Analysis of the Intellectual Structure and Evolution of Technology Roadmapping Literature

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Abstract–**The technology roadmapping field has evolved over time from the first and second generation technology roadmaps to the current third generation roadmaps. As a strategy and policy formulation tool, technology roadmaps proved to be useful in facilitating learning and consensus across the firm or across the industry. Similarly, technology roadmaps have been used as a process to operationalise the strategies by mapping the details of future research and development programs, technological capability development programs and manufacturing capability development initiatives. Practitioners and scholars alike are seeking new ways on integration of this technology market planning tool with other business processes while on the other hand, there are efforts for their customisation according to the needs of managers or policy makers. This paper maps trends in technology roadmapping and technology roadmap literature through an analysis of life cycle pattern on scientific contributions from this field. A gap exists for quantitative tracking of evolutionary patterns in terms of the three technology roadmapping generations.**

I. INTRODUCTION

Technology roadmapping as a research field is evolving, from a simple process that focused on incorporation of technology in business planning [1] processes, to a more robust knowledge generating process in managing the complex innovation systems. This increased complexity is reflected by the three generations of technology roadmaps, namely: product technology roadmap, emerging technology roadmap and the 'innovation roadmap'. The words 'technology roadmap' and 'technology roadmapping' are often used interchangeably [2, 3], and this is also the case for this paper; although it should be noted that technology roadmapping is a process and technology roadmap is a product of such a process.

The objective of this paper is to conduct a systematic evaluation of the evolution and knowledge structure of technology roadmapping field for the period of 2000 to 2013. The literature review is used to operationalise the tracking of this field's evolution and a research methodology section that follows after the literature review describes the research constructs, data and its source. In addition, the research methodology section also presents a procedure for data analysis. In section IV, the results are presented and analysed. A conclusion section summarises the practical implications for the findings of this study and also suggests the potential future research that can extend the findings of this study.

II. LITERATURE REVIEW

It is known that the technology roadmapping literature started to pick up around 2004 whereas a first formal paper was published in 1987. This section reviews this body of knowledge in terms of the three technology roadmapping generations in order to identify the concepts that are typically associated with them. A sub-section on knowledge structure evolution highlights some theoretical background on knowledge structure and scientific knowledge evolutionary mechanisms. A sub-section on the evolution of technology roadmapping literature relates the knowledge structure and evolution theory to a technology roadmapping field.

A. Three generations of technology roadmapping

There are typically three generations of technology roadmapping approaches, the first generation being a product technology roadmapping which is concerned with a continuous product technology platform and these types of technology roadmaps are typically being on a single root technology [4] such as a transistor for the semiconductor industry. The type of technologies associated with the first generation technology roadmapping are typically sustaining, of which according to Kostoff et al. [5], are known to improve the performance of existing products through the current product technology paradigm. A stable product technology platform typically has a platform leader(s) within a global value chain that coordinates an ecosystem of suppliers that have the complementary products in order to provide a complete solution to a customer [6]. Therefore first generation technology roadmaps are aimed at facilitating communication between the platform producers and complementary products suppliers in order to contextualise future technological system requirements in relation to the changing customer needs.

In the case of second generation technology roadmaps, the focus is on "forecasting the development and commercialisation of a new or emerging technology" [7], hence it is called an emerging technology roadmap. Such forecasting is achieved mainly through an analysis of life cycle differences between an emerging technology of interest and a current root technology in order to predict a potential technology transition point [4]. The emerging technologies can be sustaining or disruptive, depending on their complementarity with an existing product technology platform [8, 9], although according to Overdorf and Barragree [10], new technologies typically have some sustaining or disruptive features. The strategic role of

emerging technology roadmaps depends on whether the roadmapping effort is pursued by an incumbent with a stable product technology platform or a challenger who needs to explore the potential product platforms. Incumbents are often threatened by rapid and radical technological discontinuities [11], and as a result, technology roadmapping assists with the identification of future threats and for organisational learning in adapting to an uncertain future. Technology roadmapping in a context of a challenger, without an established product technology platform, serves a purpose of facilitating a rapid commercialisation pathway through an establishment of a new value network and in convincing the customers to adapt/ change their preferences [11].

Motorola's technology roadmapping efforts involved mainly the first generation technology roadmapping although they also made use of a second generation roadmapping approach [12]. An emerging technology roadmap was used by a company to (i) do an objective evaluation of technology capabilities, (ii) to determine the current and future comparison of Motorola's capabilities to that of its competitors, and (iii) to forecast the future technological progress [12]. According to the authors, Motorola used the product technology roadmaps to track a company's progress in product and process development in a context of the marketplace, competition and historical performance.

A third generation technology roadmapping approach proposed by several authors [4, 13, 14] recognises the changing nature of technology innovations in a sense that most of the current innovations depends on converging or competing multiple root technologies [14] with the complex interactions and technology developments are done without an obvious direct benefit of the predetermined architecturally stable product process platforms [4]. Since some main functions of technology roadmaps are to communicate the critical system requirements [15] and to communicate the relationships among markets, products and technologies over time [16, 17], with the third generation technology roadmaps communication becomes even more critical. Communication for the third generation technology roadmapping is aimed at a broader knowledge network of a company that incorporates potential complementary products and technologies. The key characteristic for third generation technology roadmapping is an absence of a clear product process platform coordinator and the presence of other drivers such as regulation and culture in addition to market drivers [4].

B. Understanding knowledge structure evolution

A scientific literature is typically regarded as a collection of formal knowledge generated [18] which represents some deductions and observations that are validated through peer review mechanisms and an interest shown to that knowledge by other scholars through citations. This knowledge is organised by distinct themes within a research domain of interest and these themes are also known as knowledge paradigm. There is a possibility of coexistence of opposing research paradigms [19] due to different schools of thought or as a result of knowledge evolution. An analysis of knowledge structure evolution is achieved through detection of a specific scientific paradigm and the associated movement of such a paradigm [20].

There is a plethora of scholars that use bibliometric analysis techniques in determining a knowledge structure evolution pattern for scientific literature on a specific discipline of interest. Bibliometric analysis is defined as "organisation, classification and quantitative evaluation of publications pattern along with their authorships by mathematical and statistical calculations [21]. This typically involves statistical and visual information on citations, co-citations, co-authorship and author network analyses. Citations serves as an indicator of the level of impact for scientific knowledge generated whereas co-citations and keywords analyses are used as indicators of relatedness for scientific publications of interest [22]. Network analysis is useful to determine an extent of scientific research collaboration among the authors [23]. The main setbacks on the reliability of bibliometric analysis are issues such as self-citations and controversial publications that can spark a stream of responses from expert authors [24], resulting with a large count of citations. Most bibliometric analysis software is built to take care of self-citations whereas it is not simple to clean notorious publications on the measures of knowledge impact.

C. Evolution of technology roadmapping literature

The three generations on technology roadmapping represents different research paradigms depending on the nature of innovation planning which is being addressed. Matured and large companies with a supporting value network of complementary partners might still prefer the use of a product technology roadmapping or emerging technology roadmapping approaches whereas some high technology small companies and most developing countries' companies, without the established global competencies, might find the third generation technology roadmapping approach being useful in planning a rapid commercialisation pathway. These opposing paradigms result with some conflicting or different definitions. As for example, a technology roadmap definition provided by Garcia and Bray [25] as "a needs-driven technology planning process to help identify, select, and develop technology alternatives to satisfy a set of product needs" applies mainly to first generation technology roadmapping practice and this result with the emergence of other definitions. An outcome of these multiple definitions is an absence of a standardised definition for technology roadmapping or technology roadmaps [1, 26].

Another method of illustrating the evolution of technology roadmapping literature is its categorisation of focus according to best practice perspective (1987 – 2000), engineering perspective (2001 – 2010) and the organisational behaviour perspective from 2011 onwards [27]. The best practice theoretical perspective according to Simonse et al. [27] is dominated by case studies of roadmapping practice within the

companies such as Motorola, Lucent, Philips, etc., whereas the engineering perspective seeks to generate a knowledge that assist with the 'how' of roadmapping efficiently and among some known processes invented are the 'fast-start' technology roadmapping workshop techniques introduced by Phaal et al. [1]. The organisational behaviour perspective balances technology scouting input with opportunity scouting input and this is achieved through exchanging and co-creation of innovation roadmaps with the suppliers and other partners [27].

The two recent articles by Carvalho et al. [28] and Gerdsri et al. [29] systematically reviewed the technology roadmapping knowledge structure evolution. A first paper used a hybrid methodological approach that combines bibliometrics, semantic analysis and content analysis to show technology roadmapping evolution from 1997 to 2011. This study identified several definitions of the technology roadmapping/ roadmaps; various phases in technology roadmapping process; analytical tools used by technology roadmapping literature's authors; conditions necessary for development of a high quality technology roadmap; as well as limitations and advantages of the roadmap. Most authors agree on the alignment of technology with overall business objectives as a major benefit for technology roadmapping although there is no consensus on the limitations. A dominant research methodology used by most authors in technology roadmapping field is a case study followed by a literature review [28].

A paper by Gerdsri et al. [29] used bibliometric analysis on technology roadmapping's selected journal and conference papers between 1987 to 2010 to show evolution of technology roadmapping literature by year, and further more shown which journals, conferences, countries and organisations are leading on technology roadmapping related research. The Unites States was shown to be the leading country followed by United Kingdom; whereas University of Cambridge followed by Portland State University were shown to be the leading organisations. The University of Cambridge group is mainly focused on the engineering perspective of technology roadmapping [27] and their research is based on issues such as fast-start technology roadmapping approach, technology strategy, product planning, business planning, competitive intelligence, citation analysis, patent analysis, text-mining and text-mining [29].

III. RESEARCH METHODOLOGY

A. Selection of the research constructs

The research constructs in **Table 1** are selected from the literature in order to measure the evolution of the three technology roadmapping generations. In order to minimise an error on the construct being measured, various variations of the words according to how they are used differently by various authors are considered. These words could also vary based on the purpose they are being utilised for, although they all converge to the same meaning. An example is a phrase 'product planning', which is derived from a fact that a technology product roadmap gives a "clear-cut, strategic product plan which is documented, tracked and updated as the relationship between developing technologies and marketplace unfolds" [12].

There are other words that can be used within the literature such as 'product plan', 'products planning', 'products plan', 'product technology planning', 'products technology planning', 'product service planning', 'product family planning', etc. In this example a wildcard (*) operator is used to show that there are other possible words in addition to those in the brackets. The codes in the first column (e.g. 1A or 2C) are used in the later sections to represent the constructs.

TABLE 1: CONSTRUCTS FOR THE THREE TECHNOLOGY ROADMAPPING GENERATIONS

	Phrase	***References***
	First Generation (product technology roadmap)	
1A	product (s) plan (-ning)/ product (s) (technology/ service/ family)* plan (-ning)	[12, 30]
1B	product platform/ product (technology/ process/line)* platform (s)	[4, 12]
1C	improved product/ product improvement/ continuous improvement	[4, 12]
1D	performance specification/ product (s) (performance/design)* specification/ critical requirements	[12]
1E	single technology/ single (root/ master/traditional)* technology	[26]
	Second Generation (emerging technology roadmap)	
2A	technology transition/ transition management/ transition timing	[7, 26, 31]
2B	emerging technology	[7, 25, 26]
2C	technology commercialisation/ commercialisation of technology	[7]
2D	radical (rapid) change/ disruptive technology/ product replacement	[7, 26]
2E	technology life cycle (s) (lifecycle (s))	[7, 26]
	Third Generation (innovation roadmap)	
3A	competing technologies/ competing (alternative/ emerging)* technologies	[32]
3B	converging technologies/ converging (new/ production)* technologies	[4, 26]
3C	co-innovate (-ion)/ innovation partnership (s)	[26, 33]
3D	multiple (root/ unproven)* technology (-ies)/ multiple technology (-ies)	[4, 26]
3E	technology readiness levels	[4]
3F	political drivers	[4]
3G	social/ cultural drivers	[26]

B. Data source and search query

Google Scholar is used as the data source for collection of technology roadmapping publications on selected constructs. Other data sources such as Web of Science and Scopus could also be used, but that has a potential of adding a bias due to various literature selection methodologies being applied on these databases [34]. Google Scholar has its own disadvantages such as a presence of low quality scholarly work, hence citations data is also collected to measure an influence and a significance of the literature being collected.

In addition to the phrases stated in **Table 1**, the search query also includes 'technology roadmapping' phrase in order to identify only the relevant literature. A phrase 'technology roadmapping' is often associated with the concepts, process and mechanics of technology roadmapping [29] while a phrase 'technology roadmap' happens to pull out the literature from other non-related fields. A search query is performed manually and a double counting for a specific construct is avoided by subtracting an output from other phrases. An example search query string is that of 'converging technologies' construct which is structured as follows:

Step 1: "technology roadmapping" "converging technologies"

Step 2: "technology roadmapping" "converging * technologies" - "converging technologies"

The total number of publications and citations for converging technologies' construct are computed by adding the results of step 1 and 2.

IV. DISCUSSION OF THE RESULTS

The results for the number of publications in each construct are presented in **Table 2** whereas **Table 3** shows the total number of citations for a period 2000 to 2013. A pattern that emerges is an observation that prior to the year 2004, most of the articles focused on first and second generation technology roadmaps of which the topical issues were 'product technology planning', 'product (s) improvement' and 'disruptive technologies'. This observation is also confirmed by the citations count. A highly cited paper in 2000 is that of Kash and Rycoft [35] with 153 citations. This paper is not within the mainstream technology roadmapping literature, although it discusses a key concept of self-organising adaptive networks that are necessary for commercialisation of complex technologies. Self-organising networks' concept is similar to the innovation partnership concept which is one of the constructs for third generation technology roadmapping. What is further interesting about this work by Kash and Rycoft [35] is the identification of the three innovation patterns, namely: normal pattern by the incumbents; transition pattern by the invaders/ challengers; and a chaotic and complex transformation pattern.

The innovation partnership concept has not been given serious attention in the field of technology roadmapping as between 2000 and 2013, the first paper that discussed this topic directly/ indirectly was only in 2005 with a single citation. The number of papers and citations on 'innovation partnerships' still remains comparatively low, even when compared to most other third generation technology roadmapping constructs. Innovation partnership is important as it facilitates access of resources from various partners at a minimal cost. As a result, one gets more output from the same number of internal inputs, and this result with an increase in productivitity and profitability.

The dominant constructs on the third generation technology roadmapping are the 'technology readiness levels' and 'converging technologies' although in terms of citations, there is an increasing interest on 'competing technologies'.

TABLE 2: TOTAL YEARLY NUMBER OF PUBLICATIONS IN TECHNOLOGY ROADMAPPING FIELD

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
1A	6	8	3	11	12	16	18	23	29	31	40	33	40	39
1B	1	1	1	1	1	8	10	8	10	8	9	12	3	18
1C	7	5	6	5	12	12	19	19	17	14	20	17	26	26
1D	-	1	2	1	4	5	5	5	3	5	2	2	7	4
1E	-	-	2	2	3	5	3	6	9	6	3	8	9	13
2A	1	1	1	1	4	1	3	5	4	7	5	7	9	11
2B	2	2	2	9	11	8	20	21	25	28	37	30	45	62
2C	2	2	2	3	4	2	4	5	4	4	9	12	6	20
2D	4	4	5	5	10	15	19	27	35	26	31	41	36	45
2E	1	-	1	-	3	5	10	8	10	11	9	15	13	17
3A	1	2	-	1	4	9	6	12	6	12	9	7	10	13
3B	-	-	-	1	1	3	3	7	5	10	4	4	6	16
3C	-	-	-	-	-	1	2	-	2	1	2	4	5	4
3D	1	2	3	-	6	5	2	7	4	10	14	15	10	11
3E	1	-	-	-	1	2	4	2	3	4	14	5	10	20
3F	-	1	-	-	-	-	1	-	-	3	-	-	3	2
3G	-	-	-	-	-	2	1	1	2	1	3	-	5	9

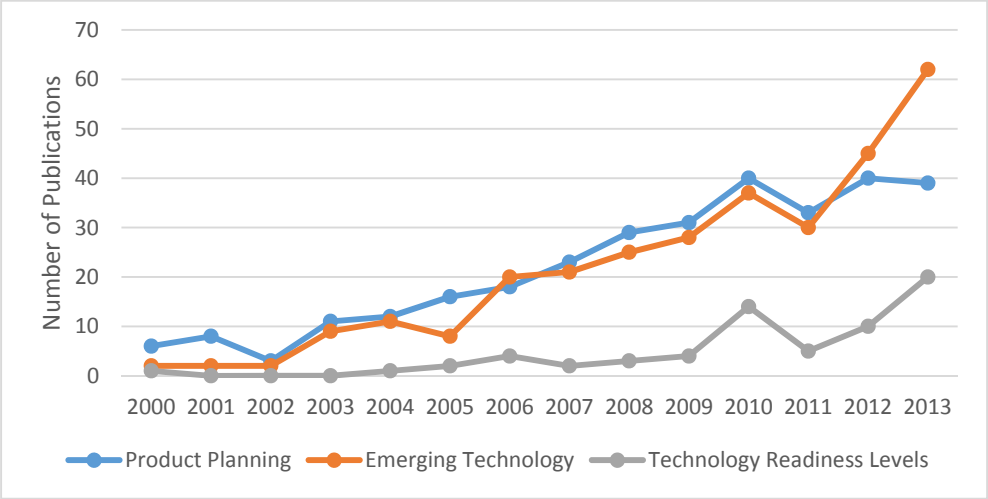

Figure 1. Technology roadmapping evolutionary trend by number of publications.

TABLE 3: TOTAL YEARLY NUMBER OF CITATIONS IN TECHNOLOGY ROADMAPPING FIELD

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
1A	131	465	15	267	1 142	395	234	293	454	432	232	142	249	82
1B	19	254	21	12	211	197	164	125	101	133	100	86	5	38
1C	139	109	89	12	337	222	150	227	533	127	153	312	241	54
1D	-	0	15	11	87	55	39	42	4	151	5	1	10	18
1E	-	-	0	13	364	200	6	39	108	148	19	30	81	31
2A	18	1	0	17	501	0	11	117	16	165	42	55	87	27
2B	31	166	15	28	1 199	391	94	263	323	570	613	27	56	165
2C	49	0	0	1	516	63	12	61	134	16	169	26	7	21
2D	194	282	88	579	1 024	269	183	661	1 146	564	281	216	253	142
2E	49	-	6	-	156	399	89	177	112	132	79	25	28	53
3A	10	25	-	-	530	212	253	129	26	236	104	70	51	73
3B	-	-	-	1	3	24	19	103	16	282	17	19	48	51
3C	-	-	-	-	-	1	0	-	11	17	10	55	18	12
3D	25	484	25	-	385	434	28	95	105	145	179	100	95	32
3E	0	-	-	-	0	4	18	1	6	22	21	57	3	72
3F	-	166	-	-	-	-	13	-	-	29	-	-	3	16
3G	-	-	-	-	-	12	0	22	10	0	51	-	46	30

Although there was a moderate increase in the number of publications in 2004, the citations increased drastically. The two constructs on the emerging technology roadmaps that gained a momentum around that year are 'emerging technologies' and 'disruptive technologies' and they are now the leading constructs that are being studied on the technology roadmapping field. **Figure 1** shows a huge increase from 2012 on the number of publications on emerging technology roadmapping, represented by 'emerging technology' construct.

Some high impact papers published in 2004 are Phaal, Farrukh and Probert [1] with 634 citations; Walsh [7] with 211 citations; and Petrick and Echols [36] with 156 citations. It is noteworthy to mention an observation that in 2004 the two constructs of third generation technology roadmapping, namely: 'competing technologies' and 'multiple technologies' attracted more citations. This is not surprising as their concepts can also feed into emerging technology roadmap [7] which was also gaining momentum at that time.

Figure 2 shows the trend in technology roadmapping literature citations counts and it is clear from that trend that the largest number of citations are for documents published in 2004. The papers that discussed disruptive technologies in 2008 also attracted a large number of citations, and some highly cited papers among these are Daim and Oliver [37] with 85 citations, Lee et al. [38] with 75 citations and Yoon, Phaal and Probert [39] with 70 citations.

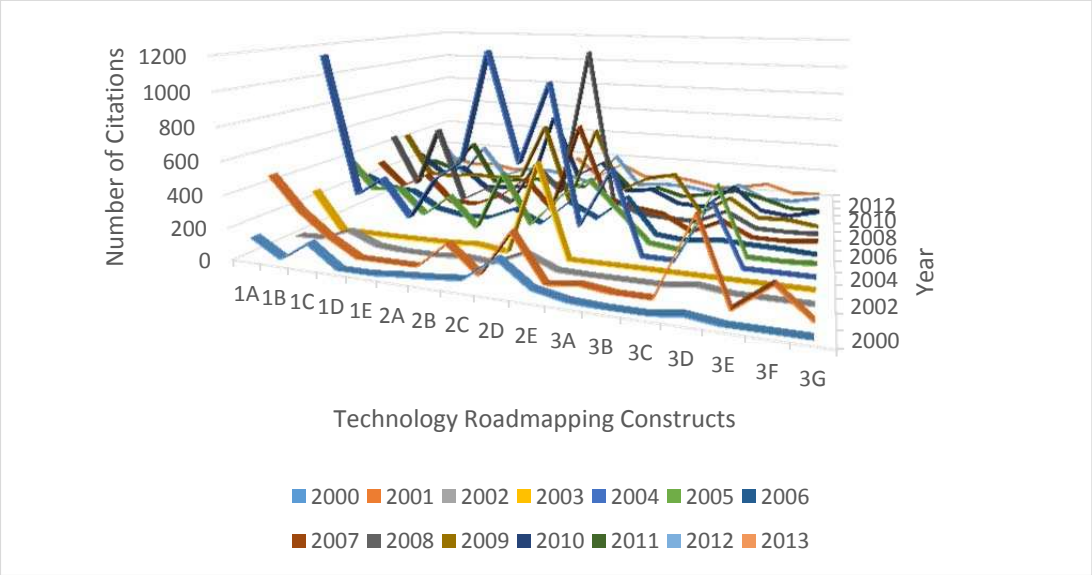

Figure 2. Pattern in technology roadmapping literature citations count.

V. CONCLUSION

The findings of this study reveal a strong co-evolution of the three generations of technology roadmapping without necessarily having one generation replacing the other as previously reported [13, 26]. While first generation technology roadmapping literature is still relevant and also growing, there is a growing interest in emerging disruptive technologies which reflects a complexity in which today's innovations are taking place. There is a slow build-up towards a third generation technology roadmapping although a dominant paradigm is still that of emerging technology roadmapping.

These findings are useful in understanding the state of technology roadmapping paradigm thinking. It is important to understand how different technology roadmapping frameworks interface with each other and how they can be applied in different circumstances for a country, industry or an institution. As for example, Holmes and Ferrill [40] discovered that most of Singaporean small and medium enterprises (SMEs) manufactured components to multinational companies in a region without producing their own product and as a result they had a very short future outlook of 4 – 6 months. Once some of these companies plan to move up on the value-chain, their future outlook had increased to an average of 3 – 5 years.

A first generation technology roadmapping as demonstrated in this study focus mainly on product planning and improvement, and most planning is done by a platform leader, which makes it difficult for the SMEs and companies from underdeveloped economies to plan ahead for technology, products and market integration. In a case of Singaporean SMEs, second generation or third generation technology roadmapping would be more ideal in planning a future growth vision. The knowledge generated through this study would be useful in deciding whether to adopt a second or a third generation technology roadmapping approach in situations where a first generation roadmapping technique is not suitable.

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