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Engineering and Technology Management

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1 Getting Value from Engineering and Technology

The impact of engineering and technology is visible in the many artefacts, infrastructure and services that form the fabric of modern life. The industrial revolution in the eighteenth century enabled new manufacturing processes that have transformed the world, spurred on by continual technological developments, both incremental and transformational. Scientific breakthroughs have enabled new technologies that disrupt

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existing industries (Bower and Christensen 1995) and enable the creation of new ones. Technological disruption will bring great benefits but also challenges, such as the impact of computerisation on skills and employment (Frey and Osborne 2013).

Scientists, engineers and other technologists have a crucial role to play in the development and deployment of technology for the economic benefit of society, and also to address challenges facing humanity, such as climate change and resource scarcity. In this context, the management of engineering and technology becomes increasingly important. Technological investment and effort needs to be aligned with organisational and wider social needs and aspirations throughout the life cycle from design, through to production and the creation of valuable services, as depicted in Fig. 1.

The word "engineer" is derived from the Latin ingeniare, meaning "to produce" (Mitcham 1978). This original form of interpretation highlights the many activities and roles that engineers undertake, deploying scientific and craft knowledge to create solutions to problems and to address needs in society, industry and the environment. The word "technology" can be broadly considered as "know-how" (Phaal et al. 2004)—i.e. the application of scientific and other knowledge in context. Thus, engineering and technological knowledge are closely related, and engineering education includes a combination of "hard" (scientific) and "soft" (craft) knowledge with a practical applied orientation.

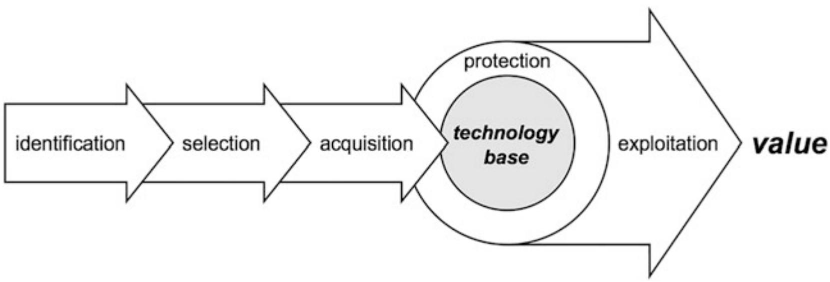

Fig. 1 Technology management process framework. Adapted from Farrukh et al. (2000)

In order to effectively manage engineering and technology, processes are needed to align inputs and activities with desired outputs. The technology management process framework developed by Gregory (1995) is used here, comprising five broad areas of activity:

- *Identification* of technologies that are (or may become) of importance to the business.
- *Selection* of technologies that should be supported by the organisation.
- *Acquisition* of and assimilation of selected technologies.
- *Exploitation* of technologies to generate profit, or other benefits.
- *Protection* of technological knowledge and expertise embedded in products, services and systems.

These process areas are elaborated below (Farrukh et al. 2000), posed as questions that managers, engineers and technologists must address for the effective management of engineering and technological knowledge and resources, from a business perspective.

1.1 How Do We Exploit Our Technology Assets?

In the competitive marketplace, firms that utilise their technological assets most effectively have a significant advantage. Continued exploitation and renewal of the technology base are essential for long-term survival. The systems which support the delivery of products and services to the market need to be clearly understood, in terms of how technology provides value to the company and its customers.

Key issues to consider include: management of the technology base; technology planning, including short- to medium-term forecasts of market requirements and technological capabilities and trends; relationships with the customer–supplier network and with other external sources (for example, standards-making bodies); communication channels and information flows; and operations and resource management.

A clear understanding of the nature of the core technologies in a company is required. How do these relate to the key skills and capabilities of staff, products and services, markets and competitor activity?

The company should be aware of the many options available to exploit its technology, including selling or licensing its technology; joint ventures or collaboration; technology fusion, whereby existing technologies are combined in innovative ways to provide new products or services; technology transfer processes (internal and external); and improved business processes and organisational structures to support the generation and exploitation of technological capability.

1.2 How Do We Identify Technology Which Will Have a Future Impact on Our Business?

Maintenance and renewal of the technology base require that processes are in place for the identification of new technologies which are, or may in the future be, important to the business. This is becoming an increasingly challenging task as the complexity, cost and pace of technological change increase and the sources of technology become more international.

Key issues to consider include: a thorough understanding of the nature of the firm's technology base, in relation to how these add value to its products and services; access to appropriate external and internal networks and sources of information; and knowledge management systems and communication channels, to ensure that the information is appropriately processed and disseminated.

Technology identification processes include a range of activities: systematic scanning of information sources, to develop an awareness of existing and emerging technologies; technology and market foresight and forecasting processes, to support the identification and appraisal of emerging technologies; monitoring of specific technical threats; ways of generating new ideas, to identify new product and process opportunities; technical benchmarking, to develop an awareness of competitors' capabilities; and specific data collection in response to new requirements.

In many organisations, technology identification is undertaken on an ad hoc basis, using informal networks, attendance of trade fairs and conferences, subscription to journals, contacts with suppliers and other means. In addition to making this more systematic, the challenge is to develop appropriate systems to collate and analyse the data collected, and to disseminate it effectively throughout the organisation.

1.3 How Do We Select Technology for Business Benefit?

Managers are commonly faced with difficult decisions about where to invest scarce resources. In the long term, it is critical to select the best technological option, as mistakes can be costly by the time products and services reach the marketplace. Technology investments must lead to increased future revenues and profits which can be re-invested in the technology base for long-term success.

Key issues to consider include: agreement of appropriate decision criteria; establishment of a visible and repeatable decision-making process; understanding the strategic implications of technological choices; and benchmarking with competitors.

Selection of technology is a decision-making process. It requires an understanding of the technology requirements of the organisation, product, service or project, together with the characteristics of identified candidate technologies and any constraints that may affect the selection process. Technology selection involves developing and evaluating alternative solutions, choosing the best option and considering significant implementation factors.

Technology selection decisions can be categorised as being proactive or reactive. Proactive selection decisions are taken in response to future needs, through technology forecasting (future investment in technology for the next generation of products) and technology portfolio analysis (current and future balance of technology). Reactive decisions are taken in response to specific current needs, in relation to current investments (project selection) and urgent problem solving (troubleshooting).

1.4 How Should We Acquire New Technologies?

Organisations need to update and restock their technology base, which can be depleted by obsolescence and diffusion of technology. Specific business reasons for acquiring new technology include: customers in a changing market demand new features in products and services; external constraints (for example, health, safety and environmental legislation) may require the introduction of new products or services; increased competition may demand improvements in technological performance; improved quality requirements may lead to the necessity for upgrading manufacturing and testing equipment; and pressures to reduce costs may require more efficient production processes.

Various routes are available for acquiring new technology, including external purchase or transfer of technology (such as company acquisition, machine purchase or licensing in technology), collaborative development (for example, joint ventures, subcontracting development projects, or supporting supplier technology development) and internal technology transfer or R&D.

Technology acquisition can be seen in terms of a general process: the choice of route for acquiring the technology should be reviewed and assessed; implementation of the chosen route should be managed so that the technology is brought into the organisation to meet required time, budget and performance level requirements; and assimilation of the technology should be achieved to ensure that it becomes a fully accepted and functioning part of the technology base of the company.

1.5 How Can We Protect Our Technology Assets?

A key part of technology management is the maintenance of the technology base. In addition to ensuring that technological resources are renewed, it is important to minimise unplanned transfer of technological assets out of the organisation. Protection of technology involves more than patents and intellectual property rights—it involves people and the knowledge and skills they control, together with other issues such as site and security of information and communications systems.

Key issues to consider include: consideration of the "protectability" of new technologies as part of the selection process; active management of the technology base to ensure awareness of obsolescence and renewal needs; and management of the technological expertise of staff, supported by appropriate reward systems to minimise the risks associated with staff turnover.

Technology protection can involve keeping ahead of competitors by identifying and appropriately securing technology assets (defensive strategy), or by keeping competitors behind by neutralising the effects of their defences (proactive strategy).

Protection of technology should be considered systematically, in terms of a repeating process, with three main stages: assessment of protection need, including a review of existing and new technology assets, in terms of their value to the company (now and in the future); choice of protection routes, based on their suitability for the technology and company; and implementation and enforcement of the protection method.

1.6 Engineering and Technology Management—An Integrated Process View

Effective engineering and technology management requires an integrated approach, so that activities in the five process areas of identification, selection, acquisition, exploitation and protection are aligned, as illustrated in Fig. 1. For reasons of simplicity, the process steps are shown as a rather linear model; in reality, the activities associated with managing engineering and technology are much more diffuse and iterative.

Technology should be considered in the early stages of strategy formulation, and the links with other activities should be clearly understood (such as marketing and other commercial functions, operations, human resources and finance). Mechanisms should be in place to ensure that technology strategies are effectively implemented at the operational level. Technology management processes are often embedded in other business processes. For instance, new technology is often acquired during development projects. It is important to be aware of technology management considerations that continue beyond the completion of the project. The interdependence of technology management processes should be understood, for instance issues of technology protection are an important consideration during technology identification and selection processes.

Engineering and technology management is a very broad subject, and there are many particular areas of importance that require specific attention. For example, innovation, knowledge management, competence and performance measurement are large subjects in themselves. The five-process technology management model presented above provides a framework for understanding how technology can be managed in relation to other relevant management concepts, methods and processes.

2 Case Study

2.1 Identification

This section will use a case study to explore the technology identification tool in terms of technology intelligence. Existing literature argues that technology intelligence has three major questions to address: (i) What do we need to know? (ii) Why do we need to know it? (iii) What decision is to be made, or action taken, once we know it?

In order to address these questions, Kerr et al. (2006) develop a conceptual model for technology intelligence that is concerned with the operating cycle for running a technology intelligence system. The cycle is composed of six phases, namely coordinate, search, filter, analyse, document and disseminate.

Researchers from the Centre of Technology Management (CTM) of the Institute for Manufacturing at the University of Cambridge have visited Xaar plc as part of a project on "Technology Intelligence", and have developed "Xaar Case Study" to provide an insight into the technology intelligence activity within Xaar, and to gain an industrial input for testing CTM's technology intelligence framework that has been mentioned above. In this case study, we limit our discussion on the process cycle of six phases (concerned with the technology intelligence system) that can be demonstrated in the Xaar case.

Xaar plc manufactures and sells high-performance, specialised print-heads and inks to original equipment manufacturers (OEMs) in the graphic arts, packaging printing and industrial printing markets. The company was founded in 1990 to commercially exploit a new digital inkjet printing technology arising out of work done by Cambridge Consultants Ltd. In October 1997, Xaar was listed on the London Stock Exchange. The company's turnover in 2015 was £93.5 Million; the gross investment in R&D was £19.9 Million; and the percentage of gross margin was 47.8%.

From Fig. 2, we can tell that the primary input into the technology intelligence process is the data on technologies from external and internal sources. Adding to this, however, another critical input is also necessary: what information needs to be collected, analysed and disseminated? This means that the second input is the decision-makers' intelligence needs. The output of the technology intelligence activity is the intelligence information for the decision-makers. There are four forms of output: identification of opportunities, awareness of threats, assessment of art and profile of trends.

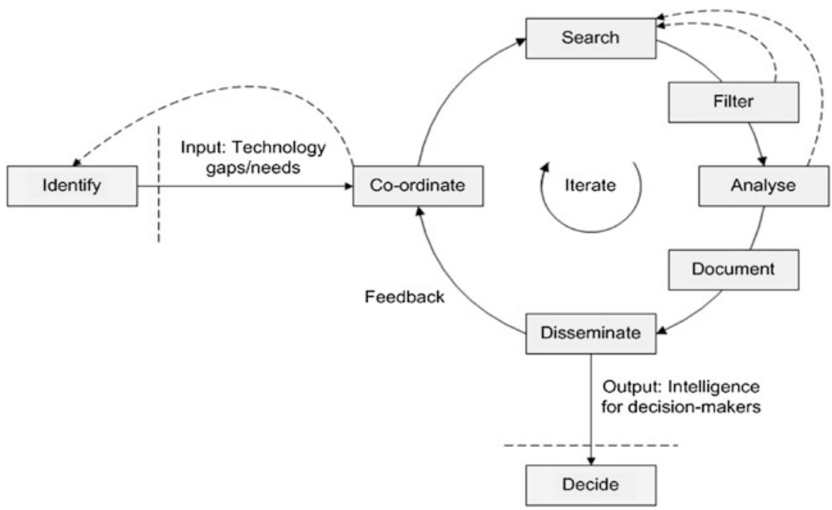

Fig. 2 Technology intelligence's system operating cycle. (Adapted from Kerr et al. 2006)

2.1.1 Coordinate

Consider the operating cycle in Fig. 2; once the input, of needs or requirements, comes into the technology intelligence activity from the intelligence consumers, the first phase is coordinating the technology intelligence efforts needed to fill the gaps in the specific technology know-how. "Coordinate" encompasses the planning of the intelligence activities, allocating resources, briefing agents and gatekeepers, alerting the technology intelligence system to the new intelligence requirements (this involves getting the system sensitive or switching-on the radar to new signals).

In the Xaar case, there exists no formal/structured coordination mechanism for technology intelligence in the sense that the activity and processes must be planned. However, Xaar's Technology Group meets weekly to discuss the company's "Executive Meeting" and this provides the opportunity to delegate specific intelligence projects to individual team members. The group is made up of five–six members who all have a broad range of knowledge, and each individual has two–three technology expertise areas. The lack of a formal coordination mechanism does not appear to cause any "real" problems as the group is small enough for day-to-day interaction. It must be pointed out that there is no form of procedure or checklist of practices. This could potentially mean that an individual on a given occasion could miss or overlook certain aspects of the intelligence activity.

2.1.2 Search

When the activity has been coordinated, the next phase is to "search". This corresponds to the four system modes of mine, trawl, target and scan. Considering searching sources of information, typical sources include: trade shows (direct/personal), patents (direct/impersonal), gatekeepers (indirect/personal), trade journals (indirect/impersonal). In Xaar's case, at the centre of their searching process are three principal sources, namely patents, the Internet and university research centres. There are also many peripheral intelligence sources such as conferences, trade shows, trade magazines and industry bodies, which will not be discussed in detail here.

Xaar has a very strong reliance on patent searching and uses this source to watch targeted companies. They also pay an external provider a subscription fee for access to a commercial inkjet patent analysis report. The company are currently investigating whether to invest in an internal patent database with pre-sorted/pre-filtered material or to commission specific reports from an appropriate external provider. The Internet is used extensively for searching, and Google appears to be the preferred search engine. One of the concerns expressed with this source is the need for validation of the "found" information. Some individuals have addressed this issue by generating their own personal list of reliable bookmarks, for example websites that are tailored to provide quality information in specific technology areas. When using Google, company names are often used as keywords and internally produced company reports published on corporate websites have been found to be good sources of pre-digested material. For certain technology areas, Xaar has links to a number of university research centres and this provides a useful source of intelligence on emerging technologies. However, Xaar does lack a structured approach to search for academic papers published in journals. They are not aware of the academic electronic libraries or bibliographic databases such as ScienceDirect, BIDS or Emerald.

2.1.3 Filter

The search phase is followed by "filter" which determines if the information gathered thus far is pertinent. If it is not, there is a loop back to the search phase for further gathering. As an example, a simple filter could take the form of three stage-gates: (i) Is the information new to me? (ii) Is the information at the correct level and coverage? (iii) Does the information fit to our context/issue?

In Xaar case, the filtering mechanism is effectively left to the individual to use their judgement. There exists no guideline. However, given that the members of the Technology Group are all experienced there is no need to formalise the process. The first filtering decision gate is whether the collected information is new (i.e. not already known); the second gate is whether the information is at the correct level of granularity and with the appropriate coverage needed; and the final decision gate in the internal filtering process is whether the information is fit for Xaar's context. This gate also provides the opportunity to share information, at an early stage of the intelligence activity, by effectively asking another colleague for a second opinion on the relevance/usefulness of the collected information.

2.1.4 Analysis

Filtering is followed by the "Analyse" phase. This is a difficult task involving interpreting the information and relating its relevance to the organisation's particular context and intelligence provision requirements. It reflects the extracting of "value" from the "volume".

Xaar's analysis of the information collected focuses on whether a targeted technology could meet Xaar's intended purpose. This is effectively an analysis for proof of concept. There are two aspects of this analysis—the engineering and the commercial judgements: (i) Is the fundamental technology appropriate? (ii) What would the payback be? Xaar feel that they are very good on making decisions about whether the technology is fit-for-purpose. Initially, the pros and cons for each concept are elicited; the poor technologies are eliminated; the good concepts are then tested in a simulation environment. The commercial perspective is the weakness in the analysis phase. Xaar felt that they were poor at judging commercial readiness of a technology and how much would be generated by incorporating a technology into their portfolio.

2.1.5 Document

"Document" is creating the necessary reporting documentation, structuring the information content of the intelligence and embedding the new knowledge into the organisational memory. This includes information warehousing and knowledge management for accessing and retrieving.

In the Xaar case, the documentation of intelligence findings is ad hoc with individuals left to their own devices to both structure and store the knowledge. There is a shared database within the Technology Group, yet it appears to not be used effectively. A lot of information is stored on team members' individual computers. There are effectively two problems with the documentation phase: (i) a lack of visibility for the intelligence reports and associated ease of locating them; (ii) the form of the information is not readily digestible by other groups. The second problem does form a barrier between the Technology Group and the other departments.

2.1.6 Disseminate

The final phase in the cycle is "Disseminate". This is the trigger mechanism for the intelligence brokers to inform the intelligence consumers to the existence of new/updated intelligence and alerts.

Xaar has a very strong culture of internal networking and "knocking on doors"—"if you want to know something, ask". This is manifested by people coming to desks and having discussions. Internal communication within the Technology Group is very good, and there is the expectation that individuals must proactively share their intelligence findings. This allows team members to gain visibility of their work and ideas. However, cross-group communication is weaker. Some of the interviewees said that information sharing at the company level was poor and as the company grows, it could weaken further. Cross-group exchange is based around "asking". There is no formal forum of "telling" or pushing out technology intelligence findings to other interested parties.

Since the process model is a cycle, there is the option to go around the loop a number of iterations and further refine or tailor the provision of intelligence. Therefore, it can be viewed as a helix process that is continuously refining the interpretation. In a small organisation, a single individual may be responsible for technology intelligence and thus conduct all of the phases (coordinate, search, filter, analyse, document and disseminate), whereas in large organisations, there may be a whole department dedicated to the technology intelligence activity. Thus in various organisational structures, four major intelligence "roles" can be identified: gatekeeper, searcher, technologist and knowledge engineer. The gatekeeper is needed for the coordinate and disseminate phases, whereas the filter and analyse phases require the technologists. The searcher is demanded for the search phase, and knowledge engineer is dedicated for the document phase.

2.2 Selection

Selection of technology is a decision-making process. It involves developing and evaluating alternative solutions, choosing the best option and considering significant implementation factors. We will use the two cases below to explain the selection function in the engineering technology management. Case 1 shows the process of selection of relative prioritisation of R&D projects at BAe, while for the case 2, we develop a technology roadmapping (TRM) framework and use life cycle analysis to select an emerging alternative energy when comparing technology readiness and low-carbon attributes.

2.2.1 Case Study: Relative Prioritisation of R&D Projects at BAe

Research and development within the military aircraft sector of industry is extremely diverse, ranging from short-term demands to satisfy new operational requirements to very long-term ones to meet future defence needs. In the current environment, BAe (like many other companies) cannot satisfy all the R&D that the business demands. It therefore looks towards innovative ways of acquiring the technology that it needs through a mixture of contracts, collaborations and partnerships with both industry and academia, in addition to its own internal R&D programmes.

BAe identified a need to develop an optimum process for the relative valuation of R&D, to enable selection and prioritisation of programmes and give maximum benefit to the military aircraft business (Fig. 3). This would allow the company to make robust decisions on where it should focus its own funding for R&D, both long term and short term, for the benefit of the business. A portfolio approach was developed to represent the cost-to-benefit ratio of each project, together with a measure of customer

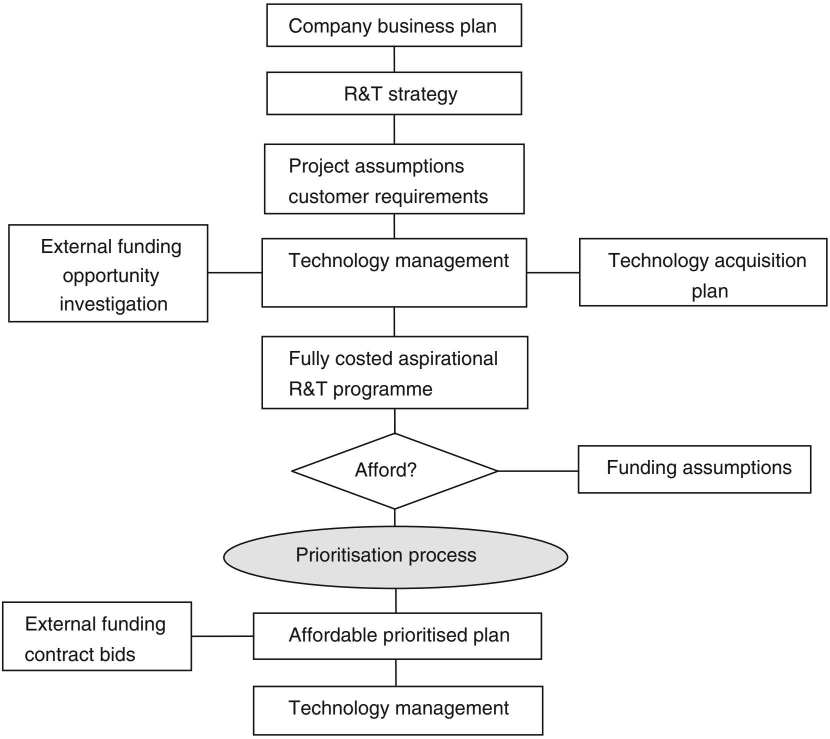

Fig. 3 The process of selection of relative prioritisation of R&D projects at BAe. (Adapted from Venus 1999)

focus. This enables resource allocation decisions to be clearly communicated; the approach has been successfully applied for several years.

2.2.2 Case Study: Roadmapping an Emerging Energy Technology—Dimethyl Ether in China

New energy technologies are becoming increasingly complex. The selection of alterative energies that may replace the existing solutions is strategically important and needs more attention. This case compares two scenarios of dimethyl ether vs diesel and finds that the superiority of dimethyl ether will not arise until 2030, when the complementary engineering technologies become available. We developed a technology roadmapping (TRM) framework to plan and strategise the emergence of a new energy industry that is based on engineering technologies. In order to explore the specific characteristics of an energy sector, we use life cycle analysis to compare both technology readiness and low-carbon attributes of a new and existing energy alternative to have a good selection for the future development.

Dimethyl ether (DME), as an alternative fuel for transportation, has been selected to become the critical case for the examination of the current potential and the future development of strategies/stages of an emerging energy. The effects of two major supporting engineering technologies, such as carbon capture and storage (CCS) and catalytic distillation technology (CDDME), are also carefully examined in this case. DME, given the combustion and auto-ignition characteristics, is an ideal clean-burning substitute for conventional or petrol. Its application helps to reduce harmful emission and alleviate the relieve energy resource shortage (Ou et al. 2010).

In China, domestic research institutions have shown strong interests and carried out many research efforts to understand DME application technology. Several universities, such as Shanghai Jiao Tong University and Tianjin University, have conducted a series of experiments and other research on the DME production process and DME engines, supported by the National Natural Science Foundation or companies like Ford Motors. Since 2007, China has launched a number of DME projects in total exceeding one million tons for operational production. For example, in August 2007, Jiu Tai Energy (Inner Mongolia) Co. Ltd celebrated the ground-breaking ceremony of a 1 million ton/year DME project. A few months later, Shenhua Ningxia Coal Industry Group announced their commissioning in 0.21 million tons DME production.

DME production capacity and output have been growing rapidly recently. In 2001, China's DME production capacity was only 31.8 thousand tons with an output of 20 thousand tons. And by 2006, the two numbers were increased to 480 thousand tons and 320 thousand tons, respectively, with annual growth rates of 97% and 96%. By 2008, there were 52 DME producers in China with existing capacity of 4.18 million tons and the capacity would reach 15.8 million tons in 2012. However, there are several main growth barriers to coal-based DME, such as high carbon emissions in the fuel stage, high production cost and low energy efficiency.

2.2.3 DME versus Diesel in Two Scenarios

Life cycle analysis will help us to plan the growth of DME when assessing the key obstacles to DME through the entire life cycle: environment impacts, economics value and energy consumption. The TRM tool, in turn, will help us to plan when and why we should select DME over diesel as a transportation fuel. As per the recommendation of the experts, two scenarios have been planned for further analysis: (i) DME versus diesel in 2020; (ii) DME versus diesel in 2030.

The use of the framework for roadmapping the emergence of the new technology is illustrated below by means of a case study, focusing on the comparison between DME and diesel. There are two scenarios analysed through LCA method, in order to explore and clarify the unknowns in an a priori framework. The development strategies and key stages have been clarified in the refined framework, and the supporting policies are subsequently suggested.

The case study aims to plan the development strategies and key stages of DME in China. Some basic assumptions have been collated as follows (Zhou et al. 2012):

- Huge market demand: By 2030, China may need to import oil for 800 million tons per year. It is urgent to find an alternative fuel (i.e. DME) for transportation to replace diesel or petrol in China.
- Complementary technologies to DME: CCS technology will develop at a fast pace. It will have market demonstration in 2020 and will be implemented in 2030. CDDME technology is in the tech-demonstration stage now and will be implemented in 2020.
- Coal production in China: In 2030–2050, the production will be 3.8 billion tons per year.

2.2.4 Scenario I: DME vs. diesel in 2020

The required experts' estimations and assumptions have been collated as follows, supported by documentary data:

- Energy consumption on production process: In 2020, CDDME technology is still in its embryonic stage, and its efficiency still remained low. In the "fuel stage" of the life cycle analysis, coal-based DME needs five times the consumption during the production stage than ordinary diesel (from crude oil).
- Carbon emission: In 2020, CCS technology is still in its infancy for technological demonstrations. Therefore, the carbon emission of DME production will be two times of diesel.
- DME production cost: DME is still in its embryonic stage, so the price in 2020 might be USD 220 per barrel.

From Table 1, we argue that DME will not be able to challenge diesel in 2020, as its key performance indicators are significantly inferior to those of diesel.

2.2.5 Scenario II: DME vs. diesel in 2030

- Energy consumption in the production process: In 2030, CDDME technology may have been significantly refined in terms of efficiency. In the "fuel stage" of the life cycle analysis, coal-based DME requires three times the energy consumed during the production stage than that of ordinary diesel (from oil).
- Carbon emission: In 2030, CCS technology may have been its early stage of implementation. Assuming 45% efficiency, the carbon emission of DME production will be 1.08 times of diesel.
- DME production cost: Including the carbon trading gain (benefit from CCS), DME might have the price of USD 135 per barrel.

Table 1 LCA analysis: DME versus diesel in 2020. Adapted from Zhou et al. (2012)

DME versus diesel	Fuel stock	Fuel	Vehicle	Total
Energy consumption	0.45:1	5:1	0.68:1	1.47:1
Price	N.A	N.A	2.2:1	2.2:1
Carbon emission	1.76:1	1.53:1	0.8:1	2:1

Table 2 LCA analysis: DME versus diesel in 2030. Adapted from Zhou et al. (2012)

DME versus diesel	Fuel stock	Fuel	Vehicle	Total
Energy consumption	0.45:1	3:1	0.68:1	0.981:1
Price	N.A	N.A	1.35:1	1.35:1
Carbon emission	1.13:1	1.2:1	0.8:1	1.08:1

From Table 2, we argue that DME will start to be able to challenge diesel in 2030, as its key performance indicators are almost on par with those of diesel. The industrial strategy would need to expand the supply and penetrate the mass market.

Through the selection and comparing of DME versus diesel, we can find that, in 2020, policy should consist predominantly of supply policies, such as giving R&D grants, encouraging its application and demonstration, etc. In 2030, policy should be more market and environment oriented, such as industrial standards, regulations and stipulations, and application networks should be supported.

2.3 Acquisition

Organisations need to update and restock their technology base, which can be obsolescence and diffusion of technology. Various methods are available for acquiring new technology, including technology transfer, such as company acquisition, machine purchase or licensing in technology; collaborative development, for example joint ventures, subcontracting development and so on. We use two cases to illustrate technology acquisition. The first one is a successful purchase of the company assets of Domino. The second is about firm-level technology transfer and technology cooperation for wind energy between Europe and China.

2.3.1 Case Study: Acquiring a Differentiating Technology for a New Range of Products at Domino

Satisfying customer requirements for improved products is a key driver for the acquisition of new technologies in manufacturing companies.

Domino Printing Sciences has been at the forefront of inkjet printing technology for marking and coding systems for many years. The requirement from customers for cleaner, more reliable coding technologies encouraged Domino to investigate potential alternatives to serve existing markets and to open up new market possibilities.

A systematic review of coding technologies was undertaken, leading to the identification of lasers as a cleaner alternative. Lasers can mark many materials directly, such as plastics or glass, where surface discoloration acts as a mark. To survey the laser marketplace, guidance was sought from a technical consultancy.

Domino had a clear strategy for acquiring laser technology. As the laser would be the main differentiating element in a product coding system, Domino required complete control over the design and manufacture of the laser. Lasers were too expensive and not sufficiently developed for this application to buy in ready-made. A programme of R&D to produce a low-cost, reliable laser development partner could be found.

Domino identified a company in the USA which had laser design and manufacturing skills and which had developed a unique, fast and robust marking product. This company had good laser technology, technologists and facilities, but had suffered from poor marketing and was not profitable. Such a company would provide Domino with the technical laser capability it needed to integrate into its new generation of marking system. A successful purchase of the company assets was made. A critical condition was the retaining of a few key specialists.

In addition to this, a key customer had identified a small laser-making company in the UK that had developed a high-resolution laser market. This company was looking for a bigger company to work with in developing its product. Domino acquired the US laser company at the same time developing an exclusive licensing partnership with this UK company. The high-resolution marker was complementary to the US product but could use the same laser technology.

There was initial concern that laser products would compete with existing inkjet technology and replace this element of the business. However, it has been realised that there was a new market waiting in anticipation for the new product and that, far from competing, both technologies have complemented each other. Domino expects to be world market leader in laser marking within 2 years.

2.3.2 Case Study: Firm-Level Technology Transfer and Technology Cooperation for Wind Energy Between Europe and China

Technology transfer and cooperation as the tools of technology acquisition are key mechanisms for transferring low-carbon innovation from high-income countries to low- and middle-income countries. In this case, we try to explore how and to what extent technology transfer and cooperation from the EU have shaped the leading firm-level wind energy technologies of China today. China is the world's largest wind energy market, and four of its biggest wind energy firms: Goldwind, Sinovel, Guodian United Power, and Mingyang are part of the global top 10. Technology acquisition plays an important role in promoting the development of wind energy in China. For example, Lema et al. (2015) argue that there is a relationship between 26 Chinese turbine manufacturers and 18 (mainly) European knowledge-intensive businesses, most of which are German.

Table 3 indicates the relationship between Chinese wind energy firms and European wind energy firms with regard to different models of technology transfer and technology cooperation. Interesting to note is that the four top Chinese wind firms (indicated in cursive in the table) have all built their wind energy expertise on technology transfer from European, mostly German, wind energy firms: Goldwind has conducted joint development with Vensys as well as licensing from Jacobs/REpower, Guodian United has licensed technology from Aerodyn, Mingyang had joint development with Aerodyn, and Sinovel had licensed technology from Fuhrländer.

Table 3 The relationship between Chinese and European wind energy firms with regard to different models of technology transfer and technology cooperation. Adapted from Lewis (2013)

Chinese company	Model of technology transfer/cooperation	European source firm
A-Power (GaoKe)	Licence	Fuhrländer
	Licence/joint development	Norwin
Beijing Beizhong	Licence	DeWind
CSIC Haizhuang	Licence	Frisia
	Joint development	Aerodyn
DEC	Licence	REpower
	Joint development	Aerodyn
Goldwind	Licence	Jacobs/REpower
	Joint venture/acquisition	Vensys
Guodian United Power	Licence	Aerodyn
Harbin Stream Turbine Co.	Licence	Aerodyn
Hewind	Joint development	Aerodyn
Huidde	Licence	Fuhrländer
Jiuhe	Licence	Windrad Engineering
Mingyang	Joint development	Aerodyn
REpower North	Joint venture	REpower
Sewind		DeWind
	Joint development	Aerodyn
Sinovel	Licence	Fuhrländer
Windey	Licence	REpower
Xi'an Aero Engine Corp.	Joint venture	Nordex
Xi'an-Nordex	Joint venture	Nordex
Yinhe Avantis	Joint development	Avantis energy

2.3.3 Technology Cooperation in Europe and China: Vensys–Goldwind Vensys

Vensys is a German wind turbine manufacturer that was acquired by the Chinese firm Goldwind in 2008. Vensys started as a small engineering bureau that emerged from an R&D centre at the University of Saarbrücken. Vensys has been commercially operating in Germany since 2000, whereas the R&D activities at the university started about 10 years earlier. Vensys was acquired by the Chinese wind firm Goldwind with a share of 70% in 2008. Vensys operates via licensing in China (Goldwind), India (ReGen Powertech), Brazil (Enerwind/IMPSA wind) and Spain (EOZEN). It has strict rules for licensing to ensure that its intellectual property rights (IPRs) are protected. It sells its turbines in Brazil, Bulgaria, Canada, China, Germany, India, Pakistan, Poland, Portugal, Russia, Romania and the USA. Goldwind provided Vensys with access to the Chinese market and contacts; it enabled small firms to upscale rapidly and to supply a huge market. Goldwind has access to Vensys' profits, technology, IPRs, its components and markets. Vensys is famous for developing the permanent magnet direct-drive (PMDD) which is a technology based on a permanent magnet that powers the drive, hence different from the electromagnetic direct-drive Enercon uses. The acquisition of Vensys by Goldwind has contributed to the internationalisation of EU wind markets and technology. German and Chinese technology cooperation has led to joint R&D and joint technology. Vensys' PMDD technology requires the use of rare earths. The PMDD fits very well for production in China since China is one of the few countries that have access to rare earths resources, whereas other countries—such as Germany—struggle to access rare earths (Nordensvard and Urban 2015; Lema et al. 2015). It sells medium to large turbines and is currently conducting R&D for a 10 MW turbine.

Goldwind was founded in 1998 and is headquartered in Xinjiang. As one of the earliest wind energy firms in China, it evolved in many parts of the wind energy business, including wind turbine design and manufacturing, wind resource assessment and wind farm operation. In recent years, Goldwind has become the largest manufacturer of wind turbines in China and the second largest globally (CIEDS 2013). It has a market share of about 20% and is said to have installed a generating capacity of about 3600 MW (Li et al. 2013). With strong, internationalised R&D capabilities, Goldwind has become the world's largest manufacturer of PMDD wind turbines. For now, Goldwind has its branches and factories located in six continents.

Goldwind experienced several key innovation paths along its development. Goldwind started the development and marketing of 600 kW and 750 kW in the 1980s, leading the Chinese wind market. The early turbines installed in China relied on imported components from

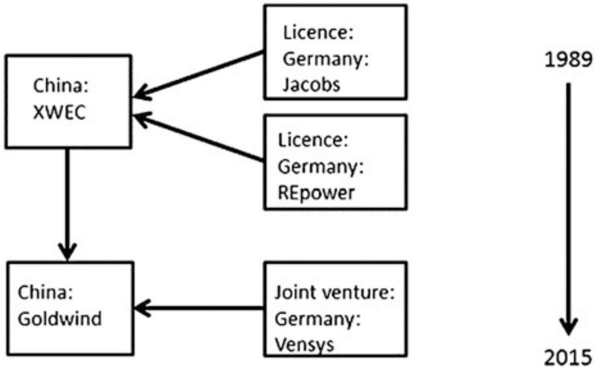

Fig. 4 Goldwind's technology cooperation with Germany from Jacobs, REpower and Vensys. Adapted from Lewis (2013)

technology transfer. Already in 1989, the predecessor of Goldwind, China XWEC, licensed wind energy technology from German wind firm Jacobs Energie (see Fig. 4). China's first five turbines installed in 1998 had only about 33% local content. In 2001, Jacobs Energie merged with another company to form the REpower Systems Group. That same year, Goldwind obtained a licence from REpower for a 750 kW turbine. In both cases, Goldwind insisted to add technician and researcher training in the contract. While Chinese engineers were sent to Germany for operational training, experts from Jacobs and REpower also went to China to work and provide on-site training. Through the immersion of design teams and experimental learning processes, Goldwind improved its innovation capacity and successfully produced turbines of 600 kW and 750 kW in 1999 and 2001, respectively. This forms the bases for later joint research of the 1.2 MW turbine with Vensys.

In 2003, Goldwind embarked on the collaborative design of a 1.2 MW PMDD wind turbines with Vensys. Unlike REpower, Vensys was a design firm who therefore was complementary to a manufacturer like Goldwind. However, Vensys only designed gearless turbine technology (direct-drive gearless wind turbine), which was uncommon back then and is different from Goldwind's previous innovation paths—Goldwind produced turbines with gears, namely doubly fed induction generators of 600 and 750 kW before. Advantages in the new innovation path meant that gearless turbines had less weight, less cost, less parts for maintenance and replacement. When considering the strategic potential, Goldwind determined to take the risk and commit to this new technology. In 2005, Goldwind had the prototype of the 1.2 MW turbine and installed it in Da Ban City wind farm for pilot operation. That became the first wind turbine produced in China over 1 MW.

Furthermore, Goldwind also acquired the licence for that 1.5 MW turbine with a larger 64-metre-diameter rotor, when integrating knowledge from Vensys to R&D teams in China (Lewis 2013). Based on this, Goldwind improved its magnetic electric direct-drive technology to produce 1.5 MW turbines in 2007. After its acquisition of Vensys in 2008, Goldwind had already commercialised the products of the 2.5 MW (2009) and 3.0 MW (2009) turbines, through internalising Vensys' R&D competences. In summarising key factors for the success of Goldwind, former CEO Wu Gang emphasised that "insisting on collaborative research, rather than licensing technology or purchasing turbine design solutions made Goldwind strong at independent technology development" (interview 2010). After acquiring Vensys by 70% in 2008, the registered patents for Goldwind increased from 3 in 2007 to over 170 in 2012 (Zhou et al. 2015).

Goldwind then established a joint venture with Vensys for developing 1.5 MW and 2.5 MW direct-drive wind turbines, which made up around 20% of the total production capacity in 2012 (Urban and Zhou 2015). These wind turbine models are estimated to dominate the majority of the wind market in China for the next 3–5 years, according to expert views. After executing its internationalisation strategy, Goldwind is developing key products for the future, including wind turbines in the size of 6.0 MW to 10 MW for offshore use.

In addition, Goldwind and Vensys are conducting joint R&D on amending turbines for the local conditions in China. This requires turbines that are suitable for low wind speed areas and extreme conditions such as desert conditions involving high heat, extreme dry weather and extreme sand exposure (e.g. in Gobi desert) and high altitude (e.g. for the Tibetan plateau).

Technology acquisitions in this case have two main implications. First, technology acquisition has a great effect on "catch-up" countries' innovation trajectories. Asian innovation paths in wind energy, particularly in China, have to some extent evolved based on the technology they acquired from their European technology cooperation partners. Wind energy technology from Europe has therefore helped shape Chinese wind energy technology. Second, technology acquisition provides an opportunity for the small firms in developed countries. The entry of Asian wind energy firms into European markets as well as the entry of European wind technology in Asian markets has led to an internationalisation of global wind energy markets and technologies. Large Asian wind energy firms such as Goldwind offer opportunities for profits, employment and economic growth for smaller wind design firms such as Vensys.

2.4 Exploitation

Exploiting technology assets involves a clear understanding of the nature of the core technologies and opportunities in a company, management of the technology base, technology planning and relationships with the customer–supplier network and other external resources. Hence, we will adopt the two cases GEC-Marconi and digital camera to explore this. For the GEC-Marconi case, which will help us to have a better understanding on how to exploit synergies between the various operating units and sharing of resources in key areas and improving technology planning in the context of the business/marketing objectives of the firm, while the case of digital camera develops a roadmapping method to explore the nature of a potential future value opportunity and articulate the route towards successful exploitations.

2.4.1 Case Study: Exploitation of Cross-Business Technology Synergies at GEC-Marconi

GEC-Marconi is a large international multi-business corporation with a turnover of over £3 billion. The company produces high-technology, electronics-based products for a large number of applications in a wide variety of military and commercial markets. A range of concurrent technology planning initiatives is being undertaken within the organisation, with the following aims: improving the exploitation of the technological synergies between the various operating units and sharing of resources in key areas; improving technology planning in the context of the business/marketing objectives of the firm and more closely integrating the role of central R&D facilities.

As part of this process, a simple matrix-based method was used to develop a framework to link technological capabilities with business objectives. This involved segmentation of the business in terms of technology and business areas in a series of senior management workshops. By ranking and assessing the impact of each technology area on each business area, it was possible to identify core technology areas which are of high value across several business units and areas of mismatch between value, effort and risk. This has enabled the organisation to focus attention on, and investment in, key areas of common interest and to achieve greater levels of coordination between historically independent business units.

2.4.2 Case Study: Charting Exploitation Strategies for Emerging Technology

Exploitation in emerging technology is a risky business, but it is crucial for a firm to achieve future economic prosperity. Continued exploitation and renewal of the technology base are essential for a long-term survival. Emergence roadmapping (ERM) is a workshop method that supports rapid strategic appraisal of early-stage technologies for the exploitation. The approach, which is based on earlier work demonstrating patterns in the historical emergence of industries (Phaal et al. 2011), has been developed and tested in collaboration with technology ventures, established businesses and academic research groups.

The ERM method follows on from the value roadmapping (VRM) approach (Dissel et al. 2006), which enables value opportunities for emerging technology to be identified and prioritised. The ERM method provides a structured process for these opportunities to be explored further, to clarify the strategic direction and to agree on technical and business development actions necessary to move forward.

2.5 The Case of the Digital Camera

The emergence of consumer digital cameras, from initial developments in the 1960s through the development of a mass consumer market in the 1990s, provides an illustration of the patterns governing the emergence of early-stage technologies (see Fig. 5).

Key milestones in this journey were:

- A 1961 paper from the Jet Propulsion Laboratory described the concept of using mosaic photosensors to produce still digital images, which led to the invention of the charge-coupled device (CCD) at the AT&T Bell Laboratories in 1969 (applied science demonstration).
- The technology was first commercialised by Fairchild Semiconductors and was rapidly incorporated into a prototype camera system by Kodak in 1975 (technology demonstration).

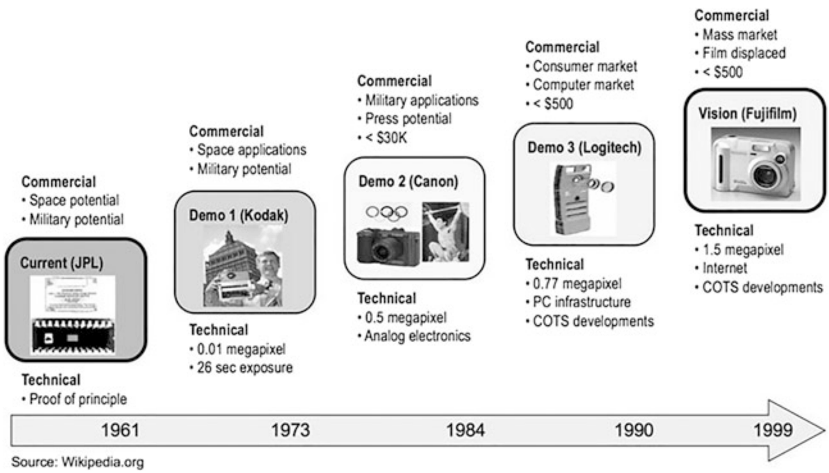

Fig. 5 Key demonstrations milestones in the emergence of consumer digital cameras. Adapted from Phaal et al. (2012a, b)

- Space and military applications enabled the technology to be improved, and the price reduced until eventually the first “mass” market (professional press) was stimulated by a demonstration of the technology by Canon—an image taken at the 1984 Olympic Games in Los Angeles was transmitted and printed in a Tokyo newspaper (application demonstration).
- The price–performance ratio of the core technology continued to improve, with parallel developments in electronics, software and computing supporting the core technological developments, leading to the first consumer digital camera product being released by Logitech in 1990 (commercial application demonstration).
- Sensor technology continued to develop, along with complementary developments in computing, communications, standards, displays, batteries, and printing and scanning systems. This led to cameras that could compete with, and eventually displace, film-based technology, typified by the Fujifilm MX-600, released in 1999, which offered all of the main features that are expected in compact consumer cameras today (price–performance demonstration).

Emergence roadmapping can facilitate the decision-making progress for early-stage technologies by allowing workshop participants to rapidly map the potential commercial exploitation paths for a technology on the industrial emergence framework, tracing its potential trajectories through a series of demonstrator steps.

The aims of the ERM workshop are:

- To clarify the innovation opportunity, in terms of application, market and technology;
- To define steps towards the opportunity, mapping the demonstration chain;
- To explore key enablers and barriers as well as next actions to move towards the first demonstrator.

The journey from science to mass consumer market was long, although there were opportunities to generate revenue earlier in specialised precursor and embryonic markets. In the 1970s and 1980s, products were developed for space, military and professional press markets, each of which would have its own science–technology–application–market life cycle. In the context of the consumer digital camera industry, these achievements can be considered as application demonstrations that enabled continued improvements in the performance of the technology and reductions in its cost.

The historical route from science to mass market application for digital cameras is clear in hindsight. Of course, the future is less predictable, and it would have been unreasonable to expect anyone in 1961 to have foreseen the key developments that would lead to mass commercialisation of this technology. However, investments must still be made, and it is necessary to imagine and explore potential future value opportunities in order to build confidence about the decisions and actions required to move forward.

The workshop allows a detailed exploration of the opportunity, the different stages of its progression towards the ultimate goal, considerations of who and what should be involved along with internal and external factors that may help or hinder progress, and associated actions. The approach requires a relatively clear focus in terms of potential future value opportunity scenarios, including application and market. The pattern of emergence typified by the development of the digital camera industry offers a framework within which to consider these high-risk decisions and make a sustainable development of the company.

2.6 Protection

As aforementioned, protection of technology involves more than the legal rights of intellectual property—it involves people and the knowledge and skills they control, together with other issues such as site and security of information and communications systems. Technology protection can involve keeping ahead of competitors by identifying and appropriately securing technology assets (defensive strategy), or by keeping competitors behind by neutralising the effects of their defences (proactive strategy). Protection should be considered systematically in a circular process. The three main stages involve: the assessment of protection that are needed, the choice of protection routes or mechanisms, and the implementation of the protection methods. Following two cases are discussed: case 1 shows the way of protection method, and case 2 demonstrates the differences of knowledge sharing in open-source innovation as well as the geographical differences between the East and the West.

2.6.1 Case Study: BG plc

In February 1997, British Gas demerged its gas trading and associated activities and renamed itself BG plc. The new company, Centrica, uses the trading name of British Gas in the UK. BG plc uses British Gas outside the UK, which was reorganised in 1999 as BG Group plc. BG plc has operations in 25 countries across Africa, Asia, Australasia, Europe, North America and South America and produces around 680,000 barrels of oil equivalent per day. It has a major liquefied natural gas (LNG) business and is the largest supplier of LNG to the USA. On 31 December 2009, it had total proven commercial reserves of 2.6 billion barrels (410,000,000 m^3) of oil equivalent. BG Group is listed on the London Stock Exchange; as of 6 July 2012 it had a market capitalisation of £44.9 billion.

Organisations such as BG plc are recognising that a significant part of their value lies in the knowledge which the company and its employees possess, rather than just in its physical assets. This is particularly true for knowledge of technology. The effective management of that knowledge can lead to an enhancement in the performance of a company. However, this can only be achieved by a change in culture and working methods, whereby the creation and sharing of knowledge is both encouraged and rewarded.

The mission of the knowledge management technologies team within BG technology is to contribute to and to facilitate the optimisation of the use of BG's world-leading knowledge base in all aspects of gas technology. The approach has been to work with the BG business to define where knowledge sharing, particularly in the field of technology, can enhance their performance, and then to design and deliver information systems which can realise that potential enhancement.

The development of a technology bank is an example of such an activity. The technology bank is maintained by programme managers within BG technology. Current and past technology knowledge is captured in databases within the bank. This then provides BG with the ability to share this knowledge worldwide between virtual teams. Highly advanced tools have also been developed to search for information simultaneously across all of these and many other databases. Information in the databases can be made visible to everybody within the company or only to restricted groups of people, depending on its level of confidentiality. It is planned to extend this capability to the sharing of selected information with partners outside the company.

This project will involve users from around the world and will also involve changing the way of working within BG technology, so that as project information is created it is automatically captured within the databases. The project is just one example of BG's move towards becoming a knowledge-based company, enabling all the knowledge to be accessed quickly and easily from anywhere in the world.

2.6.2 Case Study: Knowledge Sharing in Open-Source Software Projects

Open-source software (OSS) is a software with its source code available with a licence in which the copyright holder provides the rights to study, change and distribute the software to anyone and for any purpose. The Linux operating system, Mozilla and Chrome are all outstanding representatives of OSS, which is widely used all over the world.

OSS projects aim to develop OSS by means of groups of capable people, mainly including developers and users. In terms of developers, core members, active members and peripheral members are three major groups. For users, both developer-users and non-developer-users, their feedback is of great importance for developing work. As distinct from proprietary software with "the cathedral model", OSS works on "the bazaar model" in which everyone can get involved or leave at any time (Table 4) and any one has equal rights to contribute (Raymon 2001).

Table 4 Difference between the cathedral model and bazaar model. Adapted from Panchal and Fathianathan (2008)

Factor	Cathedral model (traditional collaboration)	Bazaar model (distributed innovation)
Structure	Hierarchical	Flat network
Participants	Task oriented	Interest oriented
Production	Management by bureaucracy	Management by objective
Division of work	Distributed by leaders	Self-control
Knowledge flow	Top-down, bottom-up	Distributed
Release	Release after final revision	Continuous revision and release
Decision	Concentrated	De-centralised

Many countries are paying much attention to the development of open source. For example, on 23 May 2012, President Obama issued a directive entitled "Building a 21st Century Digital Government" to promote open government, open data and an open-source plan. OSS is regarded as a way of making it easier for the government to share data, improve tools and services, and return value to taxpayers (Obama 2012). Taking the Columbia government of United States as an example, the government organised an open-source competition named "Apps for Democracy" for the public, and there were 47 pieces of OSS projects created within 30 days to improve government decisions (Booth 2010). The Chinese government continuously take measures to promote development of open source. On 16 March 2011, the Chinese central government issued the 12th Five-Year Plan to support the construction of the OSS ecosystem. Then, on 21 March, the OSS Innovative Lab was established with the sponsorship and collaboration of the Ministry of Industry and Information Technology, the National University of Defence Technology and the International OSS Community—Ubuntu. On 8 April 2014, the Ministry of Industry and Information Technology of the People's Republic of China claimed to support R&D and implementation of the Linux operating system after Microsoft stopped services to Windows XP users. On 16 May 2014, central governments were forbidden to install Windows 8 operating system during the Government Buying owing to the consideration of government information security. To protect government information security, it is considered more and more important to promote the OSS ecosystem.

Open-source ecosystem can be compared in view of OSS project ecological environment, and the differences between China and the West were found to be as follows:

- Different internationalisation levels caused by various languages, political and cultural backgrounds. OSS project is generally communicated and recorded in English, which forms the barriers to most Chinese developers.
- Differences between the spirit of open source and the ideology of sharing owing to the different stages of open source. Developed countries have more experience of the open-source area, while China has much room to improve concerned with the awareness of open-source spirits as well as cooperation and sharing.
- Different occupation systems and habits caused by the influence of both the values of "official standard" and "technology first". For a long time, China has been influenced by the idea of an "official standard" based on official orientation, authority and respect. So few Chinese developers remain to work as technical experts upon 35 years old, while in developed countries there are many savvy technical experts with the age of 40–45 years old.
- Different extent of support for OSS projects. In developed countries, big companies or foundations are supporting many open-source projects overseas, such as Linux, Apache, FreeBSD and Debian; however, in China, the support is limited.
- Differences in intellectual property. OSS licences are very important in OSS, which seems like the Code used in OSS. Undoubtedly, Western countries pay close attention to the licence selection and use of OSS, as deep-rooted concepts exist regarding the protection of intellectual property rights. By contrast, the environment for intellectual property is relatively poor in China

In the development of OSS, the West pays more attention to industrial orientation. That is to say, big companies, foundations and civil senior open-source people contribute a lot, but the government's role remains limited. On the contrary, Chinese government is more proactive to address the need "to support the development and application of OSS, and quicken the formation of an industrial ecological system based on the open source mode" in the 12th Five-Year Plan of Software and Information Technology Service Industry. However, at present, there are no obvious effects; for example, pirated software runs wild, and intellectual property is ineffectively protected. Therefore, in the field of OSS ecological environment construction, the government should pay attention on stressing the protection of intellectual property, formulating fair and reasonable rules, promoting the completeness of the relevant laws and regulations in China, as well as encouraging government procurement to cultivate the domestic market. University–industry collaboration with regard to OSS should also be strengthened.

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