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Cumulative dissertation

Technology dynamics in urban innovation:

Development of a System Structure, Comparison between Countries, Analysis of Technology Interactions

by

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Preface

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List of publications

The soul of the study is reflected in the combination of three articles below. The first two papers have already gone through blind peer review processes and later on they have been published in international journals. The third one has also been evaluated by qualified reviewers before being accepted for presentation in PICMET 22 Conference and inclusion in the Proceedings.

i. Paper 1: Nguyen, N. U. P. and Moehrle, M. G. (2019) 'Technological Drivers of Urban Innovation: A T-DNA Analysis Based on US Patent Data', *Sustainability*, 11(24), pp. 1–26. doi: https://doi.org/10.3390/su11246966 (status: Published).

ii. Paper 2: Nguyen, N. U. P. and Moehrle, M. G. (2021) 'Combining the Analysis of Vertical and Horizontal Technology Convergence : Insights From the Case of Urban Innovation', *IEEE Transactions on Engineering Management*. IEEE, pp. 1–14. doi: 10.1109/TEM.2021.3086320 (status: Early Access).

iii. Paper 3: Nguyen, N. U. P. 'Exploring the development of the smart city project in Vietnam based on patent analysis of resident and non-resident applicants' submitted to *PICMET 2022 Conference* (status: Accepted).

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1. Introduction

Nowadays, the increasing number of people moving from the countryside to cities leads to fast urbanization, along with its troubles, in several cities in the world (Bottero *et al.*, 2019). This serious situation makes the whole globe face many difficulties related to environment, natural resources, city infrastructures and other social problems. Many aspects, especially technologies, are combined to solve such troubles (Li *et al.*, 2019). Hence, that suggests many issues of researches.

Fast urbanization and the way to deal with it, how urban innovation or smart city is applied to cope with issues of urbanization, technological drivers of urban innovation and movements of technologies in this field, etc. are motivations for this research. Furthermore, according to Yayboke, Crumpler, and Carter (2020), recently, the strong development of "mobile payment systems and digital banking apps" in developing countries to replace "credit card-based systems" in developed nations is a famous example of "leapfrog". Leapfrogging countries skip the traditional step of development (the same process of the development of developed nations), ignore intermediate technologies and jump directly to the most advanced technologies (Fong, 2009). So the difference in strategies for developing technologies between developed and leapfrogging countries is also another motivation for this research to observe the way urban innovation grows in such two different kinds of countries.

In this dissertation, there are seven sections which show some main theories and research methods related to urban innovation in the systematic point of view and technology convergence in this field, the summary of three articles and how they are connected with each other and with this dissertation, as well as some implications and future researches. This first section opens the door to not only issues that led to the conduct of the research but also research questions and how to answer them, and the structure of the whole dissertation.

1.1. Challenges leading to urban innovation and the phenomenon of technology convergence in urban innovation

Governments and many organizations are dealing with challenges caused by rapid urbanization. This occurs because cities attract more and more people to settle down for good conditions in jobs, education, health care, etc. (Moore, Gould and Keary, 2003). Urban innovation is one of recommended methods to overcome problems of this situation by applying many fields of innovations, for instance, technological innovations. When adopting the combination of several technologies in urban innovation, the appearance of technology movement or technology convergence is also interesting in many plans for urban improvement in several countries (Yigitcanlar, 2015).

a. Challenges leading to urban innovation

Dvir and Pasher (2004) assert that a city is a place of 'population concentration' and of cultural, social, and commercial activities with its own characteristics. Thus, Huston, Rahimzad and Parsa (2015) point out that cities play the most important role in the development of their countries and the world. This is the reason why cities have been attracting a large number of people leaving rural areas to expect a better life in urban areas, bringing about rapid urbanization in all over the world. Over 50% of the world population is currently urban. In 2050, about 70% of people in the globe is projected to live in cities (Naphade *et al.*, 2011) and it is forecasted that there will be 150 cities of more than 3.000.000 people (Dvir and Pasher, 2004).

Although a very small area on earth belongs to cities, city inhabitants use the majority of the world's energy resources and emit a great deal of greenhouse gas. Several serious troubles come from this situation of fast urbanization related to lack of resources, poor health care, environmental pollution, degraded facilities, problems in traffic and in waste management, and other social and technical issues (Nam and Pardo, 2011). This fact results in a big challenge to the world in the 21st century to make plans for 'sustainable urban future' with friendly and smart transportation systems and construction works as well as replacement of fossil fuels with 'renewable energies' in industries (Han *et al.*, 2012). Therefore, an immediate solution for cities is to become smart cities. Shahidehpour, Li and Ganji (2018) believe that smart city or urban innovation is a potential means to solve matters of urbanization in many countries including developed and developing countries (Pham, 2020). This approach focuses on the improvement of city infrastructures to achieve 'sustainable urban development' and satisfy people's demands.

According to Han and Hawken (2018), smart city is carried out by various innovations including policies, technologies, culture, society, etc. Let's take some examples of aspects in smart city in namely policy innovations, management innovations, city context and smart people.

Firstly, Caragliu and Del Bo (2018) claim that policy innovations of smart city are applied to solve problems of cities regarding regulations thereby effectively influencing the development of urban economy and motivating the performance of urban innovation. They not only connect several sectors related to smart city like economy, transportation, construction and so on but also encourage the cooperation of people in cities and different levels of government. Furthermore, policies for 'city marketing' are a good way to create 'a city brand' which draws talented people, 'resources and investments' for smart city development (Nam and Pardo, 2011).

Secondly, Naphade *et al.* (2011) also give some other innovations in smart city, for instance, innovations in management. This is a smooth coordination of city infrastructures to make sure that all activities in construction or maintenance of infrastructures are performed in the most economical and planned way.

Thirdly, Han and Hawken (2018) suggest another aspect in smart city, which is the context of each city. Economic, social, cultural, political environment of a city is a very significant factor to decide that city's strategy and policies in the execution of innovations and risks of smart city (Nam and Pardo, 2011).

Fourthly, Meijer and Bolívar (2016) also recommend some other fields in smart city. They concentrate on ‘smart people’ and ‘smart collaboration’. Smart city is a result of the cooperation of many organizations and a variety of social classes, especially qualified people. Their education level is a major element of the development of city in the process of urban innovation.

Besides, many other innovations in smart city are also mentioned such as organization (Nam and Pardo, 2011), planning, operation (Naphade *et al.*, 2011), smart city governance (Meijer and Bolívar, 2016), technologies and so on. Most scientists agree that although only innovations in technologies cannot create smart city alone, it is the most crucial one in the implementation of smart city (Han and Hawken, 2018). Nam and Pardo (2011) propose that while innovations in other fields like management and policy develop quite slowly, technology innovations grow very fast so they are good tools to foster the process of smart city for people’s needs. Washburn *et al.* (2010) emphasize the importance of technologies to improve city infrastructures and services for smart city’s goal. Naphade *et al.* (2011) have the same idea as they also appreciate technologies, ICT in particular, in urban innovation. Komninos (2009) gives some examples of technologies for smart city as well such as ‘telecommunication, wired and wireless communications, the internet, laptop, smart phone, etc. Meijer and Bolívar (2016) believe that new technologies can help cities to develop their systems.

Thus, smart city is implemented based on innovations in several fields, in which technologies are very necessary.

b. <u>Convergence and technology convergence</u>

The cooperation of many aspects in urban innovation raises a question of the possibility of blurring boundaries of different fields. According to Okara, Broering and Sick (2018), convergence has been developed more and more strongly over time. Convergence process with four stages and later on, technology convergence, one of its important stages, are clearly described by many researchers.

- *Convergence process*

Forecasting convergence from the beginning in its process is very important for companies to prepare suitable plans or new technologies and to respond to the rapid changing environment at an opportune moment, so researchers delineate models of convergence process. Hacklin, Marxt and Fahrni (2009) recommend four consecutive stages including knowledge, technology, application and industry convergence, in which technology convergence have crucial relations with the other stages (Eilers *et al.*, 2019). Technology convergence is triggered by its previous stage – knowledge convergence and in turn, it also promotes its next ones - application and industry convergence.

The first stage of the process shows the development of "interdisciplinary citations" and the combinations of distinct knowledge bases. After that, technology convergence is a change from knowledge convergence to technological innovations. This stage occurs when science fields come closer, which results in the development of applied science and technology, and later on technology convergence. The second stage fosters the next one – application convergence into the new applications with "new product- or service-market combinations". Finally, in the last stage, the boundaries of related industries are blurred and new industries emerge (Hacklin, Marxt and Fahrni, 2009). Furthermore, technology convergence happens and develops before industry convergence, so understandings of the former is also the stepping stone to coping with the latter (Geum *et al.*, 2012).

- *Technology convergence in urban innovation*

Technology convergence has been taken interests since the 1980s and especially 1990s (Caviggioli, 2016). Nowadays, this phenomenon marks a remarkable development of technologies in Industry 4.0 (Kim, Jung and Hwang, 2019). It occurs when technologies are combined with each other to create new technologies (Lee, Han and Sohn, 2015). As a matter of fact, the apperance of technology convergence can be explained by many drivers. Several changes in technologies themselves and the adoption of a variety of different sectors of technology in many industries is one of the most prominent reasons of technology convergence. In addition, removing some regulations and other political issues may reduce barriers and make it easier for competitors to enter the market with alternative technologies, so merging of various technologies is encouraged (Song, Elvers and Leker, 2017). Furthermore, many changes in markets come from several consumers who expect to have various technological functions in one product (Preschitschek *et al.*, 2013). Such factors drive technology convergence with the emergence of new technologies which either exist and develop in parallel with or take the place of previous ones (Preschitschek *et al.*, 2013).

Technology convergence has been grown in many sectors (Kim and Lee, 2017) including the development of city infrastructures. According to Yigitcanlar (2015), several cities apply technology convergence as a method to build 'sustainable urban plans' by combining technologies related to city infrastructures. However, researches on this aspect still have many open issues, for instance, technology convergence in urban innovation in the systematic view. Yigitcanlar (2015) gives an example which reflects that the movement of technologies among different elements of the system of city infrastructures has not clearly answered.

In summary, urban innovation is applied in dozens of nations in the world to overcome troubles from fast urbanization, in which, technologies are seen to be the most necessary method for the success of urban innovation (Shahidehpour, Li and Ganji, 2018). In the implementation of urban innovation, merging of technologies or technology convergence absolutely occurs as urban innovation is a process of the adoption of many technological sectors for the improvement of city infrastructure (Nilssen, 2019). And these facts open some problems needed to research on.

1.2. Research questions

Urban innovation or smart city is a considerable concern of many scientists. It is easy to find several researches on smart city in many countries, for instance, the USA, Germany, Italy (Alawadhi and Scholl, 2016), the UK (Buck and While, 2017), Spain, the Netherlands, the UK (Zygiaris, 2013), India (Praharaj, Han and Hawken, 2018), China (Zhang *et al.*, 2018), Vietnam (Pham, 2020) and so on. Further, many examples of technologies for urban innovation have been also mentioned such as ICT (Naphade *et al.*, 2011), communications (Komninos, 2009), etc. However, the structure of the technology landscape, the development of technologies, technology drivers of urban innovation and urban innovation analysis in the systematic perspective have not been clear yet. These facts are really needed. According to Naphade *et al.* (2011), urban innovation is a set of many systems which are combined with each other to develop cities more effectively and efficiently. So technologies related to urban innovation should be classified into some systems for the systematic analysis to observe how those systems develop and which ones are dominant over time. This leads to the first research question.

RQ1: How can urban innovation growth be measured in a systematic view?

Relying on that, which systems strongly drive urban innovation and how they relate to each other should be identified. This will provide novel knowledge and complete viewpoint of technology dynamics in urban innovation and go into detail of each element of system levels. Further, enterprises and urban politicians can have suitable plans for each system level in their businesses and urban plans based on the technology landscape of urban innovation. Additionally, analysts of companies may apply the framework of technology development in a system structure to delineate technologies and use it as a model for their own analysis. In this research, two cases of countries which are the USA and Vietnam representing for leading countries of the world and leapfrogging ones are selected to determine the development of technologies for smart city in two different kinds of nations. However, these two types of nations have different approaches to develop technologies for their own countries, in which, leapfrogging ones do not follow strategies of developed ones but skip intermediate technologies to focus on the newest technologies. This fact stimulates interests in learning about how they adopt technologies in urban innovation in their countries, which leads to the second research question.

RQ2: What are technological drivers of urban innovation (using the Technology-DNA (T-DNA) approach) in two countries with different stages of development?

Additionally, in the development of a variety of technologies for smart city, technology convergence is also a noticeable topic. Nevertheless, analyses of technology convergence in a system structure, vertical convergence (among different system levels), horizontal convergence (among different elements in a system), and inside and outside factors affecting horizontal level are limited. Do vertical convergence and horizontal convergence occur in parallel? Do they influence each other? Thus, this fact also opens the third research question.

RQ3: How are vertical convergence and horizontal convergence in urban innovation related to each other?

This question is answered by patent co-classification analysis with the USA patent data.

1.3. Structure of the dissertation

In order to answer all research questions, this dissertation is presented in the following structure. Section 1 was the introduction of urban innovation and technology convergence as well as research questions for both cases of the most developed countries and leapfrogging ones. Section 2 will demonstrate some main points of view in theories of urban innovation, the T-DNA approach, technology convergence and patent co-classification analysis. Research framework will also be shown in section 3. In sections 4, 5 and 6, three main papers relevant to the research will be summarized. Finally, some conclusions including discussions, implications, research limitations and future researches will be pointed out in the last section.

2. Theoretical background and research methods

Urban innovation is the improvement of city infrastructures in an appropriate process for sustainable development. For a better understanding, urban innovation is deployed based on the application of many fields, in which technologies are the central importance (Naphade *et al.*, 2011). When several technologies are used in urban innovation, technology convergence occurs in the intersection among different technologies. In order to see the development and convergence of technologies in urban innovation in the system structure, it is recommended to use the T-DNA approach (Roepke and Moehrle, 2014) and patent co-classification analysis (Curran and Leker, 2011).

2.1. Urban innovation

According to Nam and Pardo (2011), urban innovation is commonly applied in order to overcome issues from fast urbanization and to make a city smart. City infrastructures are improved in a suitable process for smart visions: ‘smart economy, smart governance, smart mobility, smart environment, smart people, and smart living’. In addition, the T-DNA approach and patent co-classification method are used to clarify the development and movement of technologies in urban innovation in the system structure.

a. What is urban innovation?

Building smart city is necessary for the development of cities in the 21st century to gain competitive advantages as well as to enhance brand of cities and citizens’ life quality (Buck and While, 2017). This is a process combining various innovations in many aspects to improve urban infrastructures (including electricity, traffic, water, treatment of waste, heat and light) (Shahidehpour, Li and Ganji, 2018) and services (such as government services, public safety, education, health care and so on) (Naphade *et al.*, 2011). More concretely, urban innovation is the application of innovations in technologies with the participation of various classes of people, the government (Meijer and Bolívar, 2016), along with smart processes and policies (Nam and Pardo, 2011) in each city’s unique context (Han and

Hawken, 2018) to make city infrastructures and services smart, interconnected and efficient (Naphade et al., 2011).

There are several ideas of urban innovation. Many scientists, for instance, Washburn *et al.* (2010), Komninos (2009), Han and Hawken (2018), Naphade *et al.* (2011), etc. recommend smart technologies for the progress of smart city as the most crucial factor for smart city. Nonetheless, Meijer and Bolívar (2016) state that not only technologies, but smart city also needs the co-operation of numerous "stakeholders" such as inhabitants and governments. Citizens, especially smart ones, and their high education are a significant element for smart city activities. Further, city leaders (governments) have an important role in the enhancement of city's values by creating suitable policies thereby motivating smart city. Besides, good policies are integral to deal with urban issues, to foster economic development of cities and they are a bridge to connect many classes of inhabitants for smart city development as well (Caragliu and Del Bo, 2018). Additionally, Nam and Pardo (2011) also add another element for urban innovation, which is an appropriate process. It is the way to change, improve and transform city infrastructures and services for smart city. All of such elements above for smart city must be taken into account depending on the unique social and cultural conditions of each city (Han and Hawken, 2018). Thus, the definition of urban innovation above is chosen for this research.

b. Process of urban innovation

The idea of urban innovation is used to improve all city infrastructures and services toward urban sustainability. In order to achieve such urban sustainability, urban innovation must be performed through some approaches and processes. Han and Hawken (2018) propose two common approaches. The first way is 'greenfield' in a city which has never been built before. And the other is a 'retrofit' from a city which has existed for a period of time. Regardless of applying any approaches, all cities must combine all city infrastructures and services in the social context and technologies focus in some loop processes which are recommended by Naphade *et al.* (2011) and Shahidehpour, Li and Ganji (2018) towards the goal of smart city.

Naphade *et al.* (2011) suggest that technologies are applied to control and improve the city - a system of systems of infrastructures and services through a closed loop process in urban innovation with some repeated steps such as: collecting data from the real life by sensors (for instance, cell phones, GPS devices, weather sensors, traffic sensors, etc. and citizens); managing and sharing information among many organizations in a city in the safe way as well as analyzing data to understand all city activities; and recommending new technologies for the city to make city systems more effective and providing people with some feedback to improve their actions.

Furthermore, Shahidehpour, Li and Ganji (2018) give a more general process which has an overall view of socio-technical perspective. This is the integration of top-down and bottom-up views in urban innovation or in other words, Shahidehpour, Li and Ganji (2018) propose an urban innovation process in the cooperation of governments, citizens and technological development. In the top-down view, after collecting data from daily city operations by using smart sensors, city administrators and the government arrange and analyze them, and then adopt technologies in urban innovation, especially ICTs, to make city infrastructures smarter and to satisfy citizens. Besides, in the bottom-up view, citizens actively work with the government to point out main characteristics of smart city infrastructures; to provide the city with necessary activities, services and buildings to create innovations; and to come to decisions in city activities.

The loop process of urban innovation is summarized from two researches above (Naphade *et al.*, 2011 and Shahidehpour, Li and Ganji, 2018) in figure 1 which shows all activities and two sides: the government and city inhabitants in the progress of smart city.

Consequently, the process of urban innovation needs the collaboration of government and citizens with the assistance of technologies to develop and improve infrastructures for urban innovation in the context of each city.

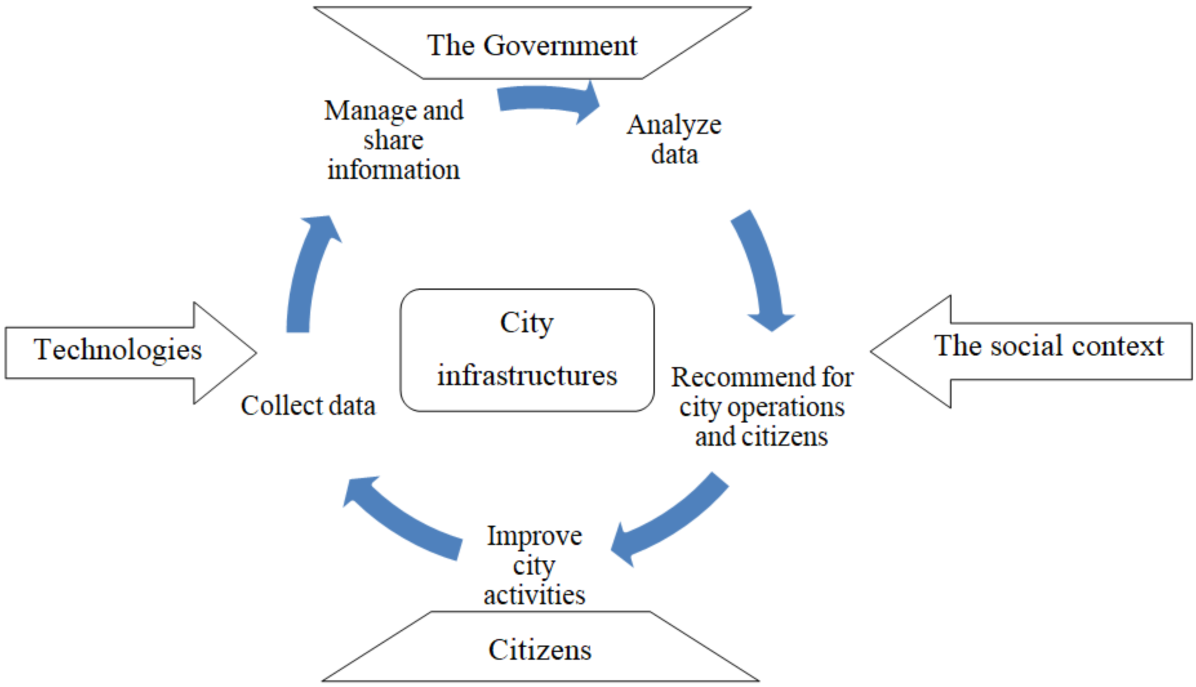

Figure 1. The process of urban innovation (Source: Authors, adapted from Naphade *et al.* (2011) and Shahidehpour, Li and Ganji (2018))

c. Urban innovation visions

According to Nam and Pardo (2011), urban innovation is executed in order to obtain 'urban sustainability' which includes 'smart economy, smart governance, smart mobility, smart environment, smart people, and smart living'.

Firstly, smart economy refers to an economy using new methods or ideas in the Industry 4.0. It is an economy operated by innovation coming from not only businesses but also research institutions, universities and inhabitants with the most advanced researches in all stages like planning, development and execution, etc. Moreover, smart economy is also a green economy which aims to decrease carbon dioxide emission (Galperina, Girenko and Mazurenko, 2016).

Secondly, smart governance is essential for smart city to deal with many issues and make people's life better. It comprises 'revised norms' related sustainability, smart policies, regulations, technologies, 'public budgeting' and so on in 'smart city framework' in which the government, enterprises and non-government organizations work together for 'accountability, transparency, and fairness' (Alawadhi and Scholl, 2016).

Thirdly, 'smart mobility' focuses on transportation of people and important changes of traffic systems. For instance, the wireless system of communication among vehicles and between vehicles and traffic infrastructures is a new idea to help drivers share information with each other and receive new signals from traffic controllers at an opportune time. As a result, this system is an effective means for drivers to forecast traffic problems and successfully control or avoid them (Shahidehpour, Li and Ganji, 2018). Moreover, Han *et al.* (2012) also add that public transport is encouraged and its system is built and developed based on ICTs in the circumstance of each city. Further, 'hybrid cars, electric cars, fuel cell cars are widely used to replace normal cars so that air pollution can be improved. In other words, the newest technologies should be applied to enhance the quality of transport management of cities, to meet people's demand by decreasing the time on street and improving environmental issues from traffic.

Fourthly, smart environment is an aspect related to environment protection and reduction of pollution emission. Zygiaris (2013) believe that a smart city is a green and clean city. It is the capability of cities to exploit or use renewable energies instead of fossil fuels, especially in industry sectors (Shahidehpour, Li and Ganji, 2018). In addition, Han *et al.* (2012) recommend building 'green belts' – the border between a city and a countryside to process products or materials from the rural areas and process them and then provide the urban areas with finished products.

Fifthly, smart people are an important factor of smart city which always attracts knowledge workers as they actively and flexibly contribute to activities for urban growth and sustainability (Zygiaris, 2013).

Sixthly, smart living concentrates on safety, quality and durability of construction works for living and working. Advanced technologies are adopted to equip modern techniques for buildings' facilities. Besides, special and new materials and methods would be developed and applied to buildings to suit cities' weather, reduce energy usage and increase house's life (Han *et al.*, 2012).

Thus, urban innovation is carried out in a smart process with the cooperation of many aspects, especially technologies, to achieve all six above pillars for a complete picture of smart city (Zygiaris, 2013). Obviously, smart city cannot be developed by the application of only technologies but Han and Hawken (2018) believe that this field is very important. This is because while other fields grow slowly, technologies develop very rapidly to stimulate the process of urban innovation (Nam and Pardo, 2011) and many researchers give many examples of technologies which are significant factors for city development (Komninos, 2009 and Meijer and Bolívar, 2016). This fact suggests observing the development and movements of technologies applied in urban innovation in the systematic perspective by some types of patent analysis to see how technologies grow and react with each other in the application of urban innovation.

2.2. T-DNA approach

In order to analyze technology development and drivers of urban innovation in a systematic view, a T-DNA approach is suggested (Roepke and Moehrle, 2014). In this part, reasons why the T-DNA method is selected and the theory of T-DNA will be explained, followed by the process of T-DNA method in general and such process applied to urban innovation reflected in construction buildings in particular.

a. Why T-DNA

There are some types of data to assess the development of technology in its life cycle. Albert, Moehrle and Meyer (2015) give an example of a data source which is blogs. Blog based analysis is applied to evaluate technology maturity. In this method, six technologies are selected based on "technology fields, economic sectors, scope of use", etc. and blog data is downloaded by using a set of search terms. Later on, data is used for sentiment analysis (relying on the appearance of certain terms) to give some results for technology development and technology maturity. Blog is a useful data source for technology analysis but the content of blogs is created by laymen, and writers may use the same sources for their blogs, which leads to “an unwanted group-effect”. In addition, maintaining a blog requires much time, effort and patience to usually update it and attract readers to visit regularly or else such blog may be closed (Hsu and Lin, 2008). Thus, in this research, patent data is chosen as patents are a reliable data generated by experts from companies or academia (Albert, Moehrle and Meyer, 2015) and there are several participants in its process, for instance, inventors, patent attorneys, governments, etc. (Ellis, 2016). Further, patent analysis is accepted to analyze technology development (Ree and Kim, 2019).

In addition, each technology field has its own features, so it produces a set of similar technologies, which leads to the arrangement of classifications in patent classification scheme (such as IPC: International Patent Classification or CPC: Cooperative Patent Classification). So patent classifications can be used in this research to search several technology fields related to smart city.

Besides, while Albert, Moehrle and Meyer (2015) do not arrange technologies in a systematic perspective, Murmann and Frenken (2006) suggest that technology sectors can be considered as dynamic systems and Naphade *et al.* (2011) also see urban innovation as the combination of several systems to develop cities. This implies a systematic analysis for urban innovation.

Therefore, patent analysis is used in the system structure to analyze urban innovation in the scope of this research. According to Roepke and Moehrle (2014), traditional methods for technology development analysis focus on technology life cycle in only core and sub-system levels. So these authors recommend a new method: T-DNA to analyze technologies in four different system levels: the super-system, the core system, the sub-system and the associated system to provide new knowledge and more holistic view of the system structure.

b. The technique of T-DNA developed by Roepke and Moehrle (2014)

T-DNA, a technique built from the idea of 'the DNA-sequence' of organisms, is a new method to analyze technologies by using patent classifications. In this measure, technology sectors are considered in a system structure composed of four system levels including 'the core system, the super-system, the sub-system and the associated system'. These four system levels are arranged in a hierarchical view in which a system level is in the relationship with other ones, and each system level is the sub-system of a bigger one. Particularly:

- *The core system level* is the nucleus part of the technology field which is being analyzed. This is also the foundation for the occurrence of other system levels.

- *The sub-system level* comprises several components of the core system.

- *The super-system level* is composed of super-ordinate technologies operating around the core system.

Technologies in the three system levels above are in the hierarchy. On the one hand, the development of each system level is affected the development of technologies in its sub-system and on the other hand, each system level also creates some requests for changes in technologies in its sub-system.

- The fourth system level - *the associated one*, is not in the hierarchic structure. Its technologies are perhaps not in the technology field but they play an important role in the development of this technology sector.

Furthermore, relevant patents are also grouped into each of those system levels to see the growth of technologies in the whole system structure as T-DNA is a series of system levels with the highest number of patents year by year. The four system levels in T-DNA are influenced by each other and by the environment, so the dominant system level might be different over time (Roepke and Moehrle, 2014).

c. Process of T-DNA

Roepke and Moehrle (2014) carry out T-DNA in three steps.

- *Step 1: Identify four system levels with relevant patent classifications* (patent classification systems are used depending on investigated countries)

The aim of this step is to create a list of related patent classifications which are arranged appropriately in the four system levels. All patent classifications must be put in the suitable code A, B, C or D (representing the super-system, the core system, the sub-system and the associated system, respectively) or considered to be not relevant to the technology sector. The arrangement can be implemented by identifying keywords for each system level and then organizing patent classifications for each of four system levels based on those keywords.

- *Step 2: Search granted patents*

The search can be executed in the data source for each system level of the investigated technology.

- *Step 3: Put relevant patents to each system levels and create T-DNA*

In this step, the results of the first two steps are combined with each other to organize related patents in the suitable system levels. After that, the dominant system level (which has the highest number of patents) for each year will be presented. In this method, Roepke and Moehrle (2014) emphasize that the application dates of each related patent are used to list them in chronological order. Finally, T-DNA is considered as a series of dominant system levels in each year in a period of time.

d. <u>Process of T-DNA applied to urban innovation</u>

According to Bonev, Wörösch and Hvam (2015), the building field in construction industry has been one of driving forces for the industrialization since the 19th century. Furthermore, construction, which is centered by buildings, is remarkably affected by the development of fast urbanization in many cities in all over the world. For this reason, Han *et al.* (2012) suggest that innovation in construction of buildings is a significant aspect in city improvement. Hence, in the scope of this research, by applying the T-DNA approach, urban innovation, which is analyzed in the systematic point of view, considers construction of buildings to be the core system. Thus, it is assumed that the nucleus of urban innovation reflected in construction, the core system level (code B), is buildings. Then, based on the definition of the four system levels above, the other system levels are defined. The sub-system (code C) includes parts of buildings such as floor, wall, door, window, etc. The super-system (code A) is technologies in the surrounding environment of the core system (buildings), for instance, energies, city infrastructures, ICTs and so on. Lastly, the associated system is not either in the hierarchical structure of the other three system levels or in the investigated technology sector. However, it significantly influences activities of other system levels. So, they are construction machines, tools and materials. The hierarchy of urban innovation in the systematic perspective is demonstrated clearly in figure 2.

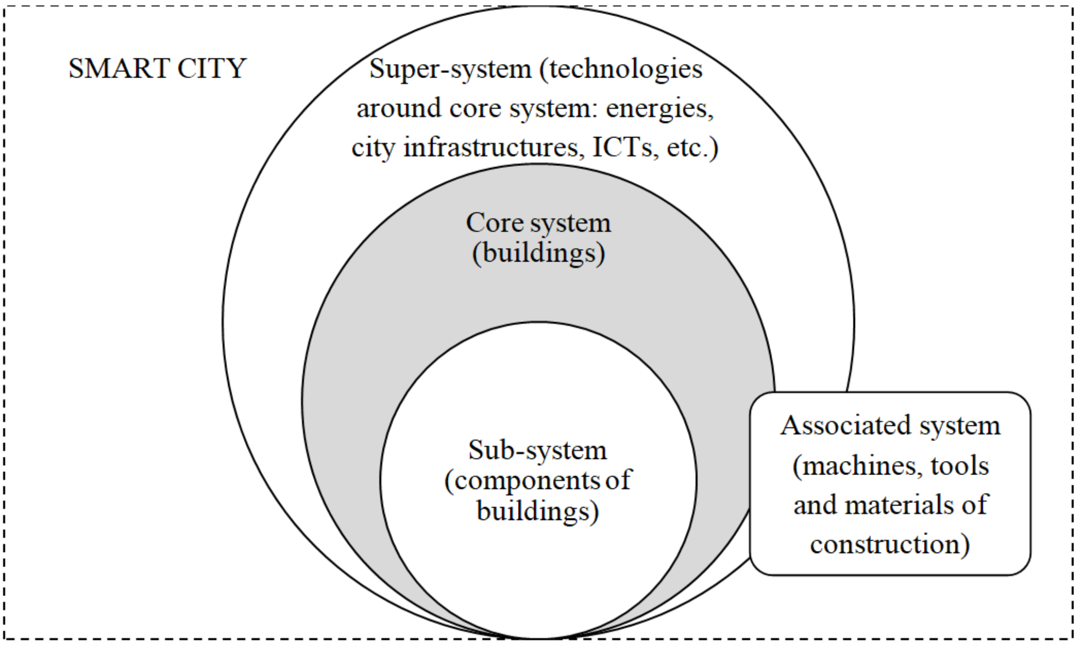

Figure 2. Urban innovation (reflected in construction of buildings) in the system structure (Source: Author)

In case of urban innovation reflected in construction of buildings, the T-DNA process is applied step by step.

- *Step 1: Code patent classifications*

All relevant patent classifications in patent classification scheme are searched and categorized into four system levels. However, as there are too many keywords related to the four systems, for instance, various types of buildings, building's parts, materials, tools, machines, embedding, etc., the search by using keywords recommended by Roepke and Moehrle (2014) cannot be used. This problem is solved by a two loop-based workflow. In the first loop, I carefully read the title and descriptions of all patent sections in the patent classification scheme and then filter them based on the definitions of each system levels. If the title of patent sections is appropriate to any of four system levels, I arrange such sections in the suitable system level. If any patent sections are not obvious, I continue to do the same activity with classes/ subclasses in succession and arrange them in the right position or remove them. In the second loop, I check reliability of the list of patent classifications for four system levels by checking random samples and asking my colleagues to do the first loop.

- *Step 2: Search patents and organize patents to the four system levels*

By using the list of patent classifications got from step 1, all relevant patents for each system level are searched based on their application dates. The number of patents in each system level in the whole time is identified. The precision of data is checked by randomly selecting samples.

- *Step 3: Form T-DNA (both absolute and relative values)*

In order to demonstrate the contribution of each system level to urban innovation in each year, T-DNA by absolute values is specified as a sequence of system levels with the highest patent count year by year. For instance, if patent count of the super-system is dominant in the whole period of time, then T-DNA by absolute values is constantly code A all the time: A, A, A,….,A, A.

In addition, to see how each system level has grown over years, T-DNA by relative values should be explored. The relative value is the number of patents in each system level in each year divided by the sum of patents of such system level in all the time. T-DNA by relative values is a series of system levels with the highest relative values.

- *Step 4: Disaggregate some system levels*

This step is added to separate the super-system, the sub-system and the associated system into small elements to see how they develop on the inside. T-DNA by absolute values and relative values are also generated. The core system level is not investigated due to its small number of patents.

2.3. Technology convergence and technology convergence in urban innovation

In the investigation of technology development by T-DNA in urban innovation, several technological changes, which lead to the attention to the combination of various disciplinary fields and merging of different technologies, are recognized. Numerous new technological fields have been created at points where at least two technologies cross (Lee, Han and Sohn, 2015). According to Kim and Lee (2017), technology convergence plays a significant part in the development of technological innovations. Further, the appearance of technology convergence not only brings opportunities but also causes several challenges to the economy, companies and scientists (Curran and Leker, 2011).

a. What is technology convergence?

In daily changing societies with a variety of complicated economic issues, looking for innovations to solve their problems by applying only a single field of technology is not enough. More and more innovations appearing from the combination of many fields of technology open a crucial chance for the development of economies, several competitive advantages for businesses and an exciting topic of research for scientists from such converging technologies (Song, Elvers and Leker, 2017). Hence, technology convergence is defined as 'the blurring of boundaries' (Curran and Leker, 2011) between separate 'technological systems[1]' to carry out the same tasks (Agarwal and Brem, 2015). This definition is suitable to this research in a systematic analysis. Emerging technologies created

[1] According to Carlsson and Stankiewicz (1991), technological system is a set of elements in 'knowledge/ competence flows' which interact with each other in a sector of the economy and in the a specific 'institutional infrastructures' to create, spread and apply technologies.

from technology convergence are considered to be a prominent feature of not only the fast development of technologies based on a wide diversity of technologies and their overlap but also a growing need of interdisciplinary researches (Kim and Kim, 2012).

Besides, when deeply investigating technology convergence as well as the movement of technologies, Curran and Leker (2011) categorize technology convergence into two patterns: convergence and fusion (or two-way convergence and one-way convergence, respectively (Eilers *et al.*, 2019)) (figure 3). Firstly, two-way convergence happens when at least two technologies move from their original places to 'a new and common place'. The emerging technology is created in a new sector and it is not components or parts of any previous technologies. For instance, "Nutraceuticals and Functional Foods", which is the new technology formed from two-way convergence between nutrition and medicines, neither replaces nor belongs to its previous technologies. Secondly, the overlap of technologies 'at the same place of at least one of them' leads to the appearance of one-way convergence. For instance, smart phones have been created from one-way convergence of 'cameras, cellular phones, portable computers' and smart phones can partly take the place of (parts of) their former technologies.

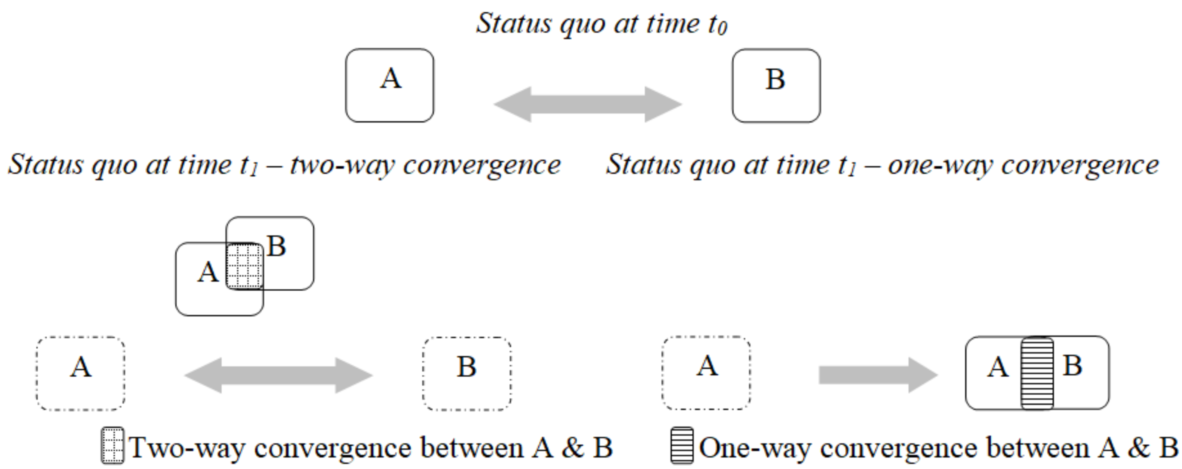

Figure 3. The process of two-way convergence and one-way convergence (adapted from Curran and Leker (2011) and (Eilers *et al.*, 2019))

b. Opportunities and challenges of technology convergence

Not only firms and the economy of many countries but also numerous scientists consider technology convergence to be very significant (Curran and Leker, 2011). Firstly, in researches, technology convergence can create novel technologies to lay the foundations of new remedies for technical issues and to develop intellectual discoveries based on many different areas of knowledge and sciences (Jeong and Lee, 2015). Moreover, Jeong, Kim and Choi (2015) give a supplementary idea that technology convergence is a catalyst for R&D organizations to improve their research abilities and skills. Secondly, learning about technology convergence carefully is an effective way to discover innovations and develop the economy. This is explained by Lee, Han and Sohn (2015) that technology convergence can generate new fields of technology and later on, encourage new industries and motivate a gradual process of change and development (Hacklin, Marxt and Fahrni, 2009). Thirdly, most companies are dealing with several opportunities and challenges from technology changes and technology convergence (Eilers *et al.*, 2019). Technology convergence creates conditions for new organizations to enter the economy by fostering new niche markets. Besides, technology convergence both encourages competition among many businesses and helps enterprises approach new knowledge of emerging technologies (Jeong, Kim and Choi, 2015) and therefore it is a stepping-stone to draw new consumers with their new technologies (Preschitschek *et al.*, 2013). Nevertheless, due to technology convergence, enterprises must study new knowledge and skills outside their strength and face several new competitors who are perhaps strong in their existing technologies before convergence (Curran and Leker, 2011). Thus, companies should specify technology convergence from the beginning in order that they can make suitable plans to grasp its opportunities and cope with its threats on time, or else, they may be supplanted by their rivals (Eilers *et al.*, 2019).

c. Drivers of technology convergence in urban innovation

The appearance of technology convergence in many sectors, including urban innovation

– an example of the adoption of numerous technologies and many fields to improve city infrastructures (Nilssen, 2019), has been derived from a variety of drivers. According to Song, Elvers and Leker (2017), there are four main determinants of technology convergence: technology development, regulations, customer satisfaction and social development. These drivers along with some examples of technology convergence in urban innovation are clearly summarized in table 1.

Firstly, technology development, one of the most important drivers, brings about changes in technologies, the overlapping of various sectors of technology and later on, technology convergence in general and in urban innovation in particular as well (Lee, Han and Sohn, 2015). Hacklin, Marxt and Fahrni (2009) give an example of this case in urban innovation by demonstrating "intelligent buildings" as a result of the growth of "building technologies", "information technology" and their convergence.

Secondly, regulations are also a significant driver for convergence. This perhaps either prevents convergence in the monopoly market or encourages convergence by decreasing entry barriers for new incumbents, emerging technologies and businesses and creating a nice environment for competition (Preschitschek *et al.*, 2013). For instance, the fact that many governments have been making their efforts and spending money on the development of the wireless technologies in their urban plans (Yigitcanlar and Han, 2010) motivates the movement of the wired system to the wireless one which assists some developed cities such as the Korean case (Yigitcanlar, 2015).

Thirdly, consumers often tend to choose products with numerous functions. In other words, convergence of many technologies is one of solutions to satisfy multiple demands of customers in only one time of shopping (Kim and Kim, 2012). Uber taxi is an example of convergence of different technology systems (such as GPS in smart phones and transportation management in urban infrastructures) coming from many customers who need not only to overcome problems of personal means of transport but also to experience luxury services on high-end limousines and to reduce taxi costs by sharing rides with other passengers (Skok and Baker, 2018).

Fourthly, social changes and globalization have an influence on blurring technologies. “Tesla Town” is a project for the sustainable life in the suburb. For instance, “solar panels and Tesla Power walls” are installed in houses to store energy for daily use (Song, Elvers and Leker, 2017).

No.	Determinants	Examples in urban innovation
1	Technology development	Intelligent houses
2	Regulations	Convergence of wired and wireless systems
3	Customer satisfaction	Uber taxi (transportation system)
4	Social development	“Tesla Town”

Table 1. Drivers of technology convergence in urban innovation and corresponding examples (Source: Authors, according to Hacklin, Marxt and Fahrni (2009), Yigitcanlar (2015), Skok and Baker (2018) and Song, Elvers and Leker (2017)).

The first and the fourth examples show the convergence of building technologies and information or energy technologies in city infrastructures. The remaining examples express the overlapping between telecommunication and infrastructures. Therefore, if technologies related to urban innovation are classified into four system levels: the core system as buildings, its sub-system as many parts of buildings, its super-system as the embedding environment of buildings - city infrastructures and its associated system as construction machines, tools and materials, the first and last examples are the combination of the core system and super-system and additionally, the other examples connect elements in the super-system.

I assume that the convergence between a system level and another one is vertical convergence and the convergence among different elements in a system is horizontal convergence. The two terms vertical and horizontal convergence have not been found in previous researches on technology convergence but have been used in other fields of science.

For instance, Sevadjian *et al.* (2015) mention these terms in case of the combination of various layers of oceans as well as sediment and phytoplankton in the same layer.

2.4. Patent analysis to identify technology convergence

Patents supply an abundant source of indispensable insights into various aspects related to technologies (Lee, Han and Sohn, 2015). Firstly, according to Park and Yoon (2014), over 90% of the newest knowledge of technology is contained in patents and up to 80% of information provided in patents has not been presented in any other places. Besides some basic information such as technology categories, inventors, applicants, application and granted date, etc. (Kim, Jung and Hwang, 2019), 'technology dynamics', 'technology trends', and technology development can be explored and analyzed in the time analysis based on related patents (Kim and Kim, 2012). Secondly, Preschitschek *et al.* (2013) explain that patent data is also a tool to forecast new technology development and emerging technologies which are formed from interdisciplinary fields of technology and the complex mutual influence of technology growth (Lee, Han and Sohn, 2015). In other words, patents are often used to measure technology convergence in many studies (Geum *et al.*, 2012). Hence, obviously, while only one source of data cannot demonstrate the whole picture of technology development, patent analysis is a good way to discover technology growth and convergence (Jeong, Kim and Choi, 2015) as patents are the latest and reliable source of data demonstrated by assignees and patent office examiners (Caviggioli, 2016).

Many methods based on patent data are applied to evaluate technology convergence process, for instance co-classification, citation (Kim and Kim, 2012), semantic analysis (Preschitschek *et al.*, 2013) and topic modeling (Reisenbichler and Reutterer, 2019).

- Firstly, patent co-classification analysis is a suitable method to assess technology convergence in case of a large amount of patent data (Preschitschek *et al.*, 2013). This approach is performed by using one of important information provided by patents: patent classification codes (such as IPC or CPC, depending on each country) (Kim, Jung and Hwang,

2019) which are specified based on technology sectors of protected inventions (Caviggioli, 2016). A patent is perhaps assigned with one or many patent classification codes. If a patent has only one classification code, there is no signal of technology convergence (Song, Elvers and Leker, 2017). On the other hand, when a patent is classified in several classifications, it is considered as co-classification (Jeon and Suh, 2019). Multiple classes in the same patent show the relationship among various sectors of technology, which is used to determine technology convergence (Miao, Guo and Wu, 2019). This is a reliable approach for technology convergence analysis as patent classification codes are arranged by specialists. Nevertheless, when researchers expect to apply this way, granted patents are needed for all patent classifications (Eilers *et al.*, 2019).

- Secondly, patent citation analysis is executed based on the mechanism that one or some patents are cited by another one (Kim and Lee, 2017). This fact shows the complicated relationships and a knowledge flow among several technologies, which demonstrates a high level of possibility of technology convergence (Kim and Kim, 2012). This approach is also trustworthy as citations are created by patent examiners (and sometimes inventors). Further, this method requires the full text of granted patents which show completely all of their citations (Trippe, 2015). However, the assessment is not accurate with new patents as they have not been cited yet and patent citation analysis does not show technology classification and 'technological structure' (Kim, Jung and Hwang, 2019). Additionally, some problems in laws restrict patent citations activities somehow, so sometimes, it is not easy to find enough citations in several patents (Jeong, Kim and Choi, 2015).

- Thirdly, semantic analysis approach is often used to assess convergence in detail (Preschitschek *et al.*, 2013). According to Niemann, Moehrle and Frischkorn (2017), semantic similarities among different patents are specified by applying text mining approach in patent description, claims, abstract and title. Patent data can be selected in both applications and granted patents sets. Nonetheless, this method is recommended for a limited database as it takes great effort and time.

- Fourthly, topic modeling is executed based on semantic properties of patents. The algorithm of topic modeling is that each document includes several hidden topics which are revealed by a collection of words. This method explores these major topics in a set of documents by grouping unigrams which co-occur in many documents, thereby indentifying similarities among those documents relying on such topics. Similarly to the third one, this approach also accepts both applications and granted patents and it is applied in case of a small sample (Blei, Ng and Jordan, 2003), (Blei, 2012).

In this research, the first method, patent co-classification analysis is used to explore technology convergence in urban innovation for some reasons. Classification codes are available in patents on their publication dates so enough data is often provided without time lag (Song, Elvers and Leker, 2017), (Jeong, Kim and Choi, 2015). Moreover, patent classification codes can supply a structured insight into technology hierarchy and technology elements in a systematic view (Kim, Jung and Hwang, 2019). Last but not least, the scope of this current research is in a long time frame, so patent co-classification analysis is suitable as Preschitschek *et al.* (2013) argue that this method is used for a large data sample to see how technologies in each system level (or element) in urban innovation move to each other over time (Curran and Leker, 2011). In addition, Song, Elvers and Leker (2017) propose that in several classifications in the same patent, the first one is often defined as the major classification. Thus, I compare the first classification of all patents in each system level (or element) with all classifications of another one to search similarities and conclude vertical and horizontal technology convergence. I assume that if the number of co-classified patents in both two sides increases, this case is considered two-way convergence. If co-classification increases in one side and it decreases or there is nothing in the other side, it is called fusion or one-way convergence.

2.5. Short summary

In conclusion, urban innovation is seen as a common way for many cities to overcome challenges of urbanization and improve their infrastructures and services to become smart (Shahidehpour, Li and Ganji, 2018). Urban innovation is the combination of many aspects and technologies are the most crucial one in this field (Han and Hawken, 2018). In the systematic view, it is recommended to use the T-DNA approach to explore dominant system levels and the growth of technologies in urban innovation over time (Nguyen and Moehrle, 2019). Further, patent co-classification analysis is also suggested to look for vertical and horizontal technology convergence in urban innovation in the system structure in case of large samples (Nguyen and Moehrle, 2021). The integration of the T-DNA method and patent co-classification analysis will build a complete research on technology dynamics and convergence in urban innovation in the system structure.

3. Research framework

Many researchers have carried out researches on urban innovation or smart city which is often adopted to solve issues coming from the fast urbanization. Several examples of countries and technologies related to this field have been specified. Nevertheless, the analysis of technology development and technology convergence in urban innovation in the systematic view is limited. Thus, this research focuses on drawing the complete picture of not only technology dynamics and technological drivers but also technology convergence, vertical and horizontal convergence of urban innovation in the system structure. Two countries which are the USA and Vietnam are chosen to go into detail about their situation of urban innovation thereby identifying some typical characteristics of technology development of smart city in leading and leapfrogging nations. Three main research questions are suggested, as already mentioned in the introduction section:

RQ1: How can urban innovation growth be measured in a systematic view?

RQ2: What are technological drivers of urban innovation (using the T-DNA approach) in two countries with different stages of development?

RQ3: How are vertical convergence and horizontal convergence in urban innovation related to each other?

Firstly, the first research question is answered by listing some types of patent analysis like T-DNA approach and patent co-classification analysis to assess urban innovation in the system structure. These methods are applied to look for answers of the other questions. Secondly, a T-DNA approach is applied for the second question to analyze technology growth and drivers of urban innovation, in which building construction is the core system, in both two cases of two nations: the USA and Vietnam, and in two kinds of local and foreign patent applicants in Vietnam. Finally, the last one is answered by patent co-classification analysis to have a look at technology convergence in smart city in the USA. All of these issues are presented in three main papers, which are connected to each other to explain a whole landscape of technology dynamics and technology convergence in smart city in the systematic perspective (figure 4). The role of each paper in the research is also explained in table 2.

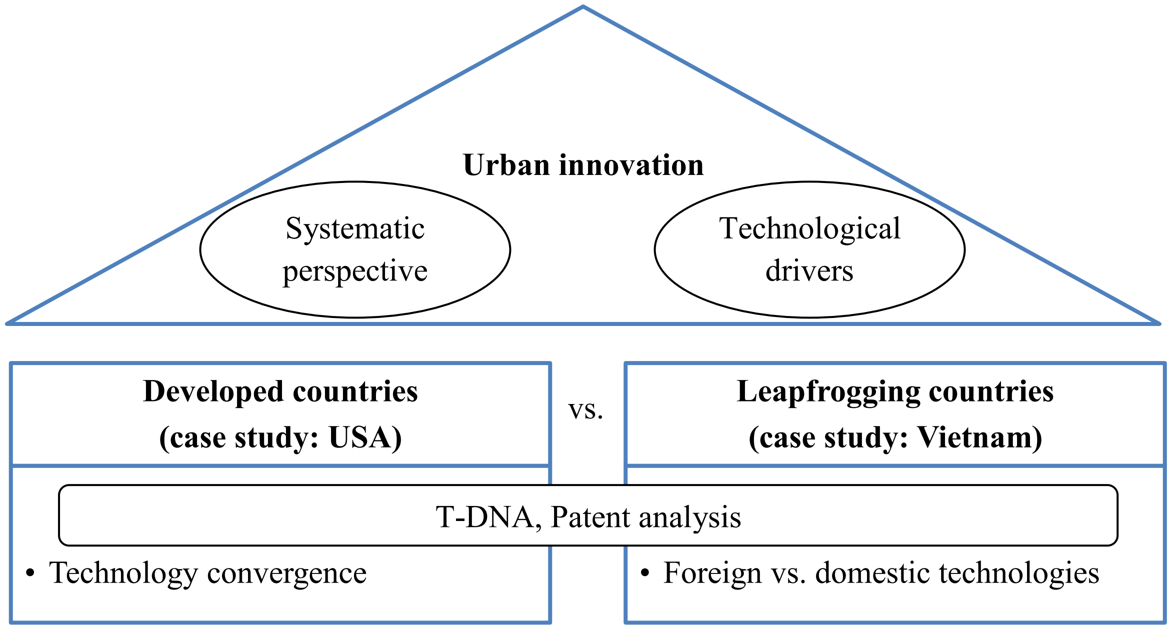

Figure 4. Research framework

	Technology dynamics	**Technology convergence**
Developed country	Paper 1 (anchor point)	Paper 2
Leapfrogging country	Paper 3	

Table 2. Technology dynamics and technology convergence in urban innovation presented in three papers

In particular, the main content of the three papers are below:

- Paper 1 is the anchor point of the research as it lays the foundation for theories and basic discoveries of urban innovation in the system structure in the USA. By using the T-DNA approach, patents protecting technologies in urban innovation are classified into four system levels (figure 2) to identify technology development and major technology drivers of urban innovation from 1976 to 2018 by determining a series of system levels and elements in each system level with the highest patent count over time. As a result, the super-system and its elements: electricity and communication as well as climate change and environment protection, are the largest drivers of urban innovation. In general, paper 1 has a big contribution in the framework of the T-DNA structure for urban innovation and in practices with some suggestions for enterprises and politicians in urban sectors.

- Paper 2 relies on the same patent database of technologies in urban innovation in the USA in the systematic perspective in paper 1 and its findings to look for technology convergence among different system levels (vertical convergence), among different elements of the super-system – city infrastructures (horizontal convergence) and the interplay between vertical and horizontal convergence in parallel by patent co-classification analysis. Additionally, some special cases of technology convergence and three kinds of constellations in the relation between horizontal and vertical convergence analyses are pointed out. This can help researchers and companies to learn more about inside and outside factors affecting horizontal convergence.

- Paper 3 develops the framework of the T-DNA approach in urban innovation (from paper 1) in a leapfrogging country – Vietnam from 1995 to 2019. Similarly, the super-system, especially electricity and communication element, is the most importance. In this paper, the same analysis is also implemented in two cases of resident and non-resident patent applicants and it shows the same result. However, these two kinds of applicants do not have the same strategies for the development of smart city, which requires some changes and efforts from both Vietnamese and foreign enterprises as well as the government. Furthermore, a significant characteristic of a leapfrogging country is explored by the case of Vietnam. In this nation which lags much behind the USA, intermediate technologies are often ignored and the advanced ones are concentrated on in their economic and technological development strategies.

In conclusion, the research framework (figure 4) and the main content of three papers (table 2) show the whole picture of the research. The development of technologies and technological drivers of in urban innovation are discovered in the system structure by using a T-DNA approach in both kinds of countries to see main features of developed and leapfrogging nations in technology dynamics of smart city. Moreover, based on such basic story, some more facts of urban innovation in the USA (horizontal and vertical convergence) and in Vietnam (the asynchronous strategies of foreign and domestic enterprises in technologies of urban innovation) partly add to the picture of smart city and make it more complete.

4. Paper 1 - Urban innovation in the case study of the USA – a leading country

This paper is the anchor point of the study as it lays the foundation of researches on urban innovation in the systematic perspective based on some forms of patent analyses with patent data of the USA from 1976 to 2018. However, data from 2015 onwards is removed due to some reasons in the patenting process.

4.1. Overview

In the situation of fast urbanization with its challenges in all over the world, the aim of paper 1 is to explore technology dynamics and technology drivers of urban innovation reflected in construction of buildings in the system structure. The research learns about how technologies in urban innovation developed in four different system levels (figure 2) to see technology landscape and which systems are dominant in urban innovation. This paper is executed in the USA - a leading nation in the world to answer the two questions:

$RQ1_{paper\ 1}$: "What have the technological drivers of urban innovation reflected in construction patents in the USA been?"

$RQ2_{paper\ 1}$: "How has urban innovation reflected in a Technology-DNA (T-DNA) approach grown in the USA over time?"

To answer research questions, the paper relies on the patent database collected from United States Patent and Trademark Office (USPTO) from 1976 to 2014. The framework of T-DNA approach is built based on CPC scheme, the patent classification system used in the USA, to specify dominant system levels over years, the structure of technology landscape and technology drivers of urban innovation. Further, term frequency – inverse document frequency (tf-idf), one kind of the semantic analysis, is also used to identify interesting technology fields in the core system in recent years, thereby looking for the relationship or movement from this system to any others.

4.2. Theories and research methods

The paper focuses on the situation of fast urbanization and challenges it brings to several cities in all over the world. Urban innovation or smart city is suggested as a suitable means to deal with urbanization by improving city infrastructures and developing cities sustainably. Through explaining urban innovation which is the integration of several fields to make city infrastructures 'interconnected, intelligent, effective and efficient', this paper emphasizes the importance of technologies among many aspects related to smart city. This fact, together with the necessity of the systematic analysis, is the reason why the process of T-DNA is carried out with CPC scheme and patent data in the USA from 1976 to 2014. Step 1 defines the super, core, sub and associated system by giving the list of all relevant CPC patent classifications belonging to each system level. Based on the list, all granted patents related to the system structure of urban innovation are searched by using their application dates and arranged to suitable system levels in step 2. The patent counts of each system level in the whole period of time and in every year are pointed out. Later on, in step 3, T-DNA by absolute values is determined to show system levels most significantly affects urban innovation. Moreover, T-DNA by relative values is also identified to point out the growth of each system level over time. In the final step, the disaggregation of system levels into smaller elements is carried out to see the development inside each system level. T-DNA by absolute values and T-DNA by relative values of each system are also pointed out in the similar process.

Besides, tf-idf is used to search interesting concepts which often appear in some patents but seldom occur in the whole patent set of the core system. This method is applied to the core system (the center of urban innovation) in the stage from 2011 to 2014 in comparison to the whole time from 1976 to 2014. Emerging technologies are expected to find out.

4.3. Results of analysis

The paper shows some major findings. In the USA from 1976 to 2014, T-DNA by absolute values is constant with code A (the super-system) all the time, which demonstrates that the super-system dominantly contributes to the picture of urban innovation. And its element - electricity and communication is the strongest driver of urban innovation (showed in T-DNA by absolute values of elements of the super-system). In addition, T-DNA by relative values of system levels is changing: from 1976 to 1995, it is mostly D (the associated system), from 1996 to 1999, it looks random (like the transformation), and from 2000 forward, it is A (the super-system). So there must be a great change in the super-system from 2000. In the disaggregation of the super-system, T-DNA by relative values of elements in this system is always code 6 (electricity and communication) and 7 (climate change and environment protection) since 2000. Patent counts of these elements grew 10 times in 2014 compared to 1976, which leads to a significant increase of patent count and relative values of the super-system from 2000 in comparison to other systems.

Furthermore, tf-idf for the core system is carried out in the period from 2011 to 2014 and in the whole time 1976 to 2014. Some interesting concepts in buildings are pointed out. Nonetheless, two new concepts: ‘panel solar’ and ‘turbine wind’ have emerged in the stage from 2011 to 2014. Such concepts are predicted as emerging technologies in the core system and they are also related to energies which belong to city infrastructures or the super-system. This means that there is perhaps a relationship or movement from the core system to the super-system.

4.4. Discussion

The paper shows the picture of technology landscape of urban innovation in the USA from 1976 to 2014. While the core system, the sub-system and the associated system have small influences on the growth of smart city, the super-system is the dominance. Especially, technologies in electricity and communication as well as climate change and environment protection in the super-system are the largest drivers of urban innovation. The period of from 2000 marks the most considerable development of the super-system and such two technologies.

Theoretical implications: This study draws a holistic picture of technology landscape of urban innovation and a list of technological classifications in this sector in the systematic viewpoint. Further, it builds the framework of T-DNA and suggests applying it to other fields of research.

Practical implications: The result of the paper helps enterprises grasp the development of technologies in urban innovation, thereby forecasting technologies and paying attention to main technological drivers to their businesses. In addition, politicians adjust their urban plans suitable to the situation of technology dynamics in urban innovation. Besides the super-system is the most important drivers, other system levels should also be taken care of.

5. Paper 2 - Technology convergence: vertical convergence, horizontal convergence and interplay analysis in urban innovation – an example of the USA

Paper 2 continues to learn about technologies in urban innovation in the system structure but it focuses on technological movements. Some findings on technology convergence among and within different system levels in urban innovation in the USA are presented.

5.1. Overview

Technology convergence, which has received attention since the 1980s, results in the appearance of many new technologies at the intersection of existing technologies' boundaries. In the systematic perspective, there are several studies of technology convergence on the horizontal level (among different elements in a system) but researches on the whole picture of technology convergence on the vertical and horizontal level (among and within different system levels, respectively) are limited. Moreover, technological drivers of the horizontal level should be identified as they are necessary for analysts in companies. These drivers are not only inside factors but also outside ones which come from other system levels. Such issues lead to some research questions.

$RQ1_{paper\ 2}$: "Do the technological movements on the horizontal level and the technological movements on the vertical level occur in parallel?"

$RQ2_{paper\ 2}$: "Do movements on the one level probably influence movements on the other level?"

Technology convergence often occurs in many fields including urban plans which are carried out by the combination of various technologies. Urban innovation is selected as the case study for the research. Patent database of urban innovation in the USA in the system structure in paper 1 and the research method of patent co-classification analysis are applied to answer research questions.

5.2. Theories and research methods: technology convergence, patent co-classification

Technology convergence is considered as the progress of "different technological systems" moving to each other to perform tasks together. It is classified into two patterns (based on the way of technological movements): convergence and fusion (or two-way and one-way convergence, respectively). Furthermore, technology convergence provides researchers and R&D organizations with new knowledge and new research abilities. It also brings new industries and contributes to the development of economies. Additionally, new technologies from technology convergence not only open opportunities for new organizations entering the economy, but also encourage more competition among companies, and help them to attract more customers, etc. However, companies must study new knowledge which comes outside their specialty and they also have more new competitors.

In order to analyze technology convergence, in this scope of this paper, the case of urban innovation in the USA is selected with patent database from 1976 to 2014 in paper 1. Firstly, based on the global maps of science by Kay *et al.* (2014), after calculating technology distances among technologies in different system levels and different elements of the super-system, it is concluded that such technologies were distant ones in the period from 2000 to 2006. Thus, the aim of this paper is to check if and how they have moved (to each other or far away) recently. In order to do so, secondly, patent co-classification analysis is applied to do vertical, horizontal convergence and interplay analysis. The main CPC classification of all patents of each system level is compared with all CPC classifications of another one to search co-classification among four system levels (vertical convergence analysis). The same process can be done with elements of the super-system - the dominant system in urban innovation, for horizontal convergence analysis. The movements between elements of the super-system and three other system levels are also checked, which is call interplay analysis. Data is analyzed in the first ten years and the final ten years of the whole period to specify how technology convergence changed before and after the appearance of urban innovation (the 1980s and

1990s). The proportion of co-classified patent count to the patent count of the underlying system or element which shows how important co-classification was in the total patent count of that system or element is compared between two periods. The values of the comparisons show different levels of convergence. Two-way convergence (if proportions increase in two sides) and one-way convergence (if proportions increase in only one side) are also considered in all of analyses.

5.3. Results of analysis

All system levels moved to the super-system but the super-system nearly did not moved to the others, which is clearly expressed a trend of vertical fusion. Besides, a clear trend of horizontal fusion and interplay fusion are demonstrated by the movements of all elements of the super-system and all three other system levels to electricity and communication. In addition, some major findings are showed in figure 5.

Furthermore, some short term movements in both system levels and elements of the super-system, which are u-shape movement and inverted u-shape movement (they are named based on the growing trend of co-classified patent count) are recognized. Firstly, in the inverted u-shape movement, let’s take the example of the sub-system and the super-system. While the movement from the super-system to the other one rose in the whole time, the movement from the sub-system to the super-system increased before 2000 and decreased later on. So two-way convergence appeared in the first phase and one-way convergence occurred in the second phase. Secondly, in the u-shape movement, let’s take an example of climate change and environment protection, and heat/ cool air (elements of the super-system). While the number of climate change and environment co-classified as heat/ cool air declined before 2000 but grew after 2000, heat/ cool air did not move vice versa.

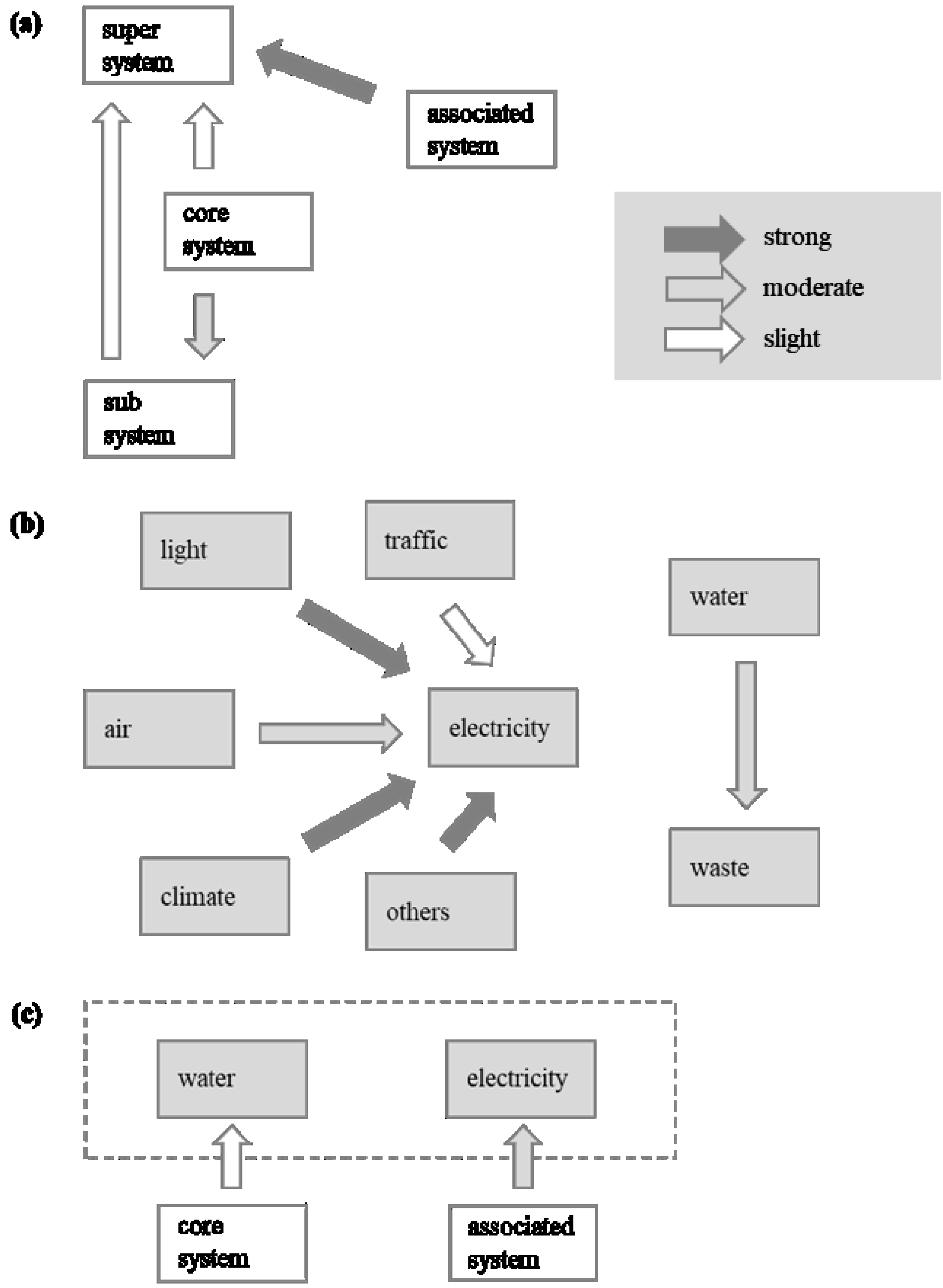

Figure 5. Some findings: (a) technology movement on the vertical level, (b) technology movement on the horizontal level, (c) interplay between two levels (Source: Author).

5.4. Discussion

Through technology convergence analysis in urban innovation in the system structure in the USA from 1976 to 2014, the paper provides not only an approach for this field including vertical, horizontal convergence and interplay analyses but also some findings of some fusion on vertical and horizontal levels and between system levels and elements of the super-system (interplay) in smart city. This also helps to answer two research questions. First, technology movements occur on both levels (horizontal and vertical ones) in parallel. Second, some movements on the horizontal and vertical levels affect each other, for instance, not only many elements of the super-system but also the associated system moved to electricity and communication. However, there were some unrelated movements, for instance, the core and sub-system moved to electricity and communication but only the core system moved to water and hydraulic engineering.

Theoretical implications: The paper provides three types of constellations in the relationship between horizontal and vertical convergence analysis. Firstly, there was no outside driving technology moving to horizontal level (for instance, no technology influenced traffic, light, heat/ cool air, climate change and environment protection which moved to electricity and communication). Secondly, there were outside driving technologies moving toward elements on the horizontal level, which moved to other elements on this level (for instance, the core system moved water and hydraulic engineering which moved to treatment of waste). Thirdly, outside technologies moved to elements on the horizontal level, which did not move to any other element on this level (for instance, the associated system moved to electricity and communication which did not move to other elements).

Practical implications: The paper can help analysts and companies to identify driving technologies influencing the horizontal level in technology convergence, to build a framework for horizontal and vertical technology convergence analysis and to develop new technological knowledge and skills.

6. Paper 3 - Urban innovation in the case study of Vietnam – a leapfrogging country

(Some parts of this section have been cut due to the author's copyright.)

This paper also applies a T-DNA approach to learn about smart city in the systematic perspective in a leapfrogging country – Vietnam. Patent data is collected from 1995 to 2021, but data of 2020 and 2021 is removed because of the patenting process.

6.1. Overview

Like others, Vietnam, a leapfrogging country, is also facing many challenges from rapid urbanization. This is why it is implementing smart city projects from 2018 to 2025 and to 2030 to develop cities sustainably.

6.2. Theories and research methods: smart city in Vietnam, T-DNA, correlation analysis

The paper describes the situation of smart city in Vietnam. Difficulties from fast urbanization in Vietnam made the government decide to follow the smart city project which is being currently implemented in about 38 provinces and cities for sustainable urban development. This project focuses on some main fields for instance, in traffic, in energies and in construction, etc.

6.3. Results of analysis

A considerable increase in patent count in smart city in Vietnam in the whole time shows that it is a promising market that is more and more attracting the trust of both Vietnamese and foreigners.

6.4. Discussion

Vietnam is a leapfrogging country that draws more and more residents and non-residents to invest in the latest technologies. In the development of industry 4.0, fast urbanization leads this country to apply smart city to overcome difficulties.

Theoretical implications: The T-DNA approach delineates technology landscape of smart city in the system structure in Vietnam.

Practical implications: The paper points out some weaknesses of smart city in Vietnam.

7. Conclusion

Urban innovation or smart city is a common way to improve city infrastructures in suitable processes so that challenges of fast urbanization are overcome for sustainable urban development. In this field, technologies are considered as the most indispensable ones. This research aims to discover the holistic view of the development, changes and movements of technologies in urban innovation in two cases: a developed country and a leapfrogging one. The research points out some main findings in order to answer three research questions.

For the first question - How can urban innovation growth be measured in a systematic view?: Technologies in urban innovation are arranged in a system structure with four system levels, in which construction of buildings is the center (core system). The growth of urban innovation in the systematic point of view is mainly measured by some types of patent analysis: T-DNA method, tf-idf, CPC patent co-classification analysis and Pearson correlation analysis. Technology landscape and drivers of smart city are analyzed in the system structure by the T-DNA approach in the USA (representing developed countries) from 1976 to 2014 and in Vietnam (representing leapfrogging countries) from 1995 to 2019. Besides, in case of the USA, based on tf-idf approach, the core system shows signs of development in the direction of the super-system. This fact results in the analysis of technology convergence in urban innovation among four different system levels (vertical convergence), among elements in the super-system (horizontal convergence) and between elements of the super-system and three other system levels (interplay) by the use of CPC patent co-classification analysis. In the case of Vietnam, T-DNA in smart city of patent Vietnamese and foreign applicants and correlation analysis of these two types of patent applicants in construction are carried out to compare their strategies in smart city.

For the second question - What are technological drivers of urban innovation (using the T-DNA approach) in two countries with different stages of development?: In both countries, the super-system (city infrastructures and energies) and its element – electricity and communication are the most significant drivers of smart city. Moreover, in case of the USA, the year of 2000 was an important milestone. From this time on, among four system levels, the super-system started to develop dominantly and its elements: electricity and communication, and climate change and environment protection significantly contributed to this fact. In case of Vietnam, patent data demonstrates that this country is a leapfrogging one which ignores intermediate technologies to develop the advanced ones. Moreover, this country is a promising market attracting interests of both local and foreign investors. Nonetheless, system levels with the highest growth rate are random year after year, which shows that the smart city project in this nation is still fragmented and it lacks the consensus among relevant parties. In addition, although patent resident and non-resident applicants have strong relationships in major fields of construction sector, they do not have the same clear strategies in smart city development.

For the third question - How are vertical convergence and horizontal convergence in urban innovation related to each other?: Horizontal convergence and vertical convergence in urban innovation appear in parallel. Additionally, in many cases, movements of technologies on both horizontal and vertical levels have relationships and impacts on each other. This fact leads to a way to identify outside technologies drivers (on the vertical level) of the horizontal level through three models of constellations.

For theoretical implications, the research provides a systematic classification of technologies and the framework of urban innovation in a system structure based on the T-DNA approach. This model is applied to two cases which are the USA – a developing country and Vietnam – a leapfrogging one to supply insights into the technology landscape and major technological drivers of urban innovation in these two nations. Besides, the development of urban innovation also shows some main features of such two countries, in which a developed country with a very high patent count in urban innovation and the most significant growth rate of the super-system, and a leapfrogging country with a not high patent count in this field but a clear sign of focusing on the development of the most advanced technologies instead of intermediate ones. Last but not least, this research also suggests three kinds of constellations in the relationship between convergence analyses on horizontal and vertical levels. Relying on them, researchers and enterprises can understand horizontal convergence more clearly by identifying important bias or inside and outside drivers.

For practical implications, the research may help urban planners, managers and analysts in companies in urban areas in both cases of two countries. Firstly, politicians and urban planners should rely on the technology landscape of urban innovation to make important plans and decisions suitable to the development of technologies in urban innovation. The super-system and technologies in electricity and communication have significant influences on this field. Furthermore, politicians can prepare their plans based on the movements and combinations of technologies in urban innovation. Secondly, managers of companies may apply the framework of T-DNA in urban innovation as “a technology monitoring system” to control and forecast technologies related to this field and to their businesses. In addition, based on technology convergence in urban innovation, they can develop new technological knowledge and skills which are necessary for their companies in new situations of convergence. Thirdly, analysts of companies can discover that horizontal convergence may be affected by not only inside factors but also the ones coming from other system levels. This model can be used as an example to analyze technologies and horizontal and vertical convergence in other fields after applying the global map of science to check if technologies have been distant before. Finally, especially in case of Vietnam, politicians, enterprises and Vietnam Business Associations should co-operate to make strategies in urban innovation for clear plans with a general consensus. Moreover, on the one hand, in the process of working with foreigners, Vietnamese companies should exchange new innovations which are needed for their business and smart city development. On the other hand, foreigners who want to operate in Vietnam may carefully research on Vietnam market and strategies of the government for smart city so that they can have a good direction.

Nonetheless, the research has some limitations. Firstly, although urban innovation is the combination of innovations in many fields, I focus on only technological innovations. Secondly, CPC and IPC patent classification, which are used to analyze technology landscape and technology convergence in urban innovation, may not cover all technology sectors. So this fact perhaps influences results of the analyses. Thirdly, in the process of CPC co-classification analysis, not all classifications but only the main classification of patents of each system/ element is compared with all CPC classifications of another one. Fourthly, CPC or IPC scheme may change over time as some classifications are perhaps deleted or added so patent data and patent counts are different if they are collected in different time. Fifthly, using patent data can give the overview of technology development and technology convergence in urban innovation but inside problems have not been clearly explained.

Some further researches are suggested to partly solve limitations. First, patent citation analysis, topic modeling or key-word based analysis can be used in each short period or each year to see clearly the inside nature of technology development and convergence. Second, semi-structured interviews are recommended with managers, for instance resident and non-resident ones in technology fields of four system levels in Vietnam, to open more useful suggestions for strategies in smart city in this nation. Third, finding out about other aspects in urban innovation, for instance policies, city context, citizens, etc., may give a more complete insight into technology dynamics of smart city.

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Appendix A - Author contribution

Paper	Author contribution	Work
Paper 1 (Nguyen, N. U. P. and Moehrle, M. G. (2019))	60%	Conceptualization, methodology, interpretation of data, analysis
Paper 2 (Nguyen, N. U. P. and Moehrle, M. G. (2021))	50%	Conceptualization, methodology, analysis
Paper 3 (Nguyen, N. U. P.) (accepted)	100%	Sole author

Table A1. Percentages of contribution to papers by the author of the dissertation

Appendix B – Bibliographic information of three papers

In the following, the bibliographic information of three papers for this dissertation is presented.

i. Paper 1: Nguyen, N. U. P. and Moehrle, M. G. (2019) 'Technological Drivers of Urban Innovation: A T-DNA Analysis Based on US Patent Data', *Sustainability*, 11(24), pp. 1–26. doi: https://doi.org/10.3390/su11246966 (status: Published).

ii. Paper 2: Nguyen, N. U. P. and Moehrle, M. G. (2021) 'Combining the Analysis of Vertical and Horizontal Technology Convergence : Insights From the Case of Urban Innovation', *IEEE Transactions on Engineering Management*. IEEE, pp. 1–14. doi: 10.1109/TEM.2021.3086320 (status: Early Access).

iii. Paper 3: Nguyen, N. U. P. 'Exploring the development of the smart city project in Vietnam based on patent analysis of resident and non-resident applicants' submitted to *PICMET 2022 Conference* (status: Accepted).

P1: Technological Drivers of Urban Innovation: A T-DNA Analysis Based on US Patent Data

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Abstract:

Fast urbanization leads to several challenges in many cities all over the world. Thus, urban innovation is considered a common approach to deal with such questions. Although technologies are important factors in urban innovation, the development of technologies over time, how they affect urban innovation, in which relationship they stand to each other, and how they can be evaluated in a system approach are still not clear. To answer these questions, in our study, a Technology-DNA (T-DNA) is applied to US patents, which represent the most developed market in the world. Our paper provides some theoretical points in urban innovation and a systematic classification of technologies in this field based on patent classes. In addition, this research shows technological drivers in different system levels in urban innovation, especially in the super-system (representing city infrastructures) in detail. Therefore, it may help researchers, managers, politicians, and planners to focus on important technologies and to integrate technological drivers in urban innovation in their plans.

P2: Combining the Analysis of Vertical and Horizontal Technology Convergence: Insights From the Case of Urban Innovation

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Nguyen, N. U. P. and Moehrle, M. G. (2021) 'Combining the Analysis of Vertical and Horizontal Technology Convergence : Insights From the Case of Urban Innovation', *IEEE Transactions on Engineering Management*. IEEE, pp. 1–14. doi: 10.1109/TEM.2021.3086320 (status: Early Access).

Abstract:

Technology convergence is "the blurring of boundaries" between many sectors of technologies, resulting in the emergence of several new technologies. This phenomenon has been happening in many fields. While technology convergence has been analyzed often on a horizontal level, the whole landscape of technology movement among and within different system levels is still a question. Answers to this question can lead to an improvement of theory as well as new approaches for practitioners working in this field. We select urban innovation with its complex infrastructure as a test-bed in order to answer the question in a case study. We apply the Cooperative Patent Classification co-classification analysis to the USA patent data related to urban innovation in a systematic view from 1976 to 2018. Our study provides some insights into technology convergence in urban innovation based on the analysis of different system levels (vertical convergence) and within the super-system regarding city infrastructures (horizontal convergence). We find that both types of technology

convergence occur in parallel. While some technological movements seem to be related to each other, others do not. This leads to the conclusion that at least in the case of related technology movements, researchers should integrate different system levels in their analysis.

P3: Exploring the development of the smart city project in Vietnam based on patent analysis of resident and non-resident applicants

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Abstract:

Vietnam, a "leapfrogging" country, is coping with the fast urbanization. This fact leads to the adoption of smart city in Vietnam, which is the combination of many aspects, especially technologies, for sustainable development. There are several researches on smart city in this nation by giving case study of some cities, but the technology landscape of smart city in Vietnam in a systematic perspective and the relationship between patent resident and non-resident applicants in smart city in Vietnam have not been investigated. For such questions, I apply patent data of Vietnam and the Technology-DNA (T-DNA) approach to analyze smart city in a system structure, including: the core system (buildings), its sub-system (parts of buildings), its super-system (the surrounding environment of buildings - city infrastructures), and its associated system (machines, tools, and materials for construction). I find that first, the super-system has the dominant patent count; second, resident and non-resident granted patent counts have strong correlations in some fields of construction; third, resident and non-resident applicants consider Vietnam as a promising market for business and a leapfrogging country.

Nevertheless, both of them have not had a clear strategic orientation for construction and smart city. This paper opens recommendations for the smart city project in Vietnam.