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Addressing resource over-exploitation via cooperative institutions: Examining how technology roadmapping could contribute

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Abstract

In a resource constrained world, valuable resources will increasingly need to be managed as part of the global commons, however the current global market has been shown to be ill-equipped to protect common resources from over-exploitation. However leading thinkers on this subject have previously identified collaboration as a fundamental successful factor in the sustainable management of small scale common resources. It follows that collaboration could play a part contributing to a resource sustainable manufacturing industry in the future.
This paper examines for the first time the potential of technology roadmapping, a strategic tool widely used by manufacturing firms, to foster collaboration between firms in an industry. The International Technology Roadmap for Semiconductors, a long running industry-wide collaborative effort, is taken as a case study. While not focused exclusively on sustainable resource use, this paper finds similarities between the features of this collaborative effort and the characteristics of successful cooperative institutions. The implications of this finding suggest that further research should be considered into identifying how technology roadmapping could contribute to a more sustainable manufacture sector.

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Keywords: common pool resources ; technology roadmapping ; roadmapping ; resource scarcity ; sustainability ; collaboration ; cooperative institutions

1. Introduction

In a resource constrained world with a growing population, firms which rely on material inputs to create value, such as those in the manufacturing sector, face a difficult challenge: increasing output to match demand with fewer resources and emissions [1–4]. As a result, many now argue that manufacturing firms' ability to improve their resource productivity will be a key competitive advantage in the future, and thus essential to remaining financially viable in the long term [5–9].

An important element of reducing the demand for resources is to improve resource efficiency, and there is large scope for savings here [5,10,11], however this paper examines the problem where the exploitation of a common resource is essential to the market, such as fish to the fishing industry. In these cases, improving resource efficiency at the individual firm level may not be sufficient to prevent the over-exploitation of the resource at the industry level [12]. In highly competitive markets, firms will often be under significant commercial pressure to over-exploit the resource for short-term economic gain [13] leaving the long term viability of the industry at risk. Without adequate resource management, the over-exploitation of a shared natural resource comes not only at the expense of the environment, but also presents significant risks to the long term viability of firms, industries and society as a whole [14]. Thus the preservation of resources to below their regeneration rate is a fundamental element to sustainable manufacturing.

As a result of commercial pressures creating market failures, it is often necessary for government to regulate against short termism to correct the failure. However top-down authoritarian regulation is not appropriate in all situations, and in certain situations is not possible or even effective, for example quotas in areas where monitoring is

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difficult, or where resources are exploited across national borders [15].

In her seminal work examining communities that successfully manage scarce resources, Ostrom [16] suggested the solution to common pool resource (CPR) dilemmas was sometimes cooperative institutions, rather than government intervention or resource privatisation. This finding builds on previous work by Levine and White [17] who theorised that under conditions of scarcity, collaboration was essential for firms to meet their strategic goals. More recently, Senge *et al.* [18] has echoed many others [19,20] in arguing that cross-sector collaboration is essential to meet present sustainability challenges, and further that these collaborations must be co-created by stakeholders.

This last point is based on the premise that users of a resource are rational beings that have the capacity to understand the need for restraint. It has been suggested that when careful understanding of diverse perspectives is required, collaborative institutions have been found to facilitate open communication channels between affected stakeholders, which build trust towards self-generated and self-managed solutions [21]. In such a way, users of a resource understand why there is a need to decouple their production from over-exploitation of the common pool resource in order to remain economically viable in the long term.

Ostrom's research into successful small community level CPR institutions provides valuable guidance on design principles to create these institutions. However there are significant differences between the small institutions she studied and the complex global supply chains in the manufacturing sector. The key difference, from the perspective of creating cooperative institutions, is that in modern manufacturing supply chains there is a lack of shared geographical location and thus social bonds which results in less awareness and accountability by individuals to protect common resources for the future.

In order to raise awareness and generate the accountability required to preserve and sustainably manage resources, some mechanism is required to bring diverse stakeholders together and create a cooperative institution. This paper puts forward the thesis that roadmapping is such a mechanism.

Roadmapping is a strategic tool that originates in the field of technology management. Until recently, little research has been conducted into the potential for roadmapping to contribute to sustainable manufacturing, however in technology settings the process leads to collaboration and institutions that exhibit similar characteristics to those examined by Ostrom. Thus this paper explores the potential for roadmapping to create collaborative institutions by first examining the roadmapping process and its properties alongside Ostrom's design principles. In doing so, this paper will shed light on whether roadmapping can contribute to successful collaboration between firms to manage resources sustainably, or even to facilitate industrial symbiosis and the transition to a circular economy.

2. Roadmapping

Roadmapping was originally developed by Motorola in the 1970s [22], and defined at the time as an extended look at the future of a chosen field composed from the collective intelligence and imagination of experts in the field. It was used primarily at the time to support firms to improve alignment between technology and product development.

Since then the approach has been adopted widely by many organisations in different sectors around the world, at company, industry and national levels. The underlying concept is very flexible, and as a result roadmapping methods have been adapted to suit many different goals, supporting innovation, strategy and policy development [23].

In essence, roadmaps are simple, adaptable 'strategic lenses' through which the evolution of complex systems can be examined, which supports dialogue and communication of planned action. As a result, roadmaps are often employed as decision aids to improve coordination of activities and resources in increasingly complex and uncertain environments [24].

Roadmapping allows the integration and alignment of a number of different perspectives across a broad time range. Typically roadmaps are used to align current underpinning science and technology to match long-term trends and drivers [23,25]. Resource scarcity can be one such trend and driver, and if future resource shortage could restrict the production of a product, the roadmap demonstrates this danger, as shown in a simplified representation of a roadmap in Fig. 1.

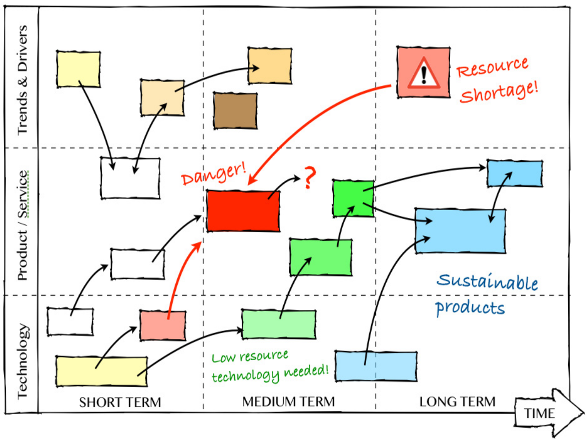

Fig 1. Simplified roadmap illustrating how a future resource shortage prompts investment in new low-resource technologies to sustainable products

Fig. 1 is a simplified representation of a firm level roadmap, but roadmaps can be applied at many different scales, ranging from international level roadmaps, for example coordinating climate change mitigation technologies [26], to industry level roadmaps for example coordinating investment in rail networks [27].

There is some existing research on the benefit of using roadmapping to achieve industry-level collaboration. In the UK automotive industry, Phaal et al. [21] documented communication and network development benefits arising from a roadmapping process to support strategic technology planning. In another example, roadmapping was found to support industrial and research networks to build consensus about research priorities in three case studies [28].

2.1. Roadmapping principles

Best practices for a roadmapping workshop process has emerged from the wealth of facilitations and research conducted over the last 40 years. Kerr *et al.* [29] synthesized the growing body of work on strategic technology management tools into seven key principles: human-centric, workshop-based, neutrally facilitated, lightly processed, modular, scalable, and visual. The principles offer guidance to decide on the appropriate form, functions, and features that should be embodied in the workshop process. Each principle is described in more detail below.

1. Human-centric - Roadmapping workshops provide a structured process to allow participants to engage with one another on an individual level, leveraging the benefits of direct social interaction to aid decision-making [30]. In addition, since roadmapping focuses on the future and thus deals with uncertainty, it often exposes conflicting opinions between participants. However the process and human-centric approach has been found to provide a platform for constructive discussion which leads to conflict resolution [31,32].

2. Workshop-based – Workshops provide the platform for group interaction through structured activities. The process and roadmap is strengthened as more varied and contrasting stakeholders are included [24,30]. De Laat and McKibbin [31] found roadmapping was "*without* exception [a] collective procedure in which all relevant stakeholders should be involved." Roadmapping is inherently a mechanism to bring people together, rather than restricting involvement [33].

3. Neutrally facilitated - Workshop facilitators aim to form a position of neutrality whereby the facilitator focuses on the process and does not contribute to the content [29]. This is important as roadmaps are inherently exploratory, and while participants will hold different views of potential futures at the outset, the workshop setting provides the opportunity to share information, debate complex issues and explore different views of potential futures. The result of this approach is that the participants co-create the solution, rather than get told what to do, which increases their endorsement (buy-in) to the required actions and restraints placed on them.

4. Lightly processed - The roadmapping process is flexible enough to enable lightweight 'fast-start' approaches [24] which avoid the danger of being too procedural and prescriptive. However this approach requires careful design and experienced facilitation to achieve the appropriate balance between depth and speed.

5. Modular – Roadmapping comprises a series of activities each building towards the final roadmap, and facilitators select appropriate tools from a toolkit to fulfill each activity [34]. However since each roadmapping session is different, the tools are adapted to fit each session. In order to ensure the overall process still flows together, the generic forms of the tools are easily configurable to create a consolidated form [29]. The result of this modularity is that roadmaps are highly comparable between sessions and can be readily scaled.

6. Scalable – The common three layer structure and the modular properties of the toolkits ensure roadmaps can be linked across scales. Product level roadmaps can be nested within business unit roadmaps, which are themselves nested into firm level and even industry level roadmaps [35]. As a result of this hierarchy property, the roadmap is able to communicate high level topics while at the same time containing detailed information upon interrogation.

7. Visual – While there exist many different approaches to roadmapping, the visual representation is an essential element [28]. The visual provides a synthesized high level representation of the topic in a multi-layered time based chart, which brings together multiple perspectives into a single visual diagram. The roadmap architecture links directly to fundamental strategic questions:

- Where do we want to go? Where are we now? How can we get there?
- Why do we need to act? What should we do? How should we fit in? By when?

The resulting single page output links all the important information together and as such acts as an excellent form of communication to disseminate among all relevant stakeholders, acting as a reference point for ongoing dialogue and action.

3. Cooperative Institutions

Scholars from many disciplines have discussed the challenge of communities self-regulating a public good [12,36–39]. Rational choice theory has been used to argue that rational actors, when faced by a common resource dilemma, will inevitably overuse it. This problem is most commonly associated with the theory put forward by Garrett Hardin [12] as the 'tragedy of the commons'.

However the problems associated with the sustainable management of communal resources lie at the very heart of society. As far back as the 4th century B.C., Aristotle noted the problems associated with the lack of care for common resources in *Politics* (Book II, ch. 3). Over the last decades, the consequences of this over-exploitation has become ever more starkly apparent in the degradation of the natural environment [40], however solutions are a challenge because the causes lie in fabric of society [41] and market failures in the economy [42,43]. As the human population grows and resources become ever more scarce, it is to be expected that an increasing number of society's social and environmental development conflicts will stem from the overexploitation of communal resources.

Ostrom summarised two traditional solutions proposed to address CPR over-exploitation: government intervention or privatisation of the resource. Both provide advantages to the unmanaged and unregulated free for all that currently exists in many CPR situations, however Ostrom found both to be inherently flawed - neither proving optimal in every case. Ostrom instead advocated for the need to create localised 'institutions for collective action' to address each CPR issue, which could tailor its solution to specific circumstances.

Ostrom documented community-based solutions to common property resource problems that have proved successful over multiple generations. These are quasi-voluntary arrangements through which a community of users (fishers, grazers, irrigators) are able to manage the resource collectively and control violators, in such a way as to preserve the resource over time.

Ostrom found from many case studies that these cooperatives, whose membership includes all the relevant stakeholders, are best placed to devise a fair and sustainable solution for a number of reasons. First the local knowledge of the stakeholders will always exceed that of a management system devised externally. Second, by placing the responsibility for the monitoring and enforcement of the resource on the local users, additional management costs are avoided.

However, it has been found that these institutions require a great deal of trust and cooperation between stakeholders, along with sufficient time for the systems to be optimised and become fair for all stakeholders [44].

Ostrom defined successful institutions as "institutions that enable individuals to achieve productive outcomes in situations where temptations to free-ride and shirk are ever present." She found that these successful institutions exhibited eight design principles.

1. Clearly defined boundaries - The community must arrive at some common consensus as the extent of the resource and who is allowed to use it. It follows that without restrictions on the use of the resource from outsiders, the benefits of restraint by local users will be eroded. This principle calls for the inclusion of all the potential users and associated stakeholders to be involved in the CPR institution.

2. Rules adapted to local conditions - A generic set of rules is impossible to establish, even for broadly similar common-pool resource systems, and therefore the rules must be tailored for each specific situation. The mechanism used to coordinate the appropriation must be flexible enough to enable tailored rules for the specifics of the resource, its users and local conditions.

3. Collective-choice arrangements - In order to ensure endorsement of the rules, the majority of stakeholders affected by the resource must have the capability to be involved in discussions over the rules on resource use. The individuals that interact directly with each other and the resource must be able to modify the rules over time.

4. Effective monitoring - Ostrom found that reputation and shared norms are insufficient to avoid the need for monitoring. Therefore monitoring is essential to ensure compliance with the rules. In addition, Ostrom argued that in order for this monitoring to be effective, monitors must be accountable to the rest of the group.

5. Graduated sanctions for resource appropriators - Closely linked to monitoring is the necessity for graduated sanctions for rule violation. In the most robust institutions studied, Ostrom found the monitoring and sanctioning to be undertaken by other users of the resource, despite the additional time and effort required to self-monitor.

6. Mechanism for conflict resolution - Conflict is to be expected where demand is great for a scarce resource, and therefore an avenue for efficient conflict resolution is essential. Where the resources are very scarce, Ostrom found that well-developed court mechanisms had been developed.

7. Self-determination of the community - External involvement can undermine the design and management of a CPR institution. Ostrom found that appropriators frequently devised their own rules without creating formal governmental jurisdictions for the purpose. Indeed provided the government gave some legitimacy to the self-devised rules, Ostrom found the appropriators would enforce the rules themselves.

8. Multiple layers of nested enterprises - Few systems are self-contained, unaffected by external factors. Small systems are often part of larger more complex systems, and therefore successful CPR institutions recognise their relative position and are able to interact with the larger system.

The most enduring CPRs exhibited these multi-layered nested enterprises, to help different sets of actors with specific local problems, to coordinate rules over a much larger complex system.

4. Roadmapping Case Study

As a result of the industry's ability to continuously deliver new technological innovations, the semiconductor industry is a global success story. The rate of innovation has sustained Moore's law – the estimation made in 1965 that computing power would continue to double every two years. Some attribute the industry's success to the cooperative nature of the semiconductor community[45] between industry, academia, research consortia, regulators and government laboratories [46]. However the cooperative nature wasn't always the case:

"[The semiconductor industry has] come a long way from the mid-1980s when the word 'confrontation' was used to accurately describe the international relationship on semiconductors. Today, the word 'cooperation' accurately describes our relationships. [45]*"*

The shift towards cooperation can be attributed to the successful implementation of industry-level roadmapping. The creation of a sector level roadmap for the semiconductor industry started in 1992. Initially confined to just to US based firms, after six years the roadmap had become an international activity, which was reflected in the name change to the International Technology Roadmap for Semiconductors (ITRS). [46]

The ITRS is *"a collaborative effort within the semiconductor industry to confront the challenges implicit in Moore's law. The roadmap's goal is to present an industry-wide consensus on the "best current estimate" of its R&D needs out to a 15-year horizon. As such, the ITRS provides a guide to the efforts of companies, research organizations, and governments to improve the quality of R&D investment decisions made at all levels. The 2001 Roadmap is notable because it was developed with truly international representation"* [47]

In essence, the ITRS became an industry-level instrument to serve the common interest of all international members.

The roadmap is a good example of the 'theory of organized innovation' which is made possible by roadmapping [45].

The roadmap is one of the building blocks to a comprehensive process that distinguishes the collaborative, yet competitive nature of this industry [45].

The ITRS provides a reference document of technology requirements, potential solutions, and their timing. It is a collaborative planning process that involves all parts of the semiconductor value chain [45].

5. Roadmapping facilitates cooperative institutions

The ITRS case study illustrates how roadmapping has the potential to create a cooperative institution which shares similarities to the institutions studied by Ostrom. The following section discusses four links between the principles proposed by Kerr *et al.* and those of Ostrom's, while Table 1 summarises how these are reflected within the ITRS.

Roadmapping creates social infrastructure. The process serves as a mechanism to bring actors together in a workshop and shape their decision and coordinate their actions to achieve a communally agreed vision of the future [24,31]. As an inherently social process, the mechanism for bringing together the relevant stakeholders into one physical space builds social cohesion between stakeholders which forms the basis for many of the resulting success criteria of the institutions.

Roadmapping is self-managed by industry. The roadmapping approach is designed to ensure minimum facilitation and external involvement. While government involvement and funding is typically required as a catalyst, the process and roadmap are created cooperatively by the participants.

Roadmaps can be nested within hierarchies. Given the common layered structure of roadmaps, families of roadmaps can be created at different scales. In the same that product level roadmaps can be drawn together into a business or sectoral level roadmap, roadmaps could be used to manage not only resource use at the river tributary level, but also at the river basin level by aggregating the roadmaps. In such a way, multiple layers of nested enterprises can be communally managed without losing sight of the bigger picture.

Roadmaps are visual and periodically updated. Roadmaps are a visual tool, synthesising the workshop activities into a single page format. The visual output presents an overview of the current state of play. As the roadmap is periodically updated, there exists the opportunity to expose any failure to maintain the resource or specific breaches of the rules, and illustrate the impacts of this non-conformity. Performance measures are typically built into roadmaps for this purpose, using balanced scorecard techniques to ensure appropriate monitoring.

Roadmapping has not been previously linked with the imposition of sanctions, however it is not unfeasible that by illustrating non-conformity, roadmapping could be used to facilitate the communication of why sanctions are imposed.

Table 1. CPR design principles enabled by roadmapping principles, illustrated by example case study

CPR institution success principles • ***enabled by* roadmapping**	**Illustrated from ITRS case study**
Clearly defined boundaries • Human-centric • Workshop based • Neutrally facilitated	As the semiconductor industry grew internationally from its origins in the US, the stakeholders involved in parallel. The ITRS states that all major global semiconductor firms and their supply chain now participate.
Rules adapted to local conditions • Human-centric • Workshop based • Scalable	The transition from the US focused SIA to the international ITRS adapted to the shifting requirement to include international manufacturers in the supply chain [45]. *"The ITRS has changed to reflect the changing needs of the community it serves"*
Collective choice arrangements • Lightly processed	With a membership of very 1000 members worldwide, the ITRS has a formal governance structure that establishes policy and provides guidance and oversight.
Effective monitoring • Visual	Future challenges are colour coded to signify their threat to the overall objective. The most challenging are red, which led to the concept of the 'red brick wall'.
Graduated Sanctions • Visual	*No mention of sanctions for members*
Conflict resolution • Human-centric • Workshop based • Neutrally facilitated	*No mention of conflict resolution*
Self determination of the community • Neutrally facilitated • Lightly processed	Initial US Government funding and involvement was phased out between 1994-7 as the roadmap became international and self-sustaining. [45]
Multiple layers of nested enterprises • Modular • Scalable	The overall ITRS provides top-down guidance for individual working groups addressing specific challenges, all coordinated by a central committee [45]. Schaller also found the ITRS roadmap fostered linked roadmapping activities from firms in the supply chain to address challenges identified in the top level ITRS.

6. Conclusion

In a resource constrained world, the sustainable management of resources to guarantee future means of production is essential for manufacturing firms looking to remain economically viable. Competing firms in an industry often rely on common resources, and to prevent over-exploitation have traditionally accepted some form of government regulation, resource privatisation or collective management.

Globalisation has led to the extension of manufacturing supply chains, and as a result has reduced firms awareness and accountability for the over-exploitation of resources. In certain circumstances, in order to manage resources sustainably resource use must be coordinated in a similar fashion to common-pool resource (CPR) institutions. This paper, by examining the principles of successful CPR institutions alongside roadmapping properties, has demonstrated that roadmapping has the potential to facilitate institutions to successfully self-manage common resources.

The case study of the International Technology Roadmap for Semiconductors (ITRS) is presented as preliminary evidence of this potential, but the thesis would be strengthened by examining further case studies. Future research is required to understand how the roadmapping process and structure could best be adapted to unlock the potential for roadmapping to raise awareness and coordinate action to address over-exploitation of common resources at both the industry and firm level.

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