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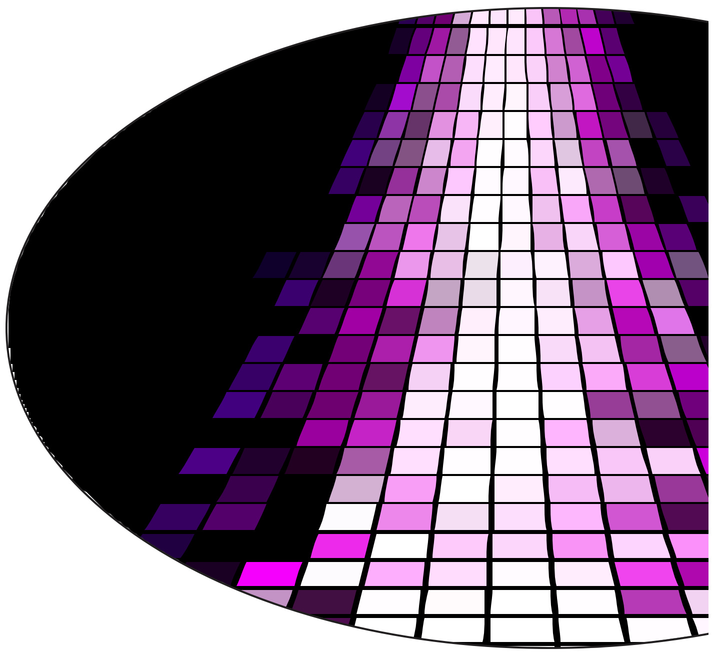

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Vibrant Eco-system Creation for Sustainability: A Lesson from Singapore's Water Industry

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Abstract

Through a stepwise national strategy of importing technology, building indigenous capabilities through learning and assimilating imported technology to exporting the indigenous capabilities, Singapore has successfully caught up with the nations that are advanced in the technologies related to water treatment. From the macro-numerical phenomenon observed, this paper aims to provide both qualitative and quantitative evidences of this co-evolutionary dynamism between innovation and institutional systems. Realising the issue as a comprehensive technology chain and its substitution for traditional resources, sophisticated combination of government stimulation and industry participation leading to a Global Hydrohub has induced world leading-edge innovation involvement. Such a vibrant eco-system aiming at overcoming the constraints for sustainable growth can be applied not only to water management but also to energy and climate change issues. Policy makers in emerging economies can adapt the successful practices and note the pitfalls in establishing the vibrant eco-system that is essential for sustainable environmental solutions for their economies.

Keywords: *Technology Substitution, Eco-system, Global Hydrohub, Sustainability.*

INTRODUCTION

The Open Innovation model was introduced by Chesbrough (2003) in the beginning of the 21st century. Since then, the concept has been widely adopted by businesses worldwide as businesses realize that the traditional concept of conducting research and development (R&D), generating, developing and commercialising research results, in-house, is no longer feasible in the fast changing business environment (Chesbrough, 2003). The new business environment takes into account that a company may not have all extraordinary people working for them and that the specific expertise needed may be found outside the company. The Open Innovation principle acknowledges that internal R&D may be necessary and that external R&D can help build significant value on top of the internal R&D. Another pull factor of the Open Innovation model is the fact that the company does not have to originate the research in order to profit from it.

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Increasingly, the concept is adopted at the national level by governments in policy formulation as Open Innovation has shown to facilitate the leapfrogging of industries, hence increasing the nation's economic growth (Lee and Lim, 2001, and Mazzoleni and Nelson, 2007). Typical success in this leapfrogging can be observed in Singapore's NEWater development leading to the creation of a vibrant eco-system (Chew et al., 2010). Given that this success can largely be attributed to the Design-Build-Own-Operate (DBOO) model, this paper attempts to elucidate its Open Innovation Dynamism. Section 2 reviews the consequence of Singapore's open innovation policy in its NEWater development. Section 3 analyzes initiatives promoting Open Innovation. Contribution of the DBOO scheme to Open Innovation is analyzed in section 4. Section 5 briefly summarizes new findings and policy implications.

THE CASE OF SINGAPORE

Water Supply

Singapore is a small island state with a land area of 699 square kilometers. Being located in the equatorial rain belt, Singapore does get a lot of rain. However, Singapore does not have the land to collect and store the water. In addition, Singapore has no other natural sources of water like ground-water aquifers. With a population of about 5 million people and a strong manufacturing industry, the national water agency, the Public Utilities Board (PUB), has come up with innovative approaches for harvesting the plentiful rainfall to replace the conventional approach of using pristine catchments for harvesting rainwater. Singapore's long term water supply management strategy, also known as the Four National Taps comprises water from local catchments, imported water, NEWater and desalinated water. Examples of these innovations include the Marina Barrage, the Deep Tunnel Sewerage System and the Variable Salinity Plant.

The Marina Barrage is an innovative approach to turning Singapore's urban, built-up areas into water catchments. It will help boost Singapore's water supply and at the same time, help alleviate flooding in the low-lying areas in the city. The Marina reservoir is also a potential venue for all kinds of water activities. The Deep Tunnel Sewerage System (DTSS) is 48-km long tunnel to divert used-water from the northern, eastern and central part of Singapore to a centralized treatment plant at the south-eastern end of Singapore (Changi Water Reclamation Plant). The DTSS together with the Changi Water Reclamation Plant will free up valuable land occupied by three existing water reclamation plants and 45 pumping stations for other economic use like housing and industrial and commercial developments. Initiated in 2000 and completed in 2008, the cost of the project was S$3.6 billion. The Variable Salinity Plant is a new water treatment technique which integrates desalination and NEWater treatment processes to treat feedwater of varying salinity to potable water.

NEWater

NEWater is the pillar of Singapore's water sustainability. NEWater is high-grade reclaimed water which gets produced using advanced membrane technologies comprising microfiltration, reverse osmosis and ultraviolet disinfection. The NEWater production process is illustrated in Figure 1. The purified water is ultra-clean and safe to drink. NEWater has passed more than 65,000 scientific tests and exceeds the Environmental Public Health (EPH) and United States Environmental Protection Agency (USEPA) drinking water standards, as well as the drinking guidelines established by the World Health Organisation (WHO).

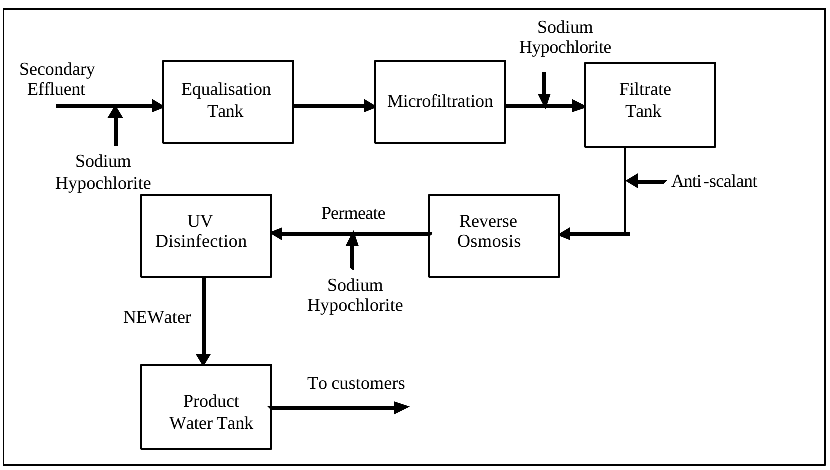

Figure 1: The NEWater Production Process

NEWater was introduced in 2003 and primarily supplied to non-domestic sectors such as wafer fabrication parks, industrial estates and commercial buildings for industrial and air-cooling purposes. A small percentage of NEWater is also mixed with raw reservoir water before being treated at the various waterworks for drinking.

OPEN INNOVATION AND POLICY

The emergence of the water ecosystem in Singapore can be traced back to August 2004, when the Ministerial Committee on Research and

Development (MCRD), chaired by then Deputy Prime Minister, Dr Tony Tan, was formed to review Singapore's (Research and Development) R&D strategies and direction. The Committee recommended that Singapore needs to refocus its research and innovation agenda to keep up with international developments. Singapore must transform itself into an innovation-driven economy that competes on knowledge and talent. The Committee also outlined a national R&D framework to implement its strategic thrusts. The Research, Innovation and Enterprise Council (RIEC), chaired by the Prime Minister, Mr Lee Hsien Loong, was set up to lead the national drive to promote knowledge creation, innovation and enterprise. The RIEC was formed within the National Research Foundation (NRF), a department formed within the Prime Minister's Office on 1 January 2006. An initial amount of S$5 billion was set aside for the period between 2006 and 2010 to promote the three key strategic growth areas identified by the NRF Board. The Environmental & Water Technologies were one of the three key economic growth pillars for the Singapore economy. The other two strategic growth areas being the Biomedical Sciences and the Interactive & Digital Media.

The framework for sustainable innovation proposed in the Science & Technology Plan 2010 is illustrated in figure 2. The concept that new knowledge can be generated from R&D conducted locally as well as being acquired from external sources is similar to Chesbrough's Open Innovation model.

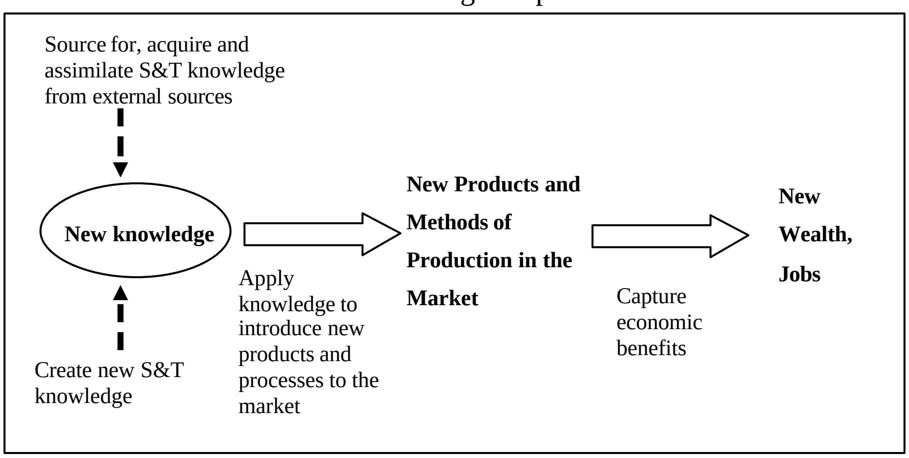

Figure 2: Open Innovation Model in Science & Technology Policy 2010

INITIATIVES PROMOTING OPEN INNOVATION

Notable government initiatives to promote open innovation are described in this section. Firstly, the Environment and Water Industry Development

Council (EWI) was set up in May 2006 under the Ministry of the Environment and Water Resources to spearhead the development of the environment and water industry in Singapore. Its vision is to develop Singapore into a 'global hydrohub' for business, investment, research and technology. Evidence of open innovation can be found in EWI's three-pronged strategy, focusing on Capability Development, Cluster Development and Internationalisation.

The Capability Development strategy aims to build up the R&D and technology base for the environment and water sector, and, at the same time, develop the necessary manpower to meet the needs of the sector. A S$100 million Environment & Water Research Programme (EWRP) was launched in 2006. The March 2009 issue of Milieu reported that since then, four Request-for-Proposals (RFPs) have been completed, with some S$30 million in research grants awarded to more than 30 research projects. The RFPs are open to research institutions and companies to submit proposals for funding. Based on the open innovation model in figure 2, new knowledge created by the private sector is contributed towards Singapore's pool of knowledge stock. These companies bring with them expertise in areas that they are strong in. Viewing water treatment as a system, the areas of research are diverse and cover the various parts of the system. Examples include membrane fouling, biomimetic membranes and rapid pathogen detection.

The Cluster Development strategy aims to develop the local water industry by attracting international players to anchor their operations in Singapore. One such way is to make available PUB (Public Utility Board) facilities for the test-building of new water technologies. The aim is to be the hub for the private sector to test their technologies here before implementation in or selling the technologies to other parts of Asia. The market may not be Singapore but Singapore is geographically located with fast access to many parts of Asia and the infrastructure for such activities is available. An example of a successful project is the Singapore-Delft Water Alliance's Aquatic Science Centre, an urban freshwater research facility located in Sungei Ulu Pandan, that will carry out in-depth studies on urban freshwater management and translate research activities into real-world applications. The Centre will help to bridge the gap between laboratory research and pilot implementation at canals and rivers. The Centre is an example of the many projects under the Singapore-Delft Water Alliance (SDWA). The SDWA was jointly established in 2007 by the PUB and leading Dutch water specialist Delft Hydraulics. Delft Hydraulics provides consultancy services to global clients.

On the academic front, the Nanyang Technological University (NTU) partnered consultancy and research firm, DHI Singapore to form the DHI-NTU Water and Environment Research Centre and Education Hub.

Another goal of the Cluster Development group is to anchor major foreign players in Singapore. By doing so, it creates opportunities for Singapore to learn from the foreign players, subsequently creating our indigenous knowledge as a result of technology spillover. The EWI has been successful in attracting global water and wastewater treatment companies, engineering design firms, and consultancy firms to anchor their R&D or technical centres in Singapore. Together with opportunities to work together with local firms on projects, either under the public-private partnership (PPP) scheme or joint research projects, opportunities are generated for the creation and building up of local indigenous capabilities. Table 1 lists the global players that have set up their corporate global R&D centres in Singapore. As the aim is to create opportunities for the public and private sectors to work together, eight public sector R&D centres were established, as listed in Table 2.

Table 1: Corporate R&D Centres Established by Global Water Players in Singapore

	Name of Company	Name of Operation in Singapore	Year of Conceptualisation	Cost of Investment
1	GE Water & Process Technologies	NUS-GE Singapore Water Technology Centre [Global R&D Centre]	2006	S$130 million
2	Siemens Water Technology	Siemens Global Water R&D Centre [International HQ outside of USA]	2007	S$60 million
3	Keppel	Keppel Environment Technology Centre (KETC)	2007	S$50 million
4	Deltares	Deltares Environment and Water R&D Centre	2007	S$63 million
5	Black & Veatch	Global Design Centre for Water	2007	NA *
6	Marmon	Hflux-Marmon R&D Centre	2007	NA *
7	Memstar Technology Ltd	Memstar Membrane R&D Centre	2008	NA *
8	Nitto Denko	Nitto Denko Water Membrane Technical Centre	2008	NA *
9	DHI	DHI-NTU Water and Environment Research Centre and Education Hub	2008	NA *
10	Optiqua	Optiqua R&D Centre	2009	NA *
11	Camp Dresser & Makee (CDM)	Camp Dresser & Makee Neysadurai Technical Centre for Water & Urban Planning	2009	NA *
12	Sembcorp	Sembcorp R&D	2009	NA *
13	Hyflux	Hyflux Global R&D Centre	2009	S$120 million
14	Toray Industries, Inc (Japan)	Toray Singapore Water Research Centre (TSWRC)	2010	NA *

*NA * - not available*

Table 2: Public Sector R&D Centres Established in Singapore

Name of R&D Centre	Host Research Institution
1. Centre for Advanced Water Technology	PUB
1. Singapore Delft Water Alliance 2. R&D Centre on Water Eco-Efficiency	NUS Environmental Research Institute
1. Singapore Membrane Technology Centre 2. DHI-NTU Water & Environment Research Centre and Education Hub 3. Residues & Resource Reclamation Centre 4. Advanced Environmental Biotechnology Centre 5. Institute of Environmental Science & Engineering	NTU-Nanyang Environment & water Research Institute

The Internationalisation group helps local companies in venturing overseas by creating networking opportunities, profiling their capabilities and helping them to export their expertise. The EWI works closely with International Enterprise Singapore (IE Singapore) to identify potential business opportunities in overseas markets and organise trade missions and conferences, as well as participate in international exhibitions. Local companies that have been invited to be part of the trade delegation include Keppel Corporation, Hyflux, Sembcorp Utilities and Salcon. The success of these activities also saw the increase of water companies established in Singapore increase from about 50 in quantity in 2006 to more than 70 companies in 2010. This has created the necessary critical mass for a vibrant eco-system, as illustrated in figure 3. Through such opportunities, local companies have been able to export the indigenous capabilities build by winning projects globally. The prominent annual Singapore International Water Week (SIWW) brings together players from the whole value chain. The value of deals sealed during the annual SIWW is listed in Table 3. The deals take into account projects awarded, tenders, investments and memorandum of understandings. The value of overseas projects clinched by Singapore-based companies increased from S$683million for the period 2004 to 2006 to S$7.7 billion for the period 2006 to 2009 (PUB, 2010).

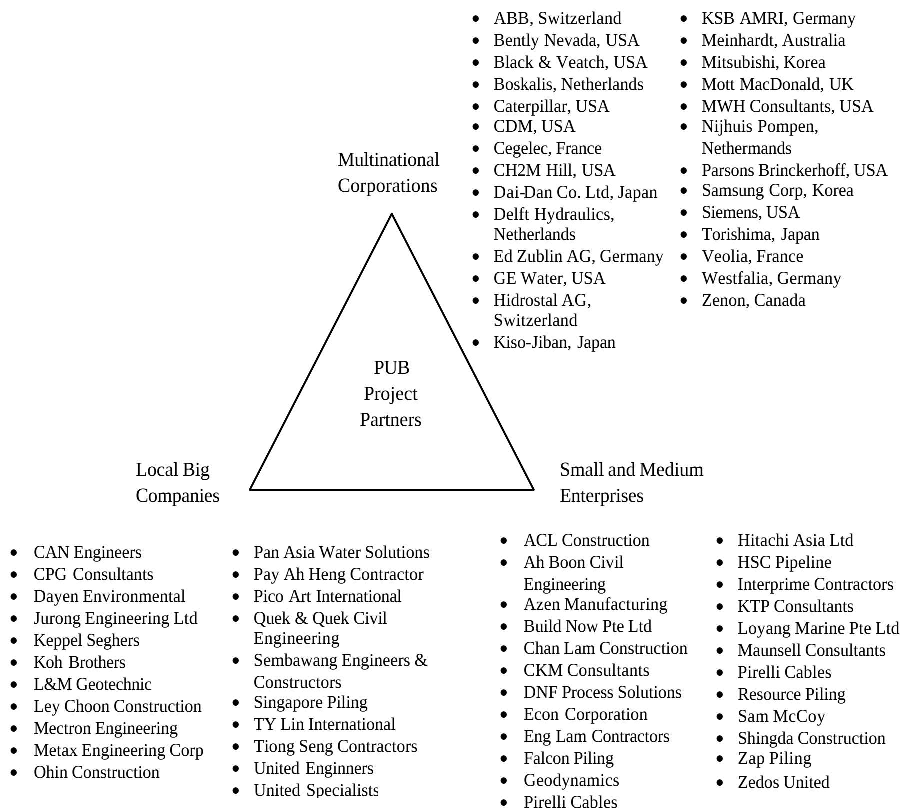

Figure 3: A Vibrant Water Ecosystem in Singapore Involving more than 70 Companies

Table 3: Values of Deals Concluded During the Singapore International Water Week

Event	Value of Deals# Sealed
1st SIWW (23 – 27 June 2008)	S$0.4 billion
2nd SIWW (22 – 26 June 2009)	S$2.2 billion
3rd SIWW (28 June – 2 July 2010)	S$2.8 billion

 # deals include projects awarded, tenders, investments, memorandum of understanding, collaborative agreements

The following are successful examples of local firms exporting the indigenous capabilities built up over the years through winning of projects overseas. The deals were negotiated during the 3rd SIWW, held from 28 June 2010 to 2 July 2010. The first example is Moya Dayen Limited, a home-grown water company, clinched a deal with the Phnom Penh Water Supply Authority in Cambodia for phase 1 of the Niroth Water Production Facilities Project. Moya Dayen will first undertake the supply, delivery, and construction of a 25 metres high intake tower located in the Mekong River, a raw water pumping station and a raw water transmission main and other ancillary works. Following the completion of the aforementioned work, Moya Dayen will construct a water treatment plant which included treated water tanks, a treated water treatment transmission main and other ancillary buildings. The second example is a Memorandum of Understanding, worth S$280 million, signed by home-grown energy, water and marine group, Sembcorp, to expand seawater desalination capacity in the United Arab Emirates (UAE). The third example is a S$21 million contract, won by local subsidiary of Boustead, a global infrastructure engineering company for the first new water recycling plant in UAE. On the research front, two collaboration agreements were signed. One is between Optiqua Technologies, a subsidiary of Dutch optical sensor company Optisense, and PUB, to develop Optiqua's real time sensor technology. The other collaboration agreement is between ITT Corporation and PUB, to conduct joint research and technology testing to further develop energy-efficient water and wastewater treatment solutions. These two collaborative research projects are excellent examples of opportunities where there is exchange of knowledge between the private and public sectors, thus creating opportunities for learning from the innovator and at the same time, for the local community to build up its indigenous capabilities through either the transfer or spillover of knowledge / technology.

Another notable initiative to promote open innovation is the adoption of the Public-Private Partnership (PPP) model in 2003. The PPP model was initially initiated by the Ministry of Finance under the Best Sourcing Framework, as it offers a win-win solution for the public sector, the private sector and all members of the public. The PPP model allows the PUB to source for expertise and innovation of the private sector at competitive costs. It also creates new business opportunities for the private sector and at the same time, private sector can build up their expertise and track record in the water business. It is in line with PUB's aim of becoming more pro-business and service-oriented by leveraging on the strengths of the public and private sectors.

Prior to the PPP initiative, contracts were awarded based on the Design-Bid-Build (DBB) model. The projects awarded under the DBB model included the Deep Tunnel Sewerage System (DTSS), the Marina Barrage, the Bedok NEWater Factory and the Kranji NEWater Factory. The estimated value of the DTSS project and the Marina Barrage were S$2.2 billion and S$226 million respectively. These two projects were excellent examples of the strong partnership among various players. As illustrated in figures 4 and 5, the strong partnership was forged among contractors, sub-contracts, manufacturers, suppliers and other players. With the success of these large-scale projects that showed the importance that no one single party holds the technology and knowledge for success, the DBOO model was initiated as it not only leveraged on the expertise of the private sector, it also offered the private sector the opportunity to have a stake in the local water market. The DBOO model was implemented. Projects awarded under the DBOO model included the Tuas Desalination Plant (30mgd), the Uu Pandan NEWater Plant (32mgd) and the Changi NEWater Plant (50mdg).

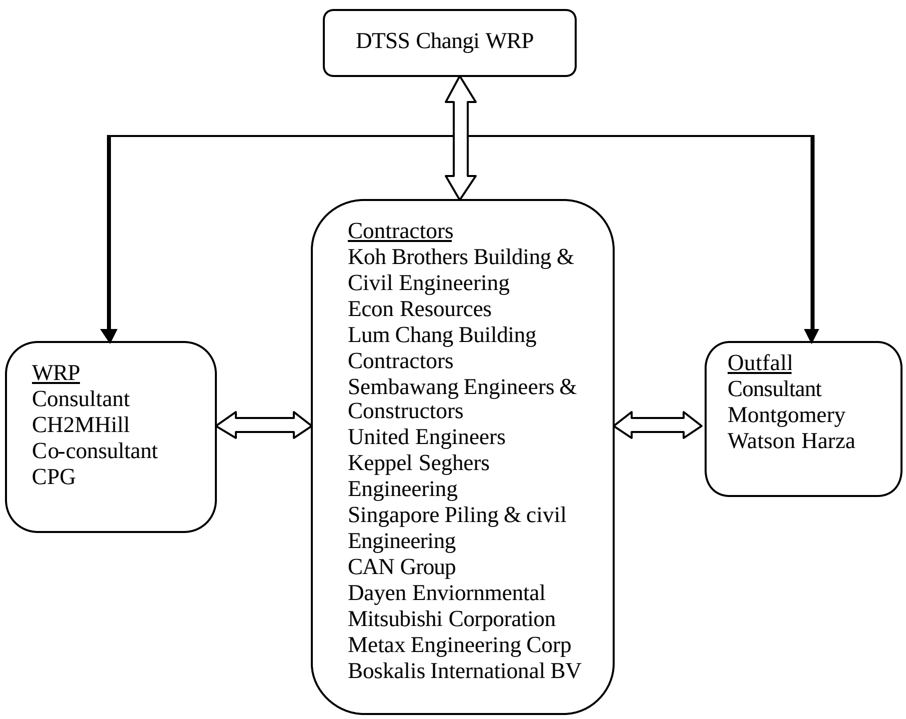

Figure 4: Strong Partnership Established in the DTSS Changi WRP.

Table 4: Water Projects Awarded Under DBOO Model

	Project	Plant Capacity	Date of Award (Date of Commission)	Contract Term	Concession Company
1	Tuas Desalination Plant	30 mgd	Apr 2003 (Sep 2005)	20 years (2005 – 2025)	SingSpring (Pte) Ltd
2	Ulu Pandan NEWater Plant	32 mgd	Jan 2005 (Mar 2007)	20 years (2007 – 2027)	Keppel Seghers NEWater Dev (Pte) Ltd
3	Changi NEWater Plant	50 mgd	Jan 2006 (May 2010)	25 years (2010 – 2035)	Sembcorp Utilities Pte Ltd

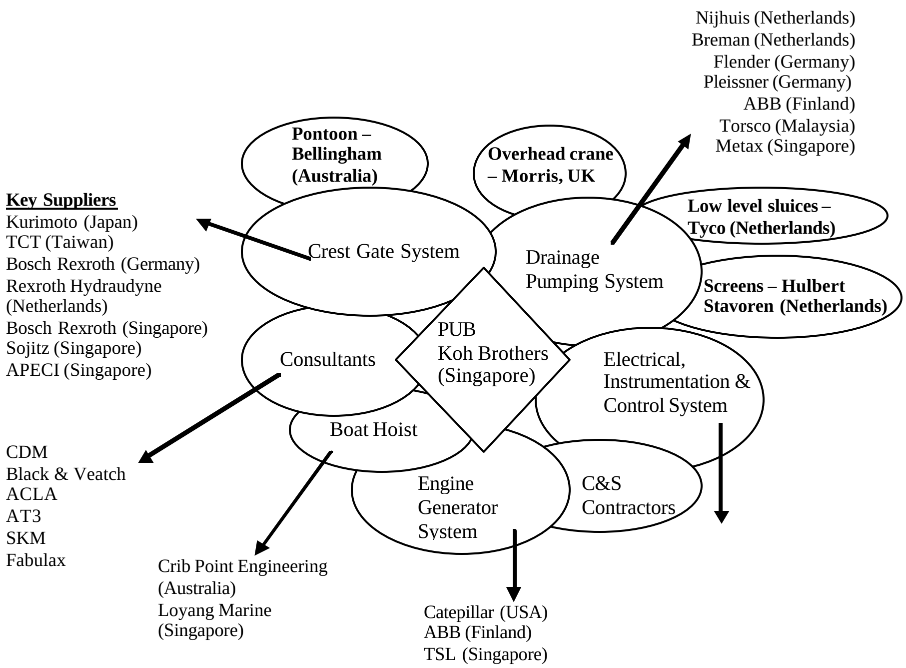

Figure 5: Strong Partnership Established in the Marina Barrage Project

CONTRIBUTION OF "DESIGN-BUILD-OWN-OPERATE" (DBOO) TO OPEN INNOVATION

Singapore's conspicuous accomplishment in NEWater development leading to current noting co-evolutionary domestication can largely be attributed to the success in open innovation. Introduction of the DBOO scheme has contributed significantly to this success (Chew, Watanabe and Tou, 2010). Aiming at elucidating this open innovation dynamism by means of imitator substitution for innovator (Watanabe et al., 2011), an empirical analysis utilizing Bi-Bass model is attempted in this section.

Four Phases of Singapore's NEWater Development Trajectory

As reviewed in the preceding analysis (Chew, Watanabe and Tou, 2010), Singapore's NEWater development trajectory over the last decade, based on five NEWater factories, as indicated in Table 5, can be divided into the following four phases:

Table 5: NEWater Factories in Singapore

Name of NEWater factory	Plant Capacity (mgd)	Year Commissioned
Bedok	18	Jan 2003
Kranji	17	Jan 2003
Seletar	5	Feb 2004
Ulu Pandan	32	Mar 2007
Changi	50	May 2010
Total	122 mgd (555 thousand m^3/d)	

Phase 1 (2000 - 2007 Q1): Imported Technology Dependent Period

The decision to adopt the use of membranes for water treatment occurred in the late 1990s when pilot tests and research studies conducted overseas, as well as technical publications suggested that the development of membrane technologies had become more reliable and cost efficient to operate and maintain. In 1999, the PUB decided to develop a NEWater Demonstration Project – the Bedok Demonstration Plant, which was subsequently commissioned in 2000. This demonstration plant was dependent on imported technology, such as advanced reverse osmosis (RO) membrane technology primarily from Dow Chemicals and Nitto Denko. Following extensive learning and assimilation of spillover technology after the demonstration plant, three advanced NEWater factories were commissioned by 2007. Bedok NEWater Factory in 2003, Kranji NEWater Factory in 2003 and Seletar NEWater Factory in 2004.

Phase 2 (2007 Q2 – 2008 Q2): Transition from Learning to Indigenous Technology Development Period

Based on the preceding learning and assimilation of spillover technology, indigenous technology was developed and demonstrated in Ulu Pandan NEWater Factory, which was commissioned in early

2007. The Ulu Pandan NEWater Factory was the first NEWater production plant that was constructed under the Design, Build, Own and Operate (DBOO) partnership with the private sector. The concession company that was awarded the project was Keppel Seghers, a local leading provider of comprehensive environmental solutions for both water and solid waste treatment. It was an agreement to develop a plant with a capacity of 32mgd (148,000 m^3/day) delivering NEWater at S$0.30 per m^3 for the first year. It was for 20 years starting 2007 and ending 2027. This was aligned to the government's strategy of attaining self reliance in water supply and being less dependent on imported water. This was the first introduction of the DBOO model in NEWater development and triggered the Open Innovation Dynamism, leading to Phase 3. Several successful innovations were implemented in this factory. An example was a new process design that allowed higher stacks of 8 and 9 membrane modules in the first and second stage respectively instead of 5 in the existing plants. Another innovation was the construction of the reverse osmosis units on top of the concrete water tanks to maximise the utilisation of the land area. Yet another evidence of indigenous capabilities was the innovative substitution of microfiltration for ultrafiltration before reverse osmosis. The microfiltration membranes used were pressure hollow fibre membranes made of polyvinylidene difluoride (PVDF) manufactured by Asahi. The ultrafiltration membranes used in the earlier plants were Zenon (flagship product of Zenon Environmental Inc., now part of GE) and Memcor (manufactured by Siemens). These innovations are evidences of the result of intense knowledge exchange between expert global players and local players and thus opportunities for indigenous capabilities to be developed.

Phase 3 (2008 Q3 – 2010)): Export Accelerating Period

The second NEWater factory to be developed under the DBOO scheme was the Changi NEWater plant which began operations in May 2010. It was developed by Sembcorp Utilities under a 25-year DBOO contract with PUB. The DBOO NEWater plants, namely the Ulu Pandan and Changi NEWater plants, contributed to increase indigenous capabilities leading to exporting them to countries such as the Middle East and Africa (Chew et al., 2010).

Phase 4 (2010 and Beyond): Co-evolutionary Domestication Period

The fusion of external knowledge acquired from export activities by means of joint export with countries possessing advanced technologies; institutional learning by the receiving party and the existing knowledge pool are disseminated to various industries, leading to the phenomenon known as co-evolutionary domestication.

ACCUMULATION OF KNOWLEDGE STOCK

During the course of development through the four phases described above, knowledge on the supply, operation and management of NEWater has been accumulated through handling imported advanced technology, learning and assimilation of spillover technology thereon, and indigenous development. As postulated by Griliches (1979) and Nadiri and Shankerman (1981), this knowledge stock increase corresponds to the cumulative stock of NEWater supply.

Following the preceding estimation with respect to yearly trajectory of NEWater development in Singapore (Chew et al., 2010) and utilizing quarterly trend in used water (MEWR), quarterly trend in NEWater supply can be estimated by the following equation:

$$NW_q = \frac{0.310\,UW_q}{1+e^{-0.76t+3.77}} \Big/ j = \frac{0.369\,UW_q}{1+e^{-0.76t+3.7}} = \frac{0.369\,UW_q}{1+e^{-0.19t_q+3.7}} \qquad (1)$$

where NW_q *: quarterly supply of NEWater,* UW_q *: quarterly consumption of water,*
t *: yearly trend,* t_q *: quarterly trend, and* j *: water supply and consumption ratio.*

The water supply and consumption ratio can be estimated as follows:

j = Used water/Water sales = 1228 $10^3 m^3$/d (2007)/1462 $10^3 m^3$/d (2007) = 0.84

Table 6 tabulates the quarterly trend in used-water and NEWater supply in Singapore over the period *2003-2009*. In order to measure the knowledge stock of NEWater, cumulative stock of NEWater supply is also tabulated in Table 6 as it corresponds to this stock.

Table 6: Quartery Trends in Used Water (UW_q), NEWater Supply (NW_q) and Cumulative Stock of NEWater (ΣNW_q) in Singapore (2003-2009)- $10^4 m^3$ /month

	year		UW_q	NW_q	?NW_q
1	2003	Q1	4473	38	38
2		Q2	4251	43	81
3		Q3	4099	50	130
4		Q4	4300	63	193
5	2004	Q1	4520	79	272
6		Q2	4220	88	360
7		Q3	4242	105	465
8		Q4	4041	119	585
9	2005	Q1	4160	146	730
10		Q2	4100	170	900
11		Q3	4252	207	1107
12		Q4	4316	246	1353
13	2006	Q1	4623	307	1660
14		Q2	4306	331	1991
15		Q3	4236	374	2365
16		Q4	4139	417	2783
17	2007	Q1	4904	560	3342
18		**Q2**	**4595**	**589**	**3931**
19		Q3	4392	626	4558
20		Q4	4427	696	5254
21	2008	Q1	4545	782	6036
22		Q2	4433	826	6862
23		Q3	4261	853	7715
24		Q4	4398	938	8652
25	2009	Q1	4209	949	9601
26		Q2	4279	1012	10613
27		Q3	4327	1067	11681
28		Q4	4372	1118	12799

Sources: MEWR (quarterly issues) and Chew, Watanabe and Tou (2010).

OPEN INNOVATION DYNAMISM IN NEWATER DEVELOPMENT TRAJECTORY

Utilizing quarterly trend in knowledge stock of NEWater development by means of cumulative stock of NEWater supply and applying this trend to Bi-Bass model, open innovation dynamism (imitator substitutes for innovator) in the process of NEWater development can be analyzed.

Two Waves in Knowledge Stock of NEWater Development

The Bass model (Bass, 1969) depicts the diffusion trajectory of the levels of innovative goods and services as a dynamic game between innovator (p) and imitator (q). Since learning process can be analyzed by tracing the process of imitator substitutes for innovator and the functionality development (ability to improve performance of production process, goods and services by means of innovation) can be induced by the increase of the ratio between q and p (q/p) in the Bass model (Watanabe *et al*., 2009, see *Appendix*), effects of learning through technology import can be analyzed by this model. Furthermore, transition dynamism from learning based trajectory to indigenous technology initiated trajectory can be analyzed by utilizing the Bi-Bass model which incorporates two Bass-models with different phases of trajectories as diffusion trajectories of fixed phones and mobile phones (Watanabe *et al*., 2011).

Utilizing the quarterly trend in knowledge stock by means of cumulative stock of NEWater supply (ΣNW_q) as estimated in equation (1), the following Bi-Bass model depicting the trends in knowledge stock of two waves of NEWater development trajectories are estimated.

$$\Sigma NW_q = \frac{N_1(1-e^{-(p_1+q_1)t_q})}{1+\dfrac{q_1}{p_1}e^{-(p_1+q_1)t_q}} + \frac{N_2(1-e^{-(p_2+q_2)t_q})}{1+\dfrac{q_2}{p_2}e^{-(p_2+q_2)t_q}} \tag{2}$$

where $N_1, p_1, q1$ and N_2, p_2, q_2 indicate upper ceiling of the trajectory (carrying capacity), innovator and imitator in the first and second wave, respectively.

Table 7 summarizes the results of the estimation with respect to diffusion parameters in knowledge stock of Singapore's NEWater development trajectories over the period 2003-2009.

Table 7: Diffusion Parameters in Knowledge Stock of Singapore's NEWater Development Trajectories (2003-2009)

		N	$p+q$	$x = q/p$	adj. R^2	p	q
Level of knowledge stock of NEWater ***Y*** (*2003-2009*)	Y_1	3.9×10^3 (1.21)	0.25 (5.56)	151.0 (2.09)	0.999	1.64×10^{-3}	2.48×10^{-1}
	Y_2	28.7×10^3 (6.18)	0.16 (17.7)	169.8 (2.61)		0.93×10^{-3}	1.57×10^{-1}

Table 7 demonstrates that diffusion trajectory of knowledge stock of Singapore's NEWater (Y) can be decomposed into two waves as Y_1 and Y_2. Parameters of innovation and imitation in respective wave can be identified as p_1 = 1.64´10^{-3}; q_1 = 2.48´10^{-1}, p_2 = 0.93´10^{-3}; and q_2 = 1.57´10^{-1}, respectively. Furthermore, carrying capacity (N) can be identified as 3.9 x 10^3 (10^4 m^3/month) and 28.7 x 10^3 (10^4 m^3/month), respectively.

Table 8 tabulates quarterly trends in knowledge stock of two waves of Singapore's NEWater development over the period 2003-2009.

Table 8: Quarterly Trends in Knowledge Stock of Two Waves of Singapore's NEWater Development (*2003-2009)* - $10^4 m^3$/month

	Year		?$NW_g=Y$	Y_1	Y_2	Y_1/Y	Y_2/Y
1	2003	Q1	38	7	29	0.19	0.76
2		Q2	81	16	63	0.20	0.77
3		Q3	130	28	102	0.22	0.78
4		Q4	193	43	148	0.22	0.77
5	2004	Q1	272	62	202	0.23	0.74
6		Q2	360	86	264	0.24	0.73
7		Q3	465	116	337	0.25	0.73
8		Q4	585	155	422	0.26	0.72
9	2005	Q1	730	203	522	0.28	0.71
10		Q2	900	263	637	0.29	0.71
11		Q3	1107	337	771	0.30	0.70
12		Q4	1353	428	926	0.32	0.68
13	2006	Q1	1660	538	1105	0.32	0.67
14		Q2	1991	669	1313	0.34	0.66
15		Q3	2365	823	1552	0.35	0.66
16		Q4	2783	1000	1826	0.36	0.66
17	2007	Q1	3342	1199	2141	0.36	0.64
18		**Q2**	**3931**	1417	2501	0.36	0.64
19		Q3	4558	1649	2910	0.36	0.64
20		Q4	5254	1889	3374	0.36	0.64
21	2008	Q1	6036	2130	3896	0.35	0.65
22		Q2	6862	2364	4481	0.34	0.65
23		Q3	7715	2585	5133	0.34	0.67
24		Q4	8652	2788	5853	0.32	0.68
25	2009	Q1	9601	2969	6642	0.31	0.69
26		Q2	10613	3127	7501	0.29	0.71
27		Q3	11681	3262	8425	0.28	0.72
28		Q4	12799	3376	9411	0.26	0.74

Figure 6 demonstrates trends in knowledge stock of these two waves (Y_1 and Y_2) and figure 7 illustrates trends in the ratios of these two waves (Y_1/Y and Y_2/Y).

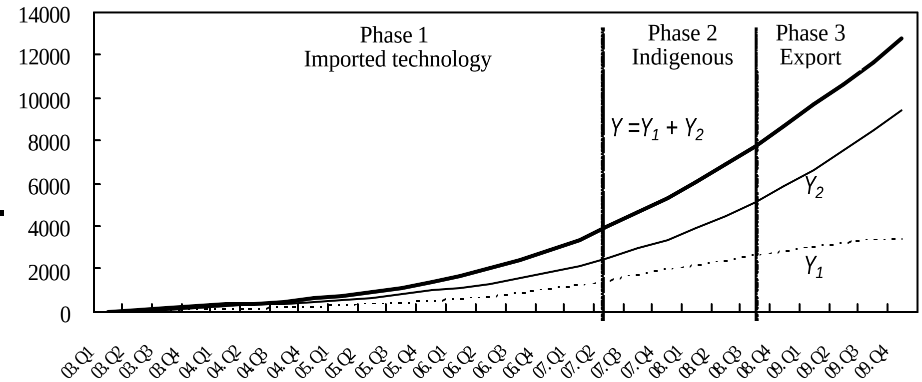

Figure 6: Trends in Knowledge Stock of Two Waves in Singapore's NEWater Development (2003-2009)

Looking at figure 6 we note that the level of knowledge stock of the second wave (Y_2) exceeded that of the first wave (Y_1) over the period examined and demonstrates conspicuous increase from the second phase. Contrary to such increase, the level of knowledge stock of the first wave (Y_1) stagnated from the second phase and its carrying capacity remained the level of the whole knowledge stock of the beginning of the second phase.

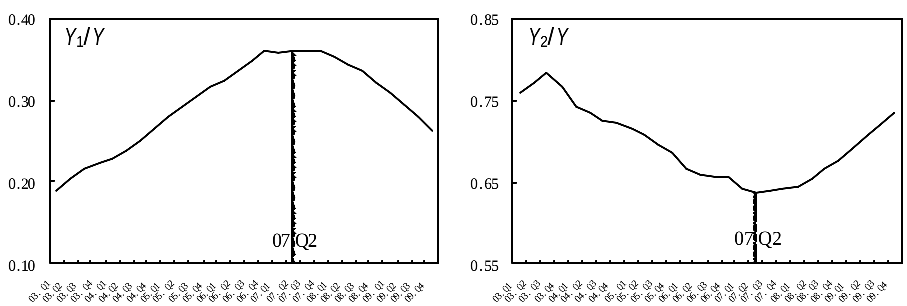

Figure 7: Trends in the Ratios of Two Waves in Knowledge Stock of Singapore's NEWater Development (2003-2009)

Figure 7 demonstrates that Y_1/Y changed from increase to decrease and Y_2/Y from decrease to increase from 2007Q2 corresponding to the transition from phase 1 to phase 2. Figure 8 analyzes the correlation between Y_1/Y and Y2/Y and demonstrates clear substitution from Y_1 *to* Y_2 starting from 2007Q2.

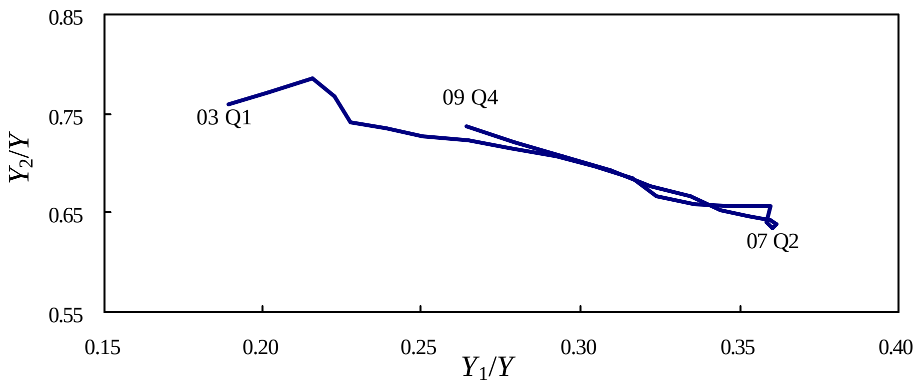

Figure 8: Correlation between the Ratio of Two Waves in Knowledge Stock in Singapore's NEWater Development (2003-2009)

Learning Based and Technology Based Knowledge Stock

Knowledge stock of Singapore's NEWater development consists of that of (i) handling exercise of imported advanced technology, (ii) learning and assimilation of spillover technology thereon, and (iii) indigenously developed technology. Figure 9 illustrates general trends in these three types of stock. Imported technology obsolescents as time goes and decreases. While learning and assimilation increase, they change to decrease substituted by indigenously developed technology which increases dramatically.

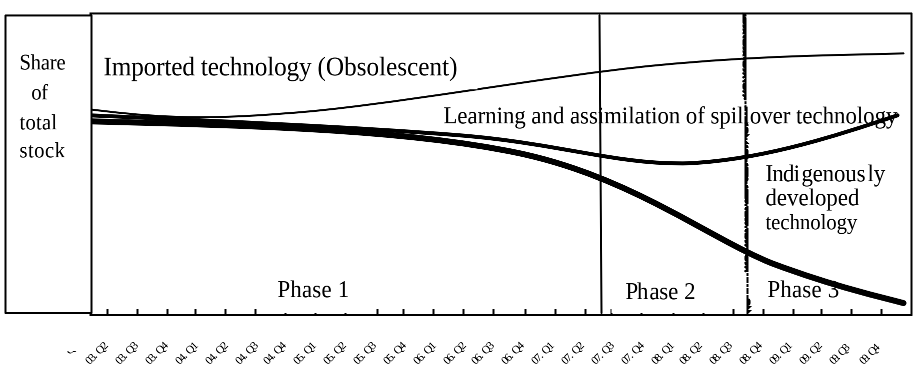

Figure 9: Scheme of Knowledge Stock Increase in Singapore's NEWater Development (2003-2009).

From the view point of the knowledge formation process, such knowledge stock can be classified into two types as (i) stocked in the technology both in imported and indigenously developed (*technology based knowledge stock: TKS*) and also (ii) stocked through learning and assimilation exercises (*learning based knowledge stock: LKS*). Given the foregoing increase and decrease nature of respective stock, while share of *TKS* out of total stock changes from decrease to increase, that of *LKS* changes from increase to decrease. Furthermore, given that dramatic shift from *LKS* to *TKS* can be attributed to the substitution of indigenous technology for learning triggered by the operation of Ulu Pandan plant based on DBOO in March 2007, TKS should substitute for LKS just after the operation of Ulu Pandan leading to emerging new functionality corresponding to its full fledged operation in the late 2008.

In light of the quite similar trends observed in the ratios of two waves (Y_1/Y and Y_2/Y) and substitution from Y_1 to Y_2 with inflection timing at 2007Q2 immediately after the operation of Ulu Pandan plant as illustrated in Figures 2 and 3, aiming at examining the correspondence of Y_1, Y_2 and LKS, TKS, following regression analyses are attempted:

$$Y_i / Y = Ae^{f_1 Dt + f_2 (1-D)t + mD} \qquad (i = 1, 2) \tag{3}$$

where A : scale factor, f : coefficient of slope dummy variable representing learning for Y_1 and obsolescence for Y_2, respectively, m : coefficient of constant dummy variable, t : time trend, and D : dummy variable.

Results of the analyses are summarized in table 9. The results demonstrate Statistical Significance and correspond to the foregoing postulate.

Table 9: Learning and Obsolescence Coefficients in Knowledge Stock of Singapore's NEWater Development (2003-2009)

$$\ln Y_1 / Y = -0.39 + 0.04Dt - 0.03(1-D)t - 1.28D \qquad adj.R^2 \; 0.981$$
$$(-6.54) \quad (31.00) \quad (-12.49) \qquad (-20.97)$$

$$\ln Y_2 / Y = -0.75 - 0.01Dt + 0.02(1-D)t + 0.51D \qquad adj.R^2 \; 0.960$$
$$(-26.46) \quad (-19.67) \quad (12.52) \qquad (17.80)$$

where t : quarterly time trend, D : dummy variable $(03Q1 - 07Q1 = 1,\ 07Q2 - 09Q4 = 0)$

Wave	Coefficient	2003Q1-2007Q1	2007Q2-2009Q4
Y_1/Y	Learning and substitution	0.04	-0.03
Y_2/Y	Obsolescence and development	-0.01	0.02

These analyses demonstrate that Y_1 and Y_2 represent behaviors of learning based knowledge stock (LKS) and technology based knowledge stock

(TKS), respectively. Y_2 substituted for Y_1 induced by the operation of Ulu Pandan plant in March 2007 based on DBOO model.

The value of q_2/p_2 (169.8) in Table 7 demonstrates higher level than q_1/p_1 (151.0) which proves the significant increase in functionality development in Y_2 through imitator substitutes for innovator (open innovation).

Functionality Development Dynamism

Inspired by these findings, further analysis on the functionality development dynamism through Y_2 substitution for Y_1 is analyzed.

Based on Rogers (1983), Mahajan *et al.* (1990), Moore (1991) and Watanabe *et al.* (2003), timing of functionality development emergence, its maturity and stagnation in the Bass model can be identified as illustrated in figure 10 (Watanabe *et al.*, 2011). Functionality development emerges at the inflection from accelerate to decelerate in the diffusion velocity increase period (t_1), matures at the inflection from diffusion velocity increase to decrease ($t^{\#}$), and stagnates at the inflection from decelerate to accelerate in the diffusion velocity decrease period (t_2).

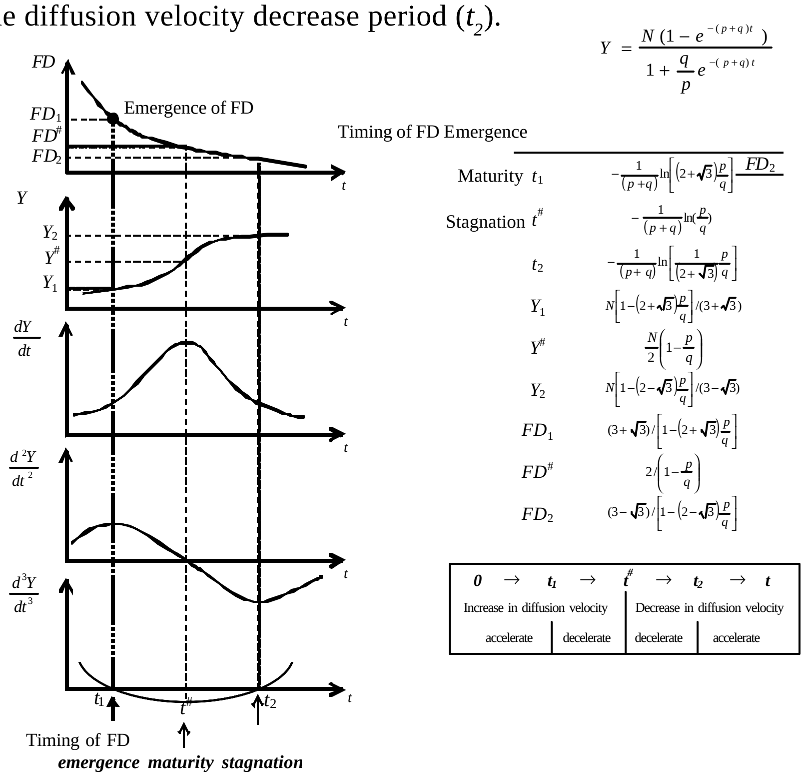

Figure 10: Level and Timing of Inflection in a Diffusion Trajectory in the Bass Model

Utilizing these identifications, timings of functionality development emergence, maturity and stagnation in two waves of knowledge stock in Singapore's NEWater development are analyzed. Figure 11 summarizes the results of the analysis.

	timing	Y_1	Y_2
FD *emergence*	t_1	14.8 2006 Q3	24.1 2008 Q4
maturity	$t^{\#}$	20.1 2007 Q4	32.4 2010 Q4
stagnation	t_2	25.4 2009 Q1	40.7 2013 Q1

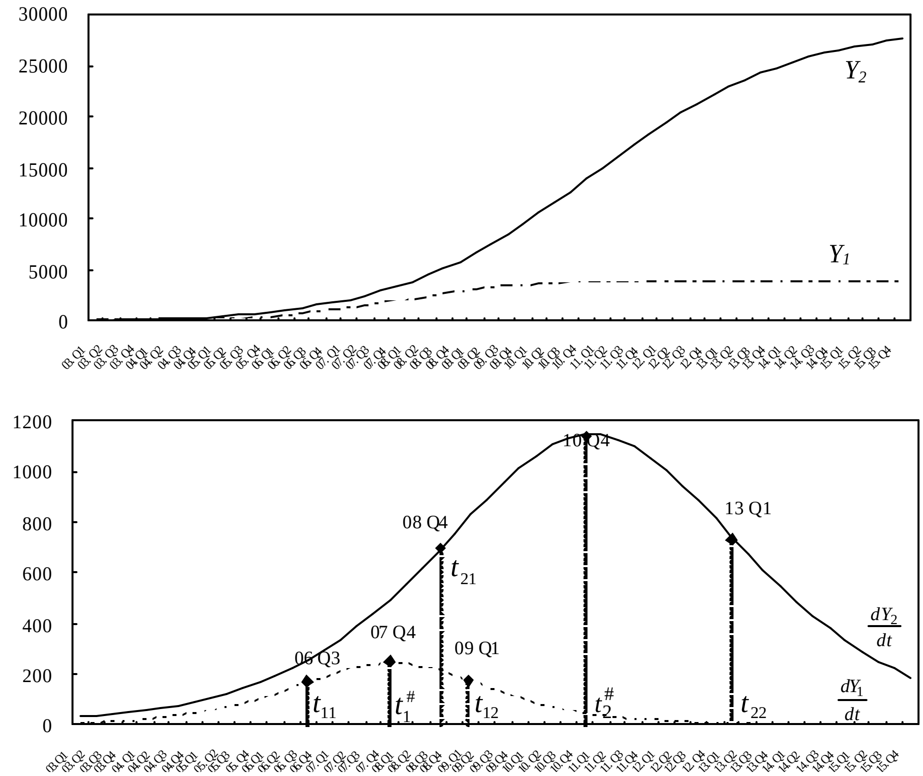

Figure 11: Inflection Points of Two Waves of Knowledge Stock of Singapore's NEWater (2003 Q1 - 2015 Q4)

As illustrated in Figure 11, functionality development of learning based knowledge stock (LKS) emerged in 2006 Q3 14 quarters after the commissioning of two NEWater factories that were dependent on imported technology – Bedok and Kranji (both commissioned in January 2003). It matured in 2007 Q4 and stagnated from 2009 Q1. Functionality development of technology based knowledge stock (TKS) emerged in 2008 Q4 7 quarters after the operation of DBOO based Ulu Plan plant (commissioned in March 2007) just before the stagnation of functionality development of LKS, matured in 2010 Q4 and is anticipated to stagnate from 2013 Q1. Noteworthy is that functionnality development of TKS emerged prior to the stagnation of functionality development of LKS thereby sustainable functionality development of Singapore's NEWater development was enabled (Watanabe *et al.*, 2009). This can be attributed to the acceleration of TKS functionality development emergence with half length of the lead-time between the operation of Ulu Pandan plant and functionality development emergence (7 quarters) than that of LKS (14 quarters). This acceleration can be attributed to the success of effective utilization of preceding innovation both by LKS and relevant innovation not necessarily NEWater development but relevant to its development through open innovation. The DBOO scheme has enabled this successful Open Innovation.

All this demonstrates the significant effects of the DBOO in inducing learning and assimilation of spillover technologies cross over the sectors involved in NEWater development under the DBOO scheme.

CONCLUSION

In light of the noteworthy contribution of the DBOO scheme to successful Open Innovation in Singapore's conspicuous NEWater development, this paper attempted to elucidate this Open Innovation Dynamism. It can be concluded that the trend in knowledge stock of NEWater development can be measured by utilizing cumulative stock of NEWater supply. In addition, the Bi-Bass model analysis could be used to decompose this stock into learning based knowledge stock (LKS) and technology based knowledge stock (TKS). From the analysis, TKS was substituted for LKS corresponding to the shift from Phase 1 to Phase 2 of the development trajectory. This was triggered by the commissioning of the DBOO based Ulu Pandan NEWater plant in March 2007. From the analysis, it can be concluded that functionality development of TKS emerged much faster than that of LKS enabling it emergence prior to the stagnation of LKS functionality development leading to sustainable functionality development in Singapore's NEWater development. Finally, the faster emergence of TKS functionality development can be attributed to the success of effective utilization of preceding innovation both by LKS and relevant innovation not necessarily NEWater development but relevant to its development through Open Innovation. In summary, the results from quantitative and qualitative analysis are supportive of the fact that the DBOO has successfully enabled Open Innovation in this paper.

The above findings provide several insightful implications suggestive to firms sustainable development in growing economies. Firstly, the effective utilization of external resources by activating such resources would be essential. Secondly, open innovation would be effective to this utilisation. Thirdly, the DBOO scheme enables acceleration of the accomplishment of successful open innovation, thereby not only preceding innovation in the same field but also broader innovation in the relevant challenge could be utilised. Lastly, co-evolutionary domestication in a global context through this Open Innovation would be decisive for sustainable growth for growing economies.

Further analysis should be undertaken for the application of this DBOO scheme in NEWater development to broader fields for global sustainability.

END NOTE

1. Population of Singapore taken from http://www.singstat.gov.sg/stats/latestdata.html#12.

A[2] Since increase in x demonstrates a shift from p to q, dp/dx demonstrates negative value.

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APPENDIX

Functionality Development Inducement by Imitator Substitution for Innovator

Bass model is depicted as follows:

$$Y(t) = \frac{N(1-e^{-(p+q)t})}{1+\frac{q}{p}e^{-(p+q)t}} \tag{A-1}$$

Functionality development (FD) can be depicted as follows:

$$FD(t) = \frac{N}{Y(t)} = \frac{N}{\frac{N\left(1-e^{-(p+q)t}\right)}{1+\frac{q}{p}e^{-(p+q)t}}} = \frac{1+\frac{q}{p}e^{-(p+q)t}}{1-e^{-(p+q)t}} \tag{A-2}$$

Equation (A-2) suggests that FD tends to declines over time. Firms' management strategy involves efforts to prolong a high level of FD. These efforts can be identified as follows:

In the Bass model, q/p demonstrates this "prolonging ability" as shown by the following mathematical development:

Provided that q/p º x and $e^{-(p+q)t}$ º y, FD can be expressed as follows:

$$FD = \frac{1+xy}{1-y} \tag{A-3}$$

Differentiation of FD with respect to x,

$$\frac{dFD}{dx} = -\frac{-\frac{dy}{dx}(1+xy)}{(1-y)^2} + \frac{y+x\frac{dy}{dx}}{(1-y)} = \frac{(1+x)\frac{dy}{dx}+y-y^2}{(1-y)^2} \tag{A-4}$$

Since $\frac{dy}{dx} = -\left[p+\frac{dp}{dx}(1+x)\right]ty$,

$$\frac{dFD}{dx} = \frac{y}{(1-y)^2}\left[1-\left\{p+\frac{dp}{dx}(1+x)\right\}(1+x)t-y\right] = \frac{y}{(1-y)^2}\left[1-p(1+x)t-\frac{dp}{dx}(1+x)^2t-y\right] \tag{A-5}$$

Since $e^{-(p+q)} = y^{-t}$ and $p+q$ <<1, y can be aproximated as follows:

$$y = [e^{-(p+q)}]^t = [1-(p+q)]^t = [1-p(1+x)]^t \approx 1-p(1+x)t \tag{A-6}$$

Therefore, equation (A-4) can be developed as follows:

$$\frac{dFD}{dx} = -\frac{y(1+x)^2}{(1-y)^2} t \cdot \frac{dp}{dx} > 0 \qquad \text{(A-7)}^{A2}$$

Since inequality (A-7) demonstrates that FD increases as the ratio of q/p increases, q/p can be identified as the "prolonging ability."

Consequently, the prolonging ability and its contribution to FD can be observed.

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