A Technology Foresight Model: Used for Foreseeing Impelling Technology in Life Science

Yunwei Chen*, Yong Deng, Fang Chen, Chenjun Ding, Ying Zheng and Shu Fang

* *chenyw@clas.ac.cn*
Chengdu Library of the Chinese Academy of Sciences, Chengdu, 610041 (China)

Abstract
This paper constructs an Impelling Technology Foresight Model (ITFM) for foreseeing impelling technology in the field of life science, which is a comprehensive model consisting of four class indicators: international scientific environment, evolving of papers and patents, collaboration features of patent assignees' collaboration networks, and impacts. A case study was carried out in the field of life science. Recombinant DNA (RbDNA) and Monoclonal Antibody (mAb) were selected as impelling technologies to carry out the case study. ELISA Diagnosis (ELISA) and Fermentation Technology (FT) were defined as non-impelling technologies to be control group. Results revealed that impelling technologies have higher evolving rates from the stage of growth to maturity. Significant policies or programs usually boost the rapid progress of impelling technologies. Impelling technologies have much higher impact than non-impelling ones. Collaboration behaviour is much more broad and general for impelling technologies. To our knowledge, this is the first study carried out to date to foreseeing impelling technologies at this way.

Conference Topic
Methods and techniques

Introduction
Technology has made enormous contributions to modern society and many future social developments can be realized only through better technical developments and better management (Compton, 1939). Nevertheless, not all technical progress makes substantial contributions to social development. Only a few techniques brought revolutionary change to the human society, such as Transistor Technology and Recombinant DNA technique, which belong to the field of information technology and biotechnology, respectively. Information technology and biotechnology are also regarded as dominant technologies and will essentially impel the social development in the 21st century (Das, 2001).
Thus, it is an attractive topic all the time for scientists from many scientific fields to foresee what kind of technologies can become such impelling technologies, especially in the field of biotechnology. Impelling technology is defined in this paper as technologies that can bolster, lead and push the scientific development and technology progress in given fields, and that can drive the industry fast development and breed emerging industry. Transistor Technology and Recombinant DNA technique are just such technologies. However, people desire to know which technologies can become impelling technologies in the near future, especially for new technologies. For example, synthetic biology, which uses unnatural molecules to reproduce emergent behaviours from natural biology with the goal of creating artificial life (Benner & Sismour, 2005), is recognized as a powerful technique that can produce re-engineered organisms that will change our lives over the coming years, leading to cheaper drugs, green fuel and targeted therapies for diseases. The de novo engineering of genetic circuits, biological modules and synthetic pathways is beginning to address these crucial problems (Khalil & Collins, 2010). If that is true, synthetic biology could be regarded as an impelling technology. However, except for synthetic biology, there are still a large number of techniques emerging in the field of biology. Which can become impelling technology in the near future? Foresight analysis provides the idea of solutions.

Technology foresight, like technology forecasting, is the generation of reasoned statements about the future, the interpretation of such statements in terms of informed action, and the collective learning processes that are involved in responding to challenges of the future (Salo & Cuhls, 2003). Amanatidou (2014) pointed out that the major impacts of foresight belong to knowledge, network creation and promoting public engagement in policy-making. The scope of technology foresight comprises not only technologies and their applications but also public policies and societal challenges (Salo & Cuhls, 2003). UNIDO defined technology foresight as the most upstream element of the technology development process. It provides inputs for the formulation of technology policies and strategies that guide the development of the technological infrastructure. In addition, technology foresight provides support to innovation, and incentives and assistance to enterprises in the domain of technology management and technology transfer, leading to enhanced competitiveness and growth (UNIDO, 2014).

Indeed, similar forms of foresight technology also include technology intelligence, technology forecasting, road mapping and assessment (Firat, 2008). Many of these forms use similar tools and get similar results. Particularly forecasting and foresight are often confused in practice. According to the interpretation from the Technology Futures Analysis Methods Working Group 1 (TFAMWG), all these similar methods could be used in technology futures analysis (TFA). Technology foresight is used to analyse the effecting development strategy, often involving participatory mechanisms. Technology forecasting is to anticipate the direction and pace of changes. But there is a general tendency that forecasting usually focuses on specific technologies. Foresight studies usually bring together people with different expertise and interests, and use instruments and procedures that allow participants to simultaneously adopt a micro view of their own disciplines and a systems view of overriding or shared objectives (Firat, 2008). Some foresight related studies are introduced below and their findings contributed partly to the theoretical and technical basis of this study.

Based on the below related works analysis, we found that although many techniques have been used to answer many kinds of questions, impelling technology foresight works were lacking, especially by the method of model construction. Therefore, this study advanced the existing works by constructing an ITFM model to carry out impelling technology foresight analysis. ITFM model can be used for impelling technology foresight. To our knowledge, none of the existing studies has done such work as ever. The significance of this work is that if an impelling technology could be known before it becomes impelling technology or at the earlier stage of its life cycle, that would be very valuable for many kinds of scientists, policy makers and stakeholders to deal with it.

Related works

The term "Technology Foresight" was introduced by Irvine and Martin and took off in the 1990s as European, and then other countries (Miles, 2010). Until now, a lot of studies have been carried out to do such analysis in recent years, which could be divided into four aspects: function, subject areas of use, features of products and results, and techniques. Related works are discussed below.

Function

The focuses of technology foresight studies have been often motivated by the desire to shape S&T policies and analyse the challenges of education, services, health, and environment, etc. (Salo & Cuhls, 2003). For example, Carlson (2004) discussed the using of technology foresight to create business value. Sanz-Menendez (2001) made technology foresight as a useful tool for policy making. Havas (2010) analysed the impact of foresight on innovation policy-making. Weigand et al. (2014) studied collaborative foresight method to complement long-horizon strategic planning.

Subject areas of use

Based on the fields of science and technology, Linstone (2011) discussed the unique impacts of technology foresight on nanotechnology, biotechnology and materials science. Weinberger, Jorissen and Schippl (2012) carried out a study about technology foresight analysis in the field of environmental technologies with the purpose of supporting the process of identifying and recommending options for the prioritisation of future research funding. Furthermore, foresight has also been used in the field of education studies (Goldbeck & Waters, 2014; King, 2014), drugs discovery (Lintonen et al., 2014).

Features of products and results

From the aspect of products and results of foresight, the works of technology foresight usually have the following products: Strategic advice or guidance, particular technologies or their consequences, price or trends of markets, and production. For example, Cook, Inayatullah and Burgman (2014) concluded that foresight could play a more significant role in environmental decisions by the following ways: monitoring existing problems, highlighting emerging threats, identifying promising new opportunities, testing the resilience of policies, and defining a research agenda. Markus and Mentzer (2014) discussed the future consequences of ICT. Weinberger, Jorissen and Schippl (2012) used foresight methods to support the process of identifying and recommending options for the prioritisation of future research funding among the wide range of environmental technologies available that can contribute to progress in the field of environment.

Techniques

At the angle of techniques used for foresight, many kinds of methods have been used to carry out technology foresight analysis. One typical technique is bibliometric methods. Van Raan (1996) overviewed the potentials and limitations of bibliometric methods for the assessment of strengths and weaknesses in research performance, and for monitoring scientific developments. The study suggested that research performance assessment is based on advanced analysis of publication and citation data. While for monitoring scientific developments, bibliometric mapping techniques are essential. Actually, mapping has been widely used for technology foresight. For example, Yoon, Lee and Lee (2010) developed a keyword-based knowledge map to use to establish a policy to support promising R&D areas and devise a long-term research plan. Another typical method is modelling and system. For instance, Shiue and Lin (2011) developed a foresight MASA model for future technology evaluation in electric vehicle industry, which integrated the concept of vision, linking analysis planning, Markov chain, and Scenario analysis (SA). Chen (2012) proposed a structural variation model for answering what kinds of information may serve as early signs of potentially valuable ideas. Peer review and Delphi have also been used in foresight as in forecasting. For example, Lintonen et al. (2014) had done a drugs foresight analysis in 2020 through the method of Delphi expert panel study. Forster & Gracht (2014) had also assessed Delphi panel composition for strategic foresight based on company-internal and external participants.

Model of Impelling Technology Foresight Model (ITFM)

Definition and Hypothesis

As is stated above, impelling technologies are such technologies that could bolster, lead and push the scientific development and technology progress and drive the existing industry fast develop and bread emerging industry in given fields. However, this definition explains only the functional feature reflecting the results generated by impelling technologies, and lacks the description of its inherent features, especially the features at the early stage of technology lifetime, which are much more important to foresee whether a technology at the early stage could become impelling technologies. Therefore, the inherent features of impelling technologies especially the features at the early stage could be used as indicators for reflecting impelling technologies. Thus, some hypothesises had been proposed as the theoretical base for constructing an Impelling Technology Foresight Model (ITFM) for foreseeing impelling technologies, particularly in the field of life science.

Hypothesis 1. Viewed by the concept of technology life cycle, technologies' development process can be divided into four stages (Little, 1981) of emerging, growth, maturity and saturation. Impelling technologies grow rapidly to the stage of maturity after short growth stage. Impelling technologies seldom show signs of turning to saturation stage for their competitive impact could remain much longer than non-impelling technologies. In order to evaluate the current stages of a technology, patents have been widespread used to do such analysis. For example, Patent analysis was applied by Zhou et al. (2014) to monitor the developmental stage of a particular New and Emerging Science & Technologies, dye-sensitized solar cells (DSSCs), and traced its potential evolutionary pathways. Some other related works have high impacts include Haupt, Kloyer & Lange (2007), Trappey & Wu (2011), Jarvenpaa, Makinen & Seppanen (2011), etc. This paper uses patent data to disclose the different/given features at the different stages of impelling technologies.

Hypothesis 2. During the development process of an impelling technology, pushing policies or programs usually would like to be attracted to boost the progress of impelling technology. For example, Human Genome Project has been the first major foray of the biological and medical research communities and it boosted the development of an array of new technologies (Collins, Morgan & Patrinos, 2003), among which Recombinant DNA technique have achieved considerable development and have also been generally recognized as an impelling technology in the field of life science.

Hypothesis 3. Impelling technologies have higher level of collaboration, especially in patent assignees' collaboration. A lot of studies have shown that there is a positive correlation between collaboration and better production of science. For instance, Guimerà, et al. (2005) pointed out that collaboration could spur creativity, solving old problems and inspiring fresh thinking. In the field of scientific researches, Whitfield (2008) pointed out that there is a picture of science's increasingly collaborative nature and which determine a team's success. Wuchty, Jones and Uzzi (2007) found that there's something about between-school collaboration that's associated with the production of better science. Kato & Ando (2013) found a positive correlation between their research performance and degree of internationalization.

Hypothesis 4. Impelling technologies have higher level of impacts. Citation-based analysis is the most frequently used method to carry impact analysis. The original use of citation for evaluation is Journal Citation Reports from Thomson Reuters to evaluate journals impact factors. Garfield (1979) pointed out that citation analysis could introduce a useful measure of objectivity into the evaluation process at relatively low financial cost. Numerous approaches have been devised to assess future technological impacts based on patent citation information with the core purpose of identifying the current technologies that will drive technological changes over the coming few years (Lee et al., 2012). There are also some network-based method were used to do technology impact analysis. For example, Ko et al. (2014) presented a combined approach for constructing a technology impact network basing on patent co-classification and identifying the impact and intermediating capability of technology areas from the perspective of a national technology system. This paper uses paper citations to compare the difference of impacts between impelling technologies and non-impelling technologies.

ITFM frame

A few factors from four aspects were introduced to validate the above hypothesis.

Technology life cycle - Evolving of patents and paper were introduced to disclose the evolving features of impelling technologies during the four stages of emerging, growth, maturity and saturation.

International environment - The ITFM model took only policy, plan or program as indicators to reflect the international scientific environment although the related factors are more.

Collaboration - The following network statistics of patent assignees collaboration networks were used to represent the collaboration features of impelling technology.

- Ratio of isolates, which have no collaborators in the assignees collaboration networks G. Counted as n (isolates)/n.
- Ratio of nodes in the largest cluster, counted as n (largest cluster)/n.
- Ratio of clusters compare to nodes, counted as #clusters/n.
- Average degree, let N(i) be the set of assignees collaborating with assignee i. The total number of collaboration assignees with assignee i is the degree of assignee i and is defined as $\eta(i) = |N(i)|$. The average degree of a network G is defined by$\eta(G)=\Sigma_{i \in N}\eta(i)/n$.
- Diameter, which is measured by shortest-path length, has been used to estimate the stage of development through documentation data (Chen, Borner & Fang, 2013, Bettencourt, Kaiser & Kaur, 2009) or patent data (Chen & Fang, 2014). There is a theory that collaboration graph that densify with constant or decreasing diameters. All these studies have showed that collaboration graphs in several scientific and technological fields exhibit initial rapid growth in their diameter, which then tends to stabilize and stay approximately constant at 12~14 (Bettencourt, Kaiser & Kaur, 2009). The assignees collaboration network diameters seem to stabilize at about 12 when a technology come into the stage of maturity (Chen & Fang, 2014).

Note that n is the total number of nodes in the network.

Impact - Two factors of times cited per paper and times cited per patent were used for expressing the technology impacts.

The ITFM frame is listed in Table 1, which is the origin of the following case study.

Table 1. Factors contributing to the ITFM.

Factors		*For validating hypothesis (purpose)*
Technology life cycle	evolving of papers	hypothesis 1
	evolving of patents	
International scientific environment	policy	hypothesis 2
	plan or program	
Collaboration-patent assignees collaboration networks	ratio of isolates	hypothesis 3
	ratio of nodes in the largest cluster	
	ratio of clusters compare to nodes	
	average degree	
	diameter	
Impact	times cited per paper	hypothesis 4
	times cited per patents	

Data and methods

According to the opinions of thirty experts in the field of life science through email consultation, Recombinant DNA (RbDNA) and Monoclonal Antibody (mAb) were selected as impelling technologies to carry out case study. ELISA Diagnosis (ELISA) and Fermentation Technology (FT) were defined as non-impelling technologies to be control group.

Publications in Web of Science™ from 1960s to 2012 (publication year) and US patents in Derwent Innovations Index℠ from 1970s to 2012 (basic patent year, defined by DII based on the earliest year of all the publication dates of all members of a patent family) were chosen as quantitative data of case study. Data was acquired from the Web of Science in May 2013. Thomson Data Analyzer (TDA) and Science of Science (Sci^2) Tool (http://cns.iu.indiana.edu) were used to extract the statistic and network information.

Search terms to retrieval papers and patents are listed in Table 2.

Table 2. Search terms used for this study.

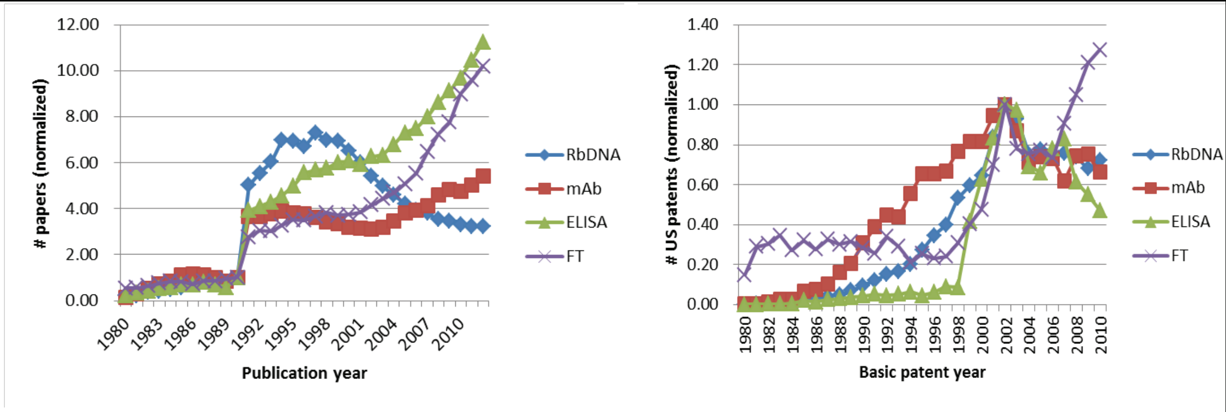
	Papers	*Patents*
RbDNA	TS=("DNA recombination" or "recombinant DNA" or "DNA cloning" or "molecular cloning" or "gene cloning")	IPCs: from C12N-015/09 to C12N-015/90
mAb	TS=(("monoclon* antibod*") OR (monoclon* same antibod*))	IP=C12P-021/08
FT	TS=ferment*	IP=(C12C-011/* OR C12G* OR C12P* OR C12J*) AND TS=ferment*
ELISA	TS=elisa, removed the papers in WC class of Spectroscopy, Optics, Physics Condensed Matter, Nuclear Science Technology, Behavioral Sciences, Astronomy Astrophysics and Microscopy.	TS=Elisa

Results and Analysis

Evolving of papers and patents

Papers and patents are two external indicators for reflecting the evolving of technologies. The output of papers and patents of the two impelling technologies and two non-impelling technologies were normalized to 1 by their numbers of papers in 1990 and numbers of patents in 2002 separately. The reason of choosing 1990 was that the year 1990 was a jumping-off year, after when the number of papers jumped at least more than three times in 1991. The reason of choosing 2002 was that the year 2002 was a dividing crest, which year had the maximum number of patents, except for FT. Fig. 1 illustrates that the number of papers of both the two impelling technologies stabled at a certain range after three or four years development following the jumping-off from 1990 to 1991. The patents trends show that the number of patents of impelling technologies stabled at a certain level after two years of the patent outputs peak. However, both the papers trends and patent trends of non-impelling technologies had no stable signal no matter which way they go, increase or decrease constantly.

In order to compare the features of impelling technologies at different stages of life cycle, time were sliced into four sections, -1986 (emerging stage), 1987-1993 (growth stage), 1994- (maturity and saturation stages). This division mainly depended on the evolving histories of the two impelling technologies. Although it was not adaptive for on-impelling technologies it had also been used for distinguishing non-impelling technologies' life cycles with the purpose of comparison.



papers-normalized by the number of papers in 1990

patents-normalized by the number of patents in 2002

Figure 1.Growth of papers and US patents.

International scientific environment

Through watching the histories of the two impelling technologies, we found that Human Genome Project, the first major foray of the biological and medical research communities launched in 1990, boosted the two impelling technologies fast into maturity stage, which could be reflected by the jump of the number of papers. Nevertheless, although the two non-impelling technologies, ELISA and FT, had also been boosted by the Human genome Project, these two technologies had not entered into maturity stage throughout. Actually, beside for the Human Genome Project, there were still more crucial policies had been drawn and put into effect. For example, USA had announced the first Recombinant DNA research Guidelines for normalizing such researches. Even till now, government still made positive policies to maintain the driving functions of impelling technologies. For instance, US Federal Court ruled that synthetic DNA could be patented, which might become a new pushing for the development of RbDNA.

In the aspect of industry, at the stage of growth there were one or a few professional companies born and the number of companies rose sharply at the stage of development and the early maturity stage. For instance, benefited from the development of RbDNA, the first biotechnology company Genentech had been established in 1976. When an impelling technology is mature, the relevant industry would expand rapidly. For example, mAb had brought a rapid growth market of 26 billion USD in 2006 while it was only 4 billion in 2002.

Patent assignees collaboration networks

Figure 2 and Figure 3 illustrate the network features of patent assignees collaboration networks. It is clearly showed in Figure 2c that as time gone on, the ratio of isolates (assignees have no collaborators) decreased year by year and seemed to stabled at a certain level. However, the ratios of isolates of the impelling technologies were much lower all along than that of the non-impelling technologies. The values of the latter were more than twice of the former. The gap was enlarged to more than three times at the stage of development. As a result of the reduction of isolates, the clusters increased and there were many a big cluster became bigger and bigger. It has to be noted that an isolate was also regarded as a cluster. Therefore, a network with high level of collaborative behaviours must has less clusters because of much more isolates and small clusters tend to merge to bigger clusters. Thus the excellent performance of collaboration leads to generate a super big cluster and less ration of clusters (see Fig. 2a). Figure 2b shows that the biggest cluster of impelling technologies gathered about more than half of the total number of assignees particularly after the stage of development, which was much higher than that of the non-impelling technologies.

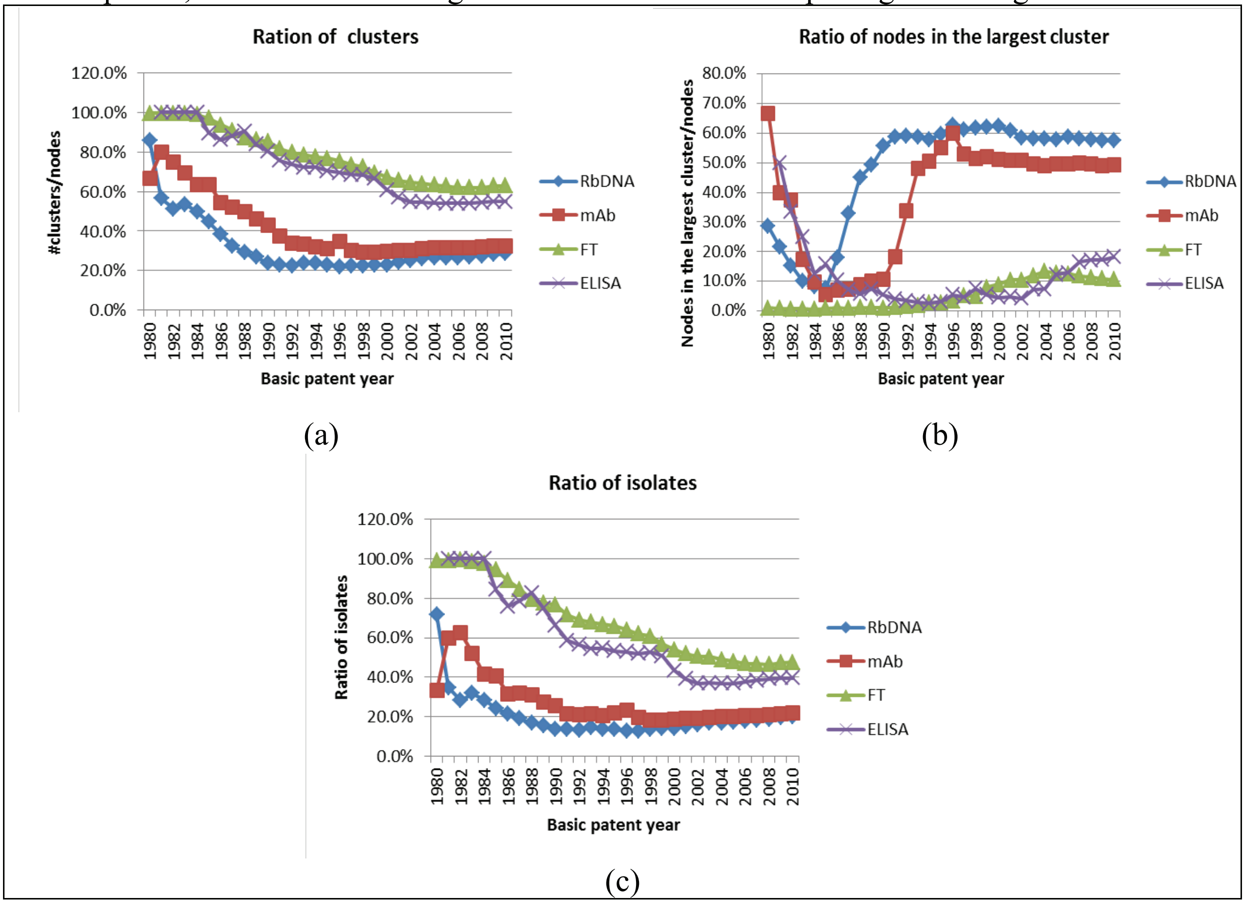


Figure 2. Network features of US patents' assignees' collaboration.

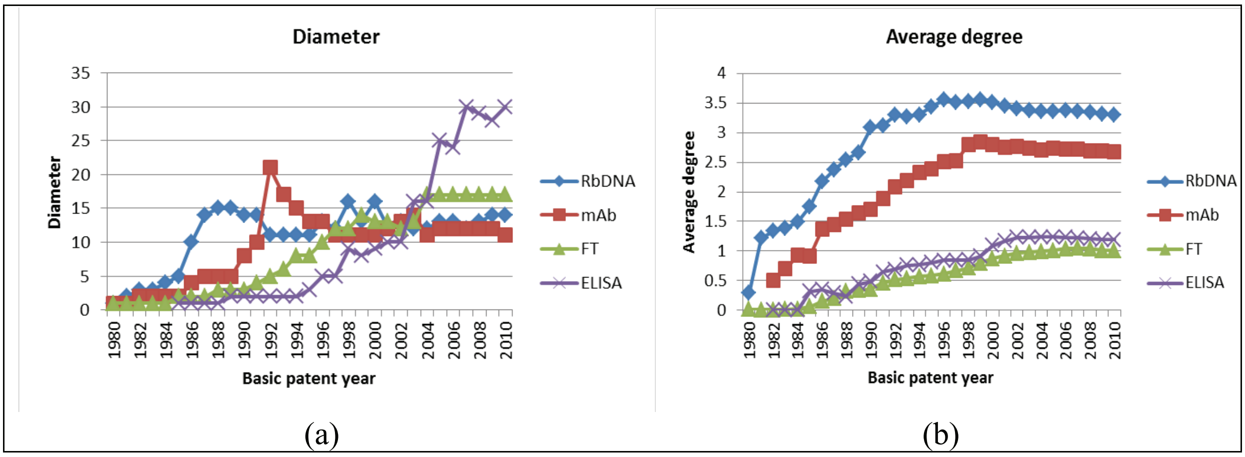


Figure 3. Diameters and average degrees of assignees collaboration network.

Benefited from the good network performance, the impelling technologies had higher average degree all the time. It was about three times higher than that of the non-impelling technologies at the stage of maturity, ten and four times during the period of growth and development respectively.

Impact

The average times cited of papers and patents of the two impelling technologies and two non-impelling technologies were illustrated in Figure 4.

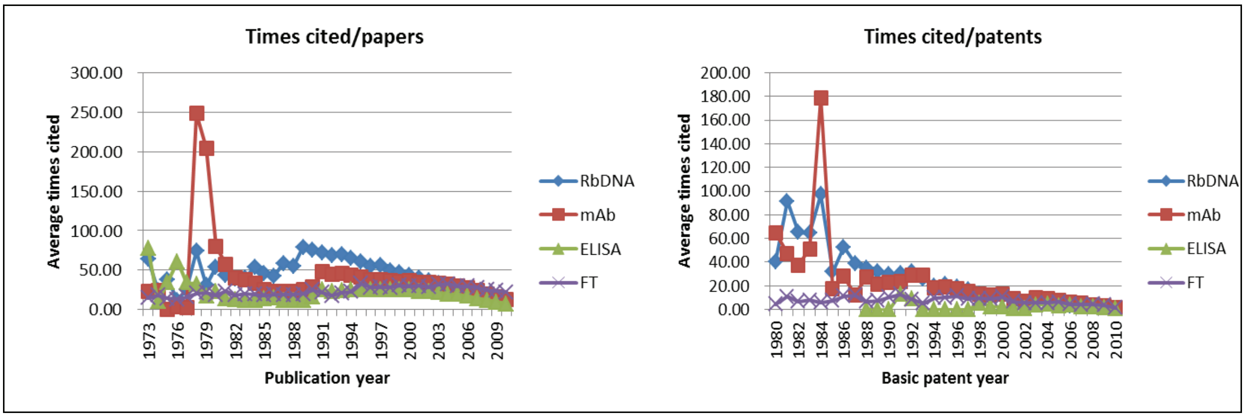


Figure 4. Average times cited of papers and US patents.

The results showed that the average times cited of papers of impelling technologies was two times higher than non-impelling technologies during the whole period of this analysis. The value of impelling technologies was 30 and 50-80 compared to 18 and 20 of non-impelling technologies at the stages of growth (before 1986) and development (1987-1993). For patents, the average times cited of impelling technologies and non-impelling technologies were 66 and 7 in stage of growth, 24 and 9 in stage of development correspondingly. However, the advantages of impelling technologies were eroded as time goes on in the stage of maturity.

Quantitative ITFM

Through the above case study we might conclude some unique features of impelling technologies in the field of life science.

First, impelling technologies had higher rates of evolution from the stage of growth to maturity, which could be illustrated particularly by the papers evolving patterns. When it comes to the technologies of RbDNA and mAb, it took only about one year that both of the two impelling technologies had finished their transform. At the same time, impelling technologies represented distinct feature at the stage of maturity. Nevertheless, the two non-impelling technologies represented no obvious such transformation. It seemed like that both the two non-impelling technologies were still at the stage of growth. However, the fermentation technology had a much longer history than both the two impelling technologies. The reason of it represented such evolutionary feature might just due to the position as a non-impelling technology, which contributes more and more to the society development, but always is a applied technology and will not play more impelling functions.

Second, significant policies or programs boosted the rapid progress of impelling technologies. Although non-impelling technologies had also been pushed by specific policies or plans, the range was lower than that of impelling technologies. When the impelling technologies switched into maturity stage, they usually drove the explosive increase of industry.

Third, impelling technologies had much higher impact than non-impelling technologies, which could be reflected by the times cited per paper/patent. The value of times cited per paper/patent of impelling technologies was two to three times higher than non-impelling technologies. It was highlighted during the process of involving from the stage of development to maturity. In the case of life science, for papers, the value of impelling technologies was 50-80 compared to 20 of non-impelling technologies, for patents, the values were 24 and 9 correspondingly.

Last, collaboration behaviour measured by the collaborations of patent assignees was much more broad and general for impelling technologies. Assignees collaboration networks of impelling technologies had fewer isolates, and there were only about 20% assignees were isolates at the stages of development and maturity. Much more assignees had collaborated with others and become much bigger clusters with a result of the number of clusters decreased. The biggest cluster (principal component) gathered a large number of assignees that took up more than half of the total number of all nodes in the networks at the stage of maturity. As a result, the average degree of impelling technologies reached to 3 which were three times to that of non-impelling technologies at the stage of maturity. The diameters of impelling technologies stabilized at 12 at the stage of maturity. Non-impelling technologies had no such features of stable diameters.

The results indicate that hypothesises listed above were answered by the case study. Based on the results of the comparison of impelling technologies and non-impelling technologies in the field of life science, a quantitative model is induced in table 3. The model can be used for foreseeing any new impelling technologies that have just born or at different stages, especially at the stages of development and maturity.

Table 3 Quantitative ITFM.

	Indicators	*Features*		
		Growth (- 1986)	*Development (1987-1993)*	*maturity (1994-)*
International scientific environment	**Policies, plans &projects**	New incentive, convenient policies enacted	Pushed significantly by major project	Still focus of policies, plans & projects
	Industry	Start-up companies	Number of companies would rise sharply	Industry expand rapidly
Evolving of papers and patents	**Papers evolution**	/	Evolved into maturity stage in few years	Stable (no sign of stable)
	Patents evolution	Steady increase	Steady increase	Stable(no sign of stable)
Collaboration-Features of patent assignees collaboration networks	**Ratio of isolates**	40% (*95%*)	20% (*70%*)	20% (*50%*)
	Nodes in the largest cluster/nodes	20% (*10%*)	35% (*3%*)	55% (*10%*)
	#clusters/#nodes	60% (*97%*)	35% (*80%*)	30% (*65%*)
	Average degree	1 (*0.1*)	2 (*0.5*)	3 (*1*)
	diameters	3 (*1*)	12 (*3*)	Stable at 11-14 (no sign of stable)
Impacts	**average times cited of papers**	30 (*18*)	50～80 (*20*)	Decreased yearly
	average times cited of patents	66 (*7*)	24 (*9*)	No difference between impelling and no-impelling technologies

Notes. The values of non-impelling technologies were listed in brackets.

Discussions

This paper defines impelling technologies and constructs an ITFM model for foreseeing technologies that have potential to become impelling technologies. There is no doubting that this is an attractive topic all the time for many kinds of scientists, policy makers and stakeholders. The theoretical basis of this study is the positive correlation between the four hypothesises and the performance of an impelling technology. Four classes of indicators were introduced into the ITFM model and demonstrated on two impelling technologies and two contrasted non-impelling technologies in the field of life science. Indeed, this work is the first study about impelling technologies foresight and got some valuable results which could be used for many new technologies foresight, such as synthetic biology. Such application study would be carried out in the near future.

Nevertheless, there are still some shortages of this study. First, the ITFM model can be used only for evaluating existed technologies and not for future technologies that have not born yet. Indeed, this topic is also interesting and important. Second, the values in the ITFM were concluded from the four technologies from life science, which might volatile when used in other fields. Actually, different impelling technologies even in the field of life science might get different values. Therefore, the values in ITFM model are referenced values. The relative performance of impelling technologies is more important when the model is used for evaluating other technologies. Third, impelling technologies foresight is a complex question, which is hard to be identified easily through one or two models or methods. There must be many other indicators that could reflect the unique features of impelling technologies. Therefore, this work is just a beginning of such efforts for foreseeing impelling technologies.

Acknowledgements

We would like to thank many fellows in the field of life science from CAS, who gave a lot of advises in choosing the technologies used for case study. The paper did benefit greatly from detailed comments by an anonymous reviewer. This work is funded by the Documentation and Information Special Project of Chinese Academy of Sciences (2013). This work is funded in part by the National High Technology Research and Development Program of China (863 Program) under grant no. 2014AA021503. This work is supported in part by the West Light Foundation of the Chinese Academy of Sciences, China under grant no. [2013]165(3-6). This work is funded in part by the Main Direction Program of Knowledge Innovation of Chinese Academy of Sciences (KSCX2-EW-G-9).

References

Amanatidou, E. (2014). Beyond the veil - The real value of Foresight. *Technological Forecasting and Social Change*, *87*, 274-291.

Benner, S. A. & Sismour, A. M. (2005). Synthetic biology. *Nature Reviews Genetics*, *6*(7), 533-543.

Bettencourt L. M. A., Kaiser D. I. & Kaur J. (2009). Scientific discovery and topological transitions in collaboration networks. *Journal of Informetrics*, *3*(3), 210-221.

Carlson, L. W. (2004). Using technology foresight to create business value. *Research-Technology Management*, *47*(5), 51-60.

Chen, C. M. (2012). Predictive effects of structural variation on citation counts. *Journal of the American Society for Information Science and Technology*, *63*(3), 431-449.

Chen, Y. W., Börner, K. & Fang, S. (2013). Evolving collaboration networks in Scientometrics in 1978-2010: a micro-macro analysis. *Scientometrics*, *95*(3), 1051-1070.

Chen, Y. W. & Fang, S. (2014). Mapping the evolving patterns of patent assignees' collaboration networks and identifying the collaboration potential. *Scientometrics*, *101*(2), 1215-1231.

Collins, F. S., Morgan, M. & Patrinos, A. (2003). The human genome project: Lessons from large-scale biology. *Science*, *300*(5617), 286-290.

Compton, K. T. (1939). Technical progress and social development. *Electrical Engineering*, *58*(1), 12-15.

Cook, C. N., Inayatullah, S., Burgman, M. A., et al. (2014). Strategic foresight: how planning for the unpredictable can improve environmental decision-making. *Trends in Ecology & Evolution*, *29*(9), 531-541.

Das, M. R. (2001). Biotechnology in the 21(st) Century. *Defence Science Journal*, *51*(4), 327-332.

Firat, A. K. (2008). Technological Forecasting – A Review. Working Paper CISL# 2008-15.

Forster B. & Gracht H. (2014). Assessing Delphi panel composition for strategic foresight - A comparison of panels based on company-internal and external participants. *Technological Forecasting and Social Change*, *84*, 215-229.

Garfield, E. (1979). Is citation analysis a legitimate evaluation tool. *Scientometrics*, *1*(4), 359-375.

Goldbeck, W. & Waters, L. H. (2014). Foresight education: When students meet the future(s). *Futurist*, *48*(5), 30.

Guimerà, R., Uzzi, B., Spira, J. & Amaral, L. A. N. (2005). Team assembly mechanisms determine collaboration network structure and team performance. *Science*. *308*, 697–702.

Haupt, R., Kloyer, M. & Lange, M. (2007). Patent indicators for the technology life cycle development. *Research Policy*, *36*(3), 387-398.

Havas, A., Schartinger, D. & Weber, M. (2010). The impact of foresight on innovation policy-making: recent experiences and future perspectives. *Research Evaluation*, *19*(2), 91-104.

Jarvenpaa, H. M., Makinen, S. J. & Seppanen, M. (2011). Patent and publishing activity sequence over a technology's life cycle. *Technological Forecasting and Social Change*, *78*(2), 283-293.

Kato, M. & Ando, A. (2013). The relationship between research performance and international collaboration in chemistry. *Scientometrics*, *97*(3), 535–553.

Khalil, A. S. & Collins, J. J. (2010). Synthetic biology: applications come of age. *Nature Reviews Genetics*, *11*(5), 367-379.

King, K. (2014). Foresight in middle school: Teaching the future for the future. *Futurist*, *48*(5), 41-42.

Ko, S. S., Ko, N., Kim, D., et al. (2014). Analyzing technology impact networks for R&D planning using patents: combined application of network approaches. *Scientometrics*, *101*(1), 917-936.

Lee, C., Cho, Y., Seol, H., et al. (2012). A stochastic patent citation analysis approach to assessing future technological impacts. *Technological Forecasting and Social Change*, *79*(1), 16-29.

Lintonen, T., Konu, A., Ronka, S., et al. (2014). Drugs foresight 2020: a Delphi expert panel study. *Substance Abuse Treatment Prevention and Policy*, 9.

Little, A. D. (1981). *The Strategic Management of Technology*. Cambridge, Mass.

Mansfield, E. (1961). Technical change and the rate of imitation. *Econometrica*, *29*(4), 741-766.

Markus, M. L. & Mentzer, K. (2014). Foresight for a responsible future with ICT. *Information Systems Frontiers*, *16*(3), 353-368.

Miles, I. (2010). The development of technology foresight: A review. *Technological Forecasting and Social Change*, *77*(9), 1448-1456.

Salo, A. & Cuhls, K. (2003). Technology foresight—past and future. *Journal of Forecasting*, *22*(2-3), 79-82.

Sanz-Menendez, L., Cabello, C. & Garcia, C. E. (2001). Understanding technology foresight: the relevance of its S & T policy context. *International Journal of Technology Management*, *21*(7-8), 661-679.

Shiue, Y. C. & Lin, C. Y. (2011). Developing a new foresight model for future technology evaluation in electric vehicle industry. *Journal of Testing and Evaluation*, *39*(2), 119-125.

Trappey, C. V., Wu, H. Y., Taghaboni-Dutta, F., et al. (2011). Using patent data for technology forecasting: China RFID patent analysis. *Advanced Engineering Informatics*, *25*(1), 53-64.

UNIDO. (2014). *Technology Foresight*. Retrieved May 10, 2014 from: http://www.unido.org/foresight.html.

Van Raan, A. F. J. (1996). Advanced bibliometric methods as quantitative core of peer review based evaluation and foresight exercises. *Scientometrics*, *36*(3): 397-420.

Weigand, K., Flanagan, T., Dye, K., & Jones, P. (2014). Collaborative foresight: Complementing long-horizon strategic planning. *Technological Forecasting and Social Change*, *85*, 134-152.

Weinberger, N., Jorissen, J. & Schippl, J. (2012). Foresight on environmental technologies: options for the prioritisation of future research funding - lessons learned from the project "Roadmap Environmental Technologies 2020+". *Journal of Cleaner Production*, *27*, 32-41.

Whitfield, J. (2008). Collaboration: Group theory. *Nature*. *455*, 720-723.

Wuchty, S., Jones, B. F. & Uzzi, B. (2007). The Increasing dominance of teams in production of knowledge. *Science*. *316*, 1036–1039.

Yoon, B., Lee, S. and Lee, G. (2010). Development and application of a keyword-based knowledge map for effective R&D planning. *Scientometrics*, *85*(3), 803-820.

Zhang, J. X., Zhang, H. S., de Pablos, P. O., et al. (2014). Challenges and foresights of global virtual worlds markets. *Journal of Global Information Technology Management*, *17*(2), 69-73.

Zhou, X., Zhang, Y., Porter, A. L., et al. (2014). A patent analysis method to trace technology evolutionary pathways. *Scientometrics*, *100*(3), 705-721.