Technology roadmapping: Industrial roots, forgotten history and unknown origins

Clive Kerr [*] and Robert Phaal

Centre for Technology Management, University of Cambridge, Cambridge, United Kingdom

ABSTRACT

Technology roadmapping has an established and proven track record for helping organizations with their strategy, long-term planning, innovation and foresight activities. *Technology Forecasting & Social Change* has played a leading role in disseminating research on roadmapping and, so, for its 50th anniversary issue, this paper provides a historical account of the emergence of roadmapping from the practices developed and deployed by technological-based organizations. Motorola, BP, Philips, EIRMA, Lucent Technologies and the Semiconductor Industry Association have all made significant contributions leading to the modern form that embodies a temporal, multi-layered, systems-based approach underpinned by the 'market-product-technology' structure (i.e. why-what-how). However, the industrial roots of technology roadmapping can be traced back to an earlier period, which is, as of yet, unacknowledged in the technology and innovation management literature. There is the overlooked or, perhaps, forgotten history where organizations such as NASA, Boeing, GE, Lockheed, USAF, Rockwell International and the U.S. Department of Energy initiated and advanced the practice of roadmapping – through this publication, their contributions will now be given the credit they so rightfully deserve.

Keywords: Roadmapping; Technology management; Strategy; Innovation

1. Introduction

Technology Forecasting & Social Change has published more roadmapping papers, with both academic and practice-oriented contributions, than any other journal and continues to play a leading supportive role. It is thus fitting as part of this 50th anniversary issue to provide a retrospective of how technology roadmapping emerged to become a recognized and established management tool. As such, this paper is not intended as a comprehensive review nor bibliometric analysis of the roadmapping literature; this has been attempted several times already by other authors such as Carvalho *et al*. (2013), Gerdsri *et al*. (2013), Letaba *et al*. (2015), de Alcantara and Martens (2018). Rather, this paper aims to provide a historical account of its beginnings within technological-based organizations. The focus is on the practice of technology roadmapping and its development to what is recognized as today's modern form.

The publication of '*Motorola's technology roadmap process*' (Willyard and McClees, 1987) had a huge impact on awareness raising of the method/tool and its subsequent popularization. Since then the practice has spread to numerous different businesses and industries, and has been adapted for various diverse purposes. It has been applied to components, products, systems (and systems-of-systems), supply chains and networks, sectors

[*] Corresponding author at: Centre for Technology Management, Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge, CB3 0FS, UK.
E-mail addresses: civk2@cam.ac.uk (C. Kerr), rp108@eng.cam.ac.uk (R. Phaal).

(applications and technologies of every type), regions and nations (Phaal *et al*., 2010). Roadmapping is widely used to great affect by companies and government agencies in the context of strategy, innovation and (policy) foresight, despite the method having a lack of theoretical underpinning. Technology roadmapping is recognized at the highest levels. For example, from an institutional perspective, the United Nations endorses roadmapping and considers it an enabling tool for setting directions and determining associated actions in a goal-oriented manner (UNIDO, 2005). Additionally, within the political sphere, there is the example of the '*Solar Technology Roadmap Act*', as legislated by the 111th U.S. Congress, to establish and support the creation and maintenance of a technology roadmap. That act directed the U.S. Secretary of Energy to develop a roadmap which "presents the best current estimate of the near-term, mid-term, and long-term research, development, and demonstration needs in solar technology" for the purposes of "meeting national priorities in energy security, United States competitiveness, mitigation of adverse environmental impacts, and energy diversification" (U.S. Congress, 2009a).

In contrast, academic research into roadmapping has lagged well behind industrial practice, with interest developing in the late 1990s in the United States, Europe and Japan, starting with research groups that had high levels of industrial engagement – typically within engineering departments. Publications on roadmapping have steadily grown since and with three principal outlets for disseminating research, namely *Research-Technology Management* (RTM), *Technological Forecasting & Social Change* (TFSC), and the *Portland International Conference on Management of Engineering and Technology* (PICMET). RTM were the first to publish a formal roadmapping paper, that of Willyard and McClees (1987) on Motorola's approach. Furthermore, the relevance and importance of technology roadmapping is evidenced by the inclusion of a roadmapping paper reprinted in the 50th anniversary edition of RTM, published by the U.S. Industrial Research Institute (IRI) – an account of the Philips approach to technology roadmapping (Groenveld, 1997; 2007). The first roadmapping paper to appear at PICMET was in 1991 and entitled '*Strategic technology planning: Developing roadmaps for competitive advantage*' (Nauda and Hall, 1991). In regards to TFSC, the first significant mention of roadmapping was by Joseph F. Coates in one of his '*From My Perspective*' columns, where he pointed out a key shift taking place in strategic planning, usually a solely internal organizational function, to mutual sector-level activities with the uptake and collective generation of industry roadmaps (Coates, 2000). The first full papers to appear in TSFC were in the 2004 special issue on roadmapping (Volume 71, Issue 1-2); containing nine papers including a perspective from Bob Galvin, CEO of Motorola.

To date, as identified in a bibliography maintained by Phaal (2019), there are more than 1,110 publications dealing specifically with roadmapping (i.e. focusing on the method/tool/process as opposed to the content of the actual subject matter under consideration). Yet, it has to be stated in no uncertain terms, 'we' the research community have consistently overlooked and neglected to acknowledge that early efforts existed well before the first formal appearance of roadmapping in journal articles. Thus, the intent of this retrospective is to provide an account of technology roadmapping's provenance, which is clearly and firmly rooted in industrial engineering practice, and also to challenge the orthodox account which some fellow academics cite without question, and encourage researchers to appreciate practitioner-based contributions and applied-research as 'worthy' for academic consideration. The aim of this paper is to highlight those forgotten/overlooked organizations and give them the credit due for their contributions, superseding some of the work in highly cited articles. Reflecting the point of view and efforts of these pioneering practitioners will not only encourage a wider appreciation of where technology roadmapping has come from, but enable a better understanding of its underpinning functions and value rooted in addressing 'real-world' challenges of 'world-class' organizations. That said, there are still gaps and remaining question marks in the story of roadmapping's journey from obscure beginnings to powerful and increasingly popular management tool.

2. 'Established' industrial roots

Roadmapping, whether it be technology roadmapping, product roadmapping, business roadmapping or strategic roadmapping, has its roots firmly embedded in industrial engineering, with development of the method being led by practitioners (as opposed to academics). In the orthodox account of roadmapping's evolution there are six organizations that deserve to be praised for their important contributions, namely: Motorola, BP, Philips, EIRMA, Lucent Technologies and the Semiconductor Industry Association (SIA). These organizations represent the recognized body of knowledge for the modern practice of roadmapping, and they were influential in the subsequent uptake by other organizations and upsurge in interest by researchers. This retrospective provides the opportunity to critically draw attention to these seminal works, re-examine and reaffirm the power and flexibility of roadmapping, during a period when it was being established as a distinctly unique method/tool within the field of technology and innovation management.

2.1. Motorola

Motorola were pivotal in elevating the profile of roadmapping and championing its use. Credit must be given to the 1987 Willyard and McClees publication, as the first journal paper on technology roadmapping. It reflected work in the mid-1970s focused on the alignment of expensive program investments in fast-changing technologies against the commercial aspirations for product innovations. Robert 'Bob' Galvin, who was CEO at the time, provided the much cited "a roadmap is an extended look at the future…" definition (Galvin, 1998). He additionally provided the following powerful statement, which positioned roadmapping as a highly credible management tool:

> "*Roadmaps communicate visions, attract resources from business and government, stimulate investigations, and monitor progress. They become the inventory of possibilities for a particular field, thus stimulating earlier, more targeted investigations. They facilitate more interdisciplinary networking and teamed pursuit. Even 'white spaces' can conjure promising investigations. In engineering, the roadmapping process has so positively influenced public and industry officials that their questioning of support for fundamental technology support is muted*" (Galvin, 1998, p. 803).

In 2004, as a special practitioner's update for *Technology Forecasting & Social Change*, Galvin further remarked that "roadmaps allow industry leaders to communicate in a convincing and coordinated way with colleagues within business and government policymakers who provide targeted support to national science and technology policy and appropriations" (Galvin, 2004). Such statements from a senior industrialist have done much to cement the role of roadmapping and have greatly promoted the method. According to Willyard and McClees (1987), technology roadmaps became fundamental tools for Motorola because they could be used to maintain a proper balance in terms of "the amount of attention paid by our business managers to short-range issues versus long-range issues; to operating versus strategic matters; and to technology versus the many other professional disciplines that must be managed in a successful company". Additionally, it was readily acknowledged that "the greatest value is not necessarily in the finished document, but rather in following the discipline of the technology roadmap process" (Willyard and McClees, 1987). This was also emphasized by Galvin (1998), who stated that "the optimal process for gathering and selecting the content of roadmaps is to include as many practicing professionals as possible in workshops periodically in order to allow all suggestions to be considered and to objectively evaluate the consensuses that will more often than not emerge. Equal treatment should be given to minority views and individual advocacies".

In regards to the specifics of what Motorola were actually doing, details are only provided through two publicly available sources: Willyard and McClees (1987) and DeGregorio (2000). Willyard and McClees (1987) reported that Motorola used two types of technology roadmaps, namely 'emerging technology' and 'product technology'. The emerging technology roadmap dealt with a single technology, providing a forecast of its progress, an evaluation of Motorola's capabilities, and a comparison of those capabilities against competitors both today and in the future. The main contribution of Willyard and McClees' (1987) seminal paper was to outline the product technology roadmap, which was in effect a "compilation of documents that provides a comprehensive description of the product line – past, present and future – of a division or operating group", and it consisted of eight parts:

1. Description of the business (including market expectations and competitive environment).
2. Technology forecast (trending of performance levels and underlying characteristics of future products).
3. Technology roadmap matrix.
4. Quality considerations.
5. Allocation of resources (engineering and financial).
6. Patent portfolio.
7. Product descriptions, status reports and summary charts.
8. Minority report.

Two elements significantly stand out. First, the 'technology roadmap matrix' shown as a single visual depiction combining the product plan and technology forecast (i.e. product evolution with corresponding functionalities against the backdrop of an explicit timeline) that "provides management with an excellent review of product direction and technology timing" (Willyard and McClees, 1987). Second, a 'minority report' was used to bring a potentially beneficial product or process lacking firm consensus or backing from a persuasive advocate to the attention of senior management and hopefully ensure it did not "slip through the cracks" (Willyard and McClees, 1987).

Gary DeGregorio, from Motorola's Software & System Engineering Research Laboratory, provided a description of another powerful type of roadmap representation. DeGregorio (2000) recognized that to support a 'best-in-class' technology management capability, roadmaps needed to embody "decision alternatives (business scenarios) over time". So, a roadmap schematic was developed which consisted of main layers for each primary set of scenarios under consideration, and then individual rows/swimlanes for each specific scenario (containing the "evolutionary threads of technologies, capabilities, etc."). The roadmap also included a 'multi-period' time scale in the sense that the timeline was framed against a planning horizon segmented into the near-term ("viewed at one-year intervals") and with the far-term/long-range segment shown as a single interval. As remarked by DeGregorio (2000), such a representation "supports the common 'rolling wave' method of planning in which greater detail and precision is applied to near term elements".

Three further remarks were made about Motorola's approach that had significant influence on the modern form of roadmapping. One was that "documents are inefficient containers for the information and knowledge created by key business and engineering processes" and thus "a roadmap may be thought of as a compact method of summarizing and communicating"

(DeGregorio, 2000). Another was that "an organization that desires to achieve effective and comprehensive use of roadmapping should promote a 'One Roadmap' vision. This vision does not imply a single, very large roadmap. Rather, it signifies that an integrated set of roadmaps can be used as a focal point to align goals and strategies across the organization" (DeGregorio, 2000). The third remark was that roadmapping enables strategic alignment and this occurs across two dimensions: (i) "roadmap linkages may be used to align strategies within a business unit 'end-to-end' across all parts of the research-to-product value chain", and (ii) "roadmap linkages may be built between business units to capture commitments for technology, capability and product sharing and reuse" (DeGregorio, 2000).

A further roadmapping paper was published in 2004. It provided a general overview of the efforts to develop an 'Enterprise Roadmap Management System' (ERMS), i.e. a collaborative enterprise-wide platform. The ERMS was to provide "a common roadmapping process, a common software solution, and a common information architecture for all of Motorola" (Richey and Grinnell, 2004). In the last paragraph of the paper, the authors stated that:

> "*Within the personal communications sector, it has been estimated that the use of roadmaps has saved the corporation hundreds of millions of dollars in the supply management area. Also, the roadmapping models indicate that more than a half billion dollars over the years have been brought to Motorola's bottom line as a result of the institutionalization of these common roadmapping processes and tools*" (Richey and Grinnell, 2004, p. 41).

2.2. BP

Barker and Smith, published an overview of BP's roadmapping foresight approach in 1995 – unfortunately this work has not been cited as often as would be expected, considering it is a foundational paper. It is worthy to note that this publication appears to be the first to formally state that roadmaps can be constructed 'top-down' and 'bottom-up', and that both modes are essential. The BP approach consisted of two principal parts. The first was concerned with "deriving technical missions from the business", i.e. unpacking corporate strategy (vision and strategic goals) leading to the identification of priorities for the 'technology' part of the organization (Barker and Smith, 1995). For those organizations adopting the balanced scorecard method and wanting to relate it to roadmapping, this work provides the earliest known indication on how these two tools could be integrated. The second part of the BP approach was orientated to the research, development and engineering programmes needed to enable commercial success; whereby the technical needs were prioritized by the business and linked to the development/engineering activities, core technologies, underlying sciences and underpinning research skills (Barker and Smith, 1995).

According to the account provided by Barker and Smith (1995), the advantages of deploying roadmapping "stem primarily from the combination of logical analysis, widespread consultation and discussion, and use of graphical techniques". More specifically, and in contrast to other methods/tools, roadmapping:

- Places greater emphasis on participation, and "provides practical assistance to facilitate the construction of the plan by enabling all the participants, whether technically expert or otherwise, to play a full part in the process". "Its very nature greatly facilitates the involvement of a wide range of topics and staff, from senior management to (relatively) junior members, and from marketing manager to fundamental researcher".
- Facilitates the 'structured dialogue' essential to the process of reaching a consensus, i.e. enabling "the sometimes conflicting and perhaps qualitatively different views, priorities

and concerns of the participants to be compared, merged, and synthesized into a coherent set of outcomes".

- "Enables the overall impact and relevance of individual technology components of a business strategy to be assimilated rapidly and reliably", and "greatly facilitates identification of gaps and/or duplications of effort".
- "Greatly aids communication, both at the operational commercial and technical level, and with senior management too".
- "Further, the audit trail aspect can be quite important in giving management confidence in the validity of R&D programmes".

Credit must be given to Barker and Smith (1995) for the coherent articulation of these features – they remain deeply embedded in roadmapping practices today and are often considered as being at the heart of the roadmapping process and its most beneficial properties.

BP were also the first to formally acknowledge and explicitly recognize the visual form of a roadmap as being essential to the method. In regards to the act of roadmapping, the visual side "has been found to help greatly in making this consensus-building process both efficient and effective" (Barker and Smith, 1995). And in terms of communicating the outcomes, the "emphasis on graphical aspects offers several benefits, including ease of understanding, ability to compress extensive and complex information into a small space, and aiding the process of checking for consistency of the data" (Barker and Smith, 1995). Further, Barker and Smith (1995) provided a number of compelling remarks about the power of visual presentation:

- "The visual nature of the maps has been especially helpful in obtaining structured discussion and constructive debate about the shape of future R&D programmes".
- "The visual presentation feature helps informed discussion and facilitates objective examination of options and routes to implementation. It addresses and integrates both commercial and technical issues and shows the inter-relationship between the two".
- "The maps can also help persuade general management, who may not be fully conversant with or even sympathetic to technical arguments, that money is well spent on the R&D programmes, including those underpinning ones which may sometimes be in danger of being regarded as esoteric and not suitable for company funding".

However, their paper did not show an actual roadmap visualization (so we do not have a sense of what 'good' might look like); and the two figures that were shown are, admittedly, 'strategy maps' (as there was no explicit timeline/timing points or implicit phasing). Additionally, there was only a single mention of 'time' in the whole publication. These are, perhaps, reasons as to why the work has not been cited as often as it should.

2.3. Philips

In 1997, Pieter Groenveld from Philips Electronics published the influential and highly regarded paper '*Roadmapping integrates business and technology*'. This was very much the European counterpart to the U.S. example from Motorola as it also focused on 'product-technology' roadmapping "in order to develop a stronger awareness of how to serve important markets with the right products at the right time and to improve the cross-functional processes required for new product creation" (Groenveld, 1997). Philips took a more holistic view of what constitutes product-technology roadmapping in that it may be "applied to systems, to a product range, to individual projects, to components, or to production processes". More crucially, they modified the layout of the roadmap to create an integrative schematic that could encapsulate the full set of potential interactions across the market-application-product-technology-project development chain. This format has led directly to the form which is most widely recognized today, i.e. the three-layer roadmap structure (with layers for markets, products and technologies). Philips appears to be the first organization to formally use the concepts of 'market pull' and 'technology push' within the roadmapping method – "building product-technology roadmaps requires the simultaneous consideration of market pull, technology push and their interaction over time" (Groenveld, 1997). A decade later, when the *Research-Technology Management* journal was celebrating their 50th year of publication (and to mark the occasion reprinted the most frequently referenced articles), the paper was updated to include the author's reflections. Groenveld (2007) then stated that "the original description 'product-technology roadmapping' has been replaced by 'business roadmapping' to emphasize the objective of this type of roadmapping, i.e. the development of a medium-term (5-7 years) vision of how the business is likely to develop when markets and product characteristics as well as technology get equal emphasis".

In regards to the deployment of roadmapping, Groenveld (1997) remarked that "management may consider roadmapping to be merely another approach or tool for improving the strategy definition and communication processes" and proposed starting the roadmapping process 'bottom-up' as it helps to demonstrate the benefits (so hopefully gaining buy-in and commitment for further roll-out). Very critically, Groenveld (1997) stressed that "roadmapping must be seen as an ongoing process that is a part of the business cycle".

An outline of the roadmap-building process was shown based on a double workshop sequence; where the first workshop was used to share information, and thus establish a 'common' view between the participants, followed by generating the actual roadmaps at the second workshop. It was emphasized that the "detailed implementation of this roadmap-building process will differ from one group to the other" (Groenveld, 1997). For instance, Philips Lighting established small roadmap drafting groups for each market segment in order to better define application needs; whereas Philips Semiconductors organized large multidisciplinary workshops in order to "stimulate cross-communication among the various product groups that were serving related markets and using the same technology base".

Philips provides the first reported example of combining roadmapping with the QFD tool. Quality Function Deployment is used to elicit the functional (customer) requirements and translate these into appropriate (technical) product characteristics. According to Groenveld (1997), "QFD offers a reliable starting point for roadmapping" feeding in to the drafting of the roadmaps were full attention can then be devoted to the time aspect. Philips also inferred the need to generate roadmap depictions with different levels of granularity and suggested a dual-tier approach, i.e. "both high-aggregation-level roadmaps (serving business strategy discussions) and related specific roadmaps (oriented toward the operational business)".

2.4. EIRMA

Also in 1997, the European Industrial Research Management Association (EIRMA) published a guidance document on technology roadmapping. EIRMA is a member-led body that concentrates its activities on helping members to learn from each other, in terms of what works well and then translating such learning into a generalized form – which is indeed what they did in respect of roadmapping. At EIRMA, the 'Working Group' is an essential means of bringing a group of members together over a period of one to two years to report on a key aspect of industrial R&D management. For roadmapping, Working Group #52 (WG52) was established (and active between March 1996 and September 1997) to explore the range of roadmapping approaches that existed within its membership. In WG52, some 27 companies were involved including ABB, BASF, BICC, Daimler-Benz, Ericsson, ICI, Krupp, Philips, Siemens, Statoil, Unilever, United Technologies and Volvo. Specific case studies were provided by ABB (roadmapping since 1991), Hoogovens (roadmapping introduced in 1996), LucasVarity (first used roadmapping in 1990, followed by group-wide application in 1993 as part of their annual budget process) and Philips (who started roadmapping in 1993 "with a small-scale pilot which has extended throughout the company over the years" leading to integrated business unit approaches).

Through sharing and building upon the diverse roadmapping experiences of its members, EIRMA (1997) outlined an eight-stage roadmapping methodology. However, the greater contribution of the EIRMA work was to produce a generic roadmapping framework that brought together the essential components as a single conceptual whole – clearly this was heavily influenced by the Philips 'market-product-technology' structure, so perhaps it is better to say that EIRMA built upon the Philips structure and 'fleshed out' the multi-layered roadmap representation. The generalized form documented by EIRMA consisted of layers for the external influences, deliverables (desired requirements or expected performance characteristics of the product or process), technology (technologies and actions needed to permit the deliverables to be attained), skills/science/know-how (required to deliver the technologies), and resources (i.e. intellectual, physical and financial assets). Critically, the Working Group on roadmapping regarded "time as the prime parameter of a TRM" – if there is no time, then it is not a roadmap.

EIRMA (1997) also outlined the 'backwards' and 'forwards' methods:

- Backwards in time (i.e. from the future) – "When working backwards in time, the targets are defined at the beginning" and the roadmapping activity "involves finding out how to reach a given target (which could be a business goal, a product, process, fulfilment of a legislative requirement, or a technology)". This method "is more natural for a marketing driven business"; and when introducing roadmapping to a company, "it is better and easier to begin with backward TRM".
- Forwards (i.e. to the future) – "When working forwards, the targets are the result" of "the process of building upon technologies"; it involves trying to "evaluate the potential of a given technology, the possibilities it opens up for the satisfaction of future needs". This method is "more natural for a technology driven business"; although "it is more difficult to interest people from outside R&D to participate in a 'forward' type of discussion"; "input from 'Marketing' is essential for forward TRM-discussions".

EIRMA (1997) shared the same sentiment as Motorola in that "the greatest value of a TRM comes from the business processes that have to be put in place to create it, rather than the possession of a TRM in itself". EIRMA also provided an important clarification to its position on this – a roadmap "is not something that can be purchased from a consultant, or created by a single individual. It must be the output of an empowered team activity, supported by commitment from senior management". Additionally, the concept of a roadmap as a 'living document' is attributable to EIRMA (1997): "a TRM is a living document and is constantly evolving as circumstances change. It is quite different from a project plan with its precisely defined milestones and objective to deliver a completely specified outcome".

2.5. Lucent Technologies

Albright and Kappel, in 2003, described the approach taken by Lucent Technologies whose product-technology roadmaps were centered at the level of 'product lines' and provided the basis for its corporate technology planning. Such positioning enabled Lucent to look across the roadmaps to identify "common needs that may be met by a single development program or technology acquisition", opportunities for reuse, overlaps, hidden gaps, weaknesses, and “key strengths that can be deployed in other areas of the business” (Albright and Kappel, 2003). It is readily apparent that Lucent were taking an informed portfolio lens.

In a very similar fashion to Motorola, Lucent’s roadmapping was organized into a number of parts:

1. Market section – Competitive assessment, market segmentation and trends.
2. Product section – Product drivers, experience curve forecast, product roadmap and product evolution plan.
3. Technology section – Technology roadmap (product/manufacturing) and forward costing model.
4. Summary/Action plan – Strategic summary (action strategy) and risk roadmap.

The visual depiction of Lucent’s technology roadmap was similar in layout to the style of Motorola. However, there was one critical difference that set it apart and means that it must be recognized as a seminal example in the roadmapping body of knowledge – Lucent had not only embedded portfolio data on their roadmap, they had in effect integrated the well-known 2x2 tool into the roadmap structure (by splitting the matrix and overlying it as two vertical columns, with the ‘bubbles’ from the classic bubble chart being aligned against the corresponding horizontal rows of the roadmap). The example shown compared the importance of the technology (low/medium/high for both current and future states) against the organization’s competitive position (lag-lead, currently and in the future). According to Albright and Kappel (2003), “movement along either scale suggests a changing investment level and becomes the highlight for an executive summary of technology”. As such, “the technology roadmap then becomes a vehicle for making all funding decisions”. Furthermore, “creating the roadmap story means explicitly describing the why’s for each key decision in the plan” (Albright and Kappel, 2003).

Lucent appear to be the first organization to develop a risk-based roadmap – this is a very unique artifact and even today it remains an underutilized, even rare, practice. The format has layers/swimlanes for market, technical, schedule, financial/legal, and resource-based risks. For instance, “market risks include assumptions about market growth” and “are placed on the timeline where one would expect to learn the validity of key assumptions”. Albright and Kappel (2003) stated that “uncertainty on a roadmap has a common-sense meaning of how sure we are about something” and is shown as a probability; “risk then combines that uncertainty estimate with the consequences of failure”. As such, the roadmap highlights the major ‘risk events’ which need to be monitored during the implementation and the ‘show stoppers’ to successful execution. The intent was not to ‘scare’ managers by showing them risks scattered across their roadmaps; as emphasized by Albright and Kappel (2003) “risk can be managed using this chart” and the risk mitigation measures should be depicted on the roadmap.

As a final observation, Lucent appears to be the first to coherently deploy a range of different types of roadmaps across the organization as a formalized set of templates. “Much in the way that standardized financial reporting permits a rapid dissemination of financial information, the roadmap template creates a common language for executive review of technology, enables cross-roadmap planning, and builds common roadmapping skills. At Lucent, having a standard template amounted to a starting point – a minimal set of information to describe an integrated product and technology strategy. Individual teams were free to embellish as the situation dictated” (Albright and Kappel, 2003).

2.6. Semiconductor Industry Association

In the orthodox account of roadmapping's evolution, there is a very significant landmark that must be highlighted, namely, in 1999 the publication of the International Technology Roadmap for Semiconductors (ITRS), which represented the first international roadmap. Behind this achievement there was obviously considerable effort, and also a lengthy trajectory, with the Semiconductor Industry Association (SIA) playing a pivotal role.

The nucleus for the ITRS can be traced back to an originating workshop in 1991, cosponsored by the U.S. National Advisory Committee on Semiconductors (NACS) and the Office of Science and Technology Policy. According to historical analysis by Schaller (2004), this workshop was the "first legitimate attempt at an industry roadmap exercise involving broad participation from industry, universities, research consortia, government agencies and labs". The workshop brought together ninety participants who were tasked with creating "technical roadmaps that, if followed, would contribute to the U.S. semiconductor industry's efforts to develop advanced technology throughout the next decade, and that would help propel the industry to a world leadership position by the year 2000" (NACS, 1991).

The following year, this roadmapping initiative went from being government-sponsored to industry-led, with the Semiconductor Industry Association (SIA) taking over the coordination role – for an in-depth account see Schaller (2004). Where the original 1991 roadmap set the challenge of achieving the next generation of technology by 2000, the SIA considered that if the United States were to continue to lead the industry then they would have to look out five succeeding generations (Spencer and Seidel, 1995). In November 1992, 178 participants took part in a 3-day workshop; the format of which included general plenary and breakout sessions involving 11 technology working groups (Schaller, 2004; Spencer and Seidel, 1995). As a result of this workshop, two documents were published in early 1993 to represent the 1992 version of the roadmap (SIA, 1993a; 1993b) – these were made freely available world-wide. Two further iterations were produced in 1994 and 1997, and classed as the National Technology Roadmap for Semiconductors (NTRS).

In 1998, what was a domestic practice went global at the World Semiconductor Council, where five trade organizations (from the United States, Europe, Korea, Japan and Taiwan) agreed to cooperate and led to the publication of the first International Technology Roadmap for Semiconductors (ITRS) in 1999. Since then, the ITRS has followed a consistent rhythm of being updated in even-numbered years and with the next completed edition released in odd-numbered years, leading to the impressive long running 1999-2001-2003-2005-2007-2009-2011-2013-2015 series. Quite the historic feat involving thousands of participants over the years and for a truly underpinning field of technology.

The principal objective of the ITRS was to capture and present the consensus view of the industry's research and development needs over a 15-year timeframe. Schaller (2004) highlighted that the roadmap "attempts to communicate requirements to two distinct audiences: near-term (suppliers with a 6-year horizon), and long-term (research with a 6 to 15 year horizon)". Moore's Law served as the basic planning assumption and the ITRS roadmaps were put together in the spirit of a challenge, i.e. what capabilities need to be developed in order to continue to realize Moore's Law?

The 2015 edition was the last ITRS – the semiconductor industry was no longer the industry it used to be… In recent years there has been an attempt to 'reboot' the ITRS through the IEEE's International Roadmap for Devices and Systems (IRDS). "Compared to the ITRS, the IRDS takes a broader perspective on technology" and the new name "reflects an expanded focus on applications and systems that drive the need for semiconductor devices" (Wright and Conte, 2018).

3. 'Forgotten' history

Motorola, BP, Philips, EIRMA, Lucent Technologies and the Semiconductor Industry Association have all made significant contributions – there is no detracting from their rightful place in the history of roadmapping. That said, there are much earlier applications of technology roadmapping well before this core set of practices and publications. Through archival research, we have uncovered a number of significant roadmap examples that existed well before the first formal accounts of the topic reported in journal articles – we have now traced technology roadmapping back to the early 1960s. Furthermore, we discovered many activities that actually constitute roadmapping despite different expressions being used at the time. It has to be remarked that even given the flexible, integrative and powerful nature of the technology roadmapping approach for business, the technology-oriented prefix can be tactically and strategically unhelpful in terms of organizational acceptance and deployment of the method/tool.

Roadmapping came from industry and it must be stressed that practitioners are 'busy doing their day jobs' (e.g. developing and applying roadmapping in companies) and so, of course, they would have little time or energy left which might be expended on publishing papers in technology and innovation management journals. Fortunately, the evidence of their roadmapping activities does exist (should academics and researchers 'really look'). It is not possible to give a full account of our findings given both the amount and richness of the documents found (to date), and also the space constraint of a journal paper. However, we have endeavored to identify those organizations that should be credited for their early works and now provide a 'headlines' account of some of their unique, interesting and potentially 'world-first' contributions to technology roadmapping.

3.1. NASA

NASA were already actively deploying roadmapping two decades before the first journal paper describing technology roadmapping. Consider Fig. 1 which was produced in 1963, and found in the '*Lecture Series on Nuclear Propulsion*' under a presentation by Finger *et al.* (1964) entitled '*Nuclear rockets based on graphite reactor technology: Their applications and development status*'. Fig. 1 is a 3x3 matrix and the authors state that it "is a coarse roadmap of space missions". When looking at this format, and noticing that there is no visible (explicit) timeline, and before criticizing the depiction (perhaps saying that it is not a roadmap), it is first necessary to consider how the authors describe the representation:

> "*I do not intend to go through this chart in detail; the important thing it infers is the flow, in both time and technology, from the comparatively low-energy, low-payload missions we are doing now to more ambitious missions in the lower right-hand half of the matrix*" (Finger *et al.*, 1964, p. II-1).

That quotation implies 'roadmapping', and time is implicit in Fig. 1; if unconvinced, then consider the following (Finger *et al.*, 1964):

- "The three regions of space flight are arranged in columns: Earth orbit, lunar and planetary". There is "a progression in each region from unmanned missions (at the top) to early manned developmental flights and, finally, operational manned flights. Current authorized programs are marked by asterisks".
- "The integrated nature of unmanned and manned programs for lunar and planetary exploration should be noted. Unmanned flights come first with both special scientific purpose and a vital role in preparing for manned missions".

- “There is also a horizontal dependency on the chart: both the long-duration manned lunar missions and the manned planetary missions will lean heavily on human and systems experience in Earth orbit”.
- “Although dates are not shown on the chart, the general timing of the missions is worth some comment. Anything worthy of the name lunar station or base should probably be placed in the latter half of the 1970’s. Similarly, in the planetary program, manned flights to Mars or Venus are probably post-1980, and planetary operations would be correspondingly later”.

Such a description does constitute roadmapping. Not only was NASA an early user of roadmapping, their mode of deployment was through workshops. Consider an example from 1976, on the subject of electronics, it involved running a series of 2-day workshops held at the relevant program offices and research centers, where participants were tasked with: (i) identifying technology needs and opportunities (in relation to prospective missions/systems); (ii) outlining major technology areas/themes; and, (iii) exploring which technologies might be appropriate/available for future flight experiments and payloads – all against the overarching ambitions of a 1,000-fold mission capability increase and a 10:1 lifecycle cost reduction (NASA, 1976a). Fig. 2 shows an example of one of the roadmap outputs from that initiative; this ‘sensing and data acquisition’ roadmap brings together three technical areas (microwave, infrared and multispectral scanning) and their respective technologies. Note the convergence of passive radiometry and active radar technologies, leading to phased array antennas, then with the development path opening out again, leading to the two options of low-noise and high-power, moving toward the specific program goals of 1/10th cost and 10x sensor performance. Note also the use of dashed bars to indicate these are estimated developments over the future timeline. There is a complete set of such roadmaps, all sharing the same style of template, and packaged in a report containing background and supplementary information (NASA, 1976a).

In roadmapping, the concept of ‘windows’ is often used in regards to technology push and market pull against the time dimension, e.g. ‘windows of availability’. The language of ‘window’ and the popular phrase ‘windows of opportunity’ seems to have been coined by Honeywell in the late 1990s (Whalen, 2007). Although the underlying idea might be attributable to NASA in the sense that they were roadmapping technologies, against ‘mission requirements’ and ‘flight readiness’ for final payload flight dates, whilst trying to synchronize with available ground/flight demonstrator programs and shuttle testing schedules (NASA, 1975).

Recently in the software/agile/digital ‘space’, there has been a lot of interest and promotion of roadmapping with books such as ‘*Strategize: Product strategy and product roadmap practices for the digital age*’ (Pichler, 2016) and ‘*Product roadmaps relaunched: How to set direction while embracing uncertainty*’ (Lombardo *et al*., 2017). However, three important comments need to be made. Firstly, these so-called roadmaps are actually product release schedules. Secondly, there is a whole body of knowledge that exists from technology roadmapping that could be applied/adopted/adapted, i.e. the multi-layered, systems-based, roadmapping approach arising from ‘hardware’ can be applied to ‘software’ to good effect (by ensuring the process cycle time fits within the demands of the agile practices). Thirdly, it appears NASA were already applying roadmapping to software systems and applications – see Fig. 3 for an example.

SOME SPACE EXPLORATION POSSIBILITIES

MISSIONS	REGION: EARTH ORBIT	REGION: LUNAR	REGION: PLANETARY
UNMANNED	[1] UNMANNED SATELLITES SCIENTIFIC ·EXPLORERS ·ORBITING OBSERVATORIES APPLICATION ·COMMUNICATION ·METEOROLOGY ·NAVIGATION ·ENGINEERING RESEARCH	[2] LUNAR PROBES ·RANGER ·SURVEYOR INTERMEDIATE SPACE PROBES ·PIONEER	[3] DEEP SPACE PROBES ·MARINER ·INTERPLANETARY MONITOR SATELLITE VOYAGER SOLAR PROBE OUT OF ECLIPTIC OUTER PLANETS AND THEIR SATELLITES LEAVE SOLAR SYSTEM SEARCH FOR EXTRATERRESTRIAL LIFE
MANNED DEVELOPMENTAL	[4] MANNED SATELLITES ·MERCURY ·GEMINI INTERIM ORBITAL LABS MANEUVERING REENTRY	[5] BEFORE 1970 MANNED LANDING ·APOLLO LUNAR LOGISTIC SYSTEM (UNMANNED)	[6] MANNED EXPEDITIONS MARS LANDING VENUS RECONNAISSANCE SEARCH FOR LIFE ON PLANETS No Authorized Programs Yet
MANNED OPERATIONAL	[7] ORBITAL OPERATIONS MANNED ORBITING LABS OPERATIONAL FERRY VEHICLE RECOVERABLE BOOSTERS ENGINEERING EXPERIMENT AND DEVELOPMENT No Authorized Programs Yet	[8] LUNAR STATION LUNAR EXPLORATIONS SCIENTIFIC OBSERVATIONS No Authorized Programs Yet	[9] PLANETARY OPERATIONS MARS STATION ADVANCED MANNED EXPEDITIONS VENUS JUPITER SATELLITES MERCURY ASTEROIDS No Authorized Programs Yet

Fig. 1. A coarse roadmap of space missions (Finger *et al.*, 1964).

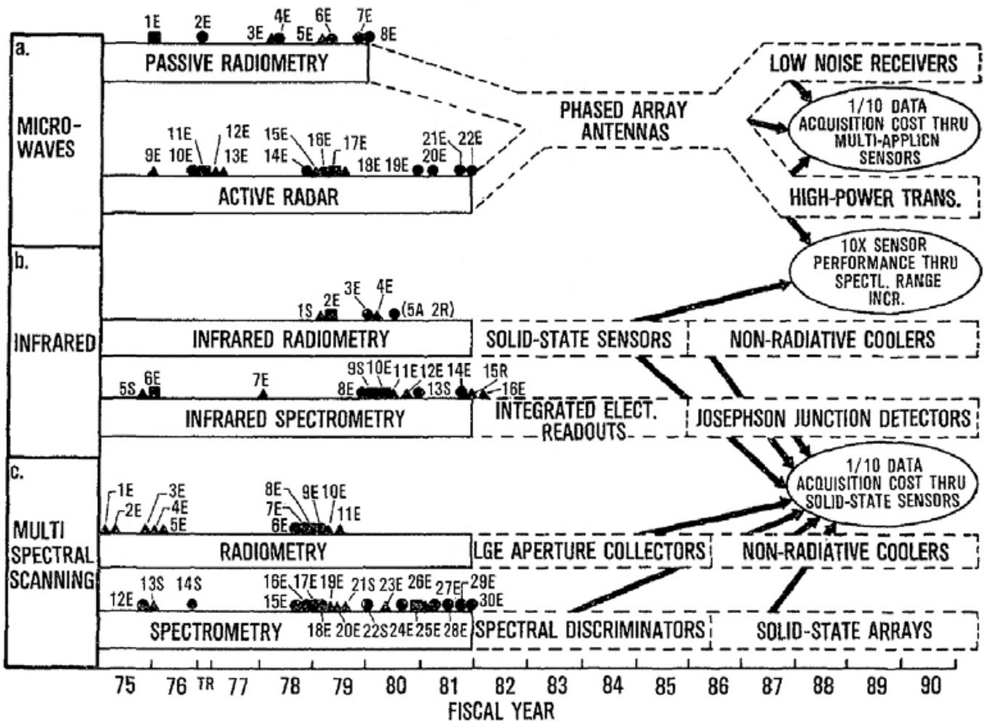

Fig. 2. Sensing and data acquisition roadmap (NASA, 1976a).

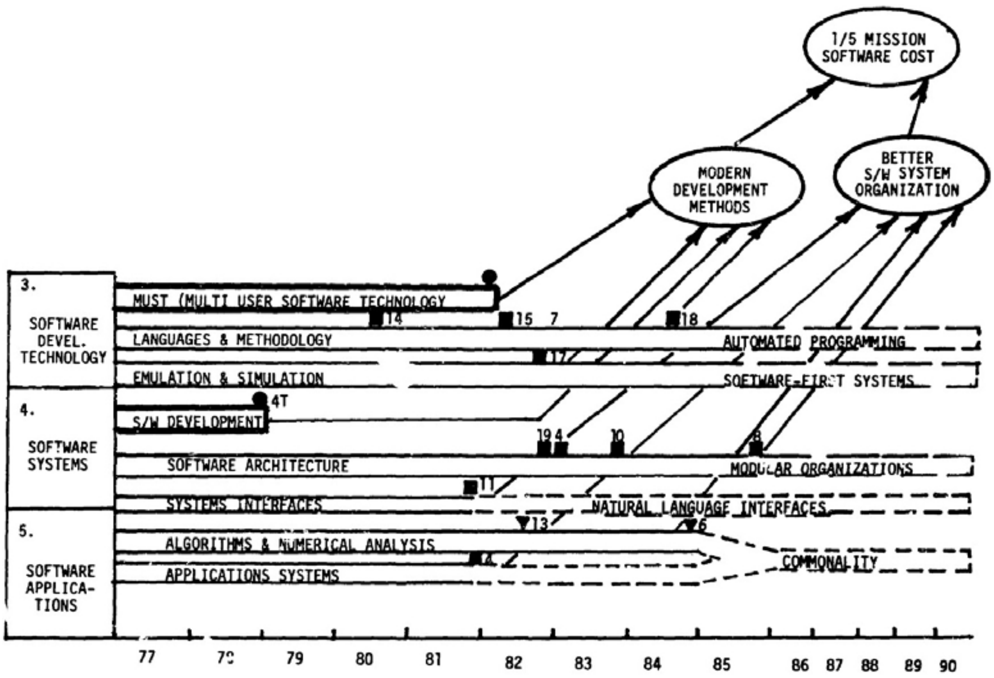

Fig. 3. Software development roadmap (NASA, 1976b).

3.2. Boeing, GE, Lockheed, USAF

NASA does not operate in a vacuum – at least not in the organizational sense – so, within the space, aerospace and defense sectors, there has obviously been some spreading and sharing of practices. Boeing's Space Division may have been roadmapping since the late 1960s, although they are much less explicit with the use of the term 'roadmap'. For instance, in a 1967 '*Voyager spacecraft system studies*' report where the term was used only once in the whole document, Boeing did show and describe charts which do appear to be roadmaps. Fig. 4 was presented as a 'postulated evolution chart' for scientific instruments (Boeing, 1967). The accompanying text stated that "this type of chart is used to plan the science missions for the various opportunities" and the task was to "determine the ways in which science payloads may evolve from the 1973 Voyager Mars mission to the subsequent 1975-1977-1979 missions" (Boeing, 1967).

There is some evidence that the Space Division of General Electric had been roadmapping too – i.e. "providing a time-phased tabulation of key management information" including trigger points for decisions, risks, alternatives, special facilities, unique manpower, etc. and combining these into a "single, time-phased plot" (General Electric, 1973). General Electric and Lockheed (Missiles & Space Company) have definitely been involved in roadmapping since the early 1980s (Hunt and Fisher, 1982). There are also examples of the United States Air Force producing roadmaps since the early 1970s, e.g. the '*Digital flight control technology roadmap*' (Blatt, 1973).

There is a unique report, produced in 1976, by the Research and Development Division of Lockheed, under contract by NASA, entitled the '*Civil uses of remotely piloted aircraft*'. The executive summary of that report opens with the paragraph:

> "*The intent of this study is to identify and assess the technology effort required to bring the civil uses of RPVs to fruition and to determine whether or not the potential market is real and economically practical, the technologies are within reach, the operational problems are manageable, and the benefits are worth the cost. To do so, the economic, technical, and environmental implications are*

examined. The time frame for application is 1980-85” (Aderhold *et al.*, 1976, p. 1).

The significance of this report for roadmapping is the inclusion of a diagram which appears to be a multi-layered, systems-based, roadmapping framework embodying a ‘market-product-technology’ structure – approximately two decades before Philips (1997) and EIRMA (1997). Lockheed’s schematic (Aderhold *et al.*, 1976) is shown in Fig. 5 and was drawn to represent “the overlapping sequence of events which will be appropriate and necessary in order to bring RPVs to the civil marketplace in the coming decade” (RPVs - Remotely Piloted Vehicles). Consider the features and different perspectives contained in this figure, there is/are:

- “Three end user classes” (i.e. markets) for the RPVs, namely federal agencies, state/local government agencies, and private firms/consortia.
- A block (or layer) for R&D, technology and subsystems development (funded by NASA and other federal agencies).
- A block (or layer) for ‘utility’ demonstrations (supported by DoD hardware).
- Elements for certification, resolution of regulatory implications and insurance/warranty provisions.
- Sub-layers for ‘Systems A-B-C’ (corresponding to the three markets) and the relative time phasing for the development, production and delivery/use of each product type.
- A layer for the transfer of know-how from the government sponsored projects into the private sector.
- The promotion, confidence-building and acceptance by firms to invest their own capital into the development, modifications, production, distribution and servicing of RPVs.
- The potential establishment of a network of lending institutions providing loans for more speculative private sector RPV applications.

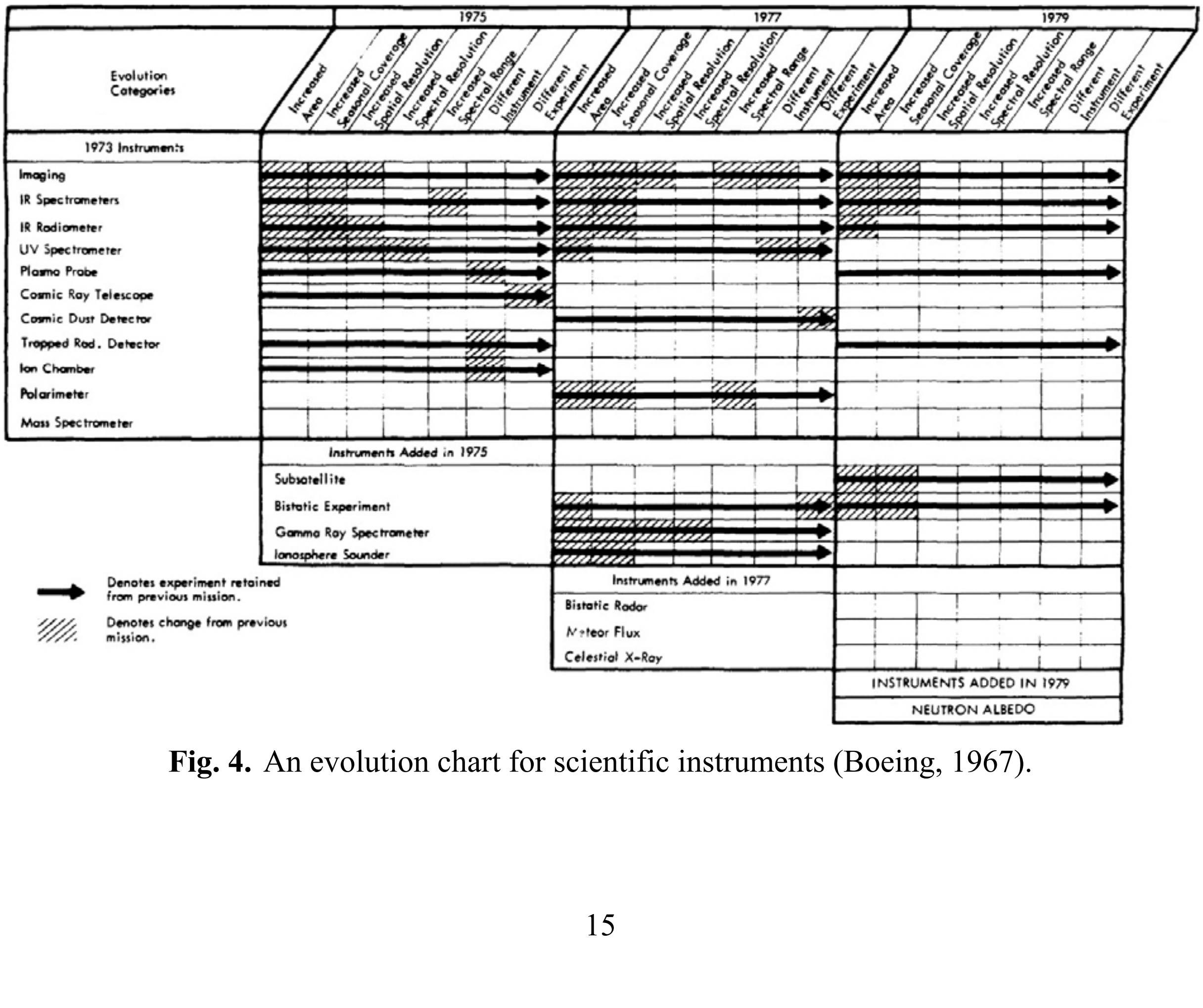

Fig. 4. An evolution chart for scientific instruments (Boeing, 1967).

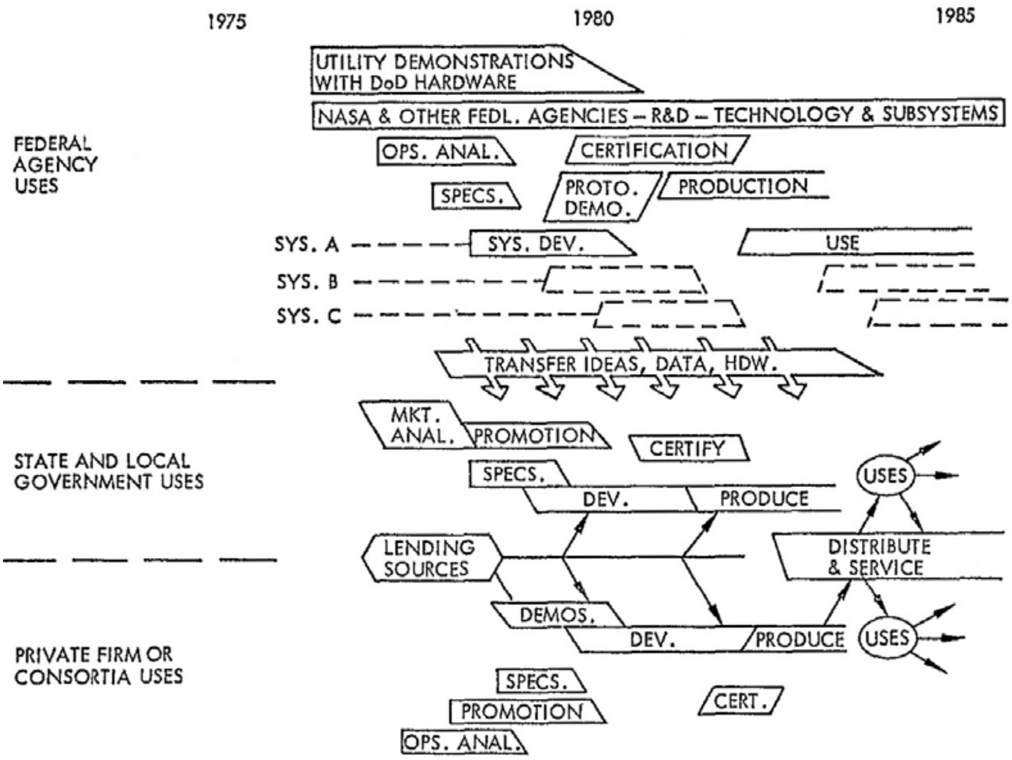

Fig. 5. Lockheed's roadmapping 'framework' (Aderhold *et al.*, 1976).

3.3. Rockwell International

Rockwell International is an interesting company when looking at the history of roadmapping as this organization bridged the space and energy sectors due to their work on nuclear reactor technologies. There is a 1965 report, by Atomics International (a division of the North American Aviation company, later acquired by Rockwell), where the term 'roadmap' is explicitly used to describe a specific form of visualization, which depicted a number of technical systems and functional components across the backdrop of a timeframe (Teresa, 1965). However, rather than charting the development in terms of R&D activities, the chart is from the testing of the actual systems in relation to a simulated flight sequence (and the roadmap only had a timeline of 5,500 seconds!). So, as such, it does not constitute technology roadmapping. However, from the accessible records, it appears Rockwell have been involved in actual technology roadmapping since the early 1980s. In a 1982 technical report on the development of future space nuclear power systems, Rockwell proposed the creation of a technology roadmap using a 'bottom-up' approach and showed a conceptual outline consisting of three levels, namely: technologies/capabilities to system building blocks to missions (Anderson, 1982). Such a proposal is akin to the 'market-product-technology' structure.

There is an extensive report from 1983 that contains a number of relevant and interesting elements (Anderson *et al.*, 1983). It indicates that Rockwell have deployed a dual 'bottom-up' and 'top-down' approach to their technology roadmapping – a decade before the BP publication (Barker and Smith, 1995). They also made use of an interlinked grid-based tool to support their roadmapping – in a comparable fashion to Philips with QFD (Groenveld, 1997). In this case, the grid used by Rockwell had a time element (whereas QFD does not) – there were sub-columns for current technology (late 1980s to early 90s), improved technology (mid 1980s), and advanced technology (late 1990s) – and was used to indicate technical capability and compatibility with the schedule requirements, i.e. 'what could be done' and on 'what time frame'. The interlinked grid was then analyzed and updated in terms of 'what needs to be done', feeding into technology roadmaps for planning the development paths. To aid communication (to a non-technical audience), Rockwell used simplified pictorial representations – an example is given in Fig. 6. Each circle in the sequence depicts a step in technology (with the specific details defined inside the circles) and 'branching' was used to indicate possible alternatives in the long-term future.

As an interesting aside in regards to 'corporate memory' (and typically the lack thereof), in the very first special issue of a journal dedicated to the topic of technology roadmapping (RTM Volume 46 Issue 2) there was a paper entitled '*Roadmapping: Agent of change*' about Rockwell Automation (McMillan, 2003). It stated that "senior Rockwell management was introduced to technology roadmapping during a Motorola visit in 1995" and that "Rockwell had no formal technology management processes at this time". And, it was then "decided that technology roadmapping would be pursued as an initial pilot program in the company" (McMillan, 2003). But the archives do show that Rockwell already had some really good roadmapping practices and tools a decade earlier.

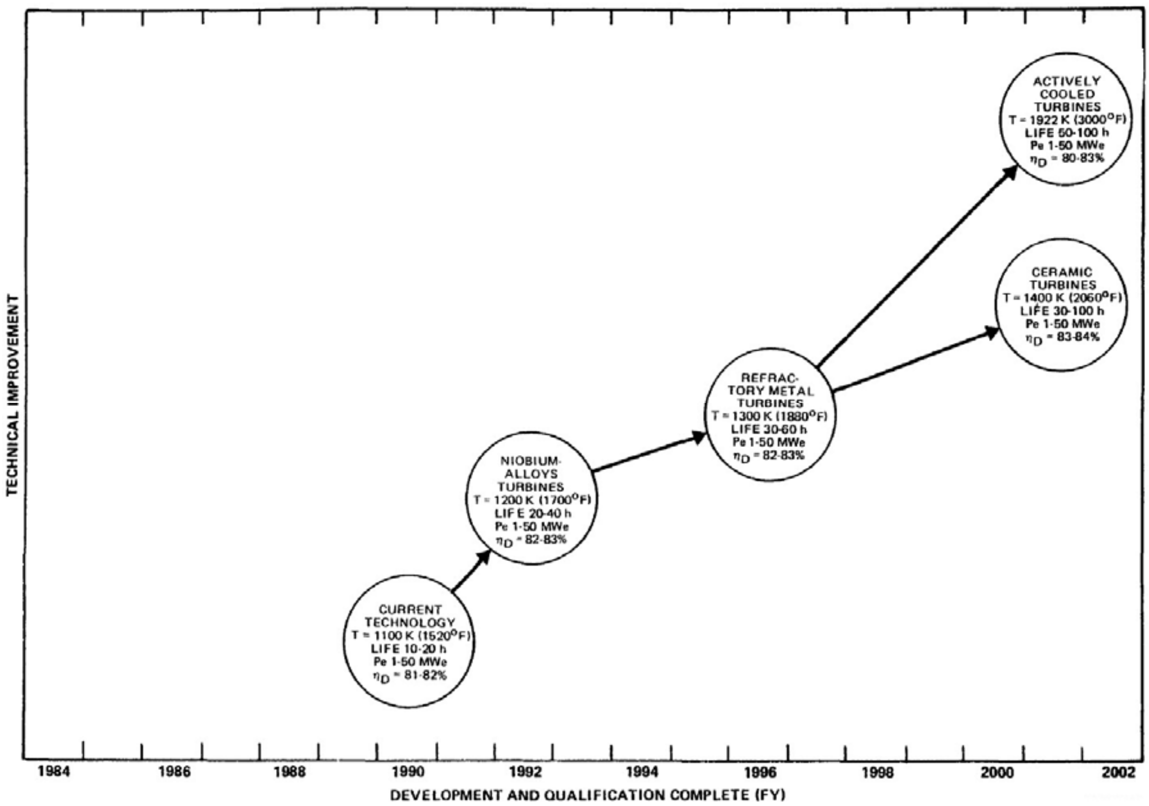

Fig. 6. 'Next step' technologies plot (Anderson *et al.*, 1983).

3.4. U.S. Department of Energy

The U.S. Department of Energy (DOE) has also had an important role in roadmapping, either leading the process of roadmap development or sponsoring the numerous initiatives and workshops over the years. The DOE's Office of Energy Efficiency and Renewable Energy has been very active and influential – and continues to be so today.

The accessible archives position the DOE's (and associated organizations) involvement with roadmapping to the mid-to-late 1970s, although it could be earlier given some of the practices that appear to have been already established during the period. For instance, the Lawrence Livermore Laboratory (1977) were applying a form of retrospective roadmapping, and with clear layers between the products/systems and underpinning activities such as engineering/physics/materials research, and with layers explicitly labelled 'What' and 'How'. Yet, reflect upon the following quotation from the System Studies Group contained within a 1,070-page report:

> "*We have developed a plan which provides for optional technical paths to commercial fusion power. The plan is not a roadmap of the most direct route to the program's end goals. Rather, it is a dynamic tool which will allow management to control the pace of the program effectively and keep it in line with changes in technical progress, national needs, and the nation's commitment to fusion*" (Lawrence Livermore Laboratory, 1977, p. 7-7).

It is unfortunate wording; perhaps a better phrasing would have been 'a roadmap is not a plan', i.e. the plan being the direct route and the roadmap being the dynamic tool depicting the optional technical paths. Then 47 pages later in the same document, they show a good example of a roadmap (over a timeframe of 1980-2008) with a 'cautious plan', 'aggressive plan' and 'accelerated plan' overlaid. Then for these 'plans', there is a follow-up set of separate visuals called 'time schedules'. Even today the language of 'roadmap-plan-schedule' is still problematic.

Consider Fig. 7 which is from a 1978 report produced by the Solar Energy Research Institute (SERI) – now the National Renewable Energy Laboratory (NREL). It was merely titled the 'Federal solar heating and cooling program' (SERI, 1978). The term 'roadmap' was not used anywhere in the report, but it is a roadmap. The visual depiction might appear simplistic, but it does appear to embody a 'market-product-technology' structure – nearly two decades before Philips (1997) and EIRMA (1997). Note the flow of technologies from R&D down into demonstrators toward the market development layer; there is even a row for standards development (which is fairly rare even today). And, in the report, there were sections labelled 'Problems, Uncertainties, Dissenting Views' – a decade before Motorola's minority report (Willyard and McClees, 1987). Additionally, John Neal (Acting Assistant Director, Division of Fossil Fuel Utilization, DOE) presented a number of vugraphs/slides at a conference in 1979, describing them as showing the "20 year transition strategy graphically". Again, not called or labelled as roadmaps, but they are. Fig. 8 shows one of the examples; note the layers for current, 2nd and 3rd generation technologies, and the fuels layers with parallel trajectory connected to the 2nd-3rd generation pathways (Neal, 1979). It is a good visually structured roadmap for the purpose of communicating a high-level overview.

Similar to NASA, the DOE were roadmapping well before the first journal papers, and have been continually involved with technology roadmapping since those early years. Making the jump to 1997, the Sandia National Laboratories (operated by the Sandia Corporation, a Lockheed Martin Company, for the DOE) published a well-known guide to roadmapping (Garcia and Bray, 1997) – which heavily referenced the roadmapping activities of the semiconductor industry. The Sandia guidance was published about 7 months before the European guide by EIRMA (1997), and so it appears that 1997 may be the pivotal year in the historical evolution of roadmapping, as it marks the coming together of the separate threads between the 'orthodox' and 'forgotten' accounts, at just about the same time as academics were starting to apply research effort to the method/tool. This then leads us into the current 'modern' era where the multi-layered, systems-based framework has become the established reference point for the practice of roadmapping.

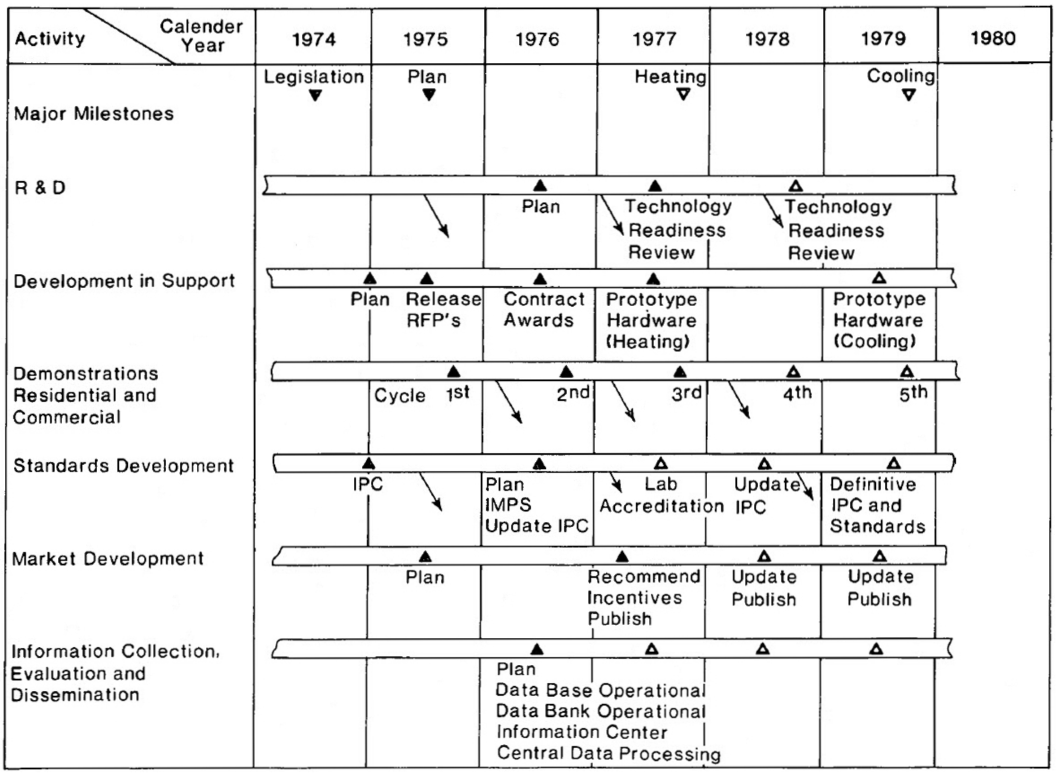

Fig. 7. Federal solar heating and cooling program (SERI, 1978).

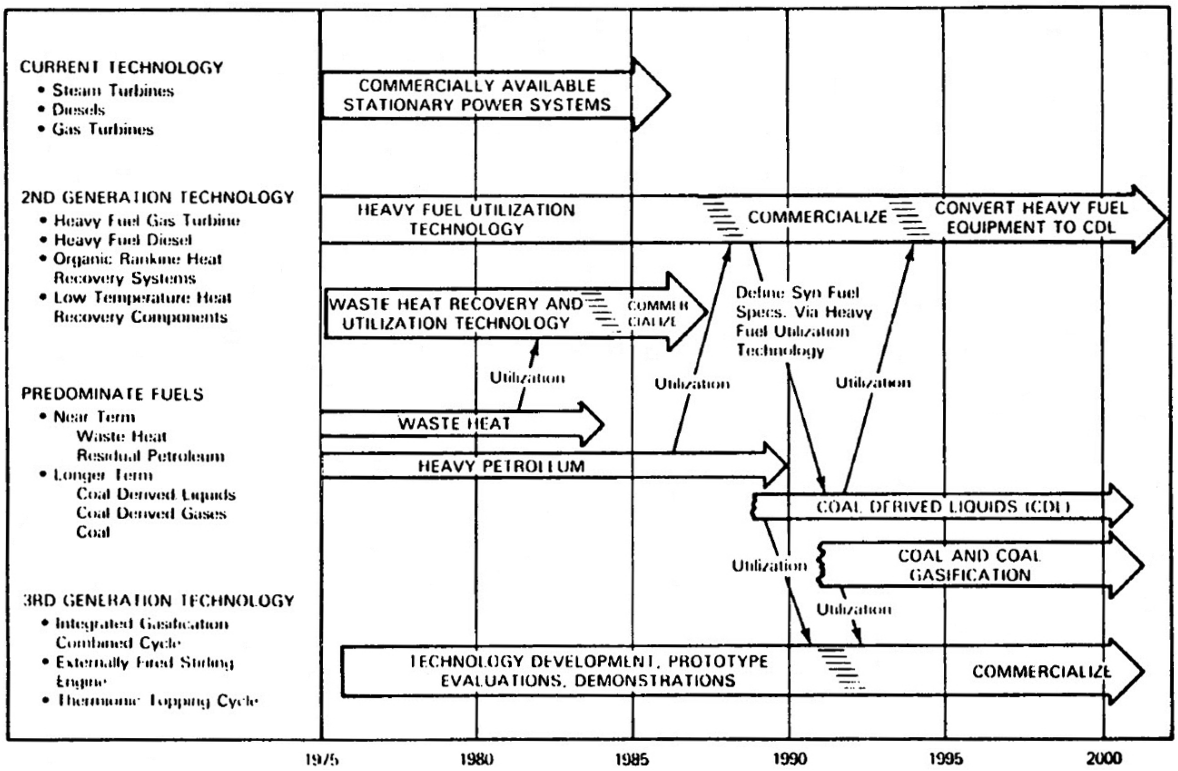

Fig. 8. Heat engines and heat recovery development strategy (Neal, 1979).

4. 'Unknown' origins

Today, an internet search for 'roadmapping' will reveal a bewildering array of examples – reports and images, and other related and unrelated material, of varying quality and provenance. There are numerous instances of the use of the terms 'roadmap' and 'roadmapping' in other contexts and taking other formats – it is, after all, an attractive metaphor for a journey (of various kinds). For example, pictorial 'roadmaps' are frequently used in the education sector to communicate the student journey to and through college; and 'roadmap' flowcharts are often found in research dissertations to outline the narrative structure of the thesis. In the popular press, the term 'roadmap' is strongly associated with the '*Roadmap for Peace*' (Middle East Quartet, 2003). There is even a book titled '*A roadmap of time*' (Steiger, 1975). As a further complication, slightly different terminology can be found, e.g. the term 'route map' is sometimes used in Europe. The following sections will highlight the uncertainty as to the exact/true origins of 'roadmapping'.

4.1. Organizational

From an organizational perspective, there are gaps in this 'updated' historical account. According to Probert and Radnor (2003), "it was Motorola and Corning that first championed roadmapping approaches in the late 1970s and early 1980s" and that "Corning advocated a critical events mapping approach to corporate and business unit strategy". However, there is a lack of documented evidence for Corning's activities and approach – Morone (1993) only acknowledges that "Corning's practice of continuing innovation is similar to Motorola's technology roadmap process". There are also indications that the U.S. Electric Power Research Institute (EPRI) were roadmapping in the late 1970s and early 1980s (SERI, 1978; Bauman *et al*., 1983). Schaller (2004) noted that IBM and Texas Instruments were deploying roadmapping around the same period as Motorola. In an interview with an IBM executive, it was stated that "Japanese firms like Toshiba and Hitachi had been using roadmaps since the late 1970s" (Schaller, 2004). Additionally, roadmaps in the form of a matrix of technical difficulties and solutions might have been presented to senior management within JVC in the early 1970s (Rosenbloom and Cusumano, 1987). So, there remain a number of question marks in regards to which organizations were early adopters and what approaches they were taking.

At the sector level, there are a number of well-known initiatives in addition to the eminent 'International Technology Roadmap for Semiconductors' (ITRS). Industry Canada, the government department responsible for industrial development, launched a sectoral level technology roadmapping initiative in 1995, and which ran until 2011 (Nimmo, 2013). During that period, Industry Canada co-sponsored 40 technology roadmaps involving "more than 2700 companies and more than 200 non-industry partners (universities, research institutions and associations)" (Nimmo, 2013). Another notable national example is the Ministry of Economy, Trade and Industry (METI) in Japan, who have been producing a consistent set of roadmaps since 2005 (Yasunaga *et al*., 2009), and with the process ongoing. Those are two prominent cases, but there lacks a thorough historical analysis of technology roadmapping applied at the sector, regional and national levels. In regards to Japan, de Laat and McKibbin (2003) identified that their first sectorial technology roadmap was published in 1996 by the Optoelectronics Industry and Technology Development Association (OITDA). Further, Probert and Radnor (2003) stated that roadmapping "had its early roots in the U.S. automotive industry" and Schaller (2004) implied that automotive research roadmaps were sponsored by the government in the late 1970s. So, again, more open question marks. Sector level roadmaps are usually one-off initiatives and reports, and this leads to another consideration – the involvement and roadmapping practices developed by consulting firms. For example, during the mid-to-late 1990s and well into the 2000s, Energetics were commissioned to facilitate numerous roadmapping activities and produced roadmap reports for various sectors/industries. So, potentially, another rich vein for historical analysis.

A separate account will be needed to trace 'business roadmapping', i.e. there are other early mentions of the term 'roadmap' in a general business sense. For example, there is a 1969 article published in the *Cornell Hotel and Restaurant Administration Quarterly* that states: "for the food service industry, the question is not will we grow but how will we grow", "what's needed is a roadmap to where you're headed", "are there any roadmaps? Only those we develop for ourselves" (O'Malley, 1969). That does seem to imply roadmapping. Whereas the paper entitled '*The corporate road-map: Planning at Babcock & Wilcox*' (Allio, 1972), which was published in *Long Range Planning*, outlined an approach to corporate planning but it did not constitute roadmapping. In the *Business and Society* journal, there is a paper from 1976 that used the following phrase: "a plan is a roadmap or blueprint of the future. It always has a futuristic orientation" (Harrison, 1976). As noted by Kappel (2001), "all kinds of forward-looking documents are sometimes called roadmaps". And there are also numerous mentions of the term 'roadmap' but with no clear description of their intended form/format. For example, Clifford (1975), a Director at McKinsey & Company, stated that "strategic planners are abandoning single scenarios for strategic 'roadmaps' reflecting a fuller range of economic and market probabilities". Furthermore, there are other forms/formats which are not called roadmaps but could potentially be viewed as such. For instance, in a report to the U.S. Secretary of the Navy dating from 1959, Arthur D. Little produced a 'schematic model of the development of a field of technology' for the purpose of showing "at a glance the typical manner in which, following its initial discovery, a whole field of technology evolves with time through basic research" (NRAC, 1959) – this could be seen as a form of retrospective roadmapping.

4.2. Educational

The term 'roadmap' is frequently used in the field of education, where it also appears to have a long history. For instance, there is the book entitled '*Gifted education: A comprehensive roadmap*' (illustrated with flowcharts) about how to develop an educational program and curriculum (Alexander and Muia, 1982). Other early examples include:

- *Journal of Planning Education and Research* – A roadmap of subjects/themes which can be constantly referred to as students move through the material (Davidson, 1986).
- *Teaching Exceptional Children* – A roadmap of the curriculum to plot where students have been, where they are and where they are going (Goldstein, 1986).
- *California Management Review* – A roadmap to provide a tangible proof of progress and what has been accomplished through the course syllabus (Culbert, 1977).
- *Journal of Accountancy* – A roadmap as a series of flowcharts to help students decide which professional development courses to take depending on their intended career path (Lux, 1975).

The 'roadmap' metaphor is obviously very strong. An early and related example dates to 1969 where Calvin Gould of Martin Marietta Corporation (which later merged with Lockheed to form Lockheed Martin) gave a talk entitled '*Anatomy of a presentation*', where he showed a 'roadmap' flowchart for creating and delivering different types of presentations and lectures (Gould, 1969).

4.3. Political

It is in the political arena where the term 'roadmap' garnered the greatest worldwide attention, and entered the public lexicon, with the publication of the seven-page '*Roadmap for Peace*' (Middle East Quartet, 2003) – a two state solution to the Israeli-Palestinian conflict – which opened by stating: "the following is a performance-based and goal-driven roadmap, with clear phases, timelines, target dates, and benchmarks aiming at progress through reciprocal steps by the two parties". It was a text-only document that outlined a timetable, comprised of three phases, aimed at a permanent status agreement. The 'performance-based' nature of the roadmap signified that the rate of progress would "depend upon the good faith efforts of the parties", and "their compliance with each of the obligations" as outlined in the roadmap (Middle East Quartet, 2003). Otterman (2005) highlighted a crucial detail (especially for a roadmap), namely, "the Palestinians, Israelis, and other parties in the Middle East were consulted, but did not directly participate in the plan's creation".

There is also the '*Roadmap to End Global Hunger*'. This is actually a U.S. congressional bill to address global hunger and improve food security (U.S. Congress, 2009b). There are the unanswered questions of how the term 'roadmap' came to be used for such documents and whether their authors were influenced by seeing other usages of the term? There may even be a separate 'parallel world' of roadmapping. For instance, there is a report entitled '*Energy strategy: Roadmap to consensus*' published in 1990 by the American Energy Assurance Council (AEAC) which looked into improving policy-making and negotiated agreements, for developing national energy strategy, through more effective consensus-building dialogue-based processes (AEAC, 1990a). They piloted an approach involving 126 senior-level executives, from twelve energy stakeholder groups, with a 1½-day workshop format using both large plenary and small working groups (i.e. caucuses and negotiation sessions). It appears to be very much akin to the 'fast-start' technology roadmapping approach (Phaal *et al*., 2013). Those involved with organizing and facilitating roadmapping workshops can appreciate the following remarks by the AEAC (1990a) and draw the necessary parallels:

- "The definition of stakeholder groups is extremely important, and is also very difficult to get exactly right".
- "The overriding process challenge has to do with the effective use of time".
- "All scheduling should be designed to facilitate (whether directly or indirectly) caucusing and coalition-building".
- "A degree of informality and flexibility should be built into the overall process".
- "The number of participants, and negotiating tables, is an important consideration".
- "All negotiation sessions should end with short debriefings, allowing participants to go on record – out loud, and in front of each other".
- "A sense of closure is important. It is not satisfactory simply to run out of time, and have participants leaving to catch planes. The risks inherent in this haphazard wind-down are twofold: first, that valuable lessons may be lost; and second, that the negotiation output may be accidentally trivialized".

In a follow-up to their initial approach, the AEAC (1990b) published an adapted process for undertaking 'consensus-building dialogue' which involved a series of four 2-day events, alternating between executive staff workshops to prepare and draft materials followed by convening the principals to review/revise/approve. To complete the process, the principals were then to take the outcome agreements and brief "the appropriate U.S. Congressional and Senate committees and relevant federal cabinet officials" (AEAC, 1990b).

4.4. Legal

The term 'roadmap' has also been used in a legal context. For example, in a 1961 paper entitled '*Law and policy in state labor relations acts*' (in regards to "racketeering unions and unscrupulous firms which exploit their employees"), the New York State Labor Relations Board issued "a roadmap charting five ways to challenge paper locals and sweetheart or collusive contracts" (Kramer, 1961). Their 'roadmap' appears to be a set of procedures. Additionally, the *University of Illinois Law Review* contained a paper entitled '*Prison overcrowding and the courts: A roadmap for the 1980s*' (Smolla, 1984) which explored "the jurisprudential conflicts that make prison overcrowding cases difficult for courts to handle, and then maps out the factors that appear to govern judicial decision making in prison overcrowding cases" – their mapping took the form of a written retrospective. So, their usage of the term is strongly procedural-based and, obviously, relevant given the context.

4.5. Financial

The earliest usage of the term 'roadmap' appears to be from 1945 with the paper entitled '*Reappraisal of depreciation and obsolescence*' published in the *Harvard Business Review*. That article examined the accounting method for depreciation and obsolescence in relation to repairs/replacement/rebuilding of production machinery and changes in technology. According to the author "there is no convenient road map for the analysis of these problems or their solutions in all companies" (Massel, 1945).

In 1972, there was a much more explicit usage of the term 'roadmap' in reference to financial planning for executive compensation and benefit packages (Petrie, 1972):

- "The final step in providing a total financial plan would be to detail all the recommendations and the thoughts expressed in the discussions in a comprehensive report – a blueprint for the future".
- "The complete plan would be an admirable financial roadmap as long as things remain unchanged, but total financial planning involves as many moving parts as a fine watch, and it's up to the financial planner to see that they are kept almost as well synchronized".

Then in 2005, there is a coming together of the financial and technology perspectives by Miller and O'Leary (2005), who analyzed "the implications of interfirm and intrafirm investment coordination" by focusing "on a hitherto neglected mechanism – the technology roadmap". The authors recognized that "while the existence of roadmapping practices has been noted in the literature outside accounting, their role in investment appraisal has not been explored to date". Miller and O'Leary (2005) positioned roadmaps as 'coordinating mechanisms' in the capital budgeting processes because they provide "the dynamic coordination of expectations where there is recurrent intra- and interfirm investment" and "in aligning capital spending decisions across sub-units of the firm and across firms" – "thus facilitating the 'active management' of investment programmes". They conducted a multi-year study with Intel looking at the firm's capital budgeting, appraisal and investment coordination practices (involving technology roadmapping). According to the authors, "ensuring that individual investment decisions are congruent with the relevant roadmap is afforded the highest priority by Intel's executive officers". In an interview with the President and CEO, he remarked: "we obviously do ROIs on products and things of that sort, but the core decisions the company makes, the core decisions are basically technology roadmap decisions" (Miller and O'Leary, 2005).

5. Summary

Technology roadmapping has established itself as a powerful and popular management tool. Its unique differentiating feature is the structured visual representation, underpinned by the 'why-what-how-when' framework, which is used to enable dialogue and consensus building and for ongoing synchronization across the relevant stakeholders. Without employing the framework as a primary lens, there is little to differentiate roadmaps and roadmapping reports from other strategic plans and business cases. Roadmapping emerged from industry through practitioners developing methods and approaches, with a strong technological focus, to ensure investments and research/development projects were aligned with expected functional performance and commercial expectations for products/systems. Motorola, BP, Philips, EIRMA, Lucent Technologies and the Semiconductor Industry Association have been recognized for their significant contributions to the practice of technology roadmapping. They played a key role in raising the profile of the tool, through providing compelling demonstrations of what can be achieved by adopting roadmapping processes. However, the practice of technology roadmapping is much older than acknowledged in the literature and there are a significant number of erroneous citations as to its origins. So, in addition to providing a retrospective on roadmapping's emergence as a tool/method, this paper identifies its roots in 1960/70s industrial engineering management. Organizations such as NASA, Boeing, GE, Lockheed, USAF, Rockwell International and the U.S. Department of Energy were all deploying a form of roadmapping and made significant contributions that pre-date some of the well-known, highly cited and seminal papers. There is also the danger that we are perhaps guilty of overlooking even earlier significant work that could lay claim to roadmapping's provenance as a management tool/method. Furthermore, it needs to be stated that the definitions of 'roadmap' and 'roadmapping' are not universally agreed; maybe this reflects its unclear origins. And to add to the difficulties of understanding what constitutes roadmapping, there are other legitimate usages and claims to the term 'roadmap', including those from politics, law, finance and education. They all, however, appear to share the common underlying feature of the 'roadmap' being both an attractive and powerful metaphor.

References

Aderhold, J.R., Gordon, G., and Scott, G.W. (1976) *Civil uses of remotely piloted aircraft*. Report: LMSC-D057323, Research and Development Division, Lockheed Missiles and Space Company, Sunnyvale, CA, United States of America.

AEAC – American Energy Assurance Council (1990a) *Energy strategy: Roadmap to consensus*. Report: DOE/PE/79073-T2, AEAC, Denver, CO, United States of America.

AEAC – American Energy Assurance Council (1990b) *A recommendation: How to build lasting consensus on a national energy strategy*. Report: DOE/PE/79073-T1, AEAC, Denver, CO, United States of America.

Albright, R.E. and Kappel, T.A. (2003) 'Roadmapping in the corporation', *Research-Technology Management*, 46(2), pp. 31–40.

Alexander, P. and Muia, J.A. (1982) *Gifted education: A comprehensive roadmap*. Rockville, MD: Aspen Systems Corporation.

Allio, R.J. (1972) 'The corporate road-map: Planning at Babcock & Wilcox', *Long Range Planning*, 5(4), pp. 9–14.

Anderson, R.V. (1982) *Technological implications of SNAP reactor power system development on future space nuclear power systems*. Report: DOE/SF/11687-T1, Energy Systems Group, Rockwell International, Canoga Park, CA, United States of America.

Anderson, R.V., Bost, D., Determan, W.R., Harty, R.B., Katz, B., Keshishian, V., Kramer, D., Lillie, A.F., Matlin, E., Moriarty, M.P., Nelson, D.K., and Thomson, W.B. (1983) *Space-reactor electric systems: Subsystem technology assessment*. Report: ESG-DOE-13398, Energy Systems Group, Rockwell International, Canoga Park, CA, United States of America.

Barker, D. and Smith, D.J.H. (1995) 'Technology foresight using roadmaps', *Long Range Planning*, 28(2), pp. 21–28.

Bauman, M.B., Pain, R.F., Van Cott, H.P., and Davidson, M.K. (1983) 'Work structure in nuclear power plants', *Proceedings of the Human Factors Society Annual Meeting*, 27(7), pp. 571–575.

Blatt, P.E. (1973) *Digital flight control technology roadmap*. Report: AFFDL-FGL-TM-73-65, Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, United States of America.

Boeing (1967) *Voyager spacecraft system studies: Volume 1 summary*. Report: D2-115002-1, Space Division, The Boeing Company, Seattle, WA, United States of America.

Carvalho, M.M., Fleury, A., and Lopes, A.P. (2013) 'An overview of the literature on technology roadmapping: Contributions and trends', *Technological Forecasting and Social Change*, 80(7), pp. 1418–1437.

Clifford, D.K. (1975) 'The case of the floundering founder', *Organizational Dynamics*, 4(2), pp. 21–33.

Coates, J.F. (2000) 'Scenario planning', *Technological Forecasting and Social Change*, 65(1), pp. 115–123.

Culbert, S.A. (1977) 'The real world and the management classroom', *California Management Review*, 19(4), pp. 65–78.

Davidson, J.M. (1986) 'Quantitative reasoning in the planning curriculum', *Journal of Planning Education and Research*, 6(1), pp. 30–36.

de Alcantara, D.P. and Martens, M.L. (2019) 'Technology roadmapping: A systematic review of the literature focusing on models', *Technological Forecasting and Social Change*, 138, pp. 127–138.

DeGregorio, G. (2000) 'Technology management via a set of dynamically linked roadmaps', *Proceedings of the IEEE Engineering Management Society Conference*, Albuquerque, NM, United States of America, 13–15 August. doi: 0.1109/EMS.2000.872498.

de Laat, B. and McKibbin, S. (2003) *The effectiveness of technology road mapping: Building a strategic vision*. Report: 03-18 (for the Dutch Ministry of Economic Affairs), Technopolis Group, Paris, France.

EIRMA – European Industrial Research Management Association (1997) *Technology roadmapping: Delivering business vision*. Working Group #52, EIRMA, Paris, France.

Finger, H.B., Johnson, P.G., Morrissey, J., and Siegel, A.R. (1964) 'Nuclear rockets based on graphite reactor technology: Their applications and development status', *Second AGARD Lecture Series on Nuclear Propulsion*, Brussels, Belgium, 28 September.

Galvin, R. (1998) 'Science roadmaps', *Science*, 280(5365), p. 803. doi: 10.1126/science.280.5365.803a.

Galvin, R. (2004) 'Roadmapping: A practitioner's update', *Technological Forecasting and Social Change*, 71(1-2), pp. 101–103.

Garcia, M.L. and Bray, O.H. (1997) *Fundamentals of technology roadmapping*. Report: SAND97-0665, Sandia National Laboratories, Albuquerque, NM, United States of America. doi: 10.2172/471364.

General Electric (1973) *Study for identification of beneficial uses of space: Volume 2 technical report.* Report: 73SD4281, Space Division, General Electric, Philadelphia, PA, United States of America.

Gerdsri, N., Kongthon, A., and Vatananan, R.S. (2013) 'Mapping the knowledge evolution and professional network in the field of technology roadmapping: A bibliometric analysis', *Technology Analysis and Strategic Management*, 25(4), pp. 403–422.
Goldstein, M.T. (1986) 'Curriculum: The keystone for special education planning', *Teaching Exceptional Children*, 18(3), pp. 220–223.
Gould, C.R. (1969) 'Anatomy of a presentation', *Ninth Annual Society of Technical Writers and Publishers (STWP) and Association of Technical Artists (ATA) Seminar*, Huntsville, AL, United States of America, 21–23 October.
Groenveld, P. (1997) 'Roadmapping integrates business and technology', *Research-Technology Management*, 40(5), pp. 48–55.
Groenveld, P. (2007) 'Roadmapping integrates business and technology', *Research-Technology Management*, 50(6), pp. 49–58.
Harrison, F. (1976) 'Synergy in professional organizations', *Business and Society*, 17(1), pp. 15–23.
Hunt, S.R. and Fisher, H.T. (1982) 'AF/AIAA military space system technology model', *NASA Workshop on Space Human Factors*, Leesburg, VA, United States of America, 24–26 August.
Kappel, T.A. (2001) 'Perspectives on roadmaps: How organizations talk about the future', *Journal of Product Innovation Management*, 18(1), pp. 39–50.
Kramer, J. (1961) 'Law and policy in state labor relations acts: The New York Board as innovator', *The Annals of the American Academy of Political and Social Science*, 333(1), pp. 59–75.
Lawrence Livermore Laboratory (1977) *Laser program annual report 1976*. Report: UCRL-50021-76, Lawrence Livermore Laboratory, Livermore, CA, United States of America.
Letaba, P., Pretorius, M.W., and Pretorius, L. (2015) 'Analysis of the intellectual structure and evolution of technology roadmapping literature', *Portland International Conference for Management of Engineering and Technology*, Portland, OR, United States of America, 2–6 August. doi: 10.1109/PICMET.2015.7273147.
Lombardo, C.T., McCarthy, B., Ryan, E., and Connors, M. (2017) *Product roadmaps relaunched: How to set direction while embracing uncertainty*. Sebastopol, CA: O'Reilly Media.
Lux, M.S. (1975) 'Tax study roadmap', *Journal of Accountancy*, 140(4), pp. 109–113.
Massel, M.S. (1945) 'Reappraisal of depreciation and obsolescence', *Harvard Business Review*, 24(1), pp. 85–96.
McMillan, A. (2003) 'Roadmapping: Agent of change', *Research-Technology Management*, 46(2), pp. 40–47.
Middle East Quartet (2003) *A performance-based roadmap to a permanent two-state solution to the Israeli-Palestinian conflict*. Available at: http://www.un.org/News/dh/mideast/roadmap122002.pdf (Accessed: 28 November 2018).
Miller, P.B. and O'Leary, T. (2005) 'Capital budgeting, coordination and strategy: A field study of interfirm and intrafirm mechanisms', in Chapman, C.S. (ed) *Controlling strategy: Management, accounting and performance measurement*. Oxford: Oxford University Press, pp. 151–182.
Morone, J.G. (1993) *Winning in high-tech markets – The role of general management: How Motorola, Corning and General Electric have built global leadership through technology*. Boston, MA: Harvard Business School Press.
NACS – National Advisory Committee on Semiconductors (1991) *Micro Tech 2000 workshop report*. Government Publishing Office, Washington, DC, United States of America.

NASA – National Aeronautics and Space Administration (1975) *OAST summer workshop: Volume 3 navigation, guidance and control*. Report: NASA-TM-X-73963, Office of Aeronautics and Space Technology, NASA, Langley Research Center, Hampton, VA, United States of America.

NASA – National Aeronautics and Space Administration (1976a) *Space electronics technology summary*. Report: NASA-TM-X-73044, NASA, Washington, DC, United States of America.

NASA – National Aeronautics and Space Administration (1976b) *OAST space theme workshop: Volume 1 summary report*. Report: NASA-TM-80001, Office of Aeronautics and Space Technology, NASA, Langley Research Center, Hampton, VA, United States of America.

Nauda, A. and Hall, D.L. (1991) 'Strategic technology planning: Developing roadmaps for competitive advantage', *Portland International Conference for Management of Engineering and Technology*, Portland, OR, United States of America, 27–31 October. doi: 10.1109/PICMET.1991.183788.

Neal, J.W. (1979) 'Heat engines and heat recovery activity', *Proceedings of the First Conference on Advanced Materials for Alternative Fuel Capable Directly Fired Heat Engines*, Maine Maritime Academy, Castine, ME, United States of America, 31 July – 3 August.

Nimmo, G. (2013) 'Technology roadmapping on the industry level: Experiences from Canada', in Moehrle, M.G., Isenmann, R., and Phaal, R. (eds) *Technology roadmapping for strategy and innovation: Charting the route to success*. Berlin Heidelberg: Springer-Verlag, pp. 47–65.

NRAC – Naval Research Advisory Committee (1959) *Basic research in the Navy: Volume 1 Report to the Secretary of the Navy*. Naval Research Advisory Committee, Washington, DC, United States of America.

O'Malley, P.L. (1969) 'Food service's year of decision', *Cornell Hotel and Restaurant Administration Quarterly*, 10(1), pp. 17–21.

Otterman, S. (2005) *Middle East: The road map to peace*. Available at: https://www.cfr.org/backgrounder/middle-east-road-map-peace (Accessed: 28 November 2018).

Petrie, D.J. (1972) 'Executive financial planning: A new fringe benefit', *Compensation Review*, 4(1), pp. 49–52.

Phaal, R., Farrukh, C., and Probert, D. (2010) *Roadmapping for strategy and innovation: Aligning technology and markets in a dynamic world*. Cambridge: Institute for Manufacturing, University of Cambridge.

Phaal, R., Farrukh, C., and Probert, D.R. (2013) 'Fast-start roadmapping workshop approaches', in Moehrle, M.G., Isenmann, R., and Phaal, R. (eds) *Technology roadmapping for strategy and innovation: Charting the route to success*. Berlin Heidelberg: Springer-Verlag, pp. 91–106.

Phaal, R. (2019) *Roadmapping bibliography*. Available at: www.ifm.eng.cam.ac.uk/uploads/Research/CTM/Roadmapping/Roadmapping_Bibliography_Phaal.pdf (Accessed: 28 November 2019).

Pichler, R. (2016) *Strategize: Product strategy and product roadmap practices for the digital age*. London: Pichler Consulting.

Probert, D. and Radnor, M. (2003) 'Frontier experiences from industry-academia consortia', *Research-Technology Management*, 46(2), pp. 27–30.

Richey, J.M. and Grinnell, M. (2004) 'Evolution of roadmapping at Motorola', *Research-Technology Management*, 47(2), pp. 37–41.

Rosenbloom, R.S. and Cusumano, M.A. (1987) 'Technological pioneering and competitive advantage: The birth of the VCR industry', *California Management Review*, 29(4), pp. 51–76.

Schaller, R.R. (2004) *Technological innovation in the semiconductor industry: A case study of the international technology roadmap for semiconductors*. PhD thesis, George Mason University, Fairfax, VA, United States of America.

SERI – Solar Energy Research Institute (1978) *Annual review of solar energy*. Report: SERI/TR-54-066, Program Evaluation Branch, Solar Energy Research Institute, Golden, CO, United States of America.

SIA – Semiconductor Industry Association (1993a). *Semiconductor technology workshop conclusions*. SIA, San Jose, CA, United States of America.

SIA – Semiconductor Industry Association (1993b). *Semiconductor technology workshop working group reports*. SIA, San Jose, CA, United States of America.

Smolla, R. (1984) 'Prison overcrowding and the courts: A roadmap for the 1980s', *University of Illinois Law Review*, 1984(2), pp. 389–421.

Spencer, W.J. and Seidel, T.E. (1995) 'National technology roadmaps: The U.S. semiconductor experience', *Proceedings of the 4th International Conference on Solid-State and IC Technology*, Beijing, China, 24–28 October. doi: 10.1109/ICSICT.1995.500069.

Steiger, B. (1975) *A roadmap of time: How the Maxwell/Wheeler weather-energy cycles predict the 'history' of the next 25 years*. Englewood Cliffs, NJ: Prentice-Hall.

Teresa, M. (1965) *SNAP 10A FSEM-3 Agena compatibility test*. Report: NAA-SR-11129, Atomics International, Canoga Park, CA, United States of America.

UNIDO – United Nations Industrial Development Organization (2005) *UNIDO technology foresight manual: Volume 1 organization and methods*. UNIDO, Vienna, Austria.

U.S. Congress (2009a) *Solar Technology Roadmap Act, H.R. 3585, 111th Congress*. Government Publishing Office, Washington, DC, United States of America.

U.S. Congress (2009b) *Roadmap to End Global Hunger and Promote Food Security Act, H.R. 2817, 111th Congress*. Government Publishing Office, Washington, DC, United States of America.

Whalen, P.J. (2007) 'Strategic and technology planning on a roadmapping foundation', *Research-Technology Management*, 50(3), pp. 40–51.

Willyard, C.H. and McClees, C.W. (1987) 'Motorola's technology roadmap process', *Research Management*, 30(5), pp. 13–19.

Wright, F.D. and Conte, T.M. (2018) 'Roadmapping computer technology trends enlightens industry', *Computer*, 51(6), pp. 100–103.

Yasunaga, Y., Watanabe, M., and Korenaga, M. (2009) 'Application of technology roadmaps to governmental innovation policy for promoting technology convergence', *Technological Forecasting and Social Change*, 76(1), pp. 61–79.