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An instrument for scenario-based technology roadmapping: How to assess the impacts of future changes on organisational plans☆

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ABSTRACT

Scenario-based technology roadmapping offers a strong capability for strategic planning to respond to increasingly volatile environments. However, previous studies cannot guide organisations towards making robust decisions against complex future conditions since they remain conceptual and rely solely on graphical mapping tools. To counter this, we propose a systematic approach to making scenario-based technology roadmapping more robust by adding the ability to assess the impacts of future changes on organisational plans. At the heart of the suggested approach is a Bayesian network that can examine uncertainty inherent in future changes and ripple impacts resulting from interdependence among activities. The proposed approach is designed to be executed in three discrete steps: defining a roadmap topology and causal relationships via qualitative and quantitative modelling; assessing the impacts of future changes on organisational plans via current state analysis and sensitivity analysis; and finally managing plans and activities via development of *plan assessment map* and *activity assessment map*. A case study of photovoltaic cell technology is presented to show the feasibility of our method. We believe the systematic process and quantitative outcomes the suggested approach offers can facilitate responsive technology planning in the face of future uncertainties.
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1. Introduction

The general need for scenario planning is not controversial in theory and practice as markets shift rapidly, technologies proliferate unceasingly, and thus innovation cycles become ever shorter [1]. It has been widely recognised that success depends on the ability to create and apply knowledge in ways that fit increasingly dynamic and volatile environments [2]. Even though the impacts of future changes vary considerably, organisations can have the opportunity to gain or maintain a competitive edge by managing crucial uncertainty inherent in strategic decision making [3]. In addition, many of these studies have shown that an inadequate response to future changes may lead to the decline of long-established organisations [4]. Consequently, recent years have witnessed a significant increase in attempts to devise models, methods, and tools to facilitate scenario planning.

One such attempt is to integrate scenarios into technology roadmapping so as to improve preparedness in the event of a range of futures [5]. At its most basic, multiple paths are mapped for different future conditions by extending a straight-line projection approach [6]. A wide variety of suggestions and issues have been presented so far to deepen understanding of scenario-based technology roadmapping—architectural formats and roadmapping process [6,7], interaction between scenarios and roadmapping [8], multiple path mapping [9], and scenario construction [10,11]. However, while these have proved useful for mapping multiple paths towards realisation of strategic goals or guiding organisations towards building scenarios, these

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still remain conceptual, and cannot provide a concrete way to facilitate decision making against different future conditions [12]; therefore, this method has not become fully inculcated into on-going management and faced credibility issues in practice. This is mainly due to the innate weakness of scenario-based technology roadmapping in analytical power that stems from its sole reliance on graphical mapping tools [13]. In this respect, highlighting possible avenues for methodological adaptation, some recent research has focused on combining quantitative methods and scenario-based technology roadmapping. Probably the most scientific approaches are offered by cross-impact analysis for examining probabilities of scenarios [14] and the analytical hierarchy process for investigating changes of technological value over time [15]. While these are both clear and useful, previous studies have focused only on future changes which are not ends in themselves but only a means for addressing uncertainty in the environment and improving the quality of technology roadmapping. A link is still missing in the literature as to how to translate future changes into organisational decisions and actions, thus leading to difficulties in consensus-building in planning and operational stages. Specifically, when organisations develop and adjust scenario-based technology roadmaps, or when organisations are confronted with uncertain futures, the methods cannot guide organisations towards making robust decisions.

These drawbacks necessitate the development of a systematic approach to assessing the impacts of future changes on organisational plans, so that such analyses adequately inform decision making. Key to this problem is three crucial issues that need to be addressed. First of all, high uncertainty inherent in the future means that future conditions cannot be described in single deterministic values. It has been found that deterministic methods should be limited, while probabilistic forecasts should be more widely used [16]. To this purpose, future conditions need to be modelled as random variables so as to provide a fair reflection of future changes, in line with the increasing demand for probabilistic forecasting [17]. Second, future changes have an impact not only directly on the compensable activities, but also indirectly on the interrelated activities, and consequently the strategic goals [3,8]. The complexity of the relationships is highlighted by the fact that one future change may also trigger the others. Such complex ripple impacts should be considered at the system level to improve robustness of analysis [18,19]. Finally, throughout scenario-based technology roadmapping, companies frequently ask "what-if" scenarios about future changes and their impacts on organisations [6], often constructing and managing a portfolio of strategic options. In this regard, the methods should be flexible and efficient in order to examine different potential future conditions easily and to aid a speedy investigation.

Taking these considerations into account, we propose a systematic approach to assessing the impacts of future changes on organisational plans by integrating the strengths of sensitivity analysis, for coping with the intrinsic variability of systems, into scenario-based technology roadmapping. At the heart of the proposed approach is a Bayesian network that can examine the uncertainty and dependence relationships associated with a complex process using a set of random variables [20]. The suggested approach, therefore, incorporates the issues of uncertainty and ripple impacts mentioned above. The flexibility and simplicity of Bayesian networks to conduct a sensitivity analysis also enable analysts to incorporate various scenarios regarding futures. Note that scenarios are used to consider some future states or conditions in which the institution is embedded, and used to stimulate analysts to develop and clarify practical choices, policies, and alternative actions that may be taken to deal with the consequences of the scenarios [2]. Moreover, we develop a software system to implement our method in a simpler way, thus allowing various "what-if" scenarios to be easily examined by modifying the probabilities of future conditions and their causal relationships. Given the complexities involved, the proposed approach is designed to be executed in three discrete steps: designing a roadmap topology and causal relationships via qualitative and quantitative modelling; assessing the impacts of future changes on organisational plans via current state analysis and sensitivity analysis; and finally managing plans and activities via development of *plan assessment map* and *activity assessment map*. It is expected that the systematic process and quantitative outcomes the suggested approach offers can facilitate more responsive technology planning in the face of future uncertainties.

The remainder of this paper is organised as follows. A general background of scenario-based technology roadmapping and Bayesian networks is presented in Section 2. The proposed approach is explained in Section 3, and illustrated with a case example of photovoltaic cell technology in Section 4. Finally, Section 5 offers our conclusions.

2. Background

2.1. Scenario-based technology roadmapping

A technology roadmap is defined as an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field [21]. It has been considered as a dynamic framework that enables the evolution of a complex system to be explored and mapped, supporting the innovation and strategy development and deployment [22]. Technology roadmapping, since its first development by the Motorola and Corning in the late 1970s, has gained acceptance by not only corporations such as Philips [23] and Lucent [24], but also industrial consortia and governments [25–27]. Specifically, this method facilitates technology forecasting and policy making at an industry level [28,29] while technology and business planning at a firm level [30,31].

However, technology roadmapping is forced to face serious challenges in terms of preparing for changes that are volatile and rapid since only a straight-line projection or single scenario has been taken into account [6]. The basic concept of scenario-based technology roadmapping was initiated in this context, integrating the flexibility of scenario planning together with the clarity of technology roadmapping. Specifically, scenario planning can capture the full context of decisions and enable the anticipation of a broad range of possible changes [32], while technology roadmapping can address the strategies, directions, and detailed tasks explicitly [22]. In light of these, researchers and industrial practitioners are now increasingly focusing attention on scenario-based technology roadmapping.

A wide variety of suggestions and issues have been presented so far to deepen understanding of scenario-based technology roadmapping. The following summarises the results of major studies on scenario-based technology roadmapping in terms of qualitative and quantitative approaches. Regarding qualitative approaches, List [10] proposed a network-based scenario approach to enabling the consideration of multiple views of the present and the past, while Saunders [11] suggested a visual technique to collect scenario planning information based on collage construction. Focusing more on integration of scenario planning and technology roadmapping, Strauss and Radnor [6] defined the architectural formats and roadmapping processes based on program evaluation and review technique (PERT) charts which encompass key tasks, sequence and interdependence, and critical decision points. Similarly, Lizaso and Reger [7] addressed a process of linking scenarios and technology roadmapping, which comprises preparation, analysis, and projection. Saritas and Aylen [8] suggested three ways of integrating scenarios into technology roadmapping and demonstrated the approach using a case of clean production, while Robinson and Propp [9] addressed multi-path mapping as a means of aligning emerging science and technology. While previous studies are useful for different purposes, these still remain conceptual and solely rely on graphical mapping tools, thus are incapable of offering a concrete way to facilitate decision making against different future conditions [12,13].

To this purpose, some recent research has focused on combining quantitative methods and scenario-based technology roadmapping. Pagani [14] proposed a systematic approach to scenario evaluation and analysis based on repeated cross impact handling, while Gerdsri and Kocaoglu [15] suggested an analytical hierarchy process approach to investigating changes of technological value over time. While they are both clear and useful, previous studies have focused only on analysis of future changes. A link between future changes and organisational plans is still missing, thus leading to difficulties in consensus-building in planning and operational stages. Specifically, in the process of developing and redefining scenario-based technology roadmaps or in the execution stage where organisations are confronted with uncertain futures, the methods cannot guide organisations towards making robust decisions. These provide our underlying motivation, and are fully addressed by integrating Bayesian network-based sensitivity analysis into scenario-based technology roadmapping.

2.2. Bayesian network

A Bayesian network, first proposed by Pearl [33] based on the Bayes' theorem [34], is a directed acyclic graph that examines the probabilistic relationships among a set of random variables. The notions of a Bayesian network are comprised of nodes, arcs, and probability tables. A node represents a random variable while an arc describes a dependence relationship between the pair of variables. The states of the parent nodes at the tails of the arrows affect the states of the child nodes at the heads of the arrows. Each node is associated with a probability table according to its dependence relationships with other nodes. Specifically, nodes without incoming arcs have prior probability tables which contain the probabilities of corresponding random variables taking on each of their possible values. All other nodes with parents have conditional probability tables that provide the conditional probabilities of corresponding random variables given all the possible combinations of their parents' values.

A simple Bayesian network composed of four nodes is shown in Fig. 1. In this example, each node denotes a binary random variable that takes either the value of true (T) or false (F). Node A is a parent of nodes B and C, and node D is a parent of node C. Reversely, node B is a child of node A, node C is a child of nodes A and D. The incoming arc from node A to node B denotes that the state of node A affects that of node B, and detailed relationships are presented in the conditional probability table attached to node B: how and how much the state of node A affects that of node B. Information on the dependence relationships between nodes A, C, and D can be elicited in a similar manner.

The basic procedure of conducting a Bayesian network consists of three steps [35]. Firstly, random variables are selected as nodes of the network. Secondly, the topology of the Bayesian network is constructed by connecting pairs of nodes with arcs based on the dependence relationships among corresponding random variables. Finally, the probability distribution of each node is specified in its probability table. At this step, the probability distribution can be specified in two different ways: (1) utilising prior knowledge of domain experts and (2) learning from the data. These two approaches can also be used in conjunction with each other. For example, a network structure is determined by prior knowledge, while the probability distribution is learned from the data. Once the Bayesian network is constructed, the prior and posterior probabilities can be inferred by Bayes' theorem. It is noteworthy that information on the state of the other variables is updated by calculating the posterior distributions when some variables are observed (evidence in Bayesian parlance).

The strengths of a Bayesian network are threefold. Above all, the dependence relationships can be considered in a single and compact model in both qualitative and quantitative manner. A network topology captures the qualitative aspects of the dependence relationships while probability tables examine their quantitative aspects. Second, a Bayesian network can deal with uncertain knowledge using probability information. Conditional probability and probabilistic reasoning provide a framework for quantitative analysis of the problem, reflecting the dependence relationships as well. Finally, the practicality of this model is drawn from the flexibility and simplicity of conducting a sensitivity test. The ability to infer posterior probabilities makes it possible to examine various "what-if" scenarios under uncertainty. Furthermore, this method is effectively in harmony with real world situations because it can utilise the knowledge of domain experts. Because of these strengths, Bayesian networks have been employed in a wide array of research areas including medical diagnosis [36], reliability prediction [37], risk assessment [20,38], and customer analysis [39,40].

3. Research framework

3.1. Concept

Since the industrial revolution, various processes and tools—flow-line, Gantt chart, and milestone chart—have been devised to help identify and control business functions. These were closely followed by the development of more advanced planning methods that are equipped with analytical power [41]. The

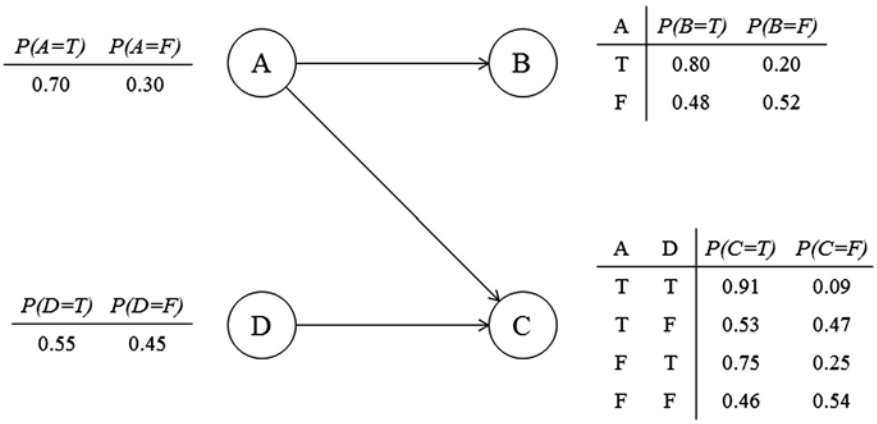

Fig. 1. Example of a Bayesian network.

suggested approach is initiated in the same vein to make scenario-based technology roadmapping more robust by adding the ability to assess the impacts of future changes on organisational plans in a systematic and quantitative manner.

The following clarifies the basic concepts of our approach in terms of data, methods, and utilities. First of all, in terms of the data issue, tuning scientific methods during the roadmapping process is crucial for practicality. Considering that technology roadmapping is mainly driven by experts in the relevant domains [42], the suggested approach is designed to be conducted based on experts' judgments given the scenario-based technology roadmap. Specifically, scenario-based technology roadmaps are employed as exploratory tools to articulate a series of activities towards predefined goals in the future [43]. Second, with regard to the method issue, we deal with the organisational plans described in the scenario-based technology roadmap as a complex process that is comprised of series of activities under uncertainty. In this context, future changes and activities are modelled as random variables to examine the uncertainty while the Bayes' theorem is adopted to measure the ripple impacts at the system level. The main advantages of the proposed approach are its systematic processes and quantitative outcomes, and thus facilitating discovery of a much stronger factual foundation. Finally, in relation to the utility issue, following the work on scenario planning [2] and scenario-based technology roadmapping [6–8], scenarios are used as a tool for considering possible future changes in this research. The proposed approach therefore helps analysts understand *what is going on* and gain sensitivity to *what if* questions. Moreover, scenario-based technology roadmapping consists of several steps that can be mainly grouped into three phases: preparation, development, and follow-up. Even though the desired shared understanding may be achieved in the preliminary and development phase, such understanding must be continually renewed to be inculcated into on-going management in the follow-up phase [44,45]. In this respect, our method focuses on implementation challenges of scenario-based technology roadmapping, and can be useful in follow-up phase, especially for such activities as validation, adjustment, and implementation of organisational plans.

3.2. Process

This section examines the overall process of the proposed approach, giving a brief explanation of each step, as shown in Fig. 2. As involvement of many tasks may lead to conceptual misunderstanding and imprecise use in practice, the suggested approach is designed to be executed in three discrete steps: designing a roadmap topology and causal relationships via qualitative and quantitative modelling; assessing the impacts of future changes on organisational plans via current state analysis and sensitivity analysis; and managing plans and activities via development of *plan assessment map* and *activity assessment map*.

3.2.1. Step 1: Designing a roadmap topology and causal relationships

3.2.1.1. Step 1-1: Qualitative modelling. This step develops the structure of roadmap topology based on the scenario-based technology roadmap. The procedure of qualitative modelling consists of two sub-parts. Firstly, future changes, activities, and targets are converted into nodes of the Bayesian network while their potential states are identified. Although scenario-based technology roadmaps vary in architectural structures, future changes, activities, and targets are crucial ingredients that have been commonly addressed in the literature. In this research, future changes focus on critical external factors, particularly ones beyond the organisation's control. Activities denote the tasks required to achieve the organisational strategic goals while targets describe the practical objectives and competitive positions. These can be defined in many different perspectives (e.g. market, technology, and product/service). Each node is a random variable whose value is shaped by the potential states of the corresponding node. Specifically, the state sets of nodes for future changes are determined by possible scenarios related to external factors. The nodes for activities and targets are shaped according to the degree of attainability of activities and targets, respectively. Secondly, nodes are connected by directed arcs based on the dependence relationships among nodes. The roadmap topology tends to have the similar direction with the scenario-based technology roadmaps since the activities are executed in a particular

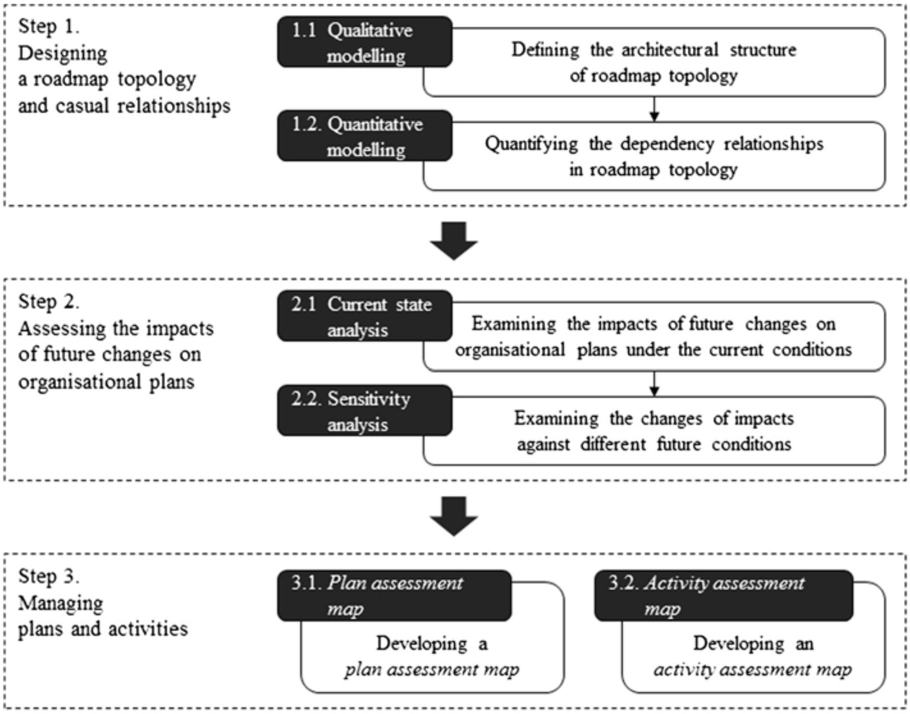

Fig. 2. Overall process of the proposed approach.

sequence. However, it differs from the scenario-based technology roadmap in that two nodes can be connected even if the corresponding nodes are not linked directly. Fig. 3 exemplifies the roadmap topology with the types of nodes and arcs employed. In terms of nodes, future changes, activities, and targets are represented by circles, rectangles, and rhombuses, respectively. As for the arcs, two different types of arcs are adopted to distinguish between direct and indirect relationships among nodes; solid arcs represent direct relationships while dotted arcs describe indirect relationships.

3.2.1.2. Step 1-2: Quantitative modelling. This step quantifies the dependence relationships among nodes by constructing probability tables based on pairwise comparisons across potential states of nodes [20]. It is similar to Saaty's analytic hierarchy process, but the details are different according to the types of nodes. The following summarises the ways of assessing the dependence relationships. Firstly, for a root node, pairwise comparisons are carried out across potential states of the node with respect to the possibility of occurrence using a scale of 1–9. For instance, the question for pairwise comparisons in this category can be: given root node N_1 and its states x_{11} and x_{12}, which state is more likely to occur and by how much. The relative priorities of the potential states are then derived from the maximum eigenvector. Secondly, when a node has a single parent node, the same procedure is performed according to the

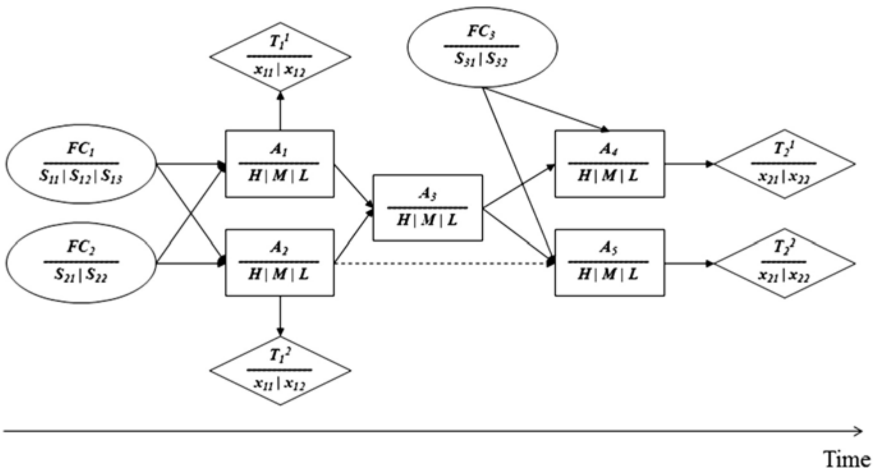

Fig. 3. Example of roadmap topology.

potential states of the parent node. As for the node N_1 with its state x_{11} and x_{12} and parent node N_2 with its state x_{21} and x_{22}, the questions are as follows: which state is more likely to occur and by how much if N_2 is in the state of x_{21}; how about N_2 is in the state of x_{22}. The conditional probability table is constructed by keeping the relative priorities together. Lastly, as for a node related to multiple parents, pairwise comparisons are conducted with respect to the potential states of each parent node. For instance, the questions for node N_1 having N_2 and N_3 as its parent nodes are as the following: which state is more likely to occur and by how much if N_2 is in the state of x_{21}; how about N_2 is in the state of x_{22}. The influences of states of N_3 are also examined in the same manner. The conditional probabilities are calculated by normalising the product of relative priorities that correspond to the combinatory states of parents.

Such a design can enhance the consistency and reduce the complexity of experts' judgments [46]. It is also noteworthy that such pairwise comparisons can consider unexpected errors [20]. The ideal way is to identify all possible future changes and incorporate them into the roadmap topology. However, unexpected errors inevitably exist due to high uncertainty associated with futures. Unexpected errors, for instance, can lead to the situation where the degree of attainability of activities or the degree of attainability of targets decreases even though no change occurs at the parent nodes. Hence, the occurrence probability of states of nodes without change at the parent node is determined by considering other unexpected errors.

3.2.2. Step 2: Assessing the impacts of future changes on organisational plans

3.2.2.1. Step 2-1: Current state analysis. This step assesses the impacts of future changes on organisational plans under the current conditions. For this purpose, the marginal probabilities of nodes ($MPN_{i,j}$)—that represent the probability of occurrence of the jth state at the ith node—are calculated based on the conditional independence assumption of the Bayesian network and the chain rule, as shown in Eq. (1). Since the calculated $MPN_{i,j}$ is based on the dependence relationships among nodes, the ripple impacts are already considered without any supplementary analysis. The unexpected errors have also been taken into account since these have been reflected in the Bayesian network through the quantitative modelling.

$$\begin{aligned}MPN_{i,j} &= P\left(N_i = x_i^j\right)\\ &= \sum_{\forall X_s \neq X_i} P\left(N_i = x_i^j, N_1 = X_1, \ldots, N_{i-1} = X_{i-1}, N_{i+1}\right.\\ &\left.= X_{i+1}, \ldots, N_{NN} = X_{NN}\right)\\ &= \sum_{\forall X_s \neq X_i}\left[\prod_{q\neq i}^{NN} P\left(N_q = X_q | N_{q+1} = X_{q+1}, \ldots, N_{NN} = X_{NN}\right)\right.\\ &\left.\times P\left(N_i = X_i^j | N_1 = X_1, \ldots, N_{i-1} = X_{i-1}, N_{i+1} = X_{i+1}, \ldots, N_{NN} = X_{NN}\right)\right]\\ &= \sum_{\forall X_s \neq X_i}\left[\prod_{q\neq i}^{NN} P\left(N_q = X_q | N_{pa,q}\right.\right.\\ &\left.= X_{pa,q} \text{ for each } N_{pa,q} \text{ which is a parent of } N_q\right)\\ &\left.\times P\left(N_i = X_i^j | N_{pa,i} = X_{pa,i} \text{ for each } N_{pa,i} \text{ which is a parent of } N_i\right)\right],\end{aligned} \tag{1}$$

where

Ni	ith node,
X_i	value of ith node, $X_i \in \left\{x_i^1, \ldots, x_i^{NS_i}\right\}$
x_i^j	jth state of ith node,
NS_i	number of states at ith *node,*
NN	number of nodes.

The state of a node that has the highest probability can be interpreted as the most plausible one under the current conditions. Taking Fig. 3 as an example, suppose that the marginal probability of x_{11} of T_1^I is 0.8. This means that the chance of x_{11} is four times higher than x_{12}. Considering this, the fitness of organisational plans (*FOP*) and the degree of attainability of activities (*DAA*) can be examined based on the marginal probabilities of nodes for targets and activities. On the one hand, *FOP* is referred to as how much the targets are achieved when a specific plan is selected, and thus is defined as the product of marginal probabilities of nodes for the relevant targets, as formulated in Eq. (2). On the other hand, *DAA* is defined as the marginal probability of nodes for activities, as formulated in Eq. (3).

$$FOP_{n,D^T} = \prod_{m=1}^{NNT} MPN_{T_m,D^T} \cdot I(T_m, P_n), \tag{2}$$

where

$$MPN_{T_m,D^T} = P\left(T_m = D^T\right),$$

$$I(T_m, P_n) = \begin{cases} 1 & \text{if } T_m \text{ is associated with } P_n, \\ 0 & \text{otherwise}, \end{cases}$$

T_m	mth node for targets
D^T	degree of attainability of targets, $D^T \in \{d_1^T, d_2^T, \ldots, d_{NDAT}^T\}$
d_r^T	rth state at nodes for targets that indicates rth category for degree of attainability of targets,
$NDAT$	number of categories for degree of attainability of targets,
P_n	nth plan,
NNT	number of nodes for targets.

$$DAA_{l,D^A} = MPN_{A_l,D^A}, \tag{3}$$

Where

$$MPN_{A_l,D^A} = P\left(A_l = D^A\right),$$

A_l	lth node for activities,
D^A	degree of attainability of activities, $D^A \in \{d_1^A, d_2^A, \ldots, d_{NDAA}^A\}$,
d_v^A	vth state at nodes for activities that indicates vth category for degree of attainability of activities,
$NDDA$	number of categories for degree of attainability of activities.

In the equations, it is found that multiple *FOP* and *DAA* can be derived according to the number of potential states of nodes for targets and activities. These indicators can be integrated into single value for investigating the overall situation (e.g. using Hurwicz principle) or indicators can be examined individually across the context of technology planning.

3.2.2.2. Step 2-2: Sensitivity analysis. This step assesses the impacts of future changes on organisational plans under conceivable future conditions. Basically, sensitivity analysis is performed by providing evidences to the Bayesian network. The whole analysis is composed of two sub-parts: sensitivity analysis of organisational plans and sensitivity analysis of activities.

On the one hand, sensitivity analysis of organisational plans examines the robustness of organisational plans against different future conditions. We develop an indicator describing the changes of fitness of organisational plans (*CFOP*) against different future conditions based on the conditional probabilities of nodes, as shown in Eq. (4).

$$CFOP_{n,D^T} = \sum_{h=1}^{NNFC} \left(\frac{\sum_{i=1}^{(NSFC_h-1)} \sum_{j=i+1}^{NSFC_h} CFOP_{n,D^T}(DFC_h(i,j))}{(NSFC_h!/2)} \right), \quad (4)$$

where

$$CFOP_{n,D^T}(DFC_h(i,j)) = \left| \prod_{m=1}^{NNT} P\left(T_m = D^T | FC_h = S_{hi}\right) \cdot I(T_m, P_n) - \prod_{m=1}^{NNT} P\left(T_m = D^T | FC_h = S_{hj}\right) \cdot I(T_m, P_n) \right|,$$

$$I(T_m, P_n) = \begin{cases} 1 & \text{if } T_m \text{ is associated with } P_n, \\ 0 & \text{otherwise,} \end{cases}$$

T_m mth node for targets,
D^T degree if attainability of targets, $D^T \in \{d_1^T, d_2^T, \ldots, d_{NDAT}^T\}$,
d_r^T tth state at nodes for targets that indicates rth category for degree of attainability of targets,
$NDAT$ number of categories for degree of attainability of targets,
FC_h hth node for future changes,
S_{hk} kth scenario for hth future change,
P_n nth plan,
NNT number of nodes for targets,
$NNFC$ number of nodes for future changes,
$NNFC_h$ number of scenarios for hth future change.

In Eq. (4), the $CFOP_n(DFC_h(i, j))$ captures the difference between the fitness of *n*th organisational plan under the *i*th scenario and that under the *j*th scenario. Hence, by calculating the average of $CFOP_n(DFC_h(i, j))$ across all scenarios regarding the *h*th future change, we can examine how much the fitness of *n*th organisational plan fluctuates depending on the *h*th future change. To aggregate the effects of all future changes on the *n*th plan, the $CFOP_n$ is finally measured by the sum of the average changes in the fitness of the *n*th plan against all future changes. If the value of $CFOP_p$ is less than $CFOP_q$, the *p*th organisational plan can be judged to be more robust than the *q*th organisational plan. In that case, the *p*th organisational plan could be a better option even if FOP_p is not higher than FOP_q.

On the other hand, sensitivity analysis of activities investigates the strategic importance of activities in terms of their ripple impacts. For this purpose, we develop two indicators capturing the ripple impacts on the subsequent activities (RIA^{out}) and the ripple impacts by the antecedent activities (RIA^{in}), as formulated in Eqs. (5) and (6). The activities having higher value of RIA^{out} can be judged to bring about higher impacts on the subsequent activities, while the activities having higher value of RIA^{in} can be considered to be strongly affected by the antecedent activities.

$$RIA^{out}_{l,D^A,P_n} = \sum_{a>l}^{NNA} \left[CMPN\left(A_a | A_l, D^A\right) \cdot I(A_a, P_n) \right], \quad (5)$$

where $CMPN\left(A_a|A_l, D^A\right) = \dfrac{\sum_{i=1}^{(NDAA-1)} \sum_{j=i+1}^{NDAA} CMPN\left(DA_a(i,j)|A_l, D^A\right)}{(NDAA!/2)}$,

$$CMPN\left(DA_a(i,j)|A_l, D^A\right) = \left| P\left(A_a = d_i^A | A_l = D^A\right) - P\left(A_a = d_j^A | A_l = D^A\right) \right|,$$

$$I(A_a, P_n) = \begin{cases} 1 & \text{if } A_a \text{ is associated with } P_n, \\ 0 & \text{otherwise,} \end{cases}$$

A_l lth node for activities,
D^A degree of attianabilty of activities $D^A \in \{d_1^A, d_2^A, \ldots, d_{NDAA}^A\}$,
d_v^A vth state at nodes for activities that indicates vth category for degree of attainability of activities,
$NDAA$ number of categories for degree of attainability,
P_n nth plan,
NNA number of nodes for activities.

$$RIA^{in}_{l,D^A,P_n} = \sum_{a<l}^{NNA} \left[CMPN\left(A_l, D^A | A_a\right) \cdot I(A_a, P_n) \right], \quad (6)$$

where

$$CMPN\left(A_l, D^A|A_a\right) = \frac{\sum_{i=1}^{(NDAA-1)} \sum_{j=i+1}^{NDAA} CMPN\left(A_l, D^A | DA_a(i,j)\right)}{(NDAA!/2)},$$

$$CMPN\left(A_l, D^A|DA_a(i,j)\right) = \left| P\left(A_l = D^A | A_a = d_i^A\right) - P\left(A_l = D^A | A_a = d_j^A\right) \right|,$$

$$I(A_a, P_n) = \begin{cases} 1 & \text{if } A_a \text{ is associated with } P_n, \\ 0 & \text{otherwise,} \end{cases}$$

A_l lth node for activiteis,
D^A degree of attainability of activities $D^A \in \{d_1^A, d_2^A, \ldots, d_{NDAA}^A\}$,
d_V^A vth state at nodes for activities that indicates vth category for degree of attainabilty of activities,
$NDAA$ number of categories for degree of attainability of activities
P_n nth plan,
NNA number of nodes for activities.

In Eq. (5), $CMPN(A_a(i, j)|A_l, D^A)$ measures the difference between the conditional probability of the degree of attainability of *a*th activity to be d_i^A and that to be d_j^A. Thus, the average of $CMPN(A_a(i,j)|A_l, D^A)$, $CMPN(A_a|A_l, D^A)$, represents the impact of lth activity on its subsequent activity a. To examine the overall impact of lth activity, RIA_l^{out} is finally measured as the sum of $CMPN(A_a|A_l, D^A)$ against all subsequent activities. Eq. (6) can be interpreted in a similar manner although the meaning of RIA_l^{in} is the opposite of RIA_l^{out}.

3.2.3. Step 3: Managing plans and activities

3.2.3.1. Step 3-1: Plan assessment map. A *plan assessment map* is constructed to explore implications on the current fitness and robustness of organisational plans effectively. It utilises the value of *FOP* and *CFOP* as the horizontal and vertical axis as shown in Fig. 4(a). Each organisational plan can be classified into one of the four areas of the map: *appropriate & robust*, *inappropriate & robust*, *inappropriate & vulnerable*, and *appropriate & vulnerable*. The plans associated with *appropriate & robust* are regarded as core plans that are suitable for the current conditions as well as a wide variety of possible futures. These can be implemented with confidence. However, additional plans are required to respond to the sudden unexpected changes. Those additional plans are categorised as *appropriate & vulnerable* and *inappropriate & vulnerable*, and function as contingent plans. These are not robust and may hinder the organisation under certain circumstances. Once contingent plans have been drawn up, it is important to improve their current suitability and reveal the favourable future conditions. To this end, continuous monitoring is required based on relevant factors and intelligence processes for supporting early warning. As for the plans classified as *inappropriate & robust*, these can be ruled out or implemented after significant improvements regarding their current suitability and robustness.

3.2.3.2. Step 3-2: Activity assessment map. An *activity assessment map* is generated to provide guidelines on management of activities effectively. It utilises the value of *DAA*, RIA^{out}, and RIA^{in} as the size of nodes, horizontal, and vertical axis, as exemplified in Fig. 4(b). Each activity can also be classified into one of four areas in the map: *influential & reliant*, *uninfluential & reliant*, *uninfluential & independent*, and *influential & independent*. Although the managerial guidelines may differ across the organisational context, the activities are generally managed in the direction shifting from those having high values of *DAA* to those having low values of *DAA*. Managers also have to focus on the activities having high values of RIA^{out} because these cause huge impacts to the subsequent activities. Such activities should be designed robustly at the very first time and continuously monitored over the whole process by focusing on the directions and magnitude of their impacts. As for the activities having high values of RIA^{in}, adequate degrees of independence from the antecedent activities should be ensured to reduce ripple impacts.

4. Case study

4.1. Overview

A case study of photovoltaic (PV) cell technology is presented to illustrate the suggested approach. We consider this case appropriate because of: (1) its large scale investment and high risks involved [47,48], (2) a variety of factors influencing the success of technology development [49], and (3) a wide range of emerging technologies for being a dominant design [50]. It is currently evident that there is no single best plan for the development of PV cell technologies. Leading companies thus need to develop several types of plans to prepare the event of a range of futures, and continually evaluate and adjust their plans according to future changes. Arguably, under these conditions, our method will be more useful than previous methods that rely solely on graphical mapping tools, providing thorough understanding of future changes and their impacts on organisational plans.

We have developed a scenario-based technology roadmap for PV cell technology development based on the work of Strauss and Radnor (2004) [6], as shown in Fig. 5. The roadmap developed is characterised by multiple separate themes, sequential, linear, and branched one, which is the most frequently used visual form in practice [22]. The detailed development process is not reported here due to lack of space. Tables 1, 2, 3, and 4 summarise the explanation about future changes, activities, targets, and organisational plans that are the main focuses of analysis in this research.

4.2. Step 1: Designing a roadmap topology

4.2.1. Step 1-1: Qualitative modelling

The roadmap topology was developed based on the scenario-based technology roadmap. Firstly, each of five future changes was converted into a node in the roadmap topology with the state set consisting of its scenarios. Secondly, nodes for activities were generated by converting an activity into a node in the roadmap topology in most cases. Some exceptions occurred if an

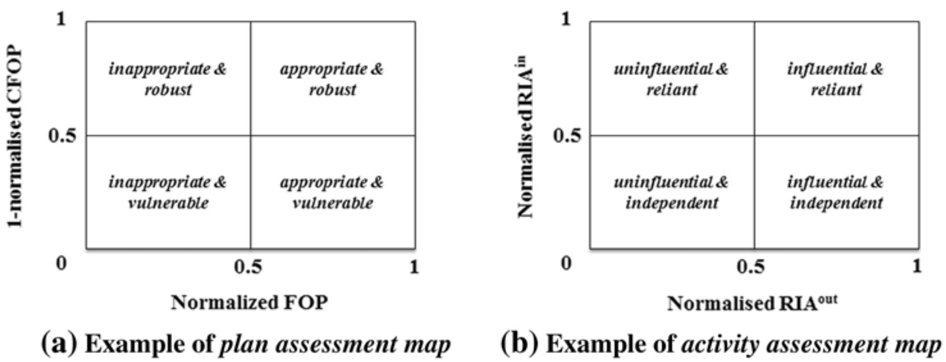

Fig. 4. Example of *plan assessment map* and *activity assessment map*.

activity was involved in multiple paths and needed to be assessed for each path. For instance, three activities for thin film Si PV cells (A_{210}, A_{211}, and A_{212}) were involved in two paths (A_{208}–A_{210}–A_{211}–A_{212} and A_{209}–A_{210}–A_{211}–A_{212}), so these were represented in both paths by using two different nodes; nodes A^1_{210} and A^2_{210} for activity A_{210}; nodes A^1_{211} and A^2_{211} for activity A_{211}; nodes A^1_{212} and A^2_{212} for A_{212}. Every node for activities had the state set consisting of *high attainability (H)*, *moderate attainability (M)*, and *low attainability (L)*. Thirdly, targets were converted into nodes. In a similar manner to nodes for activities, the number of nodes was determined according to the number of paths with which the targets were associated. For example, $T_1\_C_2$ and $T_1\_E_1$ were associated with two paths, so each of these was converted into two nodes; $T_1\_C_2$ was represented by $T_1_C^1_2$and $T_1\_C^2_2$; $T_1\_E_2$ was represented by $T_1_E^1_2$and $T_1\_E^2_2$. Every node for targets likewise had the state set consisting *high attainability (H)*, *moderate attainability (M)*, and *low attainability (L)*. Finally, the roadmap topology was constructed by connecting the pairs of nodes based on the dependence relationships, as shown in Fig. 6.

4.2.2. Step 1-2: Quantitative modelling

The probability tables were generated after the likelihood of the states of each node was evaluated by pairwise comparisons. Here, we present three cases according to the types of comparisons. Additional comparisons were made in the same manner.

Firstly, as for the root nodes, pairwise comparisons were carried out among the states of the node, and the priority values were derived as prior probabilities. The pairwise comparison matrix and the prior probabilities for *Price of poly-silicon in 2012 (FC_1)* are shown in Table 5.

Secondly, as for child nodes having a single parent node, pairwise comparisons were conducted among the states of the node with respect to each possible state of its parent node. The pairwise comparison matrices and the conditional probabilities for *Non-ruthenium dye (A_{301})* are shown in Table 6.

Lastly, as for the child nodes related to multiple parents, pairwise comparisons were performed among the states of the node with respect to the possible states of each parent node. The pairwise comparison matrices and the conditional probabilities for *New materials for transparent thin film transistor (A_{203})* are shown in Table 7.

Table 1
Summary of future changes for PV cell technology development.

Future change	Scenario
Price of poly-silicon in 2012 (FC_1)	20–30 ($/kg) ($S_{11}$) 30–50 ($/kg) (S_{12}) 50–70 ($/kg) ($S_{13}$)
Price of poly-silicon in 2017 (FC_2)	20–30 ($/kg) ($S_{21}$) 30–50 ($/kg) (S_{22}) 50–70 ($/kg) ($S_{23}$)
Wafer thickness reduction technology (FC_3)	Less than 100 μm (S_{31}) Greater than or equal to 100 μm (S_{32})
Expected demand of BIPV in 2015 (FC_4)	Greater than $15 billion ($S_{41}$) Between $5 billion and $15 billion ($S_{42}$)
Expected demand of flexible PV cells in 2020 (FC_5)	Greater than $30 billion ($S_{51}$) Between $15 billion and $30 billion ($S_{52}$)

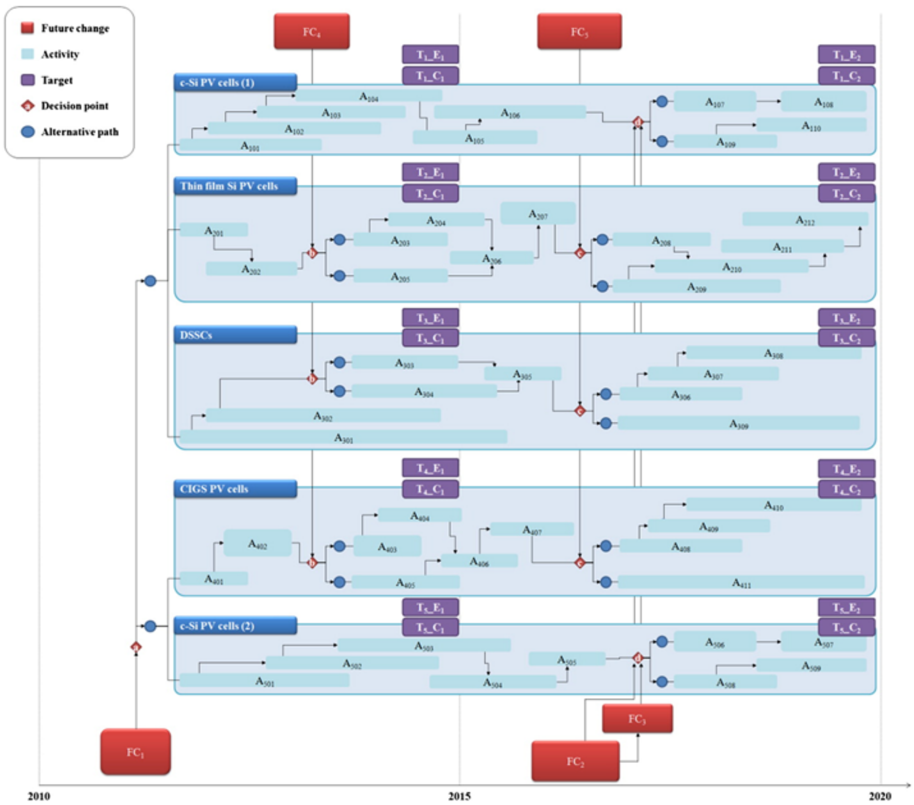

Fig. 5. Scenario-based technology roadmap for PV cell technology development.

Table 2
Summary of activities for PV cell technology development.

Technology group	Activity
c-Si PV cells (1)	Selective emitter technology (A_{101})
	PESC-type c-Si PV cells (A_{102})
	Rear passivation technology (A_{103})
	PERC-type c-Si PV cells (A_{104})
	Rear locally-diffused technology (A_{105})
	PERL-type c-Si PV cells (A_{106})
	Low-temperature passivation techniques for thin wafer-based c-Si (A_{107})
	Thin wafer-based c-Si (A_{108})
	New materials to replace poly-silicon (A_{109})
	New concept of new materials-based c-Si (A_{110})
Thin film Si PV cells	Light capturing technology (A_{201})
	Double-junction tandem structure technology (A_{202})
	New materials for transparent thin film transistor (A_{203})
	New-materials-based thin film Si (A_{204})
	See-through structure of thin film Si (A_{205})
	Mass production technology for thin film Si (A_{206})
	High speed deposition technology for large-scale thin film Si (A_{207})
	Flexible plastic substrates for thin film Si (A_{208})
	Multiple-junction structure technology (A_{209})
	Texturing technology (A_{210})
	Antireflection film technology (A_{211})
	In-situ in-line process monitoring technology (A_{212})
	Non-ruthenium dye (A_{301})
DSSCs	Quasi-solid-state electrolyte technology for DSSC (A_{302})
	Scaling up to mass production technology (A_{303})
	Solid-state electrolyte technology for DSSC (A_{304})
	TiO2 Nanotube technology for DSSC (A_{305})
	Flexible plastic conductive film-based substrates for DSSC (A_{306})
	Roll-to-roll technology for flexible DSSC (A_{307})
	Low-temperature processing technologies for flexible DSSC (A_{308})
	Quantum dot-based DSSC (A_{309})
CIGS PV cells	Double junctions CIGS (A_{401})
	Deposition technology for high speed in-line production of large scale CIGS (A_{402})
	Low cost materials for transparent electrode for CIGS (A_{403})
	New materials-based CIGS (A_{404})
	Non-vacuum processing technology of CIGS (A_{405})
	Cd-free buffer technology (A_{406})
	Multi junction CIGS (A_{407})
	Substrate technology for flexible CIGS (A_{408})
	Roll-to-roll technology for flexible CIGS (A_{409})
	Low-temperature processing technologies for flexible CIGS (A_{410})
	Quantum dot-based CIGS (A_{411})
c-Si PV cells (2)	N-type c-si PV cells (A_{501})
	Continuous production technology (A_{502})
	Screen printing technology (A_{503})
	Antireflection film technology (A_{504})
	Double junction c-Si (A_{505})
	Low-temperature passivation techniques for thin wafer-based c-Si (A_{506})
	Thin wafer-based c-Si (A_{507})
	New materials to replace poly-silicon (A_{508})
	New concept of new materials-based c-Si (A_{509})

4.3. Step 2: Assessing the impacts of future changes on organisational plans

4.3.1. Step 2-1: Current state analysis

The *MPN* of each node in the roadmap topology was first calculated based on Eq. (1). The number of nodes was large and each calculation was so complex that manual work was unrealistic. A JAVA-based program was developed based on eNIIe 2.0 and JSMILE to calculate the *MPNs* automatically. The *FOP*s for organisational plans and the *DAA*s for activities were then derived based on the *MPN*s for targets and activities. Three types of *FOP*s and *DAA*s can be obtained since the attainability of targets and activities was designed to have one of *H*, *M*, and *L*. As stated in Section 3, these can be combined into one single value or investigated individually. In this study, *FOP*s and *DAA*s for high attainability were employed for further analyses to examine the organisational plans and activities from the perspective of risk aversion.

The *FOP* for each organisational plan was calculated while D^T was set as *H* in Eq. (2). Moreover, we used an integrated index $MPN_{T\_I,H}$ which is the average of the $MPN_{T\_C,H}$ and $MPN_{T\_E,H}$ to examine the overall attainability of cost- and efficiency-related targets. The resulting *FOP*s for sixteen organisational plans are depicted in Table 8.

On the one hand, from the perspective of mid-term planning (until the year 2015), the organisational plans with the maximum *T_I*s are P_{23} and P_{24}, while the organisational plans with the minimum *T_I*s are P_{21} and P_{22}. All these plans are related to development of thin film based Si PV cells. The results also indicate that *see-through structure of thin film (A_{205})* is a better option than *new materials for transparent thin film transistor (A_{206})* and *new-materials-based thin film Si PV cells (A_{204})* for securing transparency of thin film based Si PV cells until the year 2015. On the other hand, from the perspective of long-term planning (until the year 2020), the highest *T_I*s appear when the organisational plans P_{32} and P_{34} are selected, whereas the lowest *T_I*s are shown when P_{42} and P_{44} are selected. *Quantum dot-based DSSC (A_{309})* is considered to be the best choice for high efficiency and high reliability.

Taken together, the organisational plan with the highest value of *FOP* is regarded as P_{23}, which turned out to have the highest possibility of being the best choice for the mid-term and the second highest possibility of being the best choice for the long-term. In contrast, the organisational plan with the lowest value of *FOP* is P_{22}, which has highest possibility of being the worst choice for the mid-term and the third highest possibility of being the worst choice for the long-term.

The calculated *DAA*s for activities are presented in Table 9. The values of *DAA*s ranged from 0.13 to 0.79. The five most likely activities which are expected to achieve high attainability under the current conditions are A_{305}, A_{306}, A_{309} A_{407}, and A_{408} with *DAA*s greater than 0.7. In contrast, the three least likely activities to achieve high attainability are A_{107}, A_{401}, and A_{501} having *DAA*s less than 0.3. In the case of organisational plan P_{23} that is ranked first in terms of *FOP*, the activities showed a relatively balanced distribution of *DAA*s ranging from 0.41 to 0.63. This implies that the individual activities are relatively highly attainable compared with those of other organisational plans. However, efforts to enhance the attainability of activities are still crucial especially for A_{205}, A_{206}, A_{207}, and A^1_{210} whose *DAA*s are less than 0.5.

4.3.2. Step 2-2: Sensitivity analysis

Likewise, *CFOPs* for organisational plans and RIA^{out}s and RIA^{in}s for activities were calculated based on high attainability, as shown in Tables 10 and 11.

Table 3
Summary of targets for PV cell technology development.

Group of technologies	Target
c-Si PV cells (1)	Cost < \$0.7/W ($T_1\_C_1$)
	Efficiency > 22% ($T_1\_E_1$)
	Cost < \$0.5/W ($T_1\_C_2$)
	Efficiency > 25% ($T_1\_E_2$)
Thin film Si PV cells	Cost < \$0.5/W ($T_2\_C_1$)
	Efficiency > 14% ($T_2\_E_1$)
	Cost < \$0.3/W ($T_2\_C_2$)
	Efficiency > 18% ($T_2\_E_2$)
DSSCs	Cost < \$0.3/W ($T_3\_C_1$)
	Efficiency > 10% ($T_4\_E_1$)
	Cost < \$0.1/W ($T_3\_C_2$)
	Efficiency > 15% ($T_3\_E_2$)
CIGS PV cells	Cost < \$1.0/W ($T_4\_C_1$)
	Efficiency > 18% ($T_4\_E_1$)
	Cost < \$0.7/W ($T_4\_C_2$)
	Efficiency > 22% ($T_4\_E_2$)
c-Si PV cells (2)	Cost < \$0.7/W ($T_5\_C_1$)
	Efficiency > 18% ($T_5\_E_1$)
	Cost < \$0.5/W ($T_5\_C_2$)
	Efficiency > 20% ($T_5\_E_2$)

The robustness of the organisational plans against future changes can be examined based on the resulting *CFOP*s, as shown in the last column of Table 10. Specifically, the lower the *CFOP* is, the higher the robustness of the organisational plan. In this sense, P_{23} having the smallest value of *CFOP* is regarded as the most robust organisational plan while P_{51} having the largest value of *CFOP* is considered to be the most vulnerable one. From the perspective of future changes, the most influencing future change is *Expected demand of BIPV in 2015 (FC_4)*, as presented in the last row of Table 10. In particular, the fitness of P_{31} and P_{32} related to the mass production of high-efficiency DSSC is highly sensitive to the changes of FC_4.

The impacts of activities can be investigated based on the resulting RIA^{out} and RIA^{in}, as summarised in Table 11. The most influencing activity with the highest value of RIA^{out} is A_{401} in the P_{41}, while the most sensitive activity with the lowest value of RIA^{in} is A_{207} in the P_{21}. It is obvious that the antecedent activities have relatively high values of RIA^{out}s and the small values of RIA^{in}s, and *vice versa*. The first and last activity in an organisational plan naturally has zero value of RIA^{in} and RIA^{out}. Beyond this, some exceptions are also found. It is noteworthy that although A_{207} is located in the middle of P_{21}, P_{22}, P_{23}, and P_{24}, the fitness of A_{207} is strongly affected by its antecedents.

Table 5
Pairwise comparison matrix among the states of the root node.

Price of poly-silicon in 2012 (FC_1)	S_{11}	S_{12}	S_{13}	$P(FC_1)$ (Priority)
S_{11}	1.0000	2.0000	5.0000	0.5559
S_{12}	0.5000	1.0000	5.0000	0.3537
S_{13}	0.2000	0.2000	1.0000	0.0904

4.4. Step 3: Managing plans and activities

4.4.1. Step 3-1: Plan assessment map

A *plan assessment map* was constructed based on the normalised *FOP* and (1-normalised *CFOP*), as depicted in Fig. 7(a). The organisational plans can be classified into four categories. Firstly, four organisational plans—P_{23} and P_{24} for thin film Si PV cells and P_{41} and P_{43} for CIGS PV cells—are located in *appropriate & robust*. These are core plans for PV cell technology development. Among them, P_{23} is ranked first regarding both the current fitness and the robustness, and thus should be considered as a top priority plan. Secondly, four organisational plans—P_{31} and P_{32} for DSSC and P_{51} and P_{52} for c-Si PV cells—are classified as *appropriate & vulnerable*. These are appropriate under the current conditions, but involve relatively high risks against different future conditions. The future changes that strongly affect the fitness of organisational plans should be continuously monitored to mitigate such risks. For instance, the fitness of P_{51} is affected by *Price of poly-silicon in 2012 (FC_1)*, *Price of poly-silicon in 2017 (FC_2)*, and *Wafer thickness reduction technology (FC_3)*, whereas *Expected demand of BIPV in 2015 (FC_4)* and *Expected demand of flexible PV cells in 2020 (FC_5)* has almost no impact on P_{51}. Thirdly, four organisational plans—P_{33} and P_{34} for DSSC and P_{42} and P_{44} for CIGS PV cells—are placed in the area

Table 4
Summary of organisational plans for PV cell technology development.

Technology group	Organisational plan (P_n)	Sequence of activities	Associated targets	
			Year 2015	Year 2020
c-si PV cells (1)	P_{11}	$A_{101}–A_{102}–A_{103}–A_{104}–A_{105}–A_{106}–A_{107}–A_{108}$	$T_1\_C_1$, $T_1\_E_1$	$T_1\_C_2^1$, $T_1\_E_2^1$
	P_{12}	$A_{101}–A_{102}–A_{103}–A_{104}–A_{105}–A_{106}–A_{109}–A_{110}$	$T_1\_C_1$, $T_1\_E_1$	$T_1\_C_2^2$, $T_1\_E_2^2$
Thin film Si PV cells	P_{21}	$A_{201}–A_{202}–A_{203}–A_{204}–A_{206}–A_{207}–A_{208}–A_{210}^1–A_{211}^1–A_{212}^1$	$T_2\_C_1^1$, $T_2\_E_1^1$	$T_2\_C_2^1$, $T_2\_E_2^1$
	P_{22}	$A_{201}–A_{202}–A_{203}–A_{204}–A_{206}–A_{207}–A_{209}–A_{210}^2–A_{211}^2–A_{212}^2$	$T_2\_C_1^1$, $T_2\_E_1^1$	$T_2\_C_2^2$, $T_2\_E_2^2$
	P_{23}	$A_{201}–A_{202}–A_{205}–A_{206}–A_{207}–A_{208}–A_{210}^1–A_{211}^1–A_{212}^1$	$T_2\_ C_1^2$, $T_2\_E_1^2$	$T_2\_C_2^1$, $T_2\_E_2^1$
	P_{24}	$A_{201}–A_{202}–A_{205}–A_{206}–A_{207}–A_{209}–A_{210}^2–A_{211}^2–A_{212}^2$	$T_2\_ C_1^2$, $T_2\_E_1^2$	$T_2\_C_2^2$, $T_2\_E_2^2$
DSSC	P_{31}	$A_{301}–A_{302}–A_{303}–A_{305}–A_{306}–A_{307}–A_{308}$	$T_3\_C_1^1$, $T_3\_E_1^1$	$T_3\_C_2^1$, $T_3\_E_2^1$
	P_{32}	$A_{301}–A_{302}–A_{303}–A_{305}–A_{309}$	$T_3\_C_1^1$, $T_3\_E_1^1$	$T_3\_C_2^2$, $T_3\_E_2^2$
	P_{33}	$A_{301}–A_{302}–A_{304}–A_{305}–A_{306}–A_{307}–A_{308}$	$T_3\_ C_1^2$, $T_3\_E_1^2$	$T_3\_C_2^1$, $T_3\_E_2^1$
	P_{34}	$A_{301}–A_{302}–A_{304}–A_{305}–A_{309}$	$T_3\_ C_1^2$, $T_3\_E_1^2$	$T_3\_C_2^2$, $T_3\_E_2^2$
CIGS PV cells	P_{41}	$A_{401}–A_{402}–A_{403}–A_{404}–A_{406}–A_{407}–A_{408}–A_{409}–A_{410}$	$T_4\_ C_1^1$, $T_4\_E_1^1$	$T_4\_C_2^1$, $T_4\_E_2^1$
	P_{42}	$A_{401}–A_{402}–A_{403}–A_{404}–A_{406}–A_{407}–A_{411}$	$T_4\_C_1^1$, $T_4\_E_1^1$	$T_4\_C_2^2$, $T_4\_E_2^2$
	P_{43}	$A_{401}–A_{402}–A_{405}–A_{406}–A_{407}–A_{408}–A_{409}–A_{410}$	$T_4\_C_2^1$, $T_4\_E_2^1$	$T_4\_C_2^1$, $T_4\_E_2^1$
	P_{44}	$A_{401}–A_{402}–A_{405}–A_{406}–A_{407}–A_{411}$	$T_4\_ C_2^1$, $T_4\_E_2^1$	$T_4\_C_2^2$, $T_4\_E_2^2$
c-si PV cells (2)	P_{51}	$A_{501}–A_{502}–A_{503}–A_{504}–A_{505}–A_{506}–A_{507}$	$T_5\_C_1$, $T_5\_E_1$	$T_5\_C_2^1$, $T_5\_E_2^1$
	P_{52}	$A_{501}–A_{502}–A_{503}–A_{504}–A_{505}–A_{508}–A_{509}$	$T_5\_C_1$, $T_5\_E_1$	$T_5\_C_2^2$, $T_5\_E_2^2$

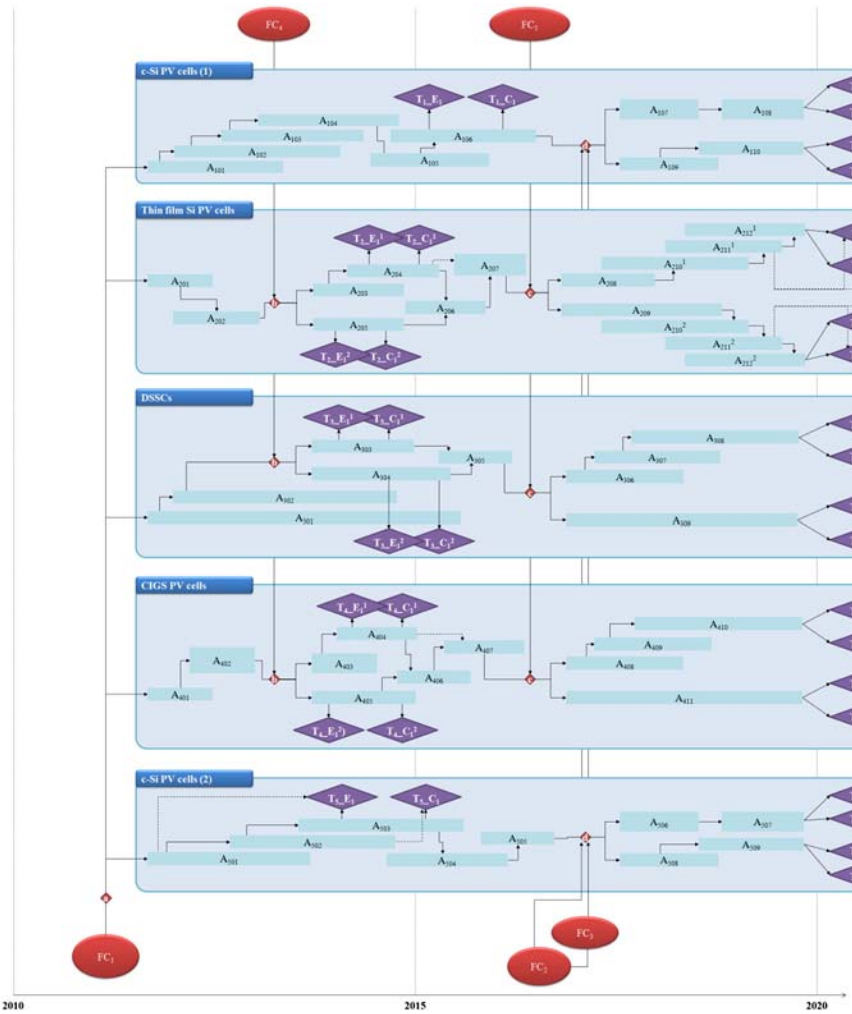

Fig. 6. Roadmap topology for PV cell technology development.

Table 6
Pairwise comparison matrix among the states of the node with a single parent.

(a) Comparison when the state of *Price of poly-silicon in 2012* (FC_1) is *20–30 ($/kg)* ($S_{11}$)

Non-ruthenium dye (A_{301})	*H*	*M*	*L*	$P(A_{301}\|FC_1 = S_{11})$ (Priority)
H	1.0000	4.0000	8.0000	0.71465
M	0.2500	1.0000	3.0000	0.20644
L	0.1250	0.3333	1.0000	0.07891

(b) Comparison when the state of *Price of poly-silicon in 2012* (FC_1) is *30–50 ($/kg)* ($S_{12}$)

Non-ruthenium dye (A_{301})	*H*	*M*	*L*	$P(A_{301}\|FC_1 = S_{12})$ (Priority)
H	1.0000	2.0000	5.0000	0.5949
M	0.5000	1.0000	2.0000	0.2766
L	0.2000	0.5000	1.0000	0.1285

(c) Comparison when the state of *Price of poly-silicon in 2012* (FC_1) is *50–70 ($/kg)* ($S_{13}$)

Non-ruthenium dye (A_{301})	*H*	*M*	*L*	$P(A_{301}\|FC_1 = S_{13})$ (Priority)
H	1.0000	0.2500	0.1429	0.0824
M	4.0000	1.0000	0.5000	0.3151
L	7.0000	2.0000	1.0000	0.6025

Table 7
Pairwise comparison matrix among the states of the nodes with multiple parent nodes.

New materials for transparent thin film transistor (A_{203})	*H*	*M*	*L*	Priority
(a-1) Comparison when the state of Expected demand of BIPV in 2015 (FC_4) is Greater than \$15 billion (S_{41})				
H	1.0000	5.0000	8.0000	0.7504
M	0.2000	1.0000	2.0000	0.1622
L	0.1250	0.5000	1.0000	0.0874
(a-2) Comparison when the state of Expected demand of BIPV in 2015 (FC_4) is Between \$5 billion and \$15 billion (S_{42})				
H	1.0000	0.5000	0.2500	0.1398
M	2.0000	1.0000	0.4000	0.2594
L	4.0000	2.5000	1.0000	0.6008
(b-1) Comparison when the state of Double-junction tandem structure technology (A_{202}) is high attainability (H)				
H	1.0000	2.0000	4.0000	0.5714
M	0.5000	1.0000	2.0000	0.2857
L	0.2500	0.5000	1.0000	0.1429
(b-2) Comparison when the state of Double-junction tandem structure technology (A_{202}) is moderate attainability (M)				
H	1.0000	0.8333	3.0000	0.4173
M	1.2000	1.0000	2.0000	0.4119
L	0.3333	0.5000	1.0000	0.1708
(b-3) Comparison when the state of Double-junction tandem structure technology (A_{202}) is low attainability (L)				
H	1.0000	0.3333	0.2500	0.21116
M	3.0000	1.0000	0.4000	0.29276
L	4.0000	2.5000	1.0000	0.58608

(c) Conditional probability table of New materials for transparent thin film transistor (A_{203})	$FC_4 = S_{41}$			$FC_4 = S_{42}$		
	$A_{202} = H$	$A_{202} = M$	$A_{202} = L$	$A_{202} = H$	$A_{202} = M$	$A_{202} = L$
H	0.8794	0.7930	0.4795	0.3331	0.2178	0.0381
M	0.0950	0.1692	0.2504	0.3090	0.3989	0.1706
L	0.0256	0.0378	0.2701	0.3579	0.3833	0.7913

of *inappropriate & vulnerable*. In contrast with the case of *appropriate & vulnerable*, these should be managed in the direction of increasing the fitness of organisational plans under the current conditions and revealing the most favourable future conditions to their suitability. As for P_{44}, the most influencing future change is FC_5; the suitability of P_{44}, which is ranked tenth under the current conditions, will be the highest among others if the *Between \$15 billion and \$30 billion (S_{52})* of FC_5 is enacted. Finally, four organisational plans P_{11}, P_{12}, P_{21}, and P_{22} are identified as *inappropriate & robust*. The problems are found to be related to the organisational plans *per se* rather than external factors.

Table 8
FOPs for organisational plans.

Technology group	Organisational plan (P_n)	$MPN_{T\_I,\ H}$				$FOP_{n,H}$
		Year 2015		Year 2020		
c-si PV cells (1)	P_{11}	$T_1\_I_1$	0.3668	$T_1\_I_2^1$	0.4702	0.1725
	P_{12}	$T_1\_I_1$	0.3668	$T_1\_I_2^2$	0.3979	0.1459
Thin film Si PV cells	P_{21}	$T_2\_I_1^1$	0.3598	$T_2\_I_2^1$	0.5038	0.1813
	P_{22}	$T_2\_I_1^1$	0.3598	$T_2\_I_2^2$	0.4019	0.1446
	P_{23}	$T_2\_I_1^2$	0.5257	$T_2\_I_2^1$	0.5038	0.2649
	P_{24}	$T_2\_I_1^2$	0.5257	$T_2\_I_2^2$	0.4019	0.2113
DSSC	P_{31}	$T_3\_I_1^1$	0.4686	$T_3\_I_2^1$	0.4503	0.2110
	P_{32}	$T_3\_I_1^1$	0.4686	$T_3\_I_2^2$	0.5064	0.2373
	P_{33}	$T_3\_I_1^2$	0.3942	$T_3\_I_2^1$	0.4503	0.1775
	P_{34}	$T_3\_I_1^2$	0.3942	$T_3\_I_2^2$	0.5064	0.1996
CIGS PV cells	P_{41}	$T_4\_I_1^1$	0.4818	$T_4\_I_2^1$	0.4839	0.2331
	P_{42}	$T_4\_I_1^1$	0.4818	$T_4\_I_2^2$	0.3935	0.1896
	P_{43}	$T_4\_I_2^1$	0.4996	$T_4\_I_2^1$	0.4839	0.2417
	P_{44}	$T_4\_I_2^1$	0.4996	$T_4\_I_2^2$	0.3935	0.1966
c-si PV cells (2)	P_{51}	$T_5\_I_1$	0.4713	$T_5\_I_2^1$	0.4952	0.2334
	P_{52}	$T_5\_I_1$	0.4713	$T_5\_I_2^2$	0.4426	0.2086

4.4.2. Step 3-2: Activity assessment map

An *activity assessment map* was developed for each organisational plan based on *DAA*, RIA^{in} and RIA^{out}. The activity assessment map for P_{23} which is regarded as the top priority plan is depicted in Fig. 7(b). From the map, two, four, and three activities of P_{23} are classified as *influential & reliant*, *uninfluential & reliant*, and *influential & independent*, respectively. All activities are found to be strongly related to each other because there is none of them in *uninfluential & independent*. First of all, A_{207} can be judged as the most problematic activity since it has low *DAA* as well as high RIA^{out} and RIA^{in}. The degree of attainability should be enhanced in conjunction with the efforts to secure independence from the other activities. Second, A_{210}, A_{211}, and A_{212} classified as *uninfluential & reliant* are highly attainable under the current conditions, but the attainability is likely to change by their antecedent activities. The degree of attainability of A_{210}, A_{211}, and A_{212} carries conviction only if a certain level of independence from the antecedent activities. Third, A_{201}, A_{202}, and A_{205} in the area of *influential & independent* show high attainability under the current conditions, which are also stable to the change of the antecedent activities. However, the change of these activities can lead to the significant change in the subsequent activities. Hence, any subsequent activities that are strongly affected should be identified and managed.

Table 9
DAAs for activities.

Technology group	Organisational plan (P_n)	*DAAs*									
c-si PV cells (1)	P_{11}	Activity	A_{101}	A_{102}	A_{103}	A_{104}	A_{105}	A_{106}	A_{107}	A_{108}		
		$DAA_{i,H}$	0.4970	0.4531	0.5316	0.4404	0.3281	0.3341	0.2970	0.4695		
	P_{12}	Activity	A_{101}	A_{102}	A_{103}	A_{104}	A_{105}	A_{106}	A_{109}	A_{110}		
		$DAA_{i,H}$	0.4970	0.4531	0.5316	0.4404	0.3281	0.3341	0.5293	0.5047		
Thin film Si PV cells	P_{21}	Activity	A_{201}	A_{202}	A_{203}	A_{204}	A_{206}	A_{207}	A_{208}	A^1_{210}	A^1_{211}	A^1_{212}
		$DAA_{i,H}$	0.6107	0.4739	0.5577	0.5015	0.4135	0.4160	0.6088	0.4810	0.6247	0.5867
	P_{22}	Activity	A_{201}	A_{202}	A_{203}	A_{204}	A_{206}	A_{207}	A_{209}	A^2_{210}	A^2_{211}	A^2_{212}
		$DAA_{i,H}$	0.6107	0.4739	0.5577	0.5015	0.4135	0.4160	0.3215	0.3156	0.4307	0.3977
	P_{23}	Activity	A_{201}	A_{202}	A_{205}	A_{206}	A_{207}	A_{208}	A^1_{210}	A^1_{211}	A^1_{212}	
		$DAA_{i,H}$	0.6107	0.4739	0.5147	0.4135	0.4160	0.6088	0.4810	0.6247	0.5867	
	P_{24}	Activity	A_{201}	A_{202}	A_{205}	A_{206}	A_{207}	A_{209}	A^2_{210}	A^2_{211}	A^2_{212}	
		$DAA_{i,H}$	0.6107	0.4739	0.5147	0.4135	0.4160	0.3215	0.3156	0.4307	0.3977	
DSSC	P_{31}	Activity	A_{301}	A_{302}	A_{303}	A_{305}	A_{306}	A_{307}	A_{308}			
		$DAA_{i,H}$	0.6151	0.4621	0.5198	0.7722	0.7261	0.6049	0.5062			
	P_{32}	Activity	A_{301}	A_{302}	A_{303}	A_{305}	A_{309}					
		$DAA_{i,H}$	0.6151	0.4621	0.5198	0.7722	0.7001					
DSSC	P_{31}	Activity	A_{301}	A_{302}	A_{304}	A_{305}	A_{306}	A_{307}	A_{308}			
		$DAA_{i,H}$	0.6151	0.4621	0.3834	0.7722	0.7261	0.6049	0.5062			
	P_{32}	Activity	A_{301}	A_{302}	A_{304}	A_{305}	A_{309}					
		$DAA_{i,H}$	0.6151	0.4621	0.3834	0.7722	0.7001					
CIGS PV cells	P_{41}	Activity	A_{401}	A_{402}	A_{403}	A_{404}	A_{406}	A_{407}	A_{408}	A_{409}	A_{410}	
		$DAA_{i,H}$	0.2066	0.3584	0.6300	0.5677	0.5927	0.7286	0.7875	0.6770	0.6491	
	P_{42}	Activity	A_{401}	A_{402}	A_{403}	A_{404}	A_{406}	A_{407}	A_{411}			
		$DAA_{i,H}$	0.2066	0.3584	0.6300	0.5677	0.5927	0.7286	0.4604			
	P_{43}	Activity	A_{401}	A_{402}	A_{405}	A_{406}	A_{407}	A_{408}	A_{409}	A_{410}		
		$DAA_{i,H}$	0.2066	0.3584	0.5394	0.5927	0.7286	0.7875	0.6770	0.6491		
	P_{44}	Activity	A_{401}	A_{402}	A_{405}	A_{406}	A_{407}	A_{411}				
		$DAA_{i,H}$	0.2066	0.3584	0.5394	0.5927	0.7286	0.4604				
c-si PV cells (2)	P_{51}	Activity	A_{501}	A_{502}	A_{503}	A_{504}	A_{505}	A_{506}	A_{507}			
		$DAA_{i,H}$	0.1299	0.4257	0.5460	0.5917	0.6086	0.3353	0.4750			
	P_{52}	Activity	A_{501}	A_{502}	A_{503}	A_{504}	A_{505}	A_{508}	A_{509}			
		$DAA_{i,H}$	0.1299	0.4257	0.5460	0.5917	0.6086	0.6258	0.5616			

5. Conclusions

5.1. Managerial and academic implications

Robust planning is beyond any other concern for organisations who wish to survive in uncertain and volatile environments. This study has proposed a systematic approach to assessing the impacts of future changes on organisational plans by integrating the strengths of sensitivity analysis into scenario-based technology roadmapping. The contribution and potential uses of this research are three-fold. Firstly, from a theoretical perspective, this study contributes to the technology roadmapping research by extending previous graphical mapping tools to analytical ones. The core advantage of this approach lies in its systematic processes and quantitative outcomes, facilitating discovery of a stronger factual foundation. Integrating sensitivity analysis into scenario-based technology roadmapping makes this possible, by helping decision

Table 10
CFOPs for organisational plans.

Technology group	Organisational plan (P_n)	FC_1	FC_2	FC_3	FC_4	FC_5	$CFOP_{n,H}$
c-si PV cells (1)	P_{11}	0.0070	0.0414	0.0691	0.0000	0.0000	0.1176
	P_{12}	0.0062	0.0217	0.0365	0.0000	0.0000	0.0644
Thin film Si PV cells	P_{21}	0.0119	0.0000	0.0000	0.0855	0.0093	0.1067
	P_{22}	0.0088	0.0000	0.0000	0.0652	0.0165	0.0905
	P_{23}	0.0022	0.0000	0.0000	0.0142	0.0136	0.0300
	P_{24}	0.0008	0.0000	0.0000	0.0162	0.0241	0.0412
DSSC	P_{31}	0.0098	0.0000	0.0000	0.1441	0.0370	0.1909
	P_{32}	0.0131	0.0000	0.0000	0.1647	0.0148	0.1926
	P_{33}	0.0285	0.0000	0.0000	0.0890	0.0311	0.1487
	P_{34}	0.0336	0.0000	0.0000	0.0972	0.0124	0.1432
CIGS PV cells	P_{41}	0.0119	0.0000	0.0000	0.0327	0.0075	0.0521
	P_{42}	0.0122	0.0000	0.0000	0.0279	0.0979	0.1380
	P_{43}	0.0213	0.0000	0.0000	0.0781	0.0078	0.1072
	P_{44}	0.0200	0.0000	0.0000	0.0621	0.1015	0.1837
c-si PV cells (2)	P_{51}	0.0916	0.0507	0.0918	0.0000	0.0000	0.2340
	P_{52}	0.0819	0.0315	0.0654	0.0000	0.0000	0.1787
Sum		0.3609	0.1452	0.2628	0.8770	0.3735	2.0195

Table 11
RIA^{out}s and RIA^{in}s of activities.

Technology group	Organisational plan (P_n)	RIA^{out}s and RIA^{in}s										
c-si PV cells (1)	P_{11}	Activity	A_{101}	A_{102}	A_{103}	A_{104}	A_{105}	A_{106}	A_{107}	A_{108}		
		$RIA^{out}_{I,H,P_{11}}$	1.3106	0.9871	0.7839	0.6108	0.6238	0.2665	0.4756	0.0000		
		$RIA^{in}_{I,H,P_{11}}$	0.0000	0.4558	0.6508	0.8377	0.6720	0.8570	0.2695	0.6164		
	P_{12}	Activity	A_{101}	A_{102}	A_{103}	A_{104}	A_{105}	A_{106}	A_{109}	A_{110}		
		$RIA^{out}_{I,H,P_{12}}$	1.5165	1.1969	1.0002	0.8491	0.9149	0.6345	0.4834	0.0000		
		$RIA^{in}_{I,H,P_{12}}$	0.0000	0.4558	0.6508	0.8377	0.6720	0.8570	0.4425	0.7739		
Thin film Si PV cells	P_{21}	Activity	A_{201}	A_{202}	A_{203}	A_{204}	A_{206}	A_{207}	A_{208}	A^1_{210}	A^1_{211}	A^1_{212}
		$RIA^{out}_{I,H,P_{21}}$	2.4187	2.2843	2.3340	2.1054	1.9093	1.4610	1.1138	0.7641	0.4198	0.0000
		$RIA^{in}_{I,H,P_{21}}$	0.0000	0.3404	0.3588	0.7212	0.6117	1.2617	0.7272	0.8266	0.6962	0.6063
	P_{22}	Activity	A_{201}	A_{202}	A_{203}	A_{204}	A_{206}	A_{207}	A_{209}	A^2_{210}	A^2_{211}	A^2_{212}
		$RIA^{out}_{I,H,P_{22}}$	1.6005	1.4502	1.4602	1.1956	0.9821	0.5086	0.8784	0.6270	0.3839	0.0000
		$RIA^{in}_{I,H,P_{22}}$	0.0000	0.3404	0.3588	0.7212	0.6117	1.2617	0.7031	0.6660	0.6765	0.6619
Thin film Si PV cells	P_{23}	Activity	A_{201}	A_{202}	A_{205}	A_{206}	A_{207}	A_{208}	A^1_{210}	A^1_{211}	A^1_{212}	
		$RIA^{out}_{I,H,P_{23}}$	2.2199	2.0036	1.8088	1.9093	1.4610	1.1138	0.7641	0.4198	0.0000	
		$RIA^{in}_{I,H,P_{23}}$	0.0000	0.3404	0.0302	0.3635	0.7774	0.5533	0.7266	0.6635	0.5952	
	P_{24}	Activity	A_{201}	A_{202}	A_{205}	A_{206}	A_{207}	A_{209}	A^2_{210}	A^2_{211}	A^2_{212}	
		$RIA^{out}_{I,H,P_{24}}$	1.4017	1.1694	0.9632	0.9821	0.5086	0.8784	0.6270	0.3839	0.0000	
		$RIA^{in}_{I,H,P_{24}}$	0.0000	0.3404	0.0302	0.3635	0.7774	0.5382	0.5861	0.6348	0.6413	
DSSC	P_{31}	Activity	A_{301}	A_{302}	A_{303}	A_{305}	A_{306}	A_{307}	A_{308}			
		$RIA^{out}_{I,H,P_{31}}$	2.0737	1.7488	1.5125	1.0819	0.7811	0.4173	0.0000			
		$RIA^{in}_{I,H,P_{31}}$	0.0000	0.3865	0.1973	0.2140	0.3003	0.6777	0.7952			
	P_{32}	Activity	A_{301}	A_{302}	A_{303}	A_{305}	A_{309}					
		$RIA^{out}_{I,H,P_{32}}$	1.4955	1.1707	0.9345	0.5212	0.0000					
		$RIA^{in}_{I,H,P_{32}}$	0.0000	0.3865	0.1973	0.2140	0.5947					
DSSC	P_{33}	Activity	A_{301}	A_{302}	A_{304}	A_{305}	A_{306}	A_{307}	A_{308}			
		$RIA^{out}_{I,H,P_{33}}$	2.0111	1.7979	1.5110	1.0819	0.7811	0.4173	0.0000			
		$RIA^{in}_{I,H,P_{33}}$	0.0000	0.3865	0.5051	0.2134	0.2993	0.6771	0.7949			
	P_{34}	Activity	A_{301}	A_{302}	A_{304}	A_{305}	A_{309}					
		$RIA^{out}_{I,H,P_{34}}$	1.4329	1.2198	0.9326	0.5212	0.0000					
		$RIA^{in}_{I,H,P_{34}}$	0.0000	0.3865	0.5051	0.2134	0.5942					
CIGS PV cells	P_{41}	Activity	A_{401}	A_{402}	A_{403}	A_{404}	A_{406}	A_{407}	A_{408}	A_{409}	A_{410}	
		$RIA^{out}_{I,H,P_{41}}$	3.2582	2.9506	2.5550	2.2246	1.8003	1.2878	0.8466	0.4291	0.0000	
		$RIA^{in}_{I,H,P_{41}}$	0.0000	0.3724	0.4522	0.6621	0.6314	1.2201	0.6263	0.8444	0.7214	
	P_{42}	Activity	A_{401}	A_{402}	A_{403}	A_{404}	A_{406}	A_{407}	A_{411}			
		$RIA^{out}_{I,H,P_{42}}$	2.1718	1.8644	1.4676	1.1379	0.7174	0.2247	0.0000			
		$RIA^{in}_{I,H,P_{42}}$	0.0000	0.3724	0.4522	0.6621	0.6314	1.2201	0.7368			
CIGS PV cells	P_{43}	Activity	A_{401}	A_{402}	A_{405}	A_{406}	A_{407}	A_{408}	A_{409}	A_{410}		
		$RIA^{out}_{I,H,P_{43}}$	2.8645	2.5648	2.1725	1.8003	1.2878	0.8466	0.4291	0.0000		
		$RIA^{in}_{I,H,P_{43}}$	0.0000	0.3724	0.4659	0.5553	0.7928	0.4945	0.7681	0.7046		
	P_{44}	Activity	A_{401}	A_{402}	A_{405}	A_{406}	A_{407}	A_{411}				
		$RIA^{out}_{I,H,P_{44}}$	1.7780	1.4786	1.0876	0.7174	0.2247	0.0000				
		$RIA^{in}_{I,H,P_{44}}$	0.0000	0.3724	0.4659	0.5553	0.7928	0.5736				
c-si PV cells (2)	P_{51}	Activity	A_{501}	A_{502}	A_{503}	A_{504}	A_{505}	A_{506}	A_{507}			
		$RIA^{out}_{I,H,P_{51}}$	1.6410	1.2920	0.8784	0.6808	0.2585	0.4756	0.0000			
		$RIA^{in}_{I,H,P_{51}}$	0.0000	0.3705	0.4594	0.1207	0.3377	0.1665	0.5303			
	P_{52}	Activity	A_{501}	A_{502}	A_{503}	A_{504}	A_{505}	A_{508}	A_{509}			
		$RIA^{out}_{I,H,P_{52}}$	1.9440	1.5954	1.1832	1.0192	0.6345	0.4834	0.0000			
		$RIA^{in}_{I,H,P_{52}}$	0.0000	0.3705	0.4594	0.1207	0.3377	0.2945	0.6807			

makers get a more comprehensive and balanced view on organisational plans. To our knowledge, this is the first attempt to assess the impacts of future changes on organisational plans in a quantitative manner. It is expected that the proposed approach can facilitate responsive technology planning and serve as a starting point for developing more general models. Secondly, from a methodological perspective, this study is not limited to the application of Bayesian networks to scenario-based technology roadmapping, as here we emphasise the systematic process of our approach in terms of inputs, throughputs, and outputs. Although this study focuses on a technology planning problem, the proposed approach could be employed in various research areas including product/service development and project management. Finally, with regard to the practical standpoint, the proposed approach is based on experts' judgments. As such, this research can fine-tune the roadmapping process. Although the probabilistic models employed in this study are somewhat complex, the operational efficiency has been enhanced by software systems, giving specific practical help to practitioners in charge of speedy and continuous investigation. The analytical results can be updated easily with minimal involvement of experts, since the data are totally reusable and new data can be added and analysed through support from the software system.

5.2. Limitations and future research

As this research is at the explorative stage, it is subject to certain limitations which are now outlined. First of all, in terms of the scope of analysis, the suggested approach needs to be more elaborated by combining other issues such as resources

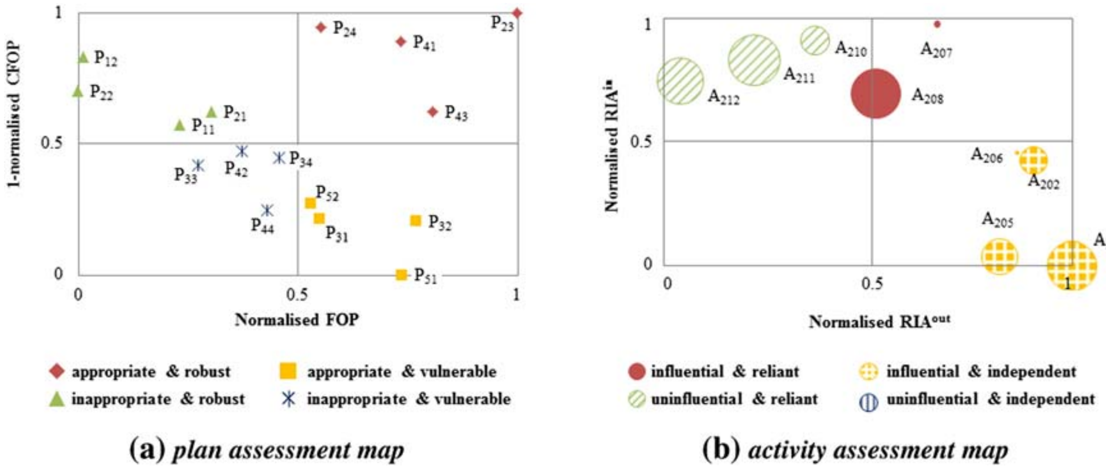

Fig. 7. Plan assessment map and activity assessment map.

and organisational expertise. While a variety of internal factors may affect the success of organisational plans, our method does not yet model and analyse such factors explicitly. Moreover, this study focuses only on implementation challenges of scenario-based technology roadmapping, although scenario-building is a critical issue in the literature. So far, various models, methods, and processes have been proposed to generate and evaluate scenarios for future changes. The proposed approach will be more powerful if carefully integrated together with the models, methods, and processes for scenario-building. Second, with regard to the role of experts, communication between experts from different domains and functions still remains essential in this approach. The specific role of experts should be defined to support creativity and innovation. Technological databases and innovative computer algorithms, such as environmental scanning and bibliometric analysis, could also help experts identify critical factors regarding future changes that might be overlooked due to psychological inertia in human thinking. Third, in terms of the customisation issue, although the proposed approach is designed to be executed in a sequential process, the process order can be modified to include the feedback loops between the steps. The whole analysis should also be implemented, so decision makers continually evaluate the pictures on futures. Moreover, the architectural structure of the scenario-based technology roadmap employed in this research is by no means fixed and exhaustive. Even though this research focuses on prospective analysis for technology development, different types of roadmaps (e.g. project roadmaps and industry roadmaps) can be employed for different purposes. Adjustments are possible for customised purposes depending on the organisational contexts. Finally, in relation to the validity issue, a newly proposed method needs to be carefully deployed in practice. Our case study has been limited to only one technology, and there are many managerial issues in its practical implementation. Further testing on a wider range of technologies could help establish the external validity of the suggested method in addition to the type of industries in which the method will be best operated. The customisation process should also be conducted based on a variety of organisational contexts. Nevertheless, we argue that the analytical power it offers makes a substantial initial contribution, both to current research and to future practice.

Acknowledgments

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