results and historical data in the industry. The trends of simulated and historical data are generally similar. However, because the model did not consider industrial business cycles, the simulation does not reflect fluctuations in the historical data brought about by the 1995 and 2001 downturns in the international semiconductor market. Notably, the number of accumulated 8-in equivalent wafer plants seems to saturate after 2000, which may indicate that Taiwan's semiconductor industry could eventually meet its growth limit. Further, Taiwan's semiconductor industry demonstrated a staggered growth in the 1996 recession, but declined significantly in the 2001 downturn, which could suggest that the industry encountered a different type of market competition once it had expanded to a certain scale. Two scenarios based on these speculations were formulated and tested in the subsection of Scenario simulation.

In Figure 9, Local Capital Endorsement has been rising since the late 1980s, as indicated by the resource attraction loop in the domestic environment that was activated in this period. Subsequently, in the mid 1990s, international cooperation increased, followed by the rapid advancement of R&D competency and the decline of the requirement on domestic capital. The result suggests that the dominating loop in this period shifted from domestic resource attraction to international cooperation.

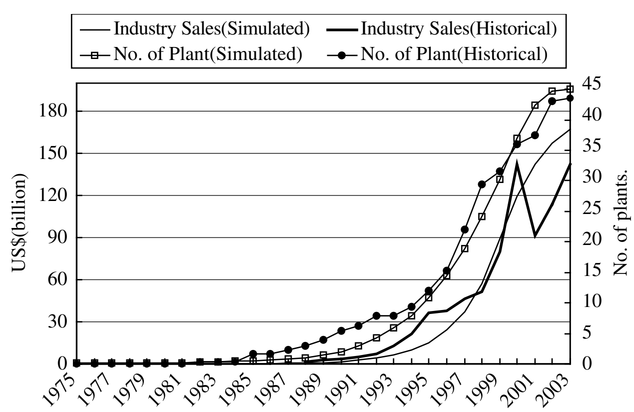

Figure 8 Simulation result—compare with historical data.

Development stages

Based on the model and simulation results, the development process of Taiwan's semiconductor industry can be classified into three stages according to the transition of the dominating loop. In the first stage, the major interactions of the development occurred between government and industry. As the private sector was weak during this period, the government established a technology-spillover mechanism through public research institutes and government-sponsored research projects. The milestone in this period

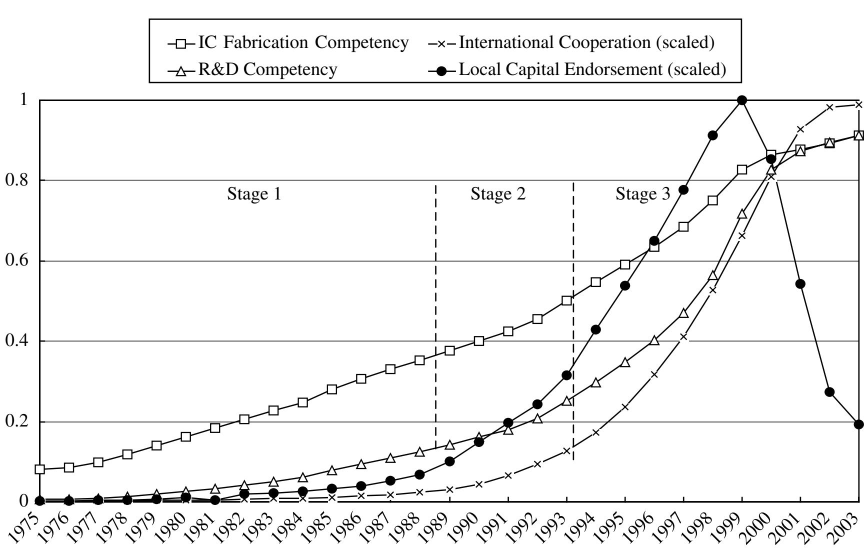

Figure 9 Simulation result: competences and expansion of resource flows.

was the spin-offs of UMC in 1980 and TSMC in 1987 from a public research institute, ITRI. In the second stage, interaction between industry and the domestic socioeconomic environment further propelled the development and then surpassed the formerly dominant government–industry interactions. The semiconductor industry firms explored various survival strategies and gradually demonstrated higher growth potential than traditional industries. After the UMC listed its stock on Taiwan Stock Exchange in 1985, more and more IC companies went public and were recognized by domestic investors. With the help of the employee profit-sharing system, reinforcement from the capital attraction loop triggered the human resources flow; together, they contributed to the accumulation of manufacturing competencies. In the third stage, industry firms rapidly expanded through interaction with the international environment. The private sector was able to attract foreign partners through its production capacity and efficiency, and leveraged advanced technologies from leading multinationals. Further, after TSMC issued and listed its American Depository Receipts on the New York Stock Exchange in 1997, Taiwanese semiconductor firms began to gain access to overseas capital resources. The industry in Taiwan expanded 11 times during this stage, and improved its process technology to the state-of-the-art.

Scenario simulation

Over the past 25 years, three consecutive reinforcing loops supported the development of Taiwan's semiconductor industry. However, the first decline in 2001 unveiled that balancing loops may become dominant. The recent crises of limited growth and leakage of human resources have been widely discussed in Taiwan. This study formulated two scenarios according to potential situations in the future, and conducted second-round simulations to assess the impacts.

To test the impact of limited resources and markets, we formulated two settings in the limited growth scenario. Historically, until the first recession in 2001, manpower supply and market demand seemed unlimited for the Taiwanese semiconductor industry. The decline in the population growth rate in Taiwan—from 2% in the 1970s to 0.66% in 2001—indicates that the manpower supply will eventually stop growing. Due to a variety of political reasons, it is difficult to introduce foreign human resources on a large scale. Further, human resources may begin to flow into other local prospective industries when semiconductor industry stops growing. The first setting assumes that the supply of local human resources will decrease by 20% after 2001. The Taiwanese semiconductor industry demonstrated different reactions to the two recessions in 1995 and 2001, which suggests that the industry could meet market limitations when expanded over a given scale. The second setting consequently assumes that the industry's average profits will decline by 20% if Taiwan's accumulated production capacity exceeds fifty wafer plants. Figure 10 shows the simulated results. In the first setting of decreased human supply, sales growth abated and eventually declined. In the second setting of limited markets, sales clearly dropped and stopped growing.

The second scenario posits an outcome in which the semiconductor industry loses its attractiveness to human resources. When an industry becomes fully mature, some personnel may choose to seek other high-growth opportunities. In fact, some Taiwanese have left for mainland China to establish new companies, such as SMIC and the Grace Semiconductor in Shanghai. The second scenario also assumes that the ratio of employee turnover has increased from 10 to 20% since 2002. Figure 11 illustrates the simulation results. The increased leakage of human resources reverses the positive human resources feedback loop. Consequently, the simulated competency of IC manufacturing in Taiwan demonstrates an accelerating decline in the simulation.

The results of the scenario simulations reveal a possible crisis for the ongoing development of the semiconductor industry in Taiwan. Under the increasing pressure of resource competition from other domestic industries (eg, TFT LCD), and foreign competitors from both leading and late-coming countries, Taiwan's semiconductor industry must internationalize further and extend its resource

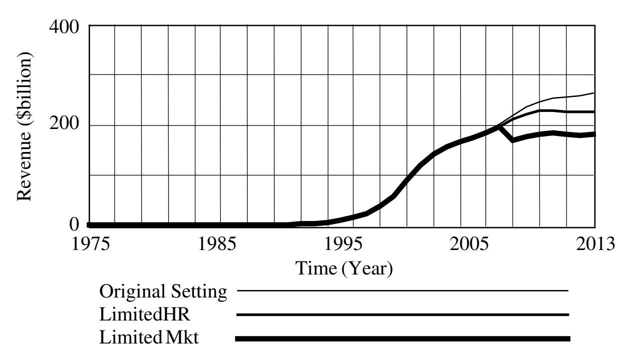

Figure 10 Simulation result: limit of growth.

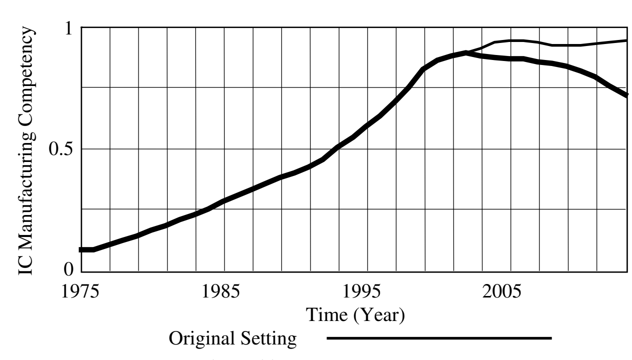

Figure 11 Simulation result: leakage on human resource.

accumulation structure. How to maintain or acquire its competitive advantages through regional interaction, as in the Greater China region, is a topic for future research.

Development of the semiconductor industry in other Asian countries

The accumulation of manpower, capital, production capacity, and technology is essential to the development of the semiconductor industry in developing countries. However, by itself this requirement, though necessary, is insufficient. Many developing countries have attempted to develop a semiconductor industry, with varying degrees of success. Among them, the small tigers in East Asia, including Korea, Singapore, and Taiwan, have been most successful.[39] Their different development patterns can be better understood in the context of the interplay among their accumulation structures, government, and industry firms. We discussed the development in these countries from three perspectives: the structure of the accumulation, the role of the government, and corporate strategies.

With respect to the structure of the accumulation, before Korea and Taiwan began to develop the semiconductor industry, they had already accumulated manpower and capital during their early industrialization process. Fifty years earlier, both countries had targeted the automotive industry as a means to technological and economic development. As a result, when these countries attempted to develop their high-tech industry, the infrastructure and resources to do so were already available. However, the Korean and Taiwanese resource structures differed in key ways. Taiwanese industry mainly comprises small- and medium-sized companies. This means that the resource attraction mechanism for the domestic socioeconomic environment is essential in early stages, before the industry has established its competency. Korean industry, by contrast, has largely been driven by chaebols (large corporations), which could apply resources to the development of the high-tech industry by themselves. For its part, Singapore relies on attracting foreign direct investment (FDI) and international human resources.

Government played an important role in the development of the industry in all of the above countries, but employed different policies in every case. The Taiwanese government established policies to initiate the process of technology accumulation, and many early semiconductor companies were spin-offs from public R&D institutes. The Korean government encouraged the country's chaebols to develop the semiconductor industry by helping them to obtain financial support from government-controlled banks. Finally, the Singaporean government attracted both FDI from MNCs and human resources from elsewhere by providing a supportive infrastructure and liberal immigration policies for professionals.

The strategies taken by the respective industries in these countries were also different. The Taiwanese semiconductor industry adopted trial-and-error and quick following strategy. In addition, owing to the country's tendency toward small- and medium-sized companies, the semiconductor industry actively sought international cooperation to avoid 'not surviving'.[40] The Korean firms took a different approach, adopting a goal-seeking strategy to focus on DRAM manufacturing from the beginning. Large Korean corporations acquired technology by acquiring small companies in Silicon Valley and then assuming the R&D burden of ongoing development. Singapore's industry, in yet another approach, was propelled by leading MNCs.

For the less successful countries—namely Hong Kong, with its enormous capital, and India with its excellent human resources—the proper interactions in the resource accumulation structure were lacking. Though Hong Kong and India possessed some of the necessary developmental resources, their government policies and firm strategies were too weak to stimulate the flows of resources into the industry development. Mainland China provides a sharp contrast to these examples, since it has attracted many overseas students since its opening policy and its recent fast-growing economy has stimulated capital flow in the region. Assisted by government intervention and the potential of domestic market, mainland China is poised to be the next success story in the development of this industry.

Conclusion

Successfully accumulating and integrating manpower, capital, technology, and production capacity is essential to the development of semiconductor industry. This study proposed a model to analyse the development process of Taiwan's semiconductor industry, using SD methodology. The model is simulated in a historical setting and two future scenarios. The result shows that the development of the semiconductor industry in Taiwan is an evolutionary process in which three reinforcing loops—government–industry interactions, industry–domestic environment interactions, and industry–multinationals interactions—successively and successfully supported the accumulation of resources in the industry. However, the result of the scenario simulations also suggests that Taiwan could face possible crises for ongoing development.

The proposed model provides a rationale to understand the development of semiconductor industry in Taiwan. Based on this rationale, and analysis of semiconductor development in other Asian countries, this study suggests that a developing country able to accumulate and integrate critical resources successfully will likewise succeed in growing its own semiconductor industry.

References

1 ITRI (various years 1991–2003). *Yearbooks of Semiconductor Industry*. Ministry of Economic Affairs: Taiwan, ROC (in Chinese).
2 Hobday M (1995). Innovation in East Asia: diversity and development. *Technovation* **15**(2): 55–63.
3 Berger S and Lester R (1997). *Made by Hong Kong*. Oxford University Press: Hong Kong.
4 Kapoor VN and Kumar V (1999). Semiconductor research and industry in India. *Electron Inform Plan* **26**(7): 374–381.
5 Mathews JA (1997). A Silicon Valley of the east: creating Taiwan's semiconductor industry. *Calif Manage Rev* **39**: 26–54.
6 Chang PL and Tsai CT (2000). Evolution of technology development strategies for Taiwan's semiconductor industry: formation of research consortia. *Ind Innov* **7**(2): 185–197.
7 Wang JC (1994). Cooperative research in a newly industrialized country: Taiwan. *Res Policy* **23**: 697–711.
8 Chen CF and Sewell G (1996). Strategies for technological development in South Korea and Taiwan: the case of the semiconductors. *Res Policy* **25**: 759–783.
9 Hsu CW and Chiang HC (2001). The government strategy for the upgrading of industrial technology in Taiwan. *Technovation* **21**: 123–132.
10 Forrester JW (1961). *Industrial Dynamics*. MIT Press: Cambridge, MA.
11 Coyle RG (1996). *System Dynamics Modeling—A practical approach*. Chapman & Hall: London, UK.
12 Morecroft J and Sterman JD (eds) (1994). *Modeling for Learning Organizations*. Productivity Press: Portland, OR.
13 Roberts EB (eds) (1978). *Managerial Applications of System Dynamics*. Productivity Press: Cambridge, MA.
14 Ford A (1997). System dynamics and the electronic power industry. *Syst Dynam Rev* **13**(1): 57–85.
15 Coyle RG and Morecroft J (eds) (1999). Special issue: system dynamics for policy, strategy and management education. *J Opl Res Soc* **50**(4): 291–449.
16 Berends PAJ and Romme AGL (2001). Cyclicality of capital-intensive industries: a system dynamics simulation study of the paper industry. *Omega Int J Manage S* **29**(6): 543–552.
17 Jan TS and Hsiao CT (2004). A four-role model of the automotive industry development in developing countries: a case in Taiwan. *J Opl Res Soc* **55**(11): 1145–1155.
18 Sterman JD (2002). All models are wrong: reflections on becoming a systems scientist. *Syst Dynam Rev* **18**(4): 501–531.
19 Chen JH and Jan TS (forthcoming). A variety-increasing view to the development of semiconductor industry in Taiwan. *Techno Forecast Soc*, to appear in doi:10.1016/j.techfore.2004.06.002.
20 Jovanovic B and Rousseau PL (2002). Moore's law and learning by doing. *Rev Econ Dynam* **5**(2): 346–375.
21 Appleyard MM and Brown C (2001). Employment practices and semiconductor manufacturing performance. *Ind Relat* **40**(3): 436–471.
22 von Hippel E and Tyre MJ (1995). How learning by doing is done: problem identification in novel process equipment. *Res Policy* **24**(1): 1–12.
23 Xue L (1997). Promoting industrial R&D and high-tech development through science parks: the Taiwan experience and its implications for developing countries. *Int J Technol Manag* **13**(7–8): 744–761.
24 Su LY (1994). *There were both stormy and sunny days—the 20 years path of ERSO*. ERSO: Taiwan, ROC (In Chinese).
25 Fwu BJ and Wang HH (2002). The social status of teachers in Taiwan. *Comp Educ* **38**(2): 211–224.
26 Bureau of International Culture and Educational Relations (2002). *Education Statistical Information*. BICER, Ministry of Education: Taiwan, ROC (in Chinese).
27 Hong CY *et al* (1998). *The Contribution of ITRI to Taiwan's Technology Management Human Resources—A Study on Resigned Employees (88IERC-1)*. ITRI: Taiwan, ROC (in Chinese).
28 Chen JF (1982). *The Employee Profit-sharing and Stock-ownership Plans in the Republic of China*. Chinese Culture University Publisher: Taiwan, ROC (in Chinese).
29 Directorate General of Budget, Accounting and Statistics (2002). *National Statistics Database*. DGBAS, Taiwan, ROC, Also available at telnet://rs570.dgbas.gov.tw Accessed September 17, 2002.
30 ICBC (2001). A review and prospect of the economic development in Taiwan. *International Commercial Bank of China Monthly Report—January 2001*. ICBC: Taiwan, ROC (in Chinese).
31 Park SH *et al* (2002). Firm resources as moderators of the relationship between market growth and strategic alliances in semiconductor start-ups. *Acad Manage J* **45**(3): 527–545.
32 Chung SG (2001). The learning curve and the yield factor: the case of Korea's semiconductor industry. *Appl Econ* **33**(4): 473–483.
33 Coyle R (1977). *Management System Dynamics*. John Wiley & Sons: Chichester.
34 Hafeez K and Abdelmeguid H (2003). Dynamics of human resource and knowledge management. *J Opl Res Soc* **54**: 153–164.
35 Andersen DF *et al* (1997). Group model building: adding more science to the craft. *Syst Dynam Rev* **13**(2): 187–201.
36 Lieberman M (1987). The learning curve, diffusion, and competitive strategy. *Strategic Manage J* **8**: 441–452.
37 Barlas Y and Carpenter S (1990). Philosophical root of model validation: two paradigms. *Syst Dynam Rev* **6**(2): 148–166.
38 Forrestor JW and Senge PM (1980). Tests for building confidence in system dynamics models. *TIMS Studies Manage Sci* **14**: 209–228.
39 Mathews JA and Cho DS (2000). *Tiger Technology—The Creation of the Semiconductor Industry in East Asia*. Cambridge University Press: Cambridge, UK.
40 Morgan G (1983). Rethinking corporate strategy: a cybernetic perspective. *Hum Relat* **36**(4): 345–360.

Received April 2004;
accepted December 2004 after one minor revision