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Research Article

A New Model Representation for Road Mapping in Emerging Sciences: A Case Study on Roadmap of Quantum Computing

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Abstract

One of the solutions for organizations to succeed in highly competitive markets is to move toward emerging sciences. These areas provide many opportunities, but, if organizations do not meet requirements of emerging sciences, they may fail and eventually, may enter a crisis. In this matter, one of the important requirements is to develop suitable roadmaps in variety fields such as strategic, capability, product, technology and etc. In this subject, it should be mentioned that there are connections among types of roadmaps, therefore, organizations need to understand these relations. According to this, we propose a model which describes relations among the roadmaps based on braid theory and appropriate methods for developing those roadmaps. The validity of developed model was conducted through the Delphi method. Additionally, we illustrate a to design a roadmap and implement it in quantum computing as an emerging science.

Keywords: Emerging sciences; Roadmap; Proposed model; Delphi method; Quantum computing.

1. Introduction

Over time, rapid and complex developments and competitive markets have resulted in businesses investing in emerging sciences. Such areas may provide many ways to gain more benefits from markets, but if they make wrong choices, they may create significant problems for companies and ultimately the company will be in crisis. The companies need to learn criteria in this matter which are relevant to emerging sciences. One such criteria is a roadmap that can be designed in various aspects such as strategic, capacity, product, technology, and research. Roadmap is a valuable method for defining an organization's path to achieving its goals. For example, in the strategic roadmap, managers will recognize the external environment's opportunities and challenges, and the internal environment's strengths and weaknesses in entering new markets.

Based on features of roadmaps, we can discover connections among roadmaps and to develop appropriate roadmaps, the organization needs to understand these connections.

According to all mentioned above, in this paper, we propose a model to explain the connections among roadmaps and appropriate methods to develop them Based on the characteristics of emerging sciences.

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1.1. Definitions of Emerging Sciences:

Sawyer (2005) explained the emergence as a situation that is created by the interactions of lower-level entities by a novel entity or an emergent. Therefore, emergence theory tries to describe a wide range of phenomena in the field of physics, biology and social. Because, science can be considered as a social phenomenon, so, the development of new sciences and research specialties can be defined as a process of social emergence (Templeton and Fleischmann, 2013). For example, we remember the reaction of people and companies when internet and computer were revealed to society. According to these, organizations may be able to optimize their situations in highly competitive markets by new sciences such as the internet of things or quantum computing. In this matter, emergent phenomena such as the exploration of new sciences are characterized by 5 characteristics (Goldstein, 1999):

1. Radical novelty: features of emergent are not previously observed and novel emergent are not able to be anticipated before they actually show themselves.
2. Coherence and correlation: emergent appears as integrated wholes which tend to keep their identity over time.
3. Global and macro level: since coherence shows a correlation which spans separate components, the locus of emergent phenomena in contrast to the

micro- level of their components occurs at a global level.

4. Dynamical: emergent phenomena evolve over time and are associated with arising of new attractors in dynamical systems.
5. Ostensive: emergents are recognized by representing themselves. Depending on the nature of complex systems, each ostensive presentation of emerging phenomena will vary from that of the previous one at some point.

1.2. Definitions of Roadmap and road mapping

In the past, organizations anticipated the possible future and planned based on that to be succeed in markets. But, nowadays, this method has lost its own effectiveness due to rapid and various changes in the market's situation. Therefore, organizations decided to enter the foresight area in which organizations describe a favorable future.

One of the effective tools to describe the appropriate way of achieving the favorable future in an understandable and common viewpoint in the organization is "roadmap". Based on the organization's needs on different levels, roadmap is classified into several categories which have unique functions. According to the definition of emerging sciences, required roadmaps can be described as follows:

- Strategic roadmap: strategic roadmap states the highest level of decisions such as vision, goals and missions which have been made by senior managers. In fact, the organization uses this roadmap as a solution to cut the gap between strategic and operational layers by presenting appropriate plans.
- Capability roadmap: nowadays, according to rapid changes of threats in the external environment, the organization needs to focus on improving capabilities instead of removing threats. A capability-based plan has more use such as higher flexibility, long-term effects, appropriate for the dynamic environment against threats-based plan. Therefore, the organization needs to develop a capability roadmap to explain its way to achieve the required capabilities.
- Product roadmap: this roadmap provides a forecast of product family evolution over time and demonstrates the entire platform of the relationship among products in a platform. The Product roadmap includes information such as product yearly changes, the high-level functionality of the product and the target customer group (Tanja, 2007).
- Technology roadmap: for taking advantage of technology, the organization needs a development plan which determines the required resources to support the development effort, the application of technology within the organization's future products and a timeline to achieve defined goals in this area. The technology roadmap can be used to capture and present this information (Petrick and Echols, 2004).
- Science roadmap: for some planned products and technologies, the organization may need to execute research & development programs. In this matter, a Science roadmap can describe and schedule programs based on high-level roadmaps.

Meanwhile, organization should operate based on an array of objectives which is called "road mapping" process to design a proper roadmap. In fact, the road mapping process provides an opportunity for people from different departments to share information and discuss about issues and new ideas (phaal, Farrukh and Robert, 2004). According to situations and required roadmaps, organizations have designed road mapping models. For example, there are several methods for Technology roadmap such as Rockwell Company (McMillan, 2003), Kappel approach (Albright and Kappel, 2003), T-Plan (phaal, Farrukh and Robert, 2004), Sandia National Labs approach (Garcia and Bray, 1997).

This paper is organized as follows. Section 2 literature review. Section 3 problem statement, Section 4 explains our proposed model, Section5 The validation of model, section 6 Implementation Instructions and section 7 expresses the results of the model in quantum computing as an emerging science.

2. Literature Review

In emerging sciences, we have found 6 models to design roadmaps. The first model has been proposed by Marin and Daim (2012) for the service sector which uses three expertise panels to identify emerging technologies, business and market drivers and gaps by mapping the emerging technologies to products and services. Eventually, their model includes drivers, services, products, technologies and R&D programs as layers of roadmaps.

Bessis et al (2011) suggested a model to provide emerging technologies roadmap for enabling collective computational intelligence in disaster management which contains 3 phases as followed:

- Preliminary activity: this phase includes activities such as the identification of stakeholders and their requirements, the definition of the scope and criteria for technology roadmap to succeed.
- Development of the technology roadmap: in the second phase, the organization identifies

technologies available for their adaption, prompts the development of future technologies and creates the technology roadmap.

- Follow-up activity: in the final phase, the roadmap should be reviewed and updated by larger group of stakeholders and experts.

Goetzler et al (2014) presented a model to create R&D roadmap for emerging HVAC technologies which includes followed stages:

1. Characterize current R&D, markets and objectives: the organization review past roadmaps, market reports and current R&D to characterize current markets and programs and also, key goals.
2. Identify Technologies: technologies will be identified based on the literature review, stakeholder forum and one-on-one interviews.
3. Prioritize Initiatives: the organization identifies and prioritizes the best opportunities by 3 steps such as preliminary ranking, qualitative scoring and quantitative scoring.
4. Develop R&D roadmap: in the final stage, detailed information like a general description of topics and markets, goals of programs, technical challenges, and key milestones of the roadmap, potential impact on markets barriers and key stakeholder roles and responsibilities will be explained in the form of a report.

Van Lente and Van Til (2006) proposed a road mapping-cluster approach for emerging technologies. This approach includes 3 layers such as markets, products and technology. The road mapping process contains 4 stages as follows:

1. The reconstruction of respective clusters within which the technologies at stake are being developed based on reports and interviews.
2. The construction of a technology roadmap in semi-structured interviews with organizations and researchers.
3. Explain challenges and barriers which are related to these two steps.
4. A comprehensive check-in interviews with involved parties.

Li et al (2015) suggested a model to provide a strategic plan for emerging technologies in dye-sensitized solar cell area. The model includes 3 steps as followed:

1. Bibliometric analysis: in this step, the organization searches for specific keywords in the emerging technology among the published papers and reports to understand the R&D activity by analyzing the changes in number and frequency of publications over time.
2. Workshop 1: in the first workshop, the organization brings experts together to identify possible future events such as opportunities, enablers or barrier.
3. Workshop 2: in this workshop, the organization will do some activities such as the selection of goals and missions, analyzing the internal and external competitive environments, creating strategies according to opportunities and barriers and implementing the strategy.

Gerdsri (2007) proposed an analytical approach for strategic planning in emerging area. This approach includes 6 steps as follows:

1. Technology forecasting: develop a model using Delphi for identifying the trend of emerging technologies.
2. Technology Characterization: identify criteria and technological factors that are related to the organization's objectives.
3. Technology Assessment: assess emerging technologies based on the measures of effectiveness.
4. Hierarchical modeling: develop a hierarchical model to determine the importance of criteria, factor under each criterion and desirability of measure of effectiveness on each factor.
5. Technology evaluation: evaluate the impact value of emerging technologies on the organization's objective.
6. Formation of TDE (Technology Development Envelope): construct technology development envelope and paths.

3. Problem Statement

In the road mapping process for emerging sciences, organizations should pay attention to connections among roadmaps. If organizations ignore this important fact, developed roadmap may not be effective to achieve their goals.

According to the description of the different approach for road mapping in emerging sciences, we summarized and compared features of them to the proposed model of this paper in Table 1.

Table 1
Comparison of previous models and our proposed model

Model	Type of Roadmap					Relationship among roadmaps
	Strategic	Capability	Product	Technology	Science	
Marin and Daim (2012)	-	-	-	☑	☑	-
Bessis et al (2011)	-	-	-	☑	-	-
Goetzler (2014)	-	-	-	-	☑	-
Van Lente and Van Til (2006)	-	-	-	☑	-	-
Li et al (2015)	☑	-	-	☑	-	-
Gerdsri (2007)	-	-	-	☑	-	-
Our proposed model	☑	☑	☑	☑	☑	☑

4. Proposed Model

Based on all mentioned in previous sections, we propose a model to show connections among roadmaps and suggest appropriate methods for road mapping process which is related to them.

In this matter, based on roadmap features, relations between roadmaps operate on the basis of braid theory which has been studied for nearly 100 years and was created in 1947 by Emil Artin (Chiodo, 2005).

A braid is a set of strings which expand between two parallel planes and every braid will be closed into a knot by joining pairs of endpoints from the bottom and top planes (Berger, 2001).

If we consider roadmaps as planes, we can draw several lines between the planes to point out the connections. For example, we explain some of these connections to prove this important fact as follows:

- Product and strategic roadmap: before making a decision about new products and designing a product roadmap to achieve them, the organization should specify vision, goals and mission which can be provided by the strategic roadmap. This is one of the connections between these two roadmaps and the other one is the capability roadmap. For more information, products may be needed to provide the required capabilities. Therefore, after determining the characteristics of the strategic roadmap, the organization should recognize required the capabilities and design a roadmap for them. At the final step, the organization can provide a product roadmap based on the capability roadmap (Fig. 1).
- Technology and science roadmap: when the organization designs a technology roadmap, they may need to define research programs to study new technologies. According to the science roadmap's definition, it can be used to explain research programs and their features which means there is a connection between the science and technology roadmaps (Fig. 2)
- Product and technology roadmap: the strongest connection among roadmaps is between the product and technology roadmaps. When the organization decides to produce a new product, it may need new technologies to operate which requires developing a technology roadmap. Therefore, this shows the connection between product and technology roadmap (Fig. 3).

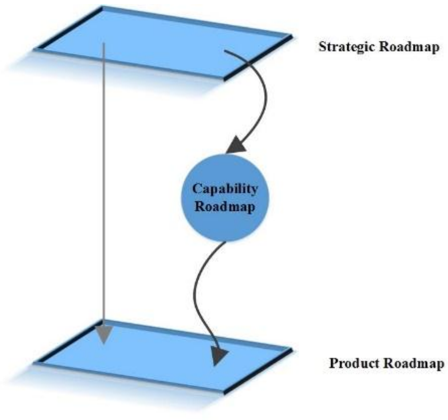

Fig. 1. Connections between strategic and product roadmap based on braid theory

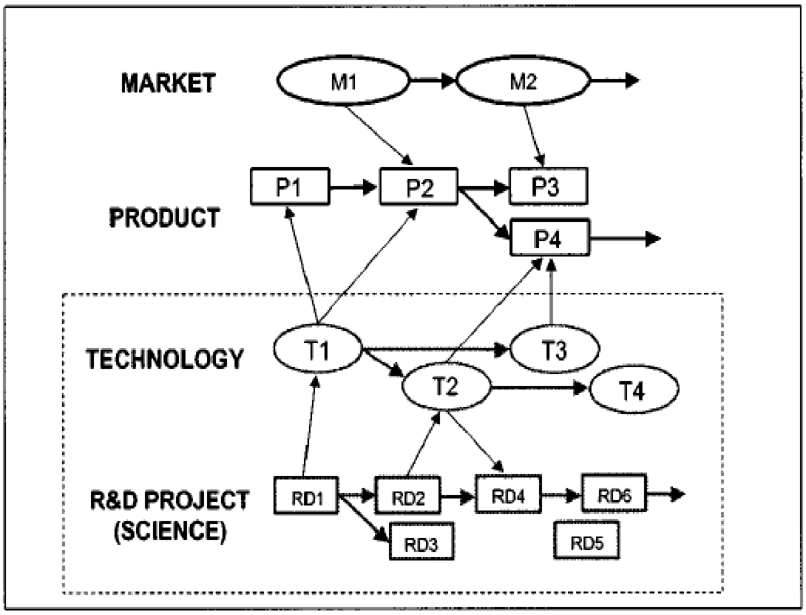

Fig 2. The Connection between technology and science roadmap (Kostoff and Schaller, 2001)

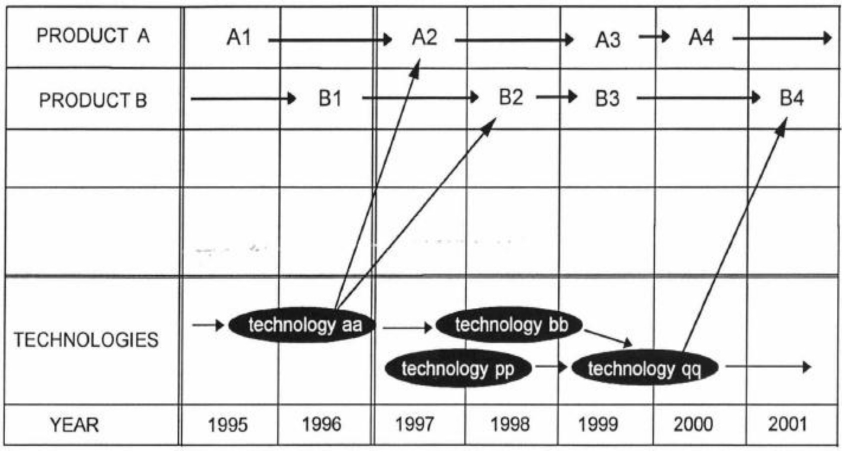

Fig 3. The Connection between technology and product roadmap (Groenveld, 1997)

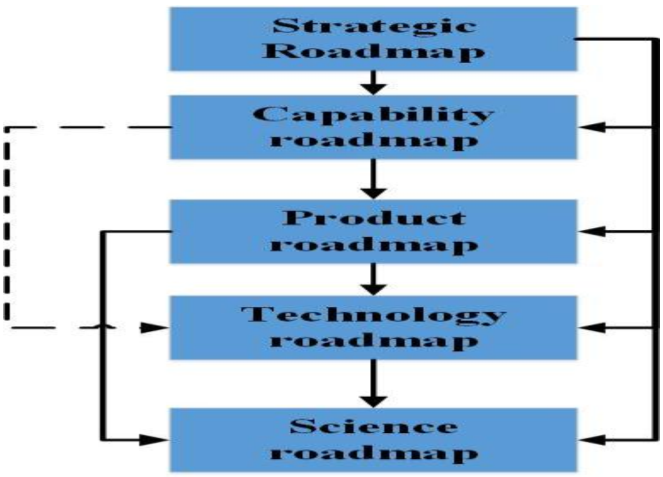

Fig 4. The Connections among the roadmaps

Figure 4 shows our proposed model of the connections.Alongside the proposed model of connections, we suggest some appropriate developing methods for each of the roadmaps as follows:

- **Strategic Roadmap**: organizations need to identify vision, strategic goals and mission in emerging sciences. For this roadmap, they can use S-plan method (Phaal, Farrukh and Robert, 2007) that includes 4 workshops. In these workshops, organizations will do followed processes:
  - Design a strategic vision
  - Identify and prioritize opportunities
  - Review high priority opportunities
  - Determine the required actions to achieve the goals.
- **Capability roadmap**: sometimes, the organization may need to have a plan for improving the capabilities based on strategic roadmap. This roadmap may contain human capability, infrastructures, diverse products, executive processes of organization and etc. for this roadmap, we can use the Kevin daily (2004) method or model of the UK railway industry (Eagar, Roos and Kolk, 2013) For example, the second method includes the following stages:
  - Study the vision of the organization and identify capability goals.
  - Determine and describe the required capabilities based on capability goals.
  - Define the required activities or enablers to reach the capabilities.
- **Product roadmap:** organizations can use the product as a proper tool to respond to their needs. In this matter, Tanja (2007) proposed a method for designing the product roadmap that includes information such as the features of the product, release time, localization, platforms, and geographical focus of the product for each year and etc. His method contains 5 stages such as capturing features, analyzing features, prioritizing features, roadmap validation and agreement and change management of the roadmap (Fig 5).

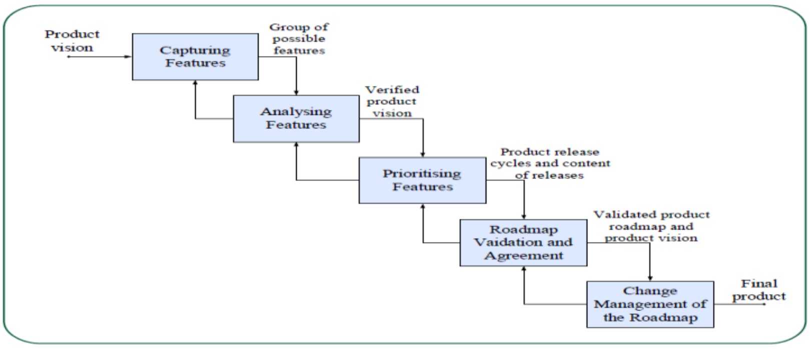

Fig 4. Tanja's method for product roadmap (Tanja, 2007)

- **Technology roadmap:** based on product or capability roadmap, organization may need to develop technologies which related to them. For this reason, organizations should provide a technology roadmap. According to wide range of technology's application, there are several methods for road mapping such as product planning, capability planning, strategic planning and etc. For example, the organization can use the T-plan approach (Phaal, Farrukh and Robert, 2004) in product planning which includes 4 workshops (Fig 6).

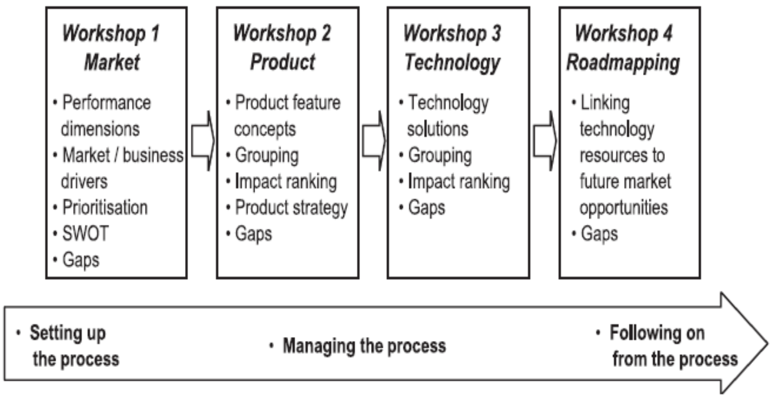

Fig 5. T-plan approach for technology roadmap (Phaal, Farrukh and Robert, 2004)

- **Science roadmap:** When you plan for new products or technologies, you may need to study different aspects of them such as feasibility, features, requirements, evaluations and etc. for this issues, organization should plan research & development programs which in this area is called "science roadmap". For developing this roadmap, organizations are able to use the agriculture science method with 10 stages. Some of these stages are as follows (Mackenzie et al., 2002):
  - Identify a leader with commitment and influence at the top of the organization.
  - Form a small working group to inventory information and solicit names of scientific exports.
  - Form a task force of 16 to 24 members, with representation that gives diversity and scientific coverage.
  - Convene the task force to explain the road mapping process and develop the plan of activities.

5. The Validation of Model

The validation of this model was conducted through the Delphi technique. According to Alves et al (2014), the Delphi technique aims to search for consensus opinions of a group of experts about future events. Thus, our conceptual model was validated by consulting selected experts in technology management, analyzing their agreement on the aggregation of the strategies proposed in the conceptual model in the same cluster representing each dimension. Therefore, we first brought together experienced people from universities and industries, and then decided to use the Delphi method with three of rounds to gather best of information. Based on the type of roadmap and the Delphi method, in the first round, we used two forms to identify products (Table 2) and technologies (Table 3). After collecting information, we delivered the first round forms (Table 4) to get ideas of specialists about products (round two). After setting required products, we use the second survey (Table 5) to determine the required technologies for the products which was selected in first survey. At the end, we use table 6 to design a timeline to achieve technologies based on TRL (Technology Readiness Level) and identify tools and resources we need to execute the roadmap (round three).

6. Implementation Instructions

In this section, we propose our road mapping instructions which contains all types of the required roadmap for emerging sciences. This instruction includes the 5 following steps:

1. **Introduction (strategic roadmap)**
   In the first step, we define visions and goals and missions to achieve them at a high-level of timeline.
   - Introduction of emerging science (history of the subject, previous activities in the world and etc.)
   - A Vision of the area
   - Application of the area to resolve the country's needs (determination of focus area)
   - Representing approaches to achieve the vision(missions)
2. **Focus areas (capability roadmap)**
   In this step, we describe focus areas of field and the capabilities we need to improve. Then, we design programs to move from current situation to favorable situation.
   - Introduction of Focus areas (describe capabilities in focus area)
   - Application of the focus areas to resolve country needs (required capabilities)
   - Goals of the focus areas based on the vision (favorable situations in required capabilities)
   - The Current state of the focus areas in the country (current situations in required capabilities)
   - The Requirement of the Focus areas for achieving the goals.
3. **Product identification**
   In this step, we can use Table 2 as a product sheet to explain the products.
4. **Technology introduction**
   In this step, we can use Table 3 as a Technology sheet to explain the technologies

Table 2
Product Identification

Product name:		Product ID: QPC		
Country:		Year:		
Approach (s):				
Product Introduction:				
Related product (s)				
Predecessor:		Successor:		
Product Characteristic (s)				
Application (s):				

Table 3
Technology Identification

Technology name:		Technology ID: QTC		
Country		Year:		
Approach (s):				
Technology Introduction:				
Related Technologies				
Predecessor:		Successor:		
Technology Characteristic (s)				
Application (s):				

7. Surveys

We designed 3 surveys to recognize the needs and resources of the country, demanded products, the relationship among products and technologies and then, set a schedule to achieve technologies and products. For this reason, we designed 3 surveys as follows:

Table 4
Product selection and country's needs

First survey							
Question 1: Country's Current state in Focus area							
Needs (Country's needs that can be resolved by the area) and prioritize them on scale of 1 to 10:							
Requirements for developing in the area:							
Question 2: selecting required products based on information from stage 3 and question 1							
	Products						
	QPC001	QPC002	QPC003	QPC004	QPC005	QPC006	QPC007
Y/N							
Priority							

Table 5
Products and technologies relationships

		Technologies					
		QTC001	QTC002	QTC003	QTC004	QTC005	QTC006
Products	QPC001						
	QPC002						
	QPC003						
	QPC004						

Table 6
Scheduling products and technologies

		Technology	Current TRL	Scheduling to achieve technologies			Scheduling to achieve Products
				TRL=3	TRL=6	TRL=9	
Products	QPC001	QTC001					
		QTC002					
	QCP002	QTC003					
		QTC004					

TRL Levels			
1	Basic principles observed and reported	2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept	4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment	6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment	8	Actual system completed and qualified through test and demonstration
9	The actual system has been proven through successful mission operations		

8. Case Study: Roadmap of Quantum Computing

In this section, we represented our implementation method for roadmap of quantum computing in detail as follows:

1. Based on figure 4, in the first step, the organization needs to build a strategic roadmap. According to this, we settled several meetings with high-level managers of related industries and universities. After hours of discussion in these meetings, they defined visions, goals and missions about the quantum computing area.
2. In step 2, we collected information about the quantum computing such as focus areas, capabilities, product and technologies and summarized it in the form of table 2 and 3.
3. After collecting information, we presented them to experts and gave them survey 1 (Table 4) for taking their ideas about the country's needs and products selection based on those needs. We executed this step in 3 rounds to achieve better results.
4. After survey1, we used survey 2 (Table 5) to determine the required technologies for products which had been selected in step 3. We repeated this step for 3 times like step 3 with the help of specialists.
5. At the final step, experts completed survey 3(Table 6) to set a timeline for achieving technologies and products. Like steps 3 and 4, we repeated this step for 3 times to schedule an appropriate executive plan.

8.1. Part of the designed roadmap of quantum computing

In this section, we publish a part of the roadmap which has been designed based on the implementation method.

1. Step one:
Quantum physics was born in the early 1900s. Quantum mechanics is known as quantum physics developed over many decades. It is the exclusive theory that defines the behaviors of the subatomic particles. the Application of quantum mechanics has been involved in many technologies such as magnetic resonance imaging, lasers, the transistor, the electron microscope, super fluid helium and superconductors. Furthermore, quantum mechanics has appeared in special subjects of the new age which are introduced as follows: computing, communications, defense, energy, biomedical which are related to emerging science. Quantum computing comprises classical information theory, computer science, and quantum physics. According to the explanations given before and available topics in the working group, key applications, target products, key technologies and requirements are recognized as four layers of the roadmap.

Step 2: Key applications

- Cryptography
- Quantum simulation
- Quantum teleportation
- Artificial intelligence

Step 3. Target products

- Qubits: A quantum system basically is used to define a bit, as a result the system is called quantum bit, or just “qubit”. A single qubit consists of 2 states as a natural binary digit or “bit” that is comparable to the “spin” of an electron. The possible values of spin are “spin up” or |↑ and, “spin-down” or |↓. It is noted that the elementary unit of quantum information is the qubit (Steane, 1998).
- Gates: Gates or quantum ‘logic gates’ are basic unitary operations on a small number of qubits. In other words, considering the quantum circuit model, gates are simple quantum circuit operating on qubits (Nielsen and Chuang, 2010)
- Algorithms: algorithms or quantum algorithms are mostly used to run on model of quantum computation. The commonly used model of quantum computation is the circuit model. Over the years, many efforts have been made to build scalable quantum computers using quantum circuits. Shor’s algorithms (1994) were the first breakthrough in the area of quantum algorithms.
- Memories: This option has key role in quantum information processing applications such as quantum repeaters (Kimble, 2008; Briegel et al., 1998), quantum networks (Sangouard et al., 2011) and linear optics quantum computing (Knill, Laflamme and Milburn, 2001)

Step 4. Key technologies

It has been demonstrated that quantum entanglement is applied in many applications like quantum cryptography, quantum teleportation, and quantum dense coding (Kok et al., 2007) .Quantum dots are semiconductor particles which can be used for quantum computing (Filikhin et al., 2012).

The advantage of a quantum computer is applying the principles of quantum mechanics to process and solve mathematical problems faster than common digital computers. Until now the forty qubits small quantum computer could solve quantum mechanical problems that are difficult for current computers. In 1989, David Deutsch realized the supremacy of quantum mechanical methods rather than classic methods to solve problems. Quantum computation has had rapid development in recent years. Peter Shor discovered a quantum algorithm that had the ability to factor large numbers, faster than today’s classical algorithms Ignacio Cirac and Peter Zoller found the capability of a physical system to implement on such quantum algorithms: single trapped ions were considered to transport the quantum information, which are manipulated with focused laser beams. David Wineland’s group at the National Institute of Standards and Technology indicated the other ion-trap quantum computer. Liquid-state nuclear magnetic resonance was used to reveal a quantum algorithm. There were many new interesting implications were found. The discovery of quantum error correction protocols by Steane and Shor for quantum computation was the most related implication (Filikhin et al., 2012). Generally, we can indicate:

- Quantum states are used to allow the secure transmission of classical information (quantum cryptography)
- Quantum entanglement is used to allow reliable transmission of quantum states (teleportation),
- The feasibility of maintaining quantum coherence in the presence of irreversible noise processes (quantum error correction),
- Controlled quantum evolution is used for efficient computation (quantum computation).
- The common and important theme of all these options is the use of quantum entanglement as a computational resource (Życzkowski et al., 2001)

In Table 7, we have showed connections between target products and key technologies which they need.

Table 7
Target products and their key technologies

		Target Products			
		Qubits	Gates	Algorithms	Memories
Key Technologies	Quantum entanglement	☑			
	Nano-Structures and Quantum dots	☑			
	Ion trapping and cooling	☑	☑		
	Semiconductors and solid-state physics	☑			☑
	Superconductors				☑
	Error corrections		☑	☑	☑

Step5. Requirements

Eventually, to fill the last layer of the roadmap, we recognized facilities and laboratories which are required for our roadmap. In figure 7, we have presented these requirements and connections between them.

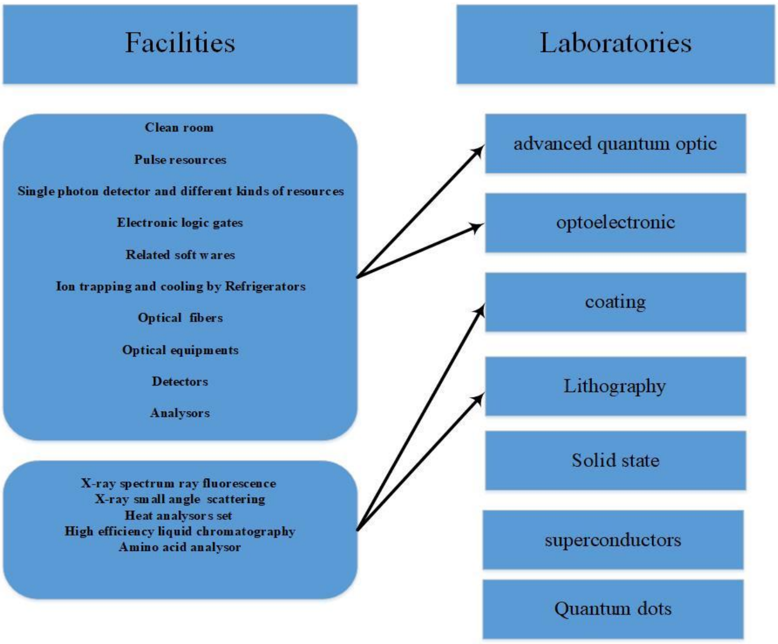

Fig 6. Requirements

9. Conclusions

Based on many reasons such as competitive markets and increasing financial profits, research & development (R&D) department has gained a huge role in organizations. The most important task of this department is to help the organization to become known as a pioneer in markets. In this matter, we developed a model that focus on emerging technologies & sciences and design the right roadmap for them to achieve its own goals such as most market share. But to design an appropriate roadmap for emerging sciences and prevent waste of resources (financial and staff), organizations need to identify types of roadmaps, relations amongst them and methods to provide them. Therefore, in this paper, we firstly introduced various types of roadmaps and processes to design them. Then, based on the braid theory and organization's need, we proposed a model of connections among the roadmaps. In the third stage, for validating our model, we illustrated and implemented a road mapping instruction and required forms to design a technology roadmap for quantum computing as an emerging science.

References

Albright, R.E., &Kappel, T.A. (2003). Road mapping in the corporation. *Research-Technology Management*, 46 (2): 31-40.

Alves,W., Colombo,C.R.,Portela ,C,R., Ferreira1,P., & Dália,R. (2014). *Proceding of the 2nd International Conference on Project Evaluation* , portugal,196-202

Berger, M. A. (2001). Topological invariants in braid theory. *Letters in Mathematical Physics*, 55 (3): 181-192.

Briegel, H. J., Dur, W., & Cirac, J.I. (1998). Quantum repeaters: the role of imperfect local operations in quantum communication. *Physical Review Letters*, 81 (26): 5932- 5935.

Bessis, N., Asimakopoulou, E., & Xhafa, F. (2011). A next generation emerging technologies roadmap for enabling collective computational intelligence in disaster management. *International Journal of Space-Based and Situated Computing*, 1 (1): 76-85.

Chiodo, M. (2005). An introduction to braid theory. *Msc Thesis, University of Melbourne*.

Eagar, R., Roos, D., & Kolk, M. (2013). Capability Road mapping – developing the means to an end. *Arthur D. Little Prism*, (2): 30-45.

Filikhin, I., Matinyan, S. G., & Vlahovic, B. (2012). Quantum mechanics of semiconductor quantum dots and rings .*Intechopen*. London.

Garcia, M. L., & Bray, O. H. (1997). Fundamentals of technology roadmapping (No. SAND-97-0665). *Sandia National Labs., Albuquerque*, United States.

Gerdsri, N. (2007). An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies. *International Journal of Innovation and Technology Management*, 4 (02): 121-135.

Goetzler, W., Guernsey, M., & Young, J. (2014). Research & development roadmap for emerging HVAC technologies. *Department of Energy*, United states.

Goldstein, J. (1999). Emergence as a construct: History and issues. *Emergence*, 1 (1): 49-72.

Groenveld, P. (1997). Roadmapping integrates business and technology. *Research-Technology Management*, 40 (5):.48-55.

Kimble, H. J. (2008). The quantum internet. *Nature*, 453 (7198): 1023-1030.

Knill, E., Laflamme, R., & Milburn, G. J. (2001). A scheme for efficient quantum computation with linear optics. *Nature*, 409(6816): 46-52.

Kok, P., Munro, W., Nemoto, K., Ralph, T., Dowling, J. P., & Milburn, G. (2007). Linear optical quantum computing with photonic qubits. *Reviews of modern physics*, 79 (1):. 135-174.

Kostoff, R. N., & Schaller, R. R. (2001). Science and technology roadmaps. *IEEE Transactions on engineering management*, 48 (2): 132-143.

Kynkaaqnniemi, T. (2007). Product roadmapping in collaboration, *Technical Research Centre* ,Finland.

Li, X., Zhou, Y., Xue, L., & Huang, L. (2015). Integrating bibliometrics and roadmapping methods: A case of dye-sensitized solar cell technology-based industry in China. *Technological Forecasting and Social Change*, 97: 205-222.

MacKenzie, D. R.,Donald, S., Harrington, M., Heil, R.; Helms, T.J.; Lund, D. (2002). Methods in science roadmapping: How to plan research priorities, *University of Maryland press, www.escop.msstate.edu/archive/roadmap-methods.doc*

Martin, H., & Daim, T. U. (2012). Technology roadmap development process (TRDP) for the service sector: A conceptual framework. *Technology in Society*, 34 (1): 94-105.

McMillan, A. (2003). Roadmapping agent of change. *Research-Technology Management*, 46 (2): 40-47.

Nielsen, M. A., & Chuang, I. (2010). Quantum Computation and Quantum Information. 10th edition.*Cambridge University Press*.UK.

Petrick, I. J., & Echols, A. E. (2004). Technology roadmapping in review: A tool for making sustainable new product development decisions. *Technological Forecasting and Social Change*, 71 (1-2): 81-100.

Phaal, R., Farrukh, C. J., & Probert, D. R. (2004). Technology roadmapping—a planning framework for evolution and revolution. *Technological forecasting and social change*, 71 (1-2): 5-26.

Phaal, R., Farrukh, C. J., & Probert, D. R. (2007). Strategic roadmapping: A workshop-based approach for identifying and exploring strategic issues and opportunities. *Engineering Management Journal*, 19 (1): 3-12.

Shor, P. W. (1994). Algorithms for quantum computation: discrete logarithms and factoring. *Proceedings of the 35th Annual Symposium on Foundations of computer Science* , 124-134. IEEE Press,124-134.

Sangouard, N., Simon, C., De Riedmatten, H., & Gisin ,N. (2011). Quantum repeaters based on atomic ensembles and linear Optics. *Reviews of Modern Physics*, 83 (1): 33-80.

Sawyer, R. K. (2005). Social emergence: Societies as complex systems. *Cambridge University Press*.UK

Steane, A. (1998). Quantum computing. *Reports on Progress in Physics*, 61 (2): 117-173.

Templeton, T. C., & Fleischmann, K. R. (2013). Research specialties as emergent phenomena: Connecting emergence theory and scientometrics. *Proceedings of the IConference 2013*.827-830

Van Lente, H., & Van Til, J. (2007). A combined roadmapping-cluster approach for emerging technologies. *International Journal of Foresight and Innovation Policy*, 3(2): 121-138.

Życzkowski, K., Horodecki, P., Horodecki, M., & Horodecki, R. (2001). Dynamics of quantum entanglement. *Physical Review A*, 65(1), 012101.

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