

Backcasting-Based Method for Designing Roadmaps to Achieve a Sustainable Future

Yuki Okada¹, Yusuke Kishita¹, Yutaka Nomaguchi, Tomoaki Yano, and Koichi Ohtomi

Abstract—Much attention has been paid internationally to the adoption of sustainable development goals to achieve sustainable outcomes. Although roadmapping is widely used by companies and other organizations to plan long-term strategies, relatively few studies have examined the development of roadmapping methods aiming at sustainability. To address this challenge, in this article, a backcasting-based method to design roadmaps that could be used to facilitate decision making and plan sustainable futures is proposed. By drawing on the concept of backcasting, the proposed roadmap design method consists of two phases: defining a sustainable vision, and describing the pathways that are required to realize that vision. In order to develop pathways that bridge the gap between the present and the vision, we develop a roadmap template called a “four-arrow model.” To demonstrate the proposed method, roadmaps are developed for Japanese manufacturing from the present to 2050 by organizing an expert workshop. As a result, two different roadmaps that connected sustainable visions and associated pathways are successfully developed. The number of ideas generated through the workshop indicates that the proposed method encouraged brainstorming and concept development. Future research will focus on making the roadmap design process more comprehensive by conducting industrial case studies.

Index Terms—Backcasting, decision making, roadmap design, sustainable vision, system analysis and design.

I. INTRODUCTION

SUSTAINABLE development goals (SDGs) were adopted by the United Nations General Assembly in 2015 to encourage companies and other organizations to implement long-term planning strategies and policies by incorporating the concept of SDGs [1]. The original definition of sustainable development is to meet the needs of present generations while maintaining the ability to meet the needs of future generations [2]. When

compared with conventional company goals, SDGs typically contain longer term and more diverse goals (e.g., climate action, human well-being, economic growth, and responsible consumption and production). Consequently, for companies to develop goals and strategies that will bring about innovation and promote sustainability is a challenging task. Roadmapping is a promising approach for achieving such goals and the concept has been widely used for strategic planning and technology management, primarily because it enables organizations to graphically represent the pathways that are required to achieve goals in a temporal context [3]–[6]. Structured as a timeline with multiple layers, a roadmap has a graph structure that depicts a variety of possible events, such as actions, and linkages between events, either horizontally within a layer or vertically across layers [3]. In practice, workshops are commonly used to develop roadmaps by facilitating knowledge exchange through brainstorming sessions involving experts and stakeholders [3].

Numerous studies have been conducted on developing roadmapping procedures that support an organization’s vision and culture [3]. However, few methodological contributions have attempted to combine roadmapping and sustainability, although examples of such approaches are increasing (e.g., [7], [8]). When attempting to clarify how roadmaps can be designed toward achieving sustainable futures, we consider that there are at least three challenges that need to be addressed as follows:

- 1) The procedure required for designing a roadmap to achieve sustainability (or sustainability roadmap) has not yet been formalized.
- 2) Limited research has been conducted on the analysis and evaluation of developed roadmaps.
- 3) Relatively few case studies have been undertaken in the manufacturing domain, even though manufacturing sectors exert a significant influence on environmental sustainability.

To resolve these challenges, this article proposes a method for designing roadmaps for sustainable futures using a backcasting approach. To formalize the procedure, we define the concept of *roadmap design* as a series of iterative processes involving development, analysis, evaluation, and revision, through which the scope and details of the roadmap increase with each iteration [9]–[11]. Based on this concept, we develop a four-step procedure for designing roadmaps that employs workshops and postworkshop processes. Since sustainability goals, including SDGs, cover a wide variety of issues (e.g., politics, economy, society, and environment), we start with decomposing sustainable goals and then reconstructing the vision to be realized. Generally, backcasting is

Manuscript received August 6, 2019; revised May 21, 2020 and June 11, 2020; accepted July 7, 2020. The work of Yusuke Kishita was supported in part by a Grant-in-Aid for Young Scientists under Grant 18K18233 and a Scientific Research B under Grant 19KT0008, awarded by the Japan Society for the Promotion of Science. Review of this manuscript was arranged by Department Editor R. Phaal. (Corresponding author: Yusuke Kishita.)

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Digital Object Identifier 10.1109/TEM.2020.3008444

used in scenario creation for delineating future visions and then drawing pathways backwards from those visions to the present [12]–[14]. To examine the advantages and limitations of the proposed method and to clarify the requirements for supporting the analysis, evaluation, and revision of the designed roadmaps, we collaborated with the Technology Roadmap Committee of the Japan Society of Mechanical Engineers (JSME) to conduct a case study of sustainability in the manufacturing sector of Japan from the present to 2050. In addition, we conducted a questionnaire survey after a workshop to analyze participants' perceptions and evaluate the efficacy of roadmap design.

In the next section, we clarify the research challenges associated with roadmap design for sustainable futures by reviewing literature. In Section III, we describe our approach and define the procedure. In Section IV, we present the results of a case study, and in Section V, we discuss the effectiveness of the proposed method. Finally, Section VI concludes this article.

II. ROADMAPMING AND SUSTAINABILITY

In this section, existing roadmapping methods and practices are described based on a literature review, and the challenges associated with roadmap design for sustainable futures are presented.

A. Literature Review

In previous studies, roadmaps have typically been used to identify promising technologies and to gain a competitive advantage by connecting market needs, business strategies, product development, and technological development [15], [16]. The first company to develop a roadmap to anticipate changes in the market and in technology, resolves customer problems, and improves productivity was Motorola, in 1970 [17], [18]. The International Technology Roadmap for Semiconductors [19], which is one of the most well-known roadmaps in global use, was published annually from 1998 to 2016 by a group of semiconductor industry experts. The roadmap incorporated quantitative technical specifications for the next 15 years based on Moore's Law. In Japan, the most famous roadmap is called strategic technology roadmaps, which were published by the Ministry of Economy, Trade and Industry, Japan to identify technological trends and set annual target for each technology area [20]. As such, most of existing roadmaps are based on forecasting approaches, which are effective for setting realistic and short-term goals based on analyses of past and present performance.

In the context of sustainability, the World Business Council for Sustainable Development published an SDG sector roadmap to facilitate the adoption of SDGs by companies, and to help them identify important challenges, develop effective solutions, and set specific goals and key performance indicators (KPIs) for each sector [8]. The REMADE Institute employed roadmapping to define priorities and identify technical and economic challenges and associated knowledge gaps, and to reduce embodied energy and carbon emissions associated with industrial-scale manufacturing [9].

From a methodological point of view, roadmapping initiatives commonly employ workshops that bring people from different

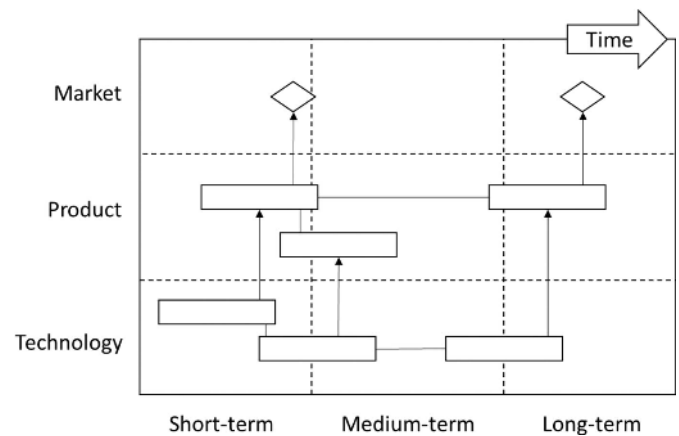


Fig. 1. Schematic technology roadmap (adapted from [4]).

parts of an organization together so that they can discuss external entities such as markets, suppliers, business partners, and competitors [4]. The most important benefit of roadmapping is considered to be the discussions and exchanges that take place when generating and sharing knowledge at these workshops [8]. At the same time, however, the content of roadmaps depends on the knowledge and experience of the workshop participants and facilitators, as well as the available data [21].

Since roadmapping is a flexible technique [4], much research has focused on developing a roadmapping process that fits specific objectives (e.g., [22], [23]). For example, T-Plan [4] aims to support product planning by proposing a standard procedure for rapid initiation of roadmapping in an organization. In this method, while the number of layers is flexible and varies according to the objective of the project, a roadmap often comprises three layers (i.e., a market layer, a product layer, and a technology layer) as shown in Fig. 1. There are two approaches involved that need to be considered in the planning of product development: market pull and technology push [4]. Market pull aims to define a product based on a customer's needs, whereas technology push seeks to identify innovative technologies that are not yet in demand in the market.

In addition, previous studies have attempted to integrate supporting tools into the roadmapping procedure to ensure the quality of knowledge employed in the development of the resulting roadmaps. Since predicting future events, such as market trends and emerging technologies, are complicated by limited data availability [24], existing tools in the field of foresight research (e.g., Delphi and scenario planning [25]) are often used to support roadmapping.

B. Problem Statement

To transform current society from being unsustainable to sustainable, long-term and drastic changes are required [12]. Since sustainable future visions are inherently normative and stakeholders have different sets of values and views, a participatory approach engaging stakeholders is often used [26]. Workshop-based roadmapping is a useful approach for identifying future challenges and developing solutions for realizing a

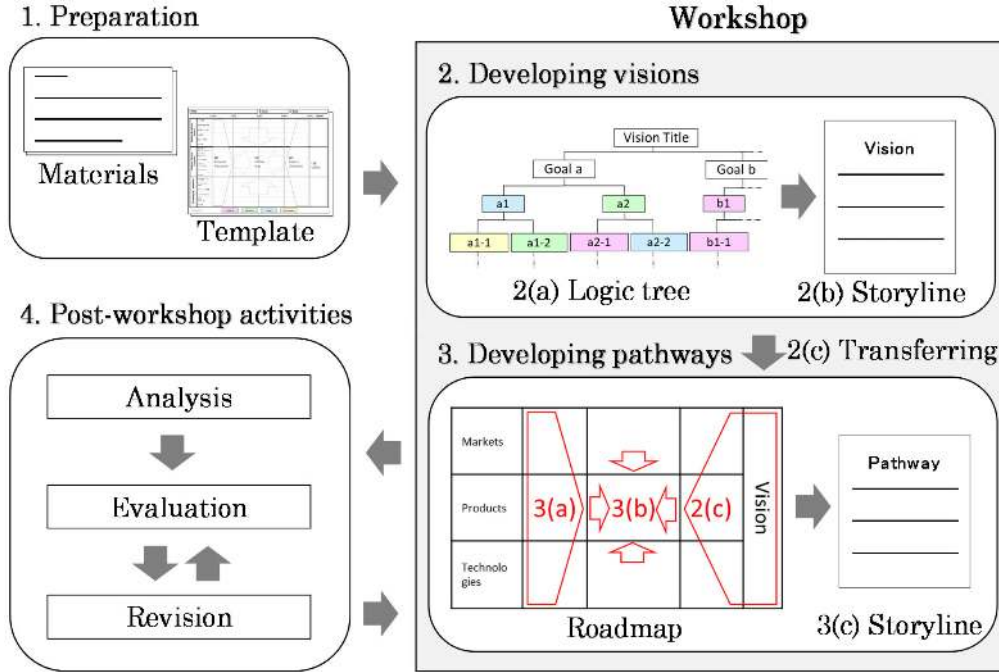


Fig. 2. Overview of the proposed method.

sustainable vision over a specified time. On the other hand, there are three challenges in applying roadmaps to clarify sustainable futures as follows:

- 1) Although much research has been conducted on connecting market and technology layers (see Fig. 1), the procedure has not yet been formalized to design a vision and identify pathways through iterative processes of development, analysis, evaluation, and revision of the roadmap during and after a workshop [27].
- 2) Limited research has been conducted on the evaluation and analysis of roadmap design [28]. Consequently, the requirements for supporting effective roadmap design have not been clarified.
- 3) Fewer case studies have been executed in the domain of manufacturing [29], even though manufacturing sectors have a significant influence on sustainability on a global scale.

III. BACKCASTING-ORIENTED ROADMAP DESIGN FOR SUSTAINABILITY

A. Approach

To address the first challenge mentioned in Section II-B, we propose the procedure for roadmap design as shown in Fig. 2. The entire process of roadmap design is comprised of four steps, i.e., preparation, developing visions, developing pathways, and postworkshop activities. Assuming that there are two types of actors (i.e., roadmap designer and workshop participant), Steps 1 and 4 are undertaken by roadmap designers, while Steps 2 and 3 are performed by participants in workshops. These steps should be iterative until the roadmap becomes sufficiently detailed. Related to the second and third challenges, we conducted a

case study of Japanese manufacturing to evaluate the workshop results and the efficacy of the proposed method to support roadmap design.

In the workshop phase (i.e., Steps 2 and 3 in Fig. 2), we integrate the concept of backcasting into the roadmap design process to clarify sustainable futures. In Step 2, we use logic trees to support idea generation for a sustainable vision. In literature on backcasting-oriented scenario design, describing a logic tree has been demonstrated to be effective for generating ideas backwards from visions by visualizing the hierarchical structure of visions based on the causal relationship between ideas [30]. A storyline is developed to clarify the relationship between important ideas selected from the logic tree. In Step 3, we develop a “four-arrow” template (see Fig. 2) to bridge two types of gap, i.e., the gap between the market and technology (vertical gap) and the gap between the vision and the present (horizontal gap). This corresponds to combining market pull vs. technology push approaches [4] and forecasting vs. backcasting approaches, respectively. A storyline can then be developed in narrative format by selecting important pathways to realize the vision.

B. Roadmap Design Process

Details of the four steps for roadmap design are described as follows.

1) *Preparation*: The roadmap designers clarify the objective of roadmap design (e.g., designing business model for sustainable mobility) and define boundaries (e.g., in a Japanese community, in 2030). In order to design a roadmap, the roadmap designers recruit participants and divide them into smaller groups (e.g.,

4–6 people per group) if necessary, before preparing materials and templates (e.g., logic tree, roadmap, and storyline).

2) *Developing Sustainable Visions*: To develop a sustainable vision, Step 2 is divided into three substeps: describing a logic tree [2(a)], describing a storyline [2(b)], and transferring the ideas to a roadmap [2(c)].

Step 2(a): Describing a logic tree

Participants engage in brainstorming ideas about sustainable futures through discussions and reviewing materials. Using a logic tree, participants then arrange these ideas into a hierarchical structure based on causal relationships. The relationship(s) between ideas is then represented as a linkage. When developing a logic tree, we employ PEST (political, economic, social, and technological) analysis [31] to cover a wide range of relevant ideas.

Step 2(b): Developing a storyline

The participants then select those clusters of ideas on the logic tree that are key concepts of the vision, and describe the vision in a narrative form by constructing sentences based on the structure of the logic tree.

Step 2(c): Transferring ideas to a roadmap

The participants transfer the ideas from the logic tree to a roadmap taking care to maintain the linkage between ideas; goals are transferred into a “Vision” column and associated means are transferred into a “Future situation” column of the roadmap (on the right-hand side of the “four-arrow” template).

3) *Developing Pathways*: Using the “four-arrow” template and PEST analysis [31], Step 3 consists of three substeps as follows.

Step 3(a): Describing present situations

Based on materials and the knowledge of the experts at the workshop, the participants describe the present situation and near-future scenarios in a “present situation” column (area 3 of roadmap in Fig. 2).

Step 3(b): Connecting the vision and present situations

Based on the results of steps 2(c) and 3(a), the participants extract the problems that need to be addressed and generate ideas related to potential solutions (e.g., market opportunities, innovations in business model, and emerging technologies) to connect the “future situation” and the “present situation” into the center of the roadmap to produce the “four-arrow” format of the roadmap template (area 4 of roadmap in Fig. 2).

Step 3(c): Developing a storyline

The participants then select important pathways that are crucial to realizing the vision and explain them in narrative form.

4) *Postworkshop Activities*: Considering time limitations, examining all of the possible linkages that exist between ideas during a workshop is difficult. In order to maximize the utility of the workshop for developing a strategy, roadmap designers need to extract key messages (e.g., policy recommendations and technological/social challenges to be addressed) from roadmaps

by analyzing and understanding the results of the workshop, and also to add ideas and linkages. To revise roadmaps, roadmap designers can then evaluate the content of roadmaps and discuss what to do next (e.g., information gathering, obtaining expert opinions, and conducting subsequent workshops).

IV. CASE STUDY OF ROADMAP DESIGN USING SUSTAINABLE MANUFACTURING IN JAPAN

To investigate the effectiveness of the proposed method, we conducted a roadmap design workshop in December 2018 in collaboration with the Technology Roadmap Committee of JSME [32]. The goal was to use a workshop format to identify which technologies should be developed and how to achieve a sustainable manufacturing sector in Japan from the present to 2050. It was assumed that the outcomes would be used in policy-making decisions within the JSME. The JSME is one of the largest academic communities in Japan, accommodating approximately 35 000 members and consisting of 22 divisions in a wide range of technological fields, such as material mechanics, robotics and mechatronics, design engineering and systems, and transportation and logistics. The Technology Roadmap Committee is comprised of representatives from each division.

A. Preparation

The definition used for manufacturing employed in this article is extensive, and includes the development and provision of both products and services. Further, it was expected that the developed roadmaps could potentially be applied to the development of a platform for sector-specific roadmaps in the future.

In December 2017, the roadmap committee conducted a preliminary workshop to test the proposed method and prototyped a roadmap. Through the outcome of this workshop, two sustainable visions were prototyped successfully, but the pathways required to realize these visions were not well addressed. Therefore, the results of a previous workshop were used as a reference for developing the visions in the workshop described in this article.

The roadmap design team planned a two-day workshop, in 2018, allocating time for participants to focus on developing visions on the first day and then to develop pathways on the second day (see Appendix A for details). As materials to support the brainstorming activities described in Step 2(a), a list of SDGs and a summary (i.e., lists of generated ideas) of the previous workshop were prepared. We customized the “four-arrow” template (Fig. 2) to produce a roadmap that incorporated into the product layer of the five key industrial areas (i.e., autonomous driving and mobility services, manufacturing and robotics, biotechnology and materials, plant and infrastructure maintenance, and smart home and lifestyles) that are highlighted by “Connected Industries” [33]. The templates for the logic tree and storyline were also prepared. The workshop participants were recruited from the members of the committee and 14 people (i.e., 10 from academia and 4 from industry) participated in the workshop. While most of the participants were engineers and not familiar with roadmapping, they had extensive knowledge of how technology can be applied to sustainability. The participants

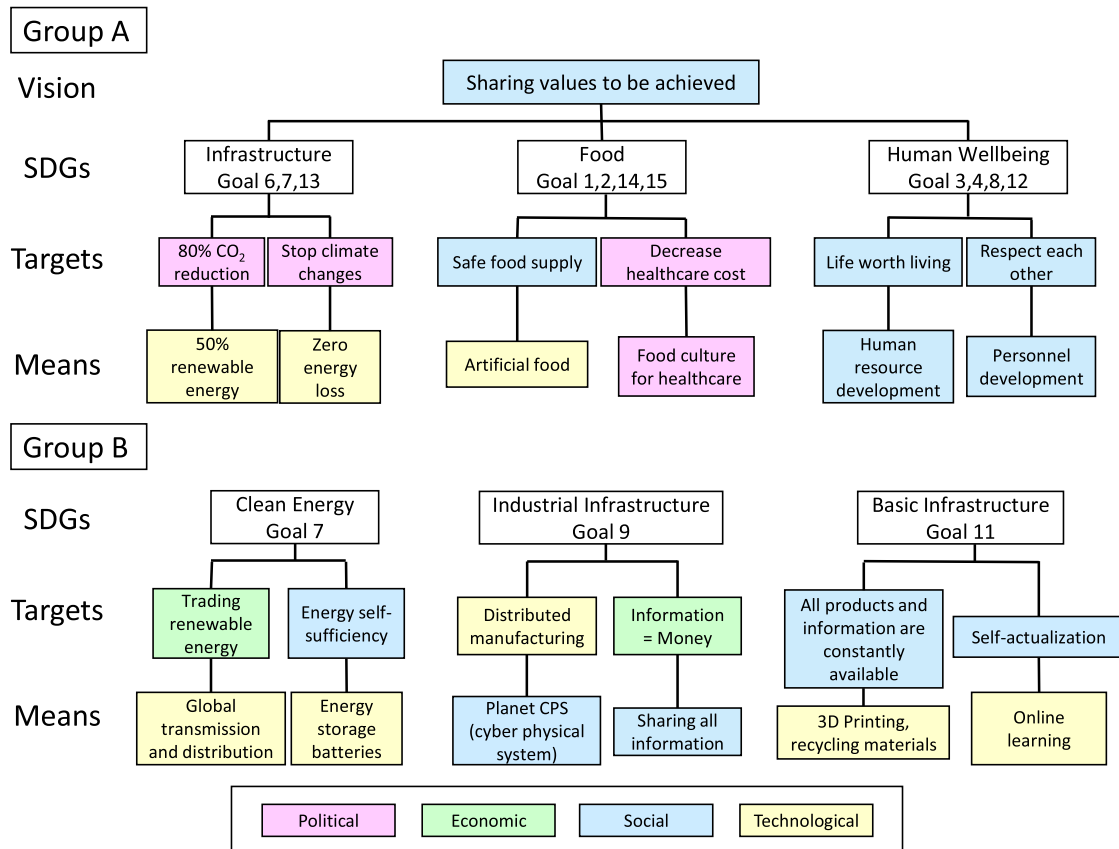


Fig. 3. Results of logic tree (not exhaustive).

were divided into two groups (A and B) to ensure that the gender ratio and the proportion of representatives from academia and industry were similar in both groups.

B. Developing Visions

In Step 2 in Fig. 2, Groups A and B developed their visions. The contents of the two logic trees are summarized in Fig. 3.

Step 2(a): Describing a logic tree

The participants selected some of the goals of the SDGs and keywords from the outcomes of the previous workshop, and discussed the topics to generate and share ideas about the future desired by 2050. A total of 57 ideas were generated by Group A and 84 ideas were generated by Group B. Group A selected 11 goals out of the SDGs and grouped them into three themes (i.e., infrastructure, food, and human well-being). Apart from the results of the previous workshop, they developed a vision in which “sharing value to be achieved” was defined as the main overarching goal of the three groups of SDGs. Group B, which examined the vision developed at the previous workshop, selected three goals of SDGs and discussed the development of a cyber-physical network for self-actualization of individuals within the context of a life and industrial infrastructure in a society with low CO₂ emissions.

Step 2(b): Developing a storyline

The participants defined the title of their visions and explained their visions in narrative form using important ideas extracted from the logic tree. Group A defined the title of their vision as “Sharing the joy of being a member of a global society,” which contrasted with some of the characteristics of the current society which is characterized by fierce competition among influential companies for information and a focus on promoting consumption. Group B defined the title of their vision as “Connected Planets,” which is an information-driven infrastructure connecting multiple planets and examines the realization of self-actualization. The key idea was that a cyber-physical network is used to develop both basic infrastructure, which enables more flexible lifestyles and workstyles for self-actualization, and industrial infrastructure, which enables a global and efficient electricity transmission and distribution network to achieve a 100% renewable society.

Step 2(c): Transferring ideas to a roadmap

The participants transferred their ideas into the “Vision” and “Future situation” components of the roadmap template (see Fig. 3).

C. Developing Pathways

By following Step 3 in Fig. 2, Groups A and B developed pathways to realize the visions.

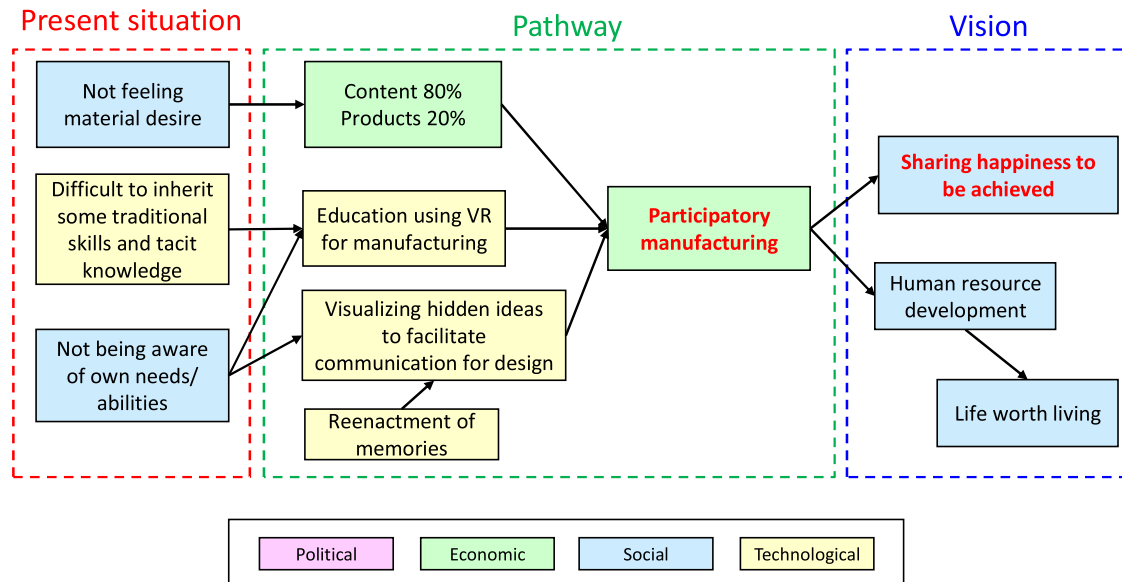


Fig. 4. Described pathways for Group A (not exhaustive).

Step 3(a): Describing present situations

The participants then examined the present situation and near-future scenarios from the viewpoint of drivers and inhibitors by brainstorming. Focusing on drivers, Group A considered utilizing virtual reality (VR) technology as a communication medium for sharing values. Group B focused on emerging products/services to discover the potential desires of individuals using the Internet of Things, like smart mirrors. As for inhibitors, Group A described the passive attitudes of the present generation as, among others, “not having any material desires” and “not being aware of one’s own ability.” Group B discussed the challenges associated with realizing their vision from social and technological perspectives. From a social perspective, the typical modern workstyle prevents us from realizing self-actualization. From a technological perspective, the current energy supply system in Japan is highly dependent on fossil-fuel-based power generation which causes significant CO₂ emissions.

Step 3(b): Connecting the vision and present situations

The participants generated ideas to connect the visions and the present. The summary of pathways is shown in Figs. 4 and 5. In total, Group A generated 161 ideas and Group B generated 122 ideas. The detailed results are summarized in Appendix B. Group A proposed a content-based business model of manufacturing for people less inclined toward material possessions. The key concept is to realize participatory manufacturing by means of, for example, a memory re-enacting service and education using VR to enable people to become aware of their potential abilities. Group B proposed the workstyle focused on the utilization of individual skills and that allows people to realize their desires by shifting from a money-based economy to an information-based economy in which value is measured through the exchange of information. In addition, Group B

also discussed the problems that need to be addressed in order to utilize renewable energy, such as improvements in efficiency and system control.

Step 3(c): Developing a storyline

The participants then described the pathways in narrative form. Group A considered that it is necessary to promote content-based participatory manufacturing, in a broad sense, in order to share values among the members of a global society. Group B proposed utilizing information technologies to get people to engage in creative activities, to utilize their individual skills, and to facilitate the efficient transmission and distribution of energy.

D. Postworkshop Activities

As part of postworkshop activities, we conducted a follow-up questionnaire and convened a core member meeting in order to evaluate the effectiveness of the proposed method and the quality of the roadmaps produced.

1) *Follow-Up Questionnaire*: We conducted a questionnaire with four questions that used a five-grade evaluation based on the Likert scale [34]. The original questionnaire and results are shown in Appendix C. Of the 14 attendees at the workshop, nine responded to the questionnaire to give a response rate of 64%. Summarizing the positive comments obtained from respondents, 100% of the respondents were satisfied with participating in the workshop because of the range of knowledge that was shared among members of industry and academia through developing the roadmaps. A total of 67% of the respondents felt that the proposed method was effective for supporting the ideas that were generated to connect the vision and the present. However, one participant commented that the logic trees and the roadmaps were not well connected. A total of 67% respondents felt that

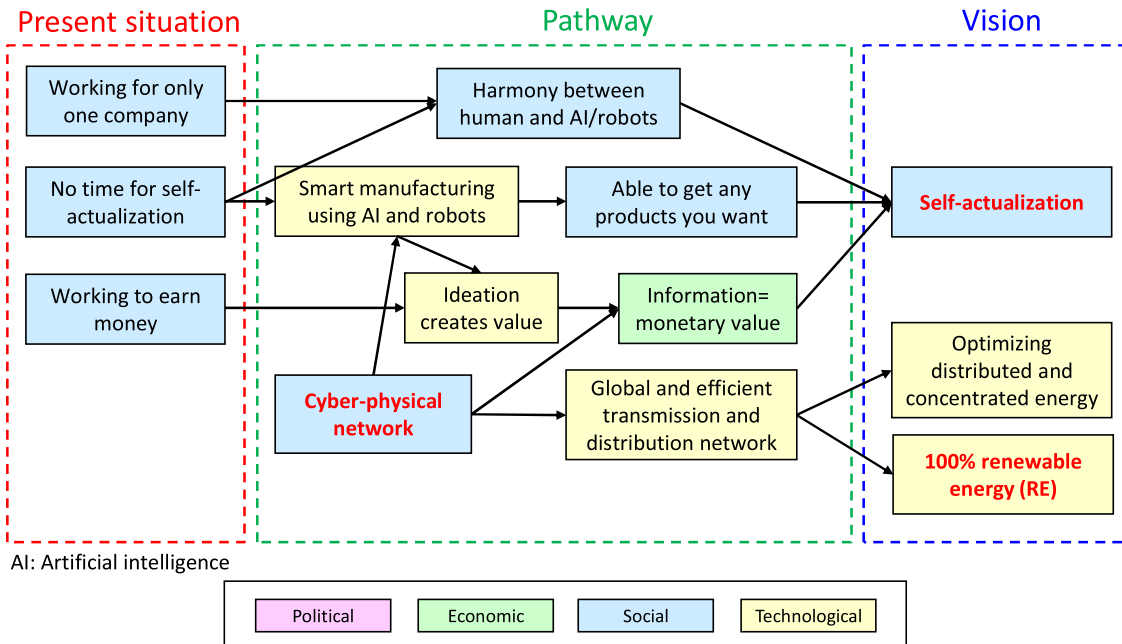


Fig. 5. Described pathways for Group B (not exhaustive).

they generally supported the direction of the proposed ideas as they were related to manufacturing. In terms of the quality of the roadmaps that were generated, most of the respondents considered them to be not sufficiently detailed and in need of further development.

2) *Evaluation and Next Steps*: The roadmap design team held a core member meeting to evaluate the workshop questionnaire results and to discuss the steps necessary to improve the content of roadmaps. Suggestions and further challenges raised by the members included the following:

- 1) Data collection and analysis are required to validate the timing of events (e.g., new market trends and emerging technologies).
- 2) While social changes were described to some extent, the connections between society and manufacturing, and manufacturing and technologies were not well-described.
- 3) It was difficult to understand the content of the roadmaps because of differences in the level of granularity of the ideas.

Possible measures to resolve these challenges included the following conditions:

- 1) Selecting important and interesting topics from the roadmaps, and then conducting workshops with people from divisions in related fields to develop more detailed roadmaps.
- 2) Adding quantitative information from experts (e.g., conducting interviews and referring to external data) in order to make the roadmaps more compelling.
- 3) Comparing the backcasting roadmaps with roadmaps that have been generated using forecasting, and then evaluating the gaps.

V. DISCUSSION

In this section, the contributions of the proposed method and the challenges for further research are discussed based on the results of the case study.

A. Methodological Contributions

The contributions of this article can be summarized in the following three points.

First, to address challenge 1) in Section II-B, we defined the roadmap design process as the development, analysis, evaluation, and revision of roadmaps, using a formalized four-step procedure to achieve a sustainable future, as shown in Fig. 2. In the case study, the processes involved in developing visions and pathways stimulated communication between participants and facilitated brainstorming; this is clear from the number of ideas generated during the workshop (i.e., 159 ideas in Group A and 122 ideas in Group B). In particular, Step 3(b) was considered effective for connecting the visions and the present where key concepts are illuminated. For example, “participatory manufacturing” was proposed as a key concept connecting the vision and the present by Group A. As a result, we confirmed that the proposed method provides the systematized process of designing roadmaps when longer term strategies and policies for sustainability are investigated. Integrating this process into actual workflows would result in more efficient roadmap design cycles in the context of strategy or policy planning.

Second, to address challenge 2) in Section II-B, we conducted a follow-up questionnaire to evaluate the roadmaps after the workshop. As seen from the questionnaire results, the workshop participants expressed satisfaction with their participation

because the roadmap design process facilitated knowledge sharing and mutual learning among the participants. This process can support value cocreation for sustainability. According to Questions 1 and 2 in Fig. 8, however, there is still some room to improve the proposed method and how the usage of the method is guided by the facilitators. Based on the results of the questionnaire and a core member meeting, we extracted the following three requirements to further support the analysis and evaluation of the generated roadmaps:

- 1) Distinguishing the granularity of ideas. In existing literature, the level of granularity is a key design parameter that needs to be considered in order to ensure that the analysis is appropriate for the target audience; typically, this is done by defining layers in advance [35]. However, in a workshop setting, the ideas that are generated by participants can span a variety of levels of granularity.
- 2) Clarifying the types of relationship that exist between ideas (e.g., causal relationship and time series). Also, identifying missing relationships that need to be added to complete the roadmap is helpful because a time constraint often prevents workshop participants from describing all necessary relationships to connect ideas.
- 3) Adding rationales for quantitative indicators such as the timing of events and KPIs (e.g., CO₂ reduction rates) to evaluate the feasibility of roadmaps.

Last, to address challenge 3) in Section II-B, we prototyped the first roadmaps for Japanese manufacturing from the present to 2050. In particular, the future direction of manufacturing was described by considering the regional characteristics of Japan. For example, not having strong material desires, which is a characteristic of many contemporary young people, was reflected in “content-based manufacturing” in Group A. The roadmaps developed through the case study would be usable as one of reference roadmaps for benchmarking. In future, it would be desirable to make these roadmaps more robust by comparing them with roadmaps developed for other countries (e.g., China [36] and Australia [37]).

B. Research Challenges and Further Research

In this article, the effectiveness of the proposed method was only tested against idea generation during the workshop. We need to develop a more detailed roadmap design procedure and conduct a case study that focuses on iterative design cycles including idea generation, analysis, evaluation, and revision. To this end, we have developed the following tentative ideas about how future tasks can be implemented in order to address the challenges associated with roadmap design:

- 1) To meet the three requirements described in Section V-A, roadmap designers need to examine the results of workshops semantically and add information to events and linkages; however, the complexity of workshop outcomes can make this difficult. One solution is to develop a computer-aided support system, in which functions for supporting roadmap design could be implemented; for example, a graphing tool to facilitate workshops, and an analysis tool to visualize the logical structure of a developed roadmap.

- 2) There are significant uncertainties in roadmaps designed for long-term goals, such as SDGs, and few studies have been conducted to evaluate the validity and feasibility of such roadmaps. One possible solution for addressing this uncertainty is to connect a roadmap and a scenario because they should complement each other; scenarios can provide detailed rationales for developing roadmaps in a narrative format. In this way, third parties could assess the process by which the roadmap was developed. Although some scholars have attempted to connect roadmaps and scenarios [38], there is considerable scope for improving the methodology employed. Moreover, integrating roadmap design and computer-aided scenario design [39] is a promising approach that we intend to examine in future research.

It should be noted that a limitation of the brainstorming-based approach is that the quality of roadmaps is highly dependent upon the knowledge and skills of the workshop participants. As seen from Tables A2 and A3 in Appendix B, the political and economic ideas generated in the roadmaps for Groups A and B accounted for relatively a small portion (8%–19%) partly because the workshop participants were mostly engineers. This suggests inviting more experts in different academic disciplines (e.g., economics, political science, and sociology) to workshops in order to collect more diversified ideas.

Furthermore, it is desirable to test the developed method at a larger scale because, in this article, the number of respondents of the follow-up questionnaire was limited (only nine respondents, see Section IV-D-1 for details) and the results might be affected by self-selection bias. Engaging real-world stakeholders (e.g., people in industry or local governments) is also helpful for gaining insights into how our method is integrated into the actual business workflow.

VI. CONCLUSION

In this article, we defined the concept of roadmap design and proposed a backcasting-oriented roadmap design method toward achieving sustainable futures. Specifically, the proposed method involved developing vision and developing pathways. By developing a pathway, participants at workshops can focus on filling the gaps between sustainable visions and the present; we developed a four-arrow template to facilitate this aim. To investigate the effectiveness of the four-arrow template against brainstorming, we conducted a case study of Japanese manufacturing in which participants used the template to generate ideas and connect their visions to the present.

The proposed method was well suited for use as a tool for thought experiments focused on developing sustainable futures. In this article, workshop participants shared their ideas that could be useful as the basis to further discuss the future direction of manufacturing in Japan. The results of the case study revealed that the method facilitated a deeper understanding of the technologies required to make Japanese manufacturing sustainable. Overall, we confirmed that the four-step roadmap design process aligned with the four-arrow template worked well to generate diversified ideas among workshop participants and

to indicate key concepts to connect a sustainable future and the present. In consequence, the proposed method can provide the codesign process involving various stakeholders to come up with strategies for sustainable innovations.

On the other hand, a methodology for analyzing and evaluating workshop outcomes needs to be developed because it is not an easy task to deal with hundreds of ideas generated during the workshops. Furthermore, it was desirable to integrate other methods and tools (e.g., quantitative simulations) into our method in order to test the feasibility of the developed roadmaps. This was part of our future work. It should also be noted that the case study presented in this article can be positioned as a preliminary experiment to demonstrate the proposed method. As described in Section IV-D-1, the developed roadmaps needed to be further detailed in order to gain deeper insights into sustainable manufacturing industry in Japan. Toward this end, we planned to develop more concrete roadmaps by organizing additional workshops in cooperation with JSME.

Future research will focus on developing such a procedure in more detail to better support the iterative design cycle of idea generation, analysis, evaluation, and revision. Another case study incorporating iterative refinement was also required. To make roadmap design more effective and efficient, integrating scenario planning and developing computer-aided support systems were considered promising areas for future research.

ACKNOWLEDGMENT

The authors would like to thank Dr. Robert Phaal (University of Cambridge, U.K.) and Prof. Yasushi Umeda (The University of Tokyo, Japan) for their valuable comments, which were helpful for developing the method.

APPENDIX

Appendix A: Schedule of the workshop.

TABLE AI
WORKSHOP STRUCTURE

Day 1 (21 December 2018)	
14:35-16:05	Session (1): Review of the previous workshop and description of a logic tree
16:20-16:50	Session (2): Description of the vision using a storyline based on the logic tree
16:50-17:50	Session (3): Copy the logic tree into the "Vision" and "Future Situation" columns of the roadmap template
17:50-18:20	Interim Presentation, Q&A
Day 2 (22 December 2018)	
9:30-9:45	Review of Day 1
9:45-10:45	Session (4): Complete the "Present situation" of the roadmap template
11:00-12:00	Session (5): Map business models and products/services that are required to connect the "Present Situation" and "Future Situation"
13:00-13:50	Session (6): Develop paths to realize such business models and products/services
13:50-14:30	Session (7): Describe the paths that connect the vision and the present using a storyline
14:30-15:00	Final Presentation, Q&A

Appendix B: Roadmaps developed during the workshop.

TABLE AII
BREAKDOWN OF THE GENERATED IDEAS IN THE ROADMAP (GROUP A)

	Political	Economic	Social	Technological	Total	Percentage
Vision	6	11	39	17	73	45%
Present situation	4	7	7	10	28	17%
Pathway	7	12	2	39	60	37%
Total	17	30	48	66	161	100%
Percentage	11%	19%	30%	41%	100%	

TABLE AIII
BREAKDOWN OF THE GENERATED IDEAS IN THE ROADMAP (GROUP B)

	Political	Economic	Social	Technological	Total	Percentage
Vision	8	5	20	38	71	58%
Present situation	2	1	3	6	12	10%
Pathway	0	6	13	20	39	32%
Total	10	12	36	64	122	100%
Percentage	8%	10%	30%	52%	100%	

Appendix C: Follow-up questionnaire after the workshop.

TABLE AIV
QUESTIONS AND CHOICES OF QUESTIONNAIRE

Q1	In the process of developing and understanding visions, how effective was the usage of logic tree based on a review of SDGs? 1: not at all effective, 2: not effective, 3: neither effective nor ineffective, 4: effective, 5: extremely effective
Q2	How effective was the series of processes in terms of supporting roadmap design using backcasting (developing visions + pathways)? 1: not at all effective, 2: not effective, 3: effective nor ineffective, 4: effective, 5: extremely effective
Q3	How was the perfection level of and satisfaction level with the outcome as the roadmap for "sustainable manufacturing in Japan in 2050"? 1: extremely low 2: low 3: neutral 4: high 5: extremely high
Q4	How satisfied were you with participating in the workshop? 1: extremely low 2: low 3: neutral 4: high 5: extremely high

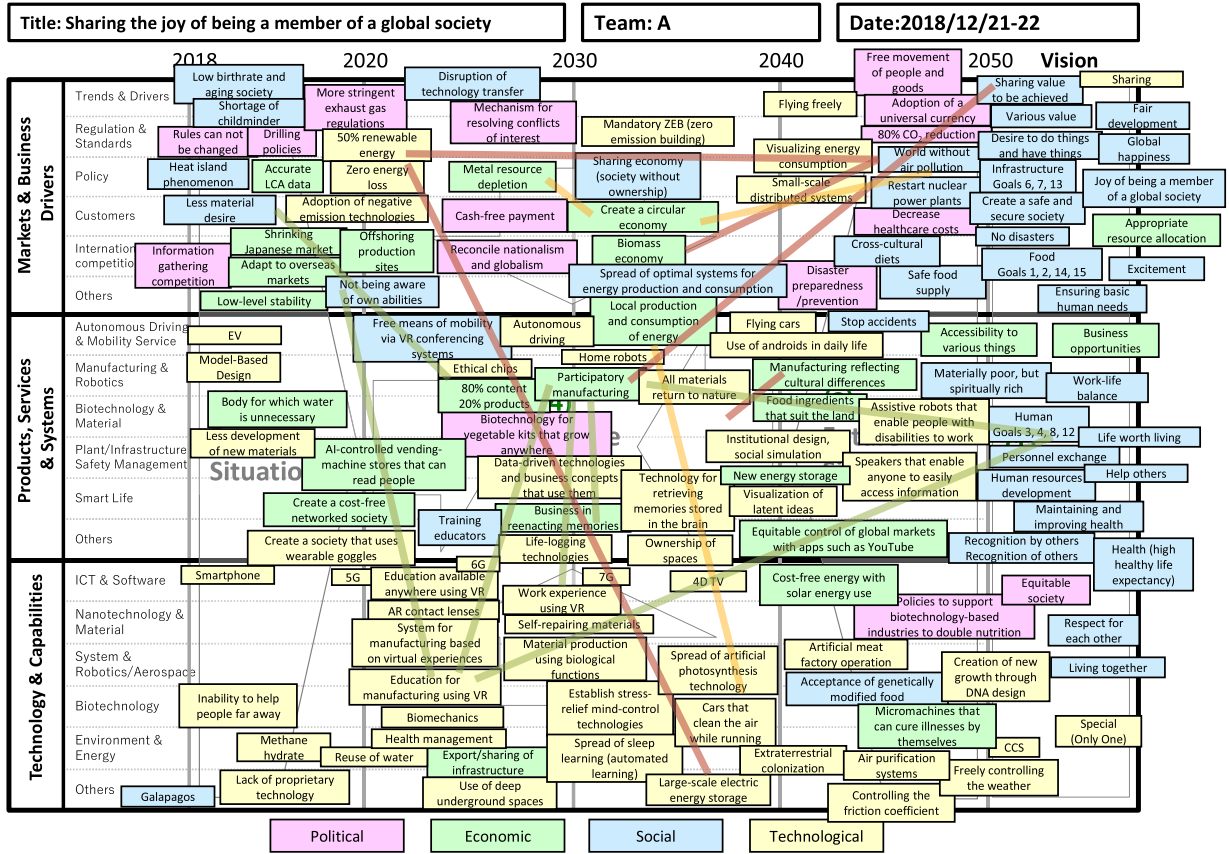


Fig. 6. Developed roadmap for Group A.

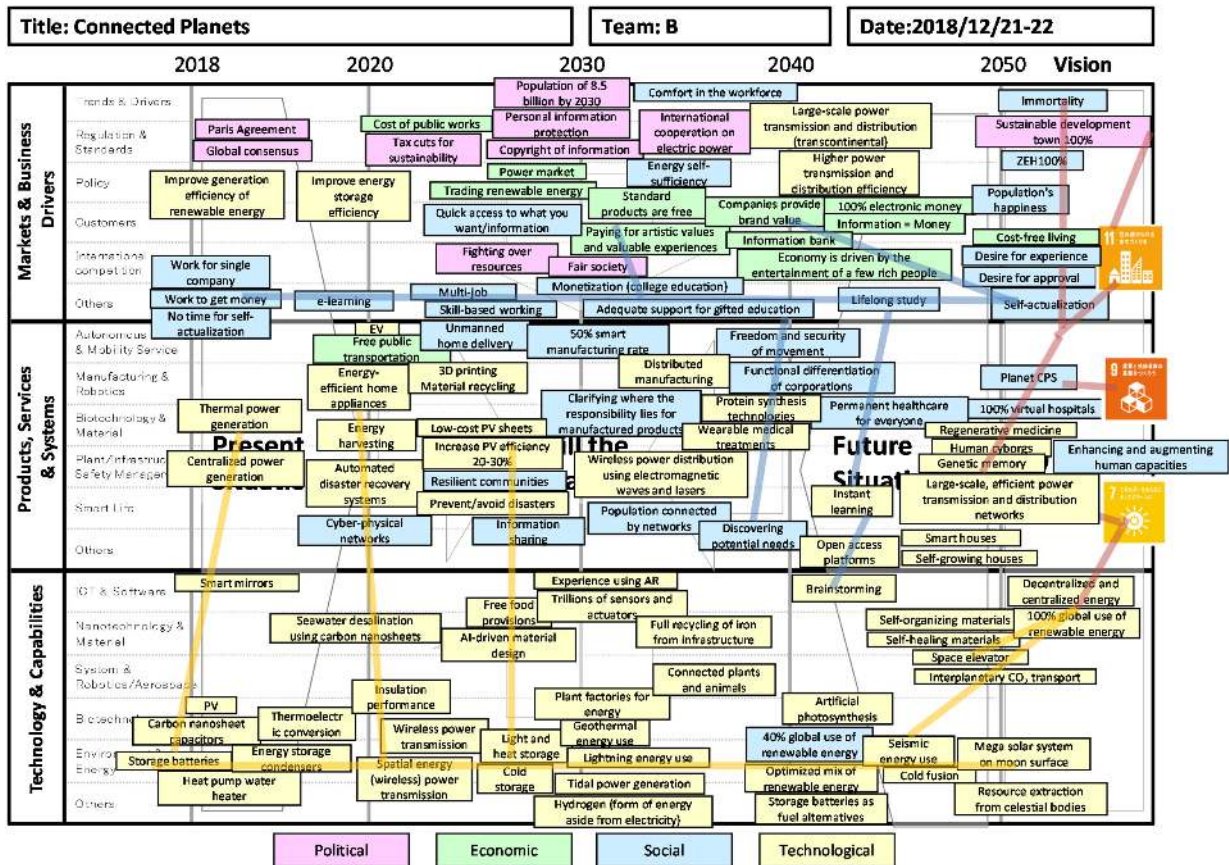


Fig. 7. Developed roadmap for Group B.

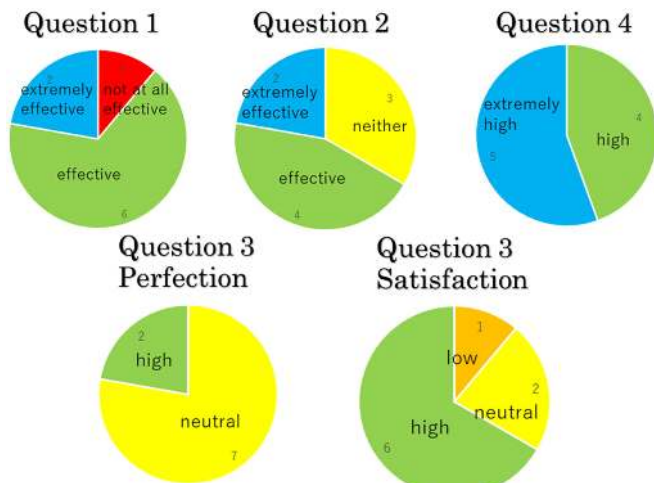


Fig. 8. Questionnaire results.

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