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Exploring technological resilience at the country level with patents

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ABSTRACT
Resilience is critical to stabilise and reduce shocks and create advantages over competitors in environments with dramatic change and unexpected crises. There is no generally agreed-upon definition of technological resilience, and there is not yet a well-developed theory of technological resilience at the country level. The objective of this paper is to contribute to technological resilience research based on patent indicators by analyzing OECD countries' technological resilience. This paper provides a framework to analyze the quality of selected patent indicators used for estimating technological crisis. More specifically, four sets of patent indicators, i.e. collaboration, knowledge, diversity, and legal protection, are employed to evaluate technological resilience, which is characterised as crisis probability, intensity, and duration. We found that higher technological coverage leads to higher crisis probability, more original technology leads to higher crisis intensity, and interpersonal collaboration enhances the chance of passing a crisis.

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Technological resilience; technological crisis; patent

Introduction

Resilience is the capacity of a system to absorb shocks and to respond to changes to allow the system to maintain its same function and structure (Walker et al. 2004). Scholars have taken an evolutionary approach to regional resilience that focuses on the long-term capacity of regions to redeploy their economic and institutional structures to develop new growth paths (Simmie and Martin 2010). Recent publications have attempted to analyze resilience in various contexts. Resilience has been applied to regional and local economic growth and has been discussed related to local economies' technological resilience in crises (Martin, Sunley, and Tyler 2015). It was argued that resilience is a dynamic feature insuring regional sustained development or rapid recovery after economic shock (Palekiene, Simanaviciene, and Bruneckiene 2015). In addition, Folke et al. (2002) investigated how to maintain and enhance adaptive capacity in a complex world of rapid changes (Folke et al. 2002). Rose (2007) suggested the combination of inherent and adaptive capabilities and their interactions within the region could enhance the region's resilience to shock (Rose 2007). Previous explorations of adaptive resilience have suggested that a successful adaptive system is capable of absorbing shock when necessary (Cowell 2013). It can be found that resilience literature spans several disciplines, but are fragmented across different foci comprising individuals, cities, nations, regions, and from the perspectives of ecology, engineers, and the economy (Adger 2000; Foster 2007).

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Technological resilience has barely been investigated, so far only two studies can be found in literature, (1) Rajib, Rahman, and McBean (2012) evaluated potential technological resilience of specific small drinking water systems from the Bangladesh perspective (Rajib, Rahman, and McBean 2012), (2) Balland, Rigby, and Boschma (2015) explored technological resilience of 366 US cities by analyzing how the three factors, i.e. technological flexibility, institutional flexibility and network flexibility influence technological resilience (Balland, Rigby, and Boschma 2015). In comparing the two studies, Rajib, Rahman, and McBean (2012) conducted a technology level investigation based on a very specific approach designed solely for evaluating small drinking water systems (Rajib, Rahman, and McBean 2012), but Balland, Rigby, and Boschma (2015) conducted a city level investigation based on multivariate regression (Balland, Rigby, and Boschma 2015) which can possibly be applied to other cities or other levels that have never been investigated.

The research gap arising from the literature review is the theoretical and empirical understanding of technological resilience at the country level. Although technological capacity has become a powerful engine for a nation's economic development, it's unclear which factors are conducive to country-level technological resilience.

To fill the research gap, this study explores factors influencing technological resilience of OECD countries. This study's contribution is to increase our understanding of technological resilience, and to heuristically explore the effectiveness of patent-based indicators for evaluating technological resilience. The study contributes empirical insights of technological resilience, and sheds further light on the roles of collaboration, knowledge, diversity, and legal protection on technological resilience in distressed periods.

This paper's structure is as follows: In Theoretical Background, we discuss technological resilience literature and the influence of collaboration, knowledge, diversity, and legal protection on technological resilience. In Research Method, we present data sources and statistics-based methods. In Results and Discussion, we analyze three regression modeling results. In the Conclusion, we provide major findings and management implications, as well as discuss research limitations and potential future research.

Theoretical background

Resilience and technology

Resilience is the ability to maintain system structure and function, and emphasises how regions and localities respond to shocks and stresses (Berkes, Colding, and Folke 2003; Martin and Sunley 2015). Being resilient is vital to strengthen a region or a country's economy. Regional economies responding to shocks will rely on their adaptability to new technologies and industrial transformations (Martin and Sunley 2015). Therefore, research related to social-ecological systems has shown that technology plays an important role on resilience. Technology stimulates economic growth and the development of social structures, which further influences social-ecological resilience (Young et al. 2006). Mark and Semaan (2008) investigated how technology influences disruptive environments and the role of technology in recovery and adaptability (Mark and Semaan 2008). Technology helps predict the change in the environment and captures social-ecological resilience (Smith and Stirling 2010). Moreover, Harding (2000) investigated a resilient technology transfer system in a period of dramatic exogenous change and concluded that a technology transfer system with resilience is capable of adapting to radical technological change (Harding 2000).

There have been limited studies dealing with technological resilience, Balland, Rigby, and Boschma (2015) first explored technological resilience of US cities and examined which factors are conducive to technological resilience during periods of patenting decline (Balland, Rigby, and Boschma 2015). Inspired by prior study (Balland, Rigby, and Boschma 2015), this study defined technological resilience of countries as the long-term capacity of countries to maintain their levels of technological knowledge creation in the context of technological crises.

Prior studies have investigated technological development in light of four key strategies, collaboration (Kaufman, Wood, and Theyel 2000; Wagner et al. 2001), knowledge (Kogut and Zander 1992; Leonard-Barton 1995), diversity (Norberg and Cumming 2013; Chelleri et al. 2015), and legal protection (Hamza 1984; Burgunder 2010). After presenting the relevant context, the relation between the four strategies and resilience are reviewed below.

Collaboration leading to resilience

Collaboration allows accessing strategic assets (Baum, Calabrese, and Silverman 2000), pooling complementary technology (Mohnen and Hoareau 2003), learning from partners (Fritsch 2002), and sharing risks and costs. Literature has examined how collaboration enhances firm-level innovation (McGill and Santoro 2009). International collaboration is one common form of international activity because technology and resources from different countries can be integrated and thus generate better output (March 1991; Levinthal and March 1993). Prior studies suggested that international R&D collaboration generates positive impact on patent value (Alnuaimi, Singh, and George 2012); patents with a foreign co-inventor are more valuable (Branstetter, Li, and Veloso 2014).

On the other hand, as Kitching, Smallbone, and Xheneti (2009) concluded that limited resources render firms vulnerable to changes in the external environment, it is important to understand the strategy and sources for achieving resilience as they may influence longer-term business performance (Kitching, Smallbone, and Xheneti 2009). Goldstein (2011) examined a range of efforts to enhance resilience through collaboration, describing communities that have survived by building trust and interdependence (Goldstein 2011). Patterson et al. (2007) highlighted that collaborative cross-checking can greatly enhance organisations' resilience (Patterson et al. 2007).

As different types of collaboration across personal, organisational, and national boundaries are important channels of knowledge sourcing, the following four patent characteristics, Inventor Count (interpersonal), Assignee Count (interorganizational), Inventor Country Count, Assignee Country Count (international) (Ma and Lee 2008; Lei et al. 2013; Su 2017), are selected as proxies for collaboration for characterising technological resilience in this study. We analyzed the explanatory power of the four collaboration-based patent indicators in estimating resilience.

The role of knowledge on resilience

There is a growing recognition that knowledge is an important economic factor (Cooke and Leydesdorff 2006). Academics and practitioners have addressed the importance of knowledge (Grant 1996). In addition to having noted the significant role knowledge plays in this society, resilience literature also emphasised the value of knowledge. For example, Berkes (2007) highlighted that increasing the range of knowledge for learning and problem-solving is a relevant factor to building resilience (Berkes 2007). It was also argued that efficiently obtaining external knowledge can lead to better resilience (Cohen and Levinthal 1990) and a knowledge network composed of many knowledge flows is important for building resilience (Balland, Suire, and Vicente 2013; Crespo, Suire, and Vicente 2014).

The patent system allows the developed technological knowledge to be preserved, exchanged, used for solving problems, and is consistent with the objective of building resilience. This study considered the association between technological knowledge and resilience, and used knowledge-related patent indicators to characterise how knowledge influences technological resilience. The following three patent indicators were used: (1) Reference Count- linkage to backward patents (Silverberg and Verspagen 2007), (2) Time Cited Count- linkage to forward patents (Blind, Cremers, and Mueller 2009), (3) Non-Patent Reference Count (NPR Count)- linkage to prior scientific knowledge (Verbeek et al. 2002).

It is to be noted that Time Cited Count (forward citation count)is the most popular indicator to measure patent value in literature (Hall, Jaffe, and Trajtenberg 2005; Blind, Cremers, and Mueller 2009). This study followed Lanjouw and Schankerman (1999) and used a five-year forward citation window to measure patent value (Lanjouw and Schankerman 1999) but the citation windows for patents after 2010 are subject to different degree of truncation. The adoption of this approach can ensure the full-length of patent application timespan (40 years) to be considered for crisis identification to facilitate this study based on crisis events.

Diversity leading to adaptability of resilience

Berkes, Colding, and Folke (2003) concluded that adaptability is the ability of a system to learn, combine experience and knowledge, and adjust how the system responses to internal and external impacts to return to its original function and structure (Martin and Sunley 2015). Ostrom (2007) argued a successful adaption relies on rich options, which were defined as the range of operational choices that have been tried in a diverse system (Ostrom 2007). This concept can apply to a bioecological system where biological diversity is a rich option for effective adaption to the bioecological system (Norberg et al. 2012).

Lemos et al. (2013) argued that technology is an important factor influencing a system's adaptability (Lemos et al. 2013) to responding to an unexpected shock (Armitage 2007). It was suggested that sustaining diversify is a critical factor to reinforcing a system's capability to cope with unforeseen events and to reduce the damage to the system (Norberg and Cumming 2013). Accordingly, we inferred that sustaining a system's technological diversity is positively correlated with high adaptability, and therefore the system has better resilience (Chelleri et al. 2015).

Following previous innovation literature that used patents to capture diversification-related concepts (Shannon and Weaver 1963; Lerner 1994; Trajtenberg, Henderson, and Jaffe 1997; Harhoff, Scherer, and Vopel 2003; Somaya 2003; Rafols and Meyer 2010), this study used four indicators to capture concepts relevant to technological diversification: (1) Diversity Index- Shannon diversity (Shannon and Weaver 1963) was used to in this study to calculate how patents are classified into the 35 industries (Ulrich Schmoch 2008), (2) IPC count- the degree of technological coverage (Lerner 1994), (3) Originality Index- originality of a patent (Trajtenberg, Henderson, and Jaffe 1997), and (4) Generality Index- generality of a patent (Trajtenberg, Henderson, and Jaffe 1997).

The influence of legal protection on resilience

Legal activity plays an essential role in shaping resource and technological development policy. A resilient country must have better governance and transparency regulated by a well-developed legal system. The legal system encourages not only knowledge sharing and collaboration, but also intellectual property rights protection. Garmestani, Allen, and Benson (2013) suggested integrating law and social-ecological resilience (Garmestani, Allen, and Benson 2013). It was suggested that weak IP rights help developing countries and least-developed countries enhance climate change resilience (Azam 2011). This study analyzed the influence of legal protection on technological resilience, using two patent-based indicators: (1) Claim Count- scope of legal protection (Tong and Frame 1994), and (2) Litigation Probability- the probability of a patent to be investigated by the court (Su, Chen, and Lee 2012).

The definitions and references of all indicators used in this study for analyzing technological resilience are provided in Table 1.

Data and method

Data

This study used USPTO patents for understanding technology resilience for the following three reasons: (1) the US is the biggest market that attracts global patent filings, (2) the USPTO database is regarded as the most reliable data source for global innovation studies (Jeeeun Kim 2015). Since

Table 1. Patent indicators used in this study.

Indicators	Definition	Reference
Collaboration		
Assignee Count	average number of inventors per patent	Lei et al. (2013); Su (2017)
Assignee Country Count	average number of assignee countries per patent	Ma and Lee (2008); Su (2017)
Inventor Count	average number of Inventors per patent	Lei et al. (2013); Su (2017)
Inventor Country Count	average number of inventor countries per patent	Ma and Lee (2008); Su (2017)
Knowledge		
Reference Count	average number of backward patent references per patent	Silverberg and Verspagen (2007)
Time Cited Count	average number of forward citations received per patent	Lanjouw and Schankerman (1999)
Non-Patent Reference Count	average number of non-patent references per patent	Allison et al. (2003)
Diversity		
Diversity Index	diversity of technology based on Shannon entropy	Rafols and Meyer (2010); Shannon and Weaver (1963)
IPC Count	averaged IPC count per patent	Lerner (1994)
Generality Index	Herfindahl index on technological classes of citing patents	Trajtenberg, Henderson, and Jaffe (1997)
Originality Index	Herfindahl index on technological classes of cited patents	Trajtenberg, Henderson, and Jaffe (1997)
Legal Protection		
Claim Count	average number of claims per patent	Tong and Frame (1994)
Litigation Probability	the probability of a patent to be investigated by the court	Su, Chen, and Lee (2012)

we are interested in the time of technological knowledge creation, USPTO patents applied between 1976 and 2015 and granted to 35 OECD member countries were downloaded from the USPTO website (USPTO 2016). A total of 4,466,192 patents were obtained. A total of 13 patent-related data as patent-based indicators, Table 1, together with gross domestic expenditure on R&D (GERD) (OECD 2016), were used as 14 independent variables in the following regression work.

Method

Inspired by Balland, Rigby, and Boschma (2015) (Balland, Rigby, and Boschma 2015), this study defined technological resilience of countries as the long-term capacity of countries to maintain their levels of technological knowledge creation in the context of technological crises. In other words, technological resilience was characterised in this study by three perspectives of technological crisis, i.e. (1) crisis probability, (2) crisis intensity, (3) crisis duration. A resilient country is expected to have low crisis probability, low crisis intensity and short crisis duration.

To illustrate this study's method for investigating resilience, a curve with patent application time as x-curve and patent count as y-axis, together with important properties and definitions relevant to resilience are schematically provided in Figure 1. As shown in Figure 1, a system experienced the first crisis by moving along the curve from peak (T_1) to trough (T_2) where the current system (T_2) is currently located, and will move from trough (T_2) to peak (T_3) to experience growth, then will further experience the second crisis and reach the new system states in trough (T_4) of the second crisis.

Technological crisis and technological growth identification

To identify technological crisis and technological growth, a time series of patent count as a function of patent application time, consistng of local maxima (peaks at T_1 or T_3) and local minima (troughs at T_2 or T_4), for each of the 35 countries is prepared, Figure 1. The time series of patent count is always noisy and complex. So we adopted the Stata module (Bracke 2012) of the algorithm to detect business cycles (Harding and Pagan 2002), and to detect turning points which are peaks or troughs in a time series.

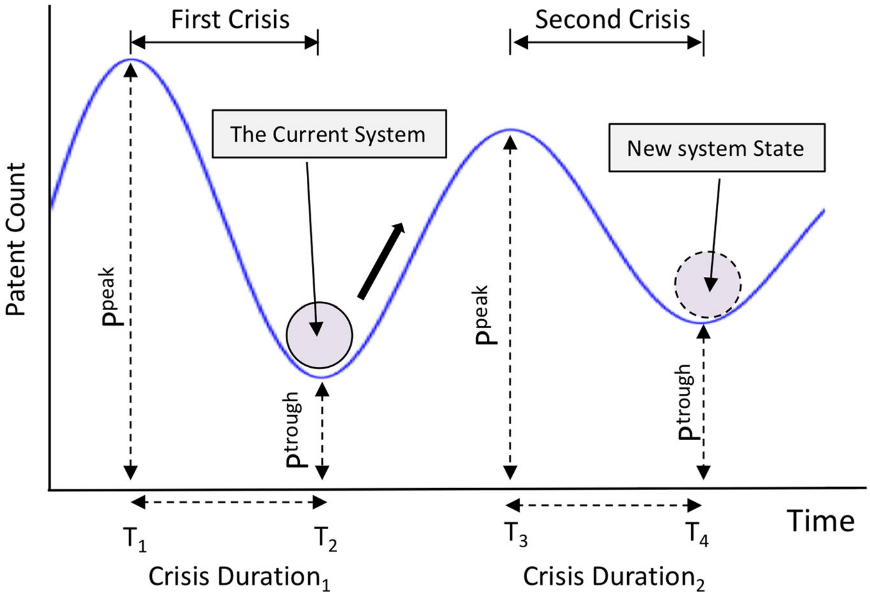

Figure 1. Technological crisis-related properties used in this study.

Identifying factors influencing technological resilience

Similar to Balland, Rigby, and Boschma (2015), the study identifies factors that may influence technological resilience from the following three perspectives: (1) which factors reduce crisis probability? (2) which factors reduce crisis intensity? and (3) which factors reduce crisis duration? To answer these three questions, three different models were chosen for multivariate regression analysis.

A total of 14 independent variables, Table 1, were used in the three regression analyses, and can be classified into five categories: (1) Collaboration: Assignee Count, Assignee Country Count, Inventor Count, Inventor Country Count, (2) Knowledge: Reference Count, Time Cited Count, Non-Patent Reference Count, (3) Diversity: Diversity Index, IPC Count, Generality Index, Originality Index, (4) Legal protection: Claim Count, Litigation Probability Index, (5) Control: gross domestic expenditure on R&D (GERD). The three different models and corresponding dependent variables were selected for three regression analyses that answer the following three questions:

(1) Which factors reduce crisis probability?

A resilient country is a country with less frequent opportunities to meet crisis. if the country enters a period of sustained negative technological growth (from peak to trough), i.e. entering into a dropping status, the dependent variable is set as 1; otherwise, it is set as 0. Since a dependent variable is binary (either 1 or 0), a logistic regression model was selected (Balland, Rigby, and Boschma 2015).

(2) Which factors reduce crisis intensity?

A resilient country tends to have lower crisis intensity. To measure crisis intensity, the difference between the maximum patent count (at the peak) and the minimum patent has to be calculated. Crisis intensity is defined as the ratio between the patent count at the peak and the patent count at the subsequent trough. Where P is the patent count, Crisis intensity is calculated as: Crisis Intensity $= (P^{peak} - P^{trough})/P^{peak}) * 100$, P^{peak} represents patent count at peak and P^{torugh} are patent count at trough (see Figure 1). Crisis intensity varies from 0 (if P^{peak} is equal to P^{torugh}) to

100 (if P^{torugh} is equal to 0). Crisis intensity is used as dependent variable. An ordinary least square (OLS) linear equation is used for regression, and the same set of independent variables was employed.

(3) Which factors reduced crisis duration?

A resilient country has smaller crisis duration and gets over the crisis quickly. Crisis duration is measured as the number of years between a peak and its subsequent trough, crisis $\text{duration}_1 = T_2$-T_1, crisis $\text{duration}_2 = T_4$-T_3 (Figure 1). Cox's proportional hazards model was used to evaluate crisis duration. Crisis duration was used as dependent variable and the same set of independent variables were also employed. However, when some countries had crises beyond 2015 (the end of the observed time series), right-censoring was used in regression.

Results and discussion

Descriptive analysis

This study investigated all patents granted to the 35 countries. A total of 4,466,192 patents were obtained. As the 35 countries comprise both technology-oriented countries and non-technology-oriented countries, as shown in Figure 2, the number of patents each country owns varies a lot (ranging from 2,398,891 to 31). The top five patent countries are the United States (2,398,891 patents), Japan (1,025,325 patents), Germany (301,002 patents), Korea (161,142 patents), and France (114,068 patents).

A comprehensive overview of the 35 countries' technological resilience between 1976 and 2015 was captured by characterising all technological crises in the following three dimensions: (1) distribution of crisis probability, Figure 3a, where y-axis is country count and x-axis is crisis probability (averaged number of crises per year); (2) distribution of crisis intensity, Figure 3b, where y a-axis is crisis count and x-axis is crisis intensity; and (3) distribution of crisis duration, Figure 3c, where y-axis is crisis count and x-axis is crisis duration. We observed that the distribution of crisis probability, crisis intensity, and crisis duration varied remarkably across the 35 countries.

The distribution of crisis probability, Figure 3a, is more well-distributed than crisis intensity and crisis duration. Thirteen countries have highest crisis probability score of around 0.2 and an

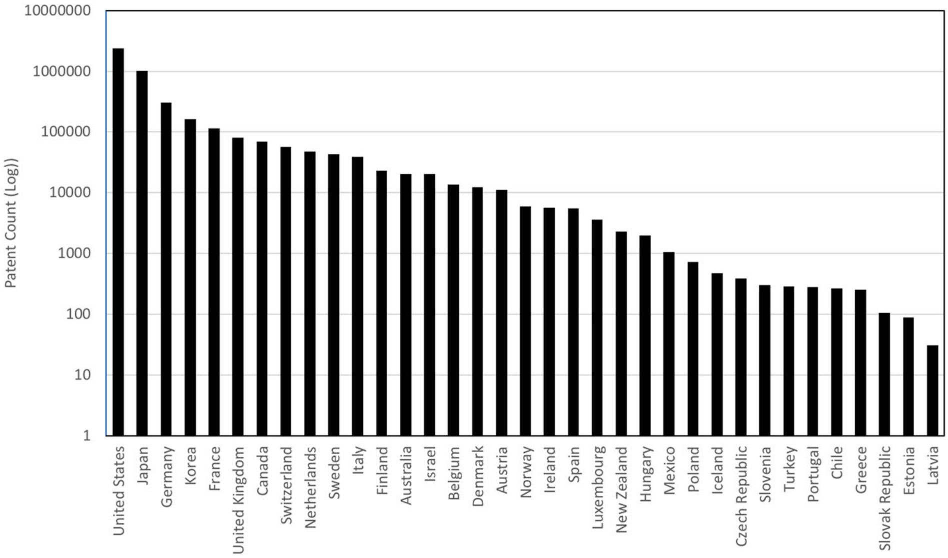

Figure 2. Patent counts for 35 countries.

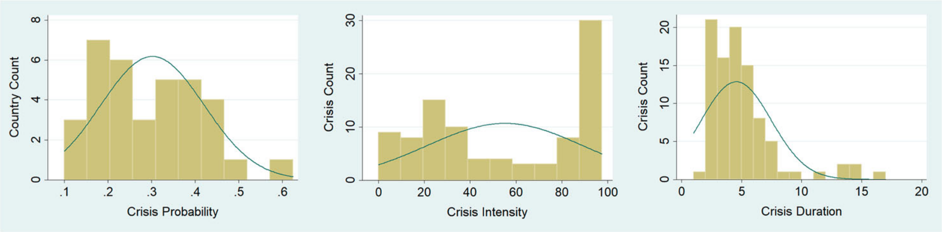

Figure 3. Probability, intensity, and duration of technological crises. (a) Distribution of crisis probability; (b) Distribution of crisis intensity; (c) Distribution of crisis duration.

average crisis probability of 0.3. The distribution of crisis intensity shown in Figure 3b indicates highly skewed distribution where a large number of crises have intensities of about 90. This reveals a strong resilience divide in terms of crisis intensity. The crisis duration provided in Figure 3c suggests a negative binomial distribution where most crises have durations of around three to six years, but some crisis durations are longer than 15 years.

Descriptive statistics were conducted to analyze all variables considered in this study. The results are shown in Table 2. On average, each country applied for 3541 patents in one year, and each patent had about 1.04 assignees and 2.88 inventors. There were 7.78 references, 1.92 received citations, and 3.59 IPCs in each patent document. The mean litigation probability was 0.0005. High standard deviations of the variables can be observed and may be viewed as an indicator for different patenting strategies pursued by different countries (Ernst 1995). The observation value is 1261 for patent related indicators and 940 for GERD (35 countries*40 years timespan = 1400 observations if no missing data) because some countries do not have any patent in some particular years and some GERD data are unavailable.

Multivariate regression

To evaluate the appropriateness of using the selected independent variables for following multivariate regressions, a correlation matrix is provided in Table 3 for checking the collinearity among variables. The absolute value of correlation coefficients lower than 0.7 indicating problem of multicollinearity does not exist (Dormann et al. 2013).

Which factors reduce crisis probability?

The factors influencing crisis probability were estimated in Table 4. A negative coefficient indicates negative influence on a country's probability of entering into a crisis. In other words, a negative

Table 2. Summary statistics of the dependent and independent variables.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Patent Application	1261	3541.7860	12551.5100	1	99714
Assignee Count	1261	1.0429	0.0944	1	3
Assignee Country Count	1261	1.0144	0.0561	1	2
Inventor Count	1261	2.8779	1.6995	1	16.6345
Inventor Country Count	1261	1.3469	0.2735	0	4
Reference Count	1261	7.7724	8.6460	0	104.32
Time Cited Count	1261	1.9244	1.6086	0	18
Non-Patent Reference Count	1261	5.3347	9.0164	0	145.5333
Diversity Index	1261	2.5309	0.8901	0	3.3969
IPC Count	1261	3.5924	1.8907	0	22
Generality Index	1261	0.1386	0.1163	0	1
Originality Index	1261	0.3340	0.1713	0	1
Claim Count	1261	13.9494	4.5071	1.5	40.5
Litigation Probability Index	1261	0.0005	0.0023	0	0.05
GERD	940	21976.9400	56915.9900	20.53	502893

Table 3. Correlation matrix for variables used in models.

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Assignee Count	1.0000													
2	Assignee Country Count	0.6226*	1.0000												
3	Inventor Count	0.0935*	0.0813*	1.0000											
4	Inventor Country Count	−0.0450	0.0145	0.3239*	1.0000										
5	Reference Count	−0.0359	0.0133	0.2674*	0.2970*	1.0000									
6	Time Cited Count	−0.0113	−0.0207	−0.3215*	0.0986*	0.0963*	1.0000								
7	Non-Patent Reference Count	0.0298	0.0858*	0.3479*	0.2600*	0.5463*	−0.0959*	1.0000							
8	IPC Count	−0.0117	0.0139	−0.2736*	0.0875*	−0.1338*	0.3984*	−0.0570*	1.0000						
9	Diversity Index	−0.0780*	−0.1076*	−0.0756*	−0.0059	0.0455	0.1521*	−0.0694*	0.0503	1.0000					
10	Generality Index	0.1377*	0.0252	−0.3355*	−0.0096	−0.0960*	0.6463*	−0.2060*	0.3560*	0.2029*	1.0000				
11	Originality Index	−0.0078	0.0116	0.1218*	0.2508*	0.4352*	0.1582*	0.2878*	−0.0029	0.1832*	0.0553*	1.0000			
12	Claim Count	−0.0653*	0.0226	0.1474*	0.3430*	0.5059*	0.1522*	0.4024*	0.0590*	0.1130*	0.0267	0.5343*	1.0000		
13	Litigation Probability Index	−0.0305	−0.0212	−0.0786*	0.0612*	0.0174	0.2262*	−0.0382	0.0801*	0.1164*	0.1958*	0.0600*	0.0891*	1.0000	
14	GERD	−0.0462	−0.0585	0.1703*	−0.0380	0.1972*	0.0785*	0.0268	−0.1100*	0.2477*	0.0248	0.1250*	0.1336*	0.0569	1.0000

*$p < 0.05$.

Table 4. Estimated results of the logistic model for crisis probability.

Independent variable	Coefficients	Robust Standard Error	*P* value
Assignee Count	−2.7302	4.5583	0.5490
Assignee Country Count	5.1072	5.6674	0.3680
Inventor Count	−0.2341	0.1515	0.1220
Inventor Country Count	−0.7160	0.7383	0.3320
Reference Count	0.0289	0.0241	0.2310
Time Cited Count	0.1058	0.1149	0.3570
Non-Patent Reference Count	−0.0645	0.0395	0.1030
Diversity Index	−0.1279	0.1900	0.5010
IPC Count	0.2635***	0.0843	0.0020
Generality Index	−2.8155	1.9425	0.1470
Originality Index	−0.5984	1.0826	0.5800
Claim Count	−0.0720	0.0487	0.1390
Litigation Probability Index*1000	−0.1147	0.1478	0.4380
GERD	0.0000*	0.0000	0.0790
Constant	−2.9222	3.1153	0.3480
Observations	911		

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

contribution to crisis probability means the increase of resilience and a positive contribution means the increase of vulnerability in terms of crisis probability. The coefficient of IPC count is positive and significant, suggesting there is strong relationship between IPC count and crisis probability in the 35 countries. As the level of technological coverage increases (indicated by the positive coefficient of IPC count), the likelihood that a country enters a crisis rises. It maybe because higher technological coverage of a patent leads to perplexed understanding on the quality of such unclear patented technology (Guellec and van Pottelsberghe de la Potterie, 2000; Lanjouw and Schankerman 2001). In addition, high technological coverage can increase R&D and commercialisation costs, and complicate organisational rules (Durand, Bruyaka, and Mangematin 2008). Most of the rest of the dependent variables have negative coefficients, suggesting the increase of these values leads to the decreased crisis probability, but their *P* values reveal they are not significant factors. Other than IPC counts that represent technology diversity, the other variables show nonsignificant coefficients, so their relationships to crisis probability are very limited. In this estimation, the observation value is 911 because not all the 35 countries have both patent and GERD data in each of the 40 years (1976~2015).

Which factors reduce crisis intensity?

The factors influencing crisis intensity were estimated in Table 5. A negative coefficient indicates negative influence on crisis intensity. Similarly, negative contributions mean the increase of resilience,

Table 5. Estimated results of the OLS model for crisis intensity.

Independent variable	Coefficients	Robust Standard Error	*P* value
Assignee Count	−15.2134	74.8675	0.8400
Assignee Country Count	26.3853	85.1509	0.7580
Inventor Count	−1.5521	4.2093	0.7140
Inventor Country Count	−1.2600	15.7791	0.9370
Reference Count	0.0307	0.3950	0.9380
Time Cited Count	−7.4210	5.7149	0.2000
Non-Patent Reference Count	0.2888	0.5000	0.5660
Diversity Index	−4.3474	5.8525	0.4610
IPC Count	−3.6704	2.2871	0.1140
Generality Index	−132.1589	87.6062	0.1370
Originality Index	89.9523**	38.6757	0.0240
Claim Count	1.5340	1.0609	0.1540
Litigation Probability Index*1000	−4.7497	6.6712	0.4800
GERD	−0.0001	0.0000	0.2190
Constant	49.8104	56.2385	0.3800
Observations	68		

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Table 6. Estimated results of the Cox proportional hazard model for crisis duration.

Independent variable	Hazard Ratio	Robust Standard Error	*P* value
Assignee Count	0.4869	1.9786	0.8590
Assignee Country Count	15.6974	71.2600	0.5440
Inventor Count	1.3685**	0.2291	0.0610
Inventor Country Count	0.3316	0.2380	0.1240
Reference Count	1.0073	0.0154	0.6350
Time Cited Count	1.5777	0.4396	0.1020
Non-Patent Reference Count	1.0112	0.0228	0.6210
Diversity Index	1.1894	0.3222	0.5220
IPC Count	1.0065	0.1081	0.9520
Generality Index	0.0329	0.1225	0.3590
Originality Index	0.0649	0.1081	0.1010
Claim Count	0.9718	0.0482	0.5640
Litigation Probability Index*1000	1.3993	0.4434	0.2890
GERD	1.0000	0.0000	0.6590
Observations	68		
Wald chi2 (14)	11.82		

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

and positive contribution means the increase of crisis intensity. The results show that Originality Index has significant relationship to crisis intensity. Technology with higher originality leads to higher crisis intensity, or a patent that cites prior knowledge distributed in very diverse technology fields tends to have high crisis intensity (significant at 0.05 level). The Originality Index relates to the technological diversities of backward patents. The decrease of Originality Index, meaning higher association to prior technology fields, will lead to enhanced technological resilience for crisis intensity. The observation value indicates the total 68 crises of the 35 countries between 1976 and 2015.

Which factors reduce crisis duration?

The factors influencing crisis duration were estimated in Table 6. The Cox proportional hazard model was used to estimate the hazard of leaving a crisis. A coefficient larger than one indicates that the chance of leaving the crisis increases. In Table 6, the hazard ratio for inventor count is 1.3685 and significant. This indicates that the increase of one inventor per patent will increase the probability of leaving a crisis by 36%. The result is in line with what have been suggested in literature that interpersonal collaboration in a R&D team is an imperative strategy to learn from a partner (Simonin 1999a, 1999b; Fritsch 2002), pool complementary technology (Duysters and Hagedoorn 1998; Mohnen and Hoareau 2003) and thus enhance R&D efficiency. The high levels of professionalisation among R&D personnel may encourage greater communication and idea exchange as R&D team size increases (Dailey 1980). It was argued that R&D team size is positively related to team innovation (Peltokorpi and Hasu 2014), team performance and team creative environment (Bornay-Barrachina and Herrero 2017). The observation value indicates the total 68 crises of the 35 countries between 1976 and 2015.

Conclusion

Scholars have well recognised the importance of resilience but technological resilience has been scarcely investigated. This study tentatively explored 13 factors that may influence 35 countries' technological resilience between 1976 and 2015. The selected factors can be categorised into four critical dimensions, collaboration, knowledge, diversity, and legal protection, to reflect important strategies for technological development in knowledge-based economies. On the other hand, technological resilience is characterised by three independent crisis properties, i.e. crisis probability, crisis intensity, and crisis duration, to capture a comprehensive scope of resilience. Several important findings can be summarised as follows: (1) the Logistic model showing decreasing technological coverage can lower the probability for a country to enter a crisis, (2) the OLS model revealing that decreasing originality enhances technological resilience by reducing crisis intensity, and (3) the Cox proportional hazard model suggesting interpersonal collaboration reinforces technological resilience by shortening crisis duration.

It is found that indicators in both perspectives of knowledge and legal protection have non-significant effects on technological resilience. This might be because of low number of observation or the selected indicators do not effectively capture how knowledge and legal protection influence technological resilience. Due to the well- accepted concept that knowledge and legal protection play vital roles in technological development of knowledge economy, this study therefore does not conclude that knowledge and legal protection have nothing to do with technological resilience but only suggests the selected knowledge and legal protection related indicators might not be feasible enough for capturing technological resilience.

Management implications

Several management implications can be drawn from this study. First, the reduction of crisis probability caused by a decrease in technological coverage per patent implies that firms are encouraged to concentrate its R&D resources on specific technology fields and stay focus on a small number of core technology fields. The resilience of county can be enhanced if firms developed a portfolio with a clear technology focus (Fisher-Vanden and Jefferson 2008). Second, as referring to more prior technology fields leads to high-originality technologies and increased crisis intensity, it is suggested that the exploration of prior knowledge for developing new technologies should be kept in focus and properly linked to prior knowledge. Although high-originality represents radical innovation or creativity, a certain level of association to prior technologies is still necessary for incrementally and continuously developing new technologies required in a resilient country. Third, interpersonal collaboration reinforces technological resilience by shortening crisis duration, and thus it is suggested that R&D collaboration be encouraged by providing a platform to facilitate better communication, resource exchange, and idea sharing among R&D personnel, as well as an incentive system to award inventors for their collaborative works.

Contribution to theory

This research is the first study using patents to investigate technological resilience at the country level. We employed 13 patent-based indicators, categorised into four critical dimensions, collaboration, knowledge, diversity, and legal protection, to test their significance to contributing to technological resilience. As technology has been regarded as a core-competence for a country to survive global competition, the study used patent-based indicators to provide a channel to correlate technological resilience and global developments in a general manner. For example, the missing link between technological resilience and relevant research fields, i.e. sustainability science, Sci-Tech policy, and innovation, shown in literature can be bridged by this study, based on systematic examination of technological resilience using patent-based indicators.

Research limitations and future study

There are two major limitations in this research. First, the selected indicators in this study might not be able to effectively capture technological resilience, therefore it is suggested to test other indicators such as knowledge stock (Park and Park 2006), knowledge transfer (Amesse and Cohendet 2001), Stirling diversity (Stirling 2007), Simpson diversity (Simpson 1949) and patent protection index (Park 2008). Second, patent might not be a proper approach for less technology-oriented countries, so it is suggested to use non-patent approach such as survey or interview and compares the results with current study based on patent.

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