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Conceptual framework to assess the impacts of changes on the status of a roadmap

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ABSTRACT

The major challenges for most organizations that use roadmaps are to keep a roadmap alive. Under today's fast-changing market and economic conditions, organizations have to effectively adjust themselves as the changes of internal and external environment always impact an organization's strategies and roadmaps. There is a clear interest from the management to know whether their roadmaps are still valid to the changing situations or whether there is a need to adjust their roadmaps. Therefore, it is important to assess the impacts of changes on the status of a roadmap which will indicate whether a roadmap needs to be slightly adjusted, totally revised, or just kept it unchanged. The management would also like to take proactive actions in monitoring the status of a roadmap and calling for an immediate action to review or revise a roadmap as major changes affect rather than waiting for the next periodical review schedule. This paper proposes the conceptual framework to determine the status of a technology roadmap by evaluating the impacts of changes from both internal and external environment.

1. Introduction

Technology roadmapping (TRM) is a strategic approach that allows organizations to link their technology strategies with their business strategies (Groenveld, 1997; Nauda and Hall, 1991; Wells et al., 2004). Some organizations implement technology roadmapping to support the visualization of their strategies and guide their operations or activities. Since 2000, several studies have been taken to systemize the TRM development process as well as compare the cases of TRM implementation from different organizations to see whether the implementation process can be standardized (Gerdsri, 2013).

The example structure of a product-technology roadmap (Fig. 1) is separated into two key dimensions. The first dimension is a timeframe, which may incorporate short-term, medium-term and long-term viewpoints (Phaal and Muller, 2009). The time horizon can be adjusted based on the speed with changes are introduced to the industry. However in general, a ten-year time horizon is considered to be appropriate for many organizations (Phaal and Muller, 2009). The second dimension is consisted of multi-layers, which addresses critical components to be analyzed in the roadmap development. As shown in Fig. 1, the layer of business drivers is regarded as the "external" factors. These external factors indicate the reason WHY any particular market opportunities should be considered as a focal point of a roadmap. The product development layer indicates WHAT targets of market opportunities an organization should plan to achieve within the specified timeline. To complete the product development, an organization may require to prepare for technology development as well as R&D activities. The layers of technology development and R&D program are

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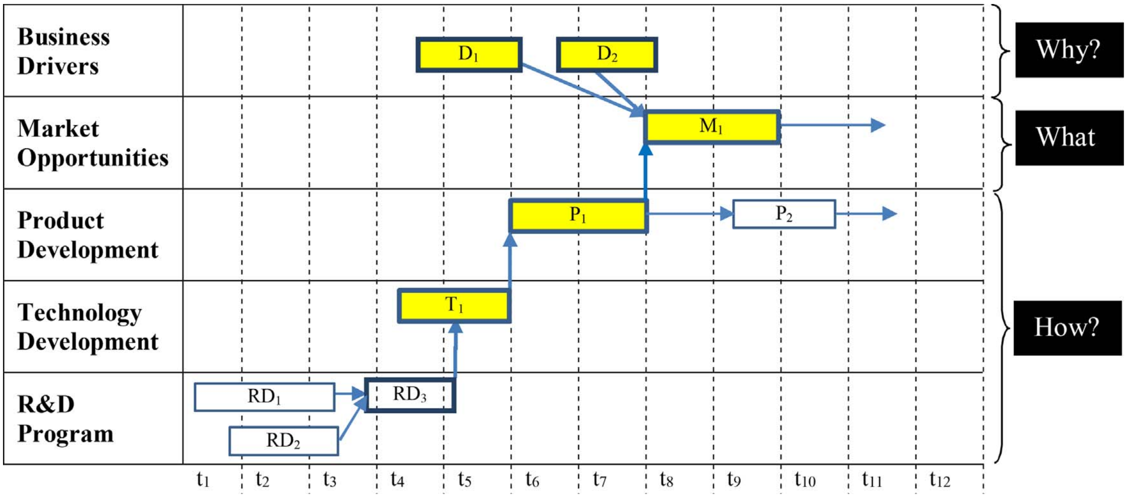


Fig. 1. The example structure of a product-technology roadmap.

regarded as the "internal" factors which indicate HOW an organization should plan, prepare, and execute actions in order to achieve the strategic focal points as specified on a roadmap. Thus, the technology roadmapping approach helps address the abovementioned issues by answering the fundamental management questions like what, why and how. The components in each layer can also be customized according to the intended use (objectives) of each roadmap.

As the current global environment becomes more complex, organizational managers have to face with many complicated challenges. Challenges may result from several causes including rapid changes from internal factors (e.g., technology development, Research and Development programs) and/or external factors (e.g., business drivers, market opportunities). Once the changes in any of these factors (internal/external factors) occur, it may impact the strategic targets of a roadmap. If the impacts are significant enough, a roadmap should then be adjusted or totally revised to align with the changing situations. Otherwise, a roadmap could become obsolete.

As shown in Fig. 1, the changes of external drivers; D_1 and/or D_2, would affect the market opportunity; M_1. If the changes of D_1 and/or D_2 turn out to be more severe than the initial anticipation, then it would cause market opportunity M_1 to be materialized sooner. Therefore, an organization should consider to revise its roadmap to set the target of M_1 sooner; otherwise, an organization will miss this opportunity. The same way of thinking is also applied if the changes of D_1 and/or D_2 turn out to be less severe than the initial anticipation. An organization can consider to push out the target of M_1 so that an organization would not end up in a premature market.

The changes of internal factors also affect a roadmap. For example, product P_1 is a product that an organization initially plans to capture the market opportunity M_1 at the time of t_8. And technology T_1 is a new technology that is required to develop product P_1. Technology T_1 can be developed either from within or outside a firm; however the development of T_1 has to be finished by the time of t_6 in order to start the development of product P_1. If technology T_1 is not ready by the time of t_6, the delay in the development of product P_1 may occur. As a result, P_1 may be ready and able to launch to the market later than the initial schedule of t_8. For instance, if product development of P_1 finishes at the time of t_{10}, this leads to the loss of market opportunities M_1 which P_1 intends to capture. In this situation, the delay of the technology development impacts the strategic focal point of a roadmap. Therefore, the strategy and roadmap need to be constantly reviewed and updated to reflect the actual situation.

On the other hand, if the development of technology T_1 finishes sooner than the targeted schedule of t_6, the development of product P_1 can start earlier than the specified time of t_6. The product development of P_1 may finish prior the targeted strategic time of t_8. As a result, P_1 would end up being too early for the market opportunity M_1. The managers should, in this case, review and revise their strategies either trying to slow down the product development to wait for the market opportunity to arise or trying to put more efforts in developing the new market opportunity so that the market can be materialized sooner. The updated version of a roadmap should be communicated to all related stakeholders. This is to ensure that the updated plan on a roadmap is acknowledged by every related team.

In brief, the changes in both external drivers and internal factors can impact the status of a roadmap. It is important for a firm to assess whether the changes are significant enough that an updated version of a roadmap is required. Some researchers have addressed the challenge of keeping the roadmapping process alive by proposing the operation guideline to periodically update and review technology roadmaps (Brown and O'Hare, 2001; Phaal et al., 2001a, 2001b, 2005; Wells et al., 2004; Holmes and Ferrill, 2008; Phaal and Muller, 2009; Gerdsri, 2013). However, under today's fast changing business environments and the emergence of breakthrough technologies, the periodic review may not be proactive enough in monitoring the status of a roadmap and allowing the management to make a timely decision to revise their roadmap. Also, when an organization conducts the unnecessarily updates of a roadmap, it leads to the extra costs for an organization.

Assessing the status of a roadmap in a systematic approach can help the management come to the conclusion in a transparent way whether a current roadmap needs to be just updated or totally revised. Also, as the assessment scheme (level of importance or the tolerance limit on the changes) is set based on the agreement from key stakeholders before a roadmap is taken into action, the case of misrepresentation and bias on the impacts of changes from external and internal environment can be reduced.

By applying a systematic approach, it would be benefit to TRM practitioners not only to conduct roadmapping at a large scale but also to support the management's interests in turning a traditional roadmap to be more computerized with data-driven and real-time reflection to any changing condition.

This paper attempts to propose the conceptual framework to assess the status of a technology roadmap by evaluating the impacts of changes from both internal and external environment. The proposed framework can help the management to take proactive actions in monitoring the status of a roadmap and calling for an immediate action to review or revise a roadmap rather than waiting for the next periodical review schedule. The result of status assessment would also help the management to make a proper decision whether a roadmap needs to be slightly adjusted, totally revised, or just kept it unchanged.

2. Literature review

2.1. Current approaches in TRM development

There are three approaches commonly used to develop a roadmap (i.e., expert-based approach, computer-based approach and hybrid approach) (Kostoff and Schaller, 2001). The expert-based approach requires a group or groups of experts to develop roadmaps by identifying the nodes, links and structural relationships within the network of a roadmap. The computer-based approach uses computer analysis as the means to develop a roadmap by analyzing textual databases related to technology, science, engineering and products. The databases can be referred to the collection of published papers, letters or reports. Through this method, all critical components (e.g. technology, research, product areas and engineering) and their structural relationships should be identified. The hybrid approach is a combination of the expert-based and computer-based approaches. The advantage of this approach comes from diminishing the limitations of these two approaches. As a result, the subjectivity from the expert-based approach is reduced while the interaction among experts still remains.

In general, the approach for TRM development is an expert-based approach organized through a series of workshop facilitated by TRM experts (Phaal et al., 2007, 2001a, 2001b). During a series of workshop, the process of TRM development is designed through iterative steps focusing on the details gained from each iteration (Phaal et al., 2005; Phaal and Muller, 2009; Wells et al., 2004). The process requires the involvement of cross-functional teams including staffs from different levels of an organization (Kostoff and Schaller, 2001; Phaal et al., 2003a). Since the success of TRM development highly depends on individuals' ability to innovate, share information, and justify decisions, it is important to assure that the process is properly customized to match with an organization's vision. Moreover, the sufficient level of knowledge is provided in the process (Gerdsri et al., 2010; Kostoff and Schaller, 2001; Phaal et al., 2004a).

The following are examples of different approaches and processes applied to develop a roadmap. Sandia National Laboratories designed its TRM development process in seven steps to focus on identifying drivers and requirements for choosing technology alternatives (Garcia and Bray, 1997). Philips Electronics comprehended a TRM process that develops their approach around scenario planning and information sharing (Groenveld, 1997). The expert-based approach (workshop) and a computer-based approach that use the methods of bibliometric and patent analysis are mentioned by Kostoff and Schaller (2001). Phaal et al. (2003a, 2003b) has developed the T-Plan process to support product planning by proposing an option to fast-start the roadmap implementation process. Dissel et al. (2006) developed upon the T-Plan process and creates a value roadmapping process that determines value streams of a firm to allocate resources to projects properly. Gerdsri (2007) proposed the process called technology development envelop (TDE) to develop a roadmap for emerging technologies.

2.2. TRM implementation

Many scholars have addressed several challenges throughout the different stages of TRM implementation. Fig. 2 presents the summary of key challenges in each stages of TRM implementation.

In the initiation stage, an organization may encounter challenges in defining an organization's objective for TRM implementation (Gerdsri et al., 2009), ensuring commitment from senior management (Groenveld, 1997, 2007; Kappel, 2001; Kostoff and Schaller, 2001; McMillan, 2003), and choosing the right key players from different teams to engage in TRM implementation (Brown and O'Hare, 2001; Gerdsri et al., 2009).

In the development stage, the challenges are in selecting and customizing a proper TRM approach to fit with an organization's objective (Brown and O'Hare, 2001; Fleury et al., 2006; Lee and Park, 2005; Phaal et al., 2003b; Phaal et al., 2001a, 2001b; Phaal et al., 2004b). Even though an organization has agreed with a suitable TRM process as it has been customized, the design and arrangement of TRM workshops for sharing the required knowledge during the process of TRM development is still proven to be challenging (Gerdsri et al., 2009; Kerr et al., 2012; Phaal et al., 2007). The quality of inputs and innovative ideas shared by workshop participants is also important (Brown and O'Hare, 2001; Li and Kameoka, 2003; McCarthy, 2003). Especially, analyzing the future trend may be quite challenging due to the unavailability of data for emerging technologies or market dynamics (Gerdsri, 2007; Strauss and Radnor, 2004; Vojak and Chambers, 2004).

In the integration stage, it is vital to ensure the sustainability of TRM implementation by integrating the TRM process into an organization's current business operation (Farrukh et al., 2001; Gerdsri et al., 2009; Groenveld, 1997, 2007; Phaal et al., 2004a; Phaal

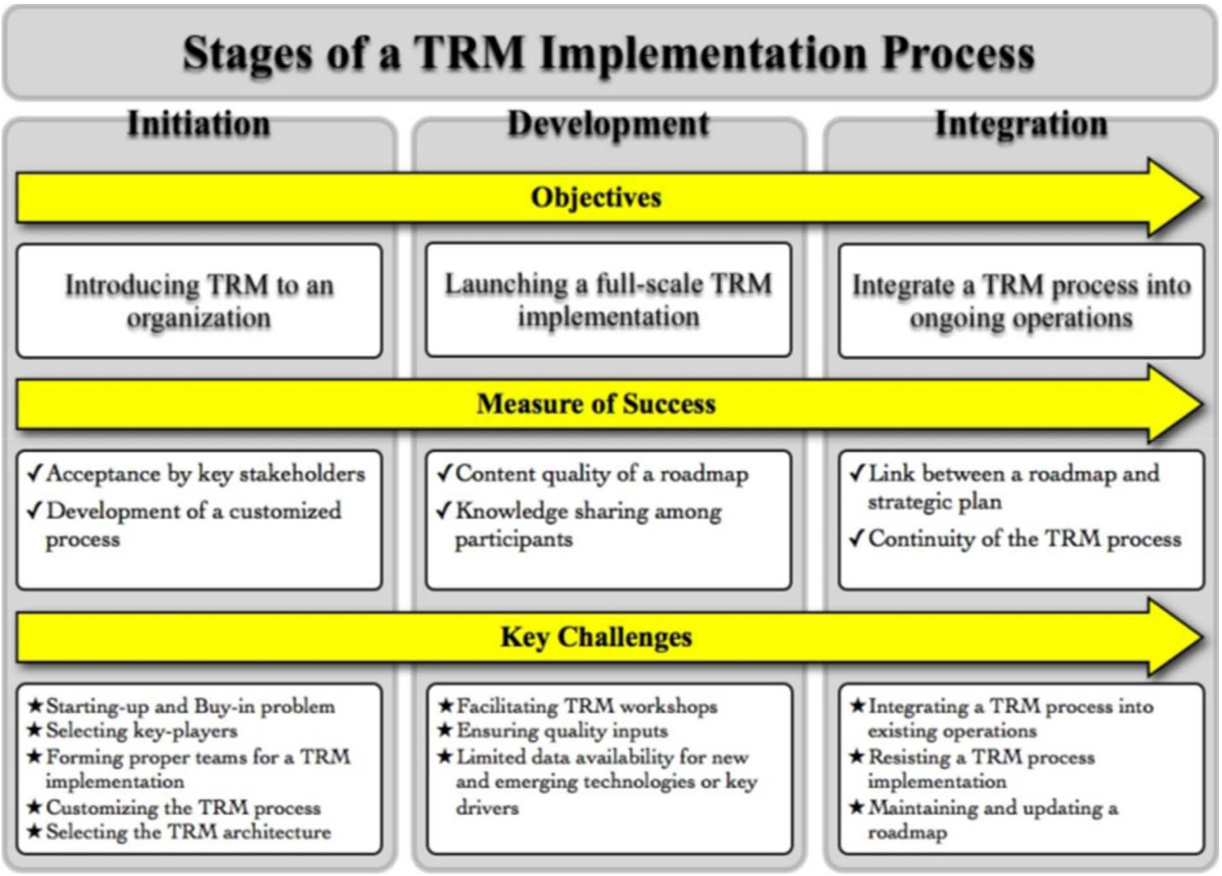


Fig. 2. Key challenges of each stages of TRM implementation (Gerdsri et al., 2013).

et al., 2001a, 2001b, 2005; Rinne and Gerdsri, 2003; Strauss and Radnor, 2004). An organization may encounter some resistance from staffs as an organization attempt to integrate roadmapping into an on-going business process. This issue could result in changes in an organization's culture and structure in which it can be managed by using change management techniques (Cosner et al., 2007; Gerdsri et al., 2010; McMillan, 2003; Waddell and Sohal, 1998). Moreover, there are challenges in maintaining and updating a roadmap to reflect any changes in key external and internal factors (Kappel, 2001; Kostoff and Schaller, 2001; Strauss and Radnor, 2004).

2.3. Challenges in maintaining and updating roadmaps

Keeping a roadmap alive seems to be a major challenge for many firms (Brown and O'Hare, 2001; Phaal et al., 2001a, 2001b, 2005; Phaal and Muller, 2009; Vatananan and Gerdsri, 2012; Wells et al., 2004, Strauss and Radnor, 2004). One reason is that a roadmap itself reflects only a snapshot of an organization's strategic plan including information up to the point when the roadmap was developed. However, an organization is always exposed to changes in its internal and external environment, which have different effects on a roadmap.

To keep a roadmap alive, an organization has to constantly review and update its roadmap. Few studies propose that the schedule of roadmap maintenance should be set (Holmes and Ferrill, 2008). For example, the roadmap is set to be reviewed every six months. However, this practice may sometimes result in the ambiguity of whether the original set period is the right timing to update a roadmap, especially when the time of tight business competition as well as disruption from new technology and market development. To be effective, a firm has to monitor the changes on these drivers that may affect the state of their roadmap and thus their strategic plan.

3. Proposed framework

3.1. Status of a roadmap and its signaling

Once a roadmap is implemented, a TRM operation team is responsible for monitoring the status of a roadmap. The status of a roadmap is determined based on the impact assessment of changes from both external and internal factors on a roadmap. The status

Table 1
Description of a Roadmap Status and Managerial Implications.

Status	Color code	Managerial Implications
"Maintain"	Green	Changes from both external and internal factors are still within the acceptable range and there is no impact or minor impact on a roadmap. Therefore, a roadmap can still stay as it is without revision.
"Adjust"	Yellow	Changes from both external and internal factors have impacts to a certain extent on a roadmap. Therefore, there should be some minor amendments on a roadmap.
"Revise"	Red	Changes from both external and internal factors are severe and have critical impacts on a roadmap. It causes a roadmap to be invalid. Therefore, there should be some major amendments on a roadmap.

signal of a roadmap indicates whether a roadmap is still usable or it is required to be updated. If the assessment results indicate that the roadmap is not usable, the major revision of a roadmap must be implemented. If the roadmap is still usable but need to be adjusted, the minor adjustment of a roadmap is then required. If the roadmap is not impacted from the changes, the roadmap can maintain as it is. Therefore, the definition of the status of a technology roadmap in this study is described in Table 1 along with the different color codes; red, yellow, and green, as shown below.

3.2. Managerial procedure for monitoring the status of a roadmap and making decisions to review a roadmap

A roadmap is a snapshot at the time of its development. However, the changes from external and/or internal factors could possibly occur after the development of a roadmap is completed. As aforementioned, the changes to certain degrees from these factors can impact the initial plan on a roadmap. An organization should monitor the changes of these factors and then evaluate whether the changing situation has impacted the targets/strategic focal points of a roadmap.

It is important for an organization to have a certain managerial procedure for monitoring the status of a roadmap. The mechanisms for data collection and analysis should also be defined to track changes and evaluate the impacts of changes from both external and internal factors on a roadmap. Once the impacts from the changes have gone beyond the acceptable level of an organization, a roadmap should then be considered to make an amendment. In this study, the managerial procedure is proposed in five steps as shown in Fig. 3.

The first step is to apply a roadmap after it has been developed. All involved people can refer to a roadmap and use it as checkpoints at each key milestone. Some involved teams can also manage their operation in accordance with the plan and timeline initially set on a roadmap. Thus, the plan which identified on a roadmap should be clearly communicated to all stakeholders. This would help ensure the achievement of the strategic targets within a specified timeline identified on a roadmap.

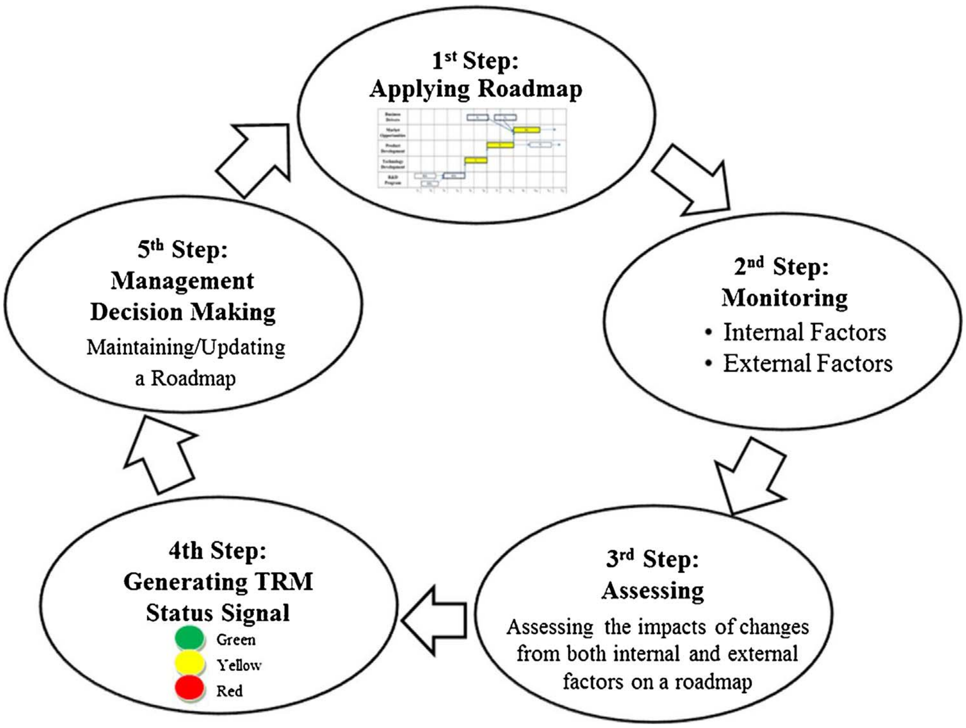


Fig. 3. The conceptual framework to assess the TRM status signal by considering the impacts of changes from both internal and external factors.

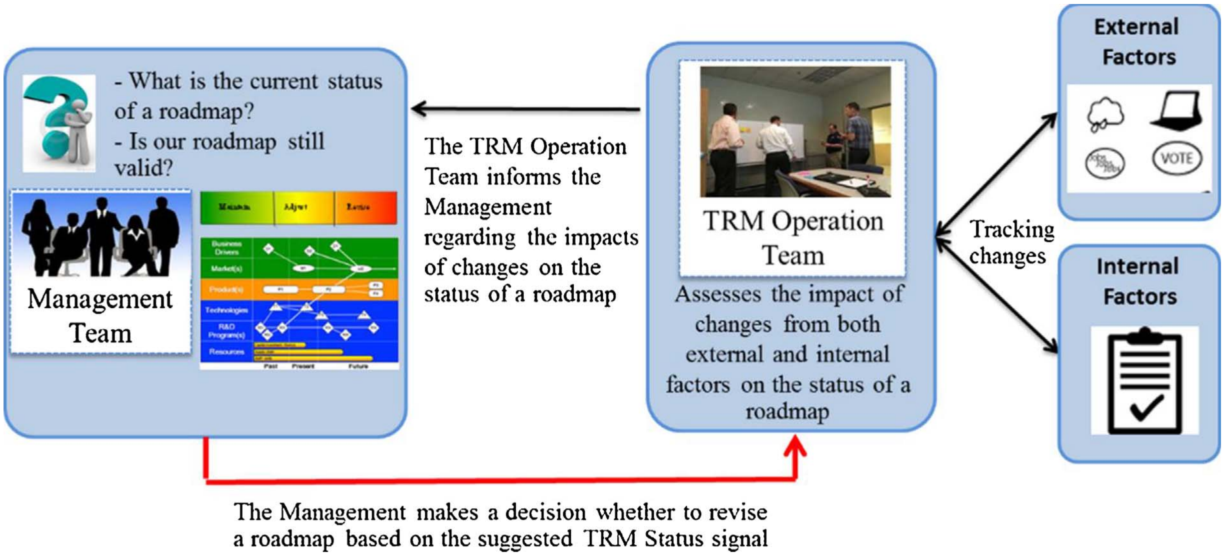


Fig. 4. Roles and interaction between the management and TRM operation team in monitoring the status of a roadmap and making decisions to review a roadmap.

The second step is to monitor the changes from both internal and external factors as specified on a roadmap. The components of external factors can be considered from social, technology, economic, environmental, policy, whereas internal factors can be considered from the progress of technology development.

The third step is to assess the impacts of changes on a roadmap. As the changes from the external and/or internal factors have already been notified, the identified changes will be used in this step to evaluate the impacts of the changes on a roadmap. Different organizations have different perception on the impacts of the changes. Some organizations are sensitive to the changes while the others are not. Therefore, this step is defined based on the perception of the organization.

The fourth step is to generate the TRM status signal. After evaluating the impacts of changes from both internal and external factors, the TRM status signal can be generated and visualized in the form of color-coded signals; red, yellow, and green. The meaning of each status signal is already discussed in Section 3.1.

The fifth step is the step which management makes a final decision whether a roadmap needs to be slightly adjusted, totally revised, or just kept it unchanged.

Throughout this procedure, the TRM operation team is responsible to monitor the changes of external and internal factors and then assess the impact of changing conditions on a roadmap. If the changes are more severe than the initial anticipation, the TRM status signal will indicate that a roadmap needs to be updated or totally revised. The TRM operation team has to inform the management team. The management will review their business contexts and decide whether they would follow the suggested TRM status signal. If so, then the management has to communicate their new vision and strategy to the TRM operation team.

The TRM operation team will take action to engage involved parties to review a roadmap. Once a roadmap has been revised, the updated version of a roadmap should be communicated again to all related stakeholders. Then, the stakeholders can brush up their plan and manage their operation in accordance with the updated roadmap. Fig. 4 presents the roles and interaction between the management team and TRM operation team in monitoring the status of a roadmap and making decisions to review a roadmap.

3.3. *Conceptual framework*

The conceptual framework has been developed to monitor the changes from both external and internal factors and assess the impacts from those changes on the status of a roadmap. The degree of impacts is pre-determined to reflect the management's perception on how much changes can be accepted. Three levels of impacts; revise, adjust, maintain, are defined as described in Section 3.1. The tolerance intervals associated with each level of impact are also determined. The status assessment of a roadmap is executed by analyzing the deviation between the actual and the predetermined baseline values at the measurement level of the evaluation models. Then, the changes are compared with the tolerance intervals to determine the degree of impact.

Fig. 5 demonstrates the proposed framework. The upper evaluation model is used to determine the impacts from changes in external factors; particularly the changes in key drivers, on a roadmap status. The lower evaluation model is used to determine the impacts from changes in internal factors; particularly the changes in technology development progress, on the status of a roadmap. The result obtained from the evaluation models will be calculated to determine the status of a roadmap. The TRM status signal will then be generated in green, yellow or red status.

3.3.1. *Assessing the impacts on the changes of external drivers*

This section presents the conceptual framework using analytical approach to construct and operate an evaluation model that can

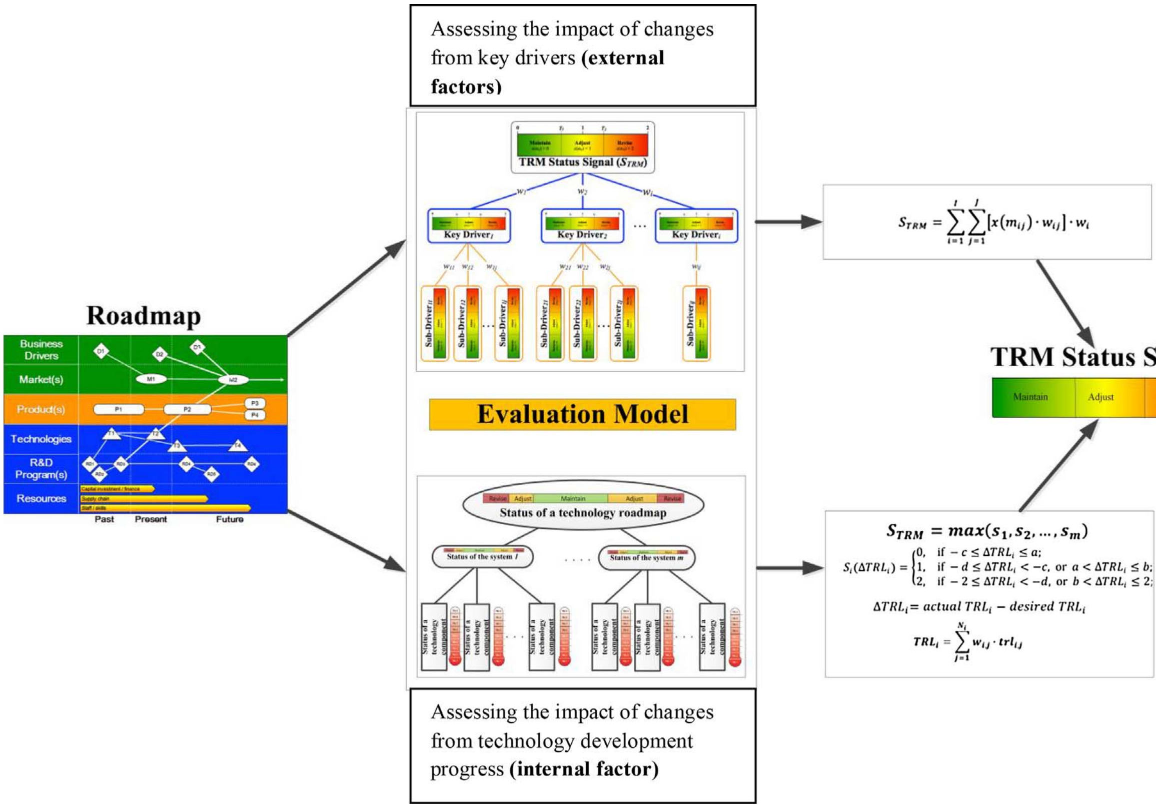


Fig. 5. Conceptual Framework to Assess the Impacts of Changes on the Status of a Roadmap.

assess the impact of changes from the external business environment on the current status of a roadmap. The objective of the model is to *determine the status of the organization's roadmap by analyzing changes in key drivers and their collective effect on the roadmap.*

3.3.1.1. Development of an evaluation model. The key drivers affecting the changes on the status of a roadmap are identified. Each key driver is also broken down into sub-drivers in which their changes can be measured directly. Fig. 6 shows the hierarchical structure of key drivers and sub-drivers analyzed in the evaluation model.

Level 1–Model Objective: The top level of the evaluation model represents the overall objective of the model, which is to analyze the effect of changes in key drivers on an organization's roadmap to determine its current status.

Level 2–Key Drivers: The key drivers (KD_i) are identified to reflect the organization's external business environment. The relative importance (w_i) of each key driver with respect to an organization's objective is determined. The value of w_i represents the intensity, with which a key driver affects an organization's strategy. However, an organization's environment is composed of numerous key drivers that can influence its operations and strategic plan. As a part of the roadmap development, it might be unpractical if not impossible to include all of the organization's key drivers. Therefore, only the most influential key drivers of an organization's environment are considered for the evaluation model.

Level 3–Sub-Drivers: A set of sub-drivers (SD_{ij}) is identified and their relative importance (w_{ij}) with respect to the key driver (i) is determined. Next, a unit of measurement is set for each sub-driver measurement value (m_{ij}) together with a data source to support the measurement. Now, for each SD_{ij} experts need to define the tolerance limits and intervals of the measurement values, to specify the various degree of impact from a change in these measurements as shown in Fig. 7. The baseline value (m_{base}) of each sub-driver is specified as the assumption in the roadmap development. The tolerance intervals are defined by the management to classify for the level of impact $x(m_{ij})$ on any changes (m_{ij}) from the baseline value (m_{base}).

3.3.1.2. Computational model. As a part of assessing the current state of a roadmap, changes in the organization's external factors; key drivers (KD_i) and sub-drivers (SD_{ij}), are tracked. The baseline values (m_{base}) and tolerance limits for each measurable sub-driver are determined. The level of impact $x(m_{ij})$ from such a change is assessed by analyzing the deviation of the sub-driver measurement values (m_{ij}) from their baseline values (m_{base}).

As a result the computational model produces the TRM status signal (S_{TRM}) as shown in Eq. (1), which serves as an indicator for the current state of a roadmap.

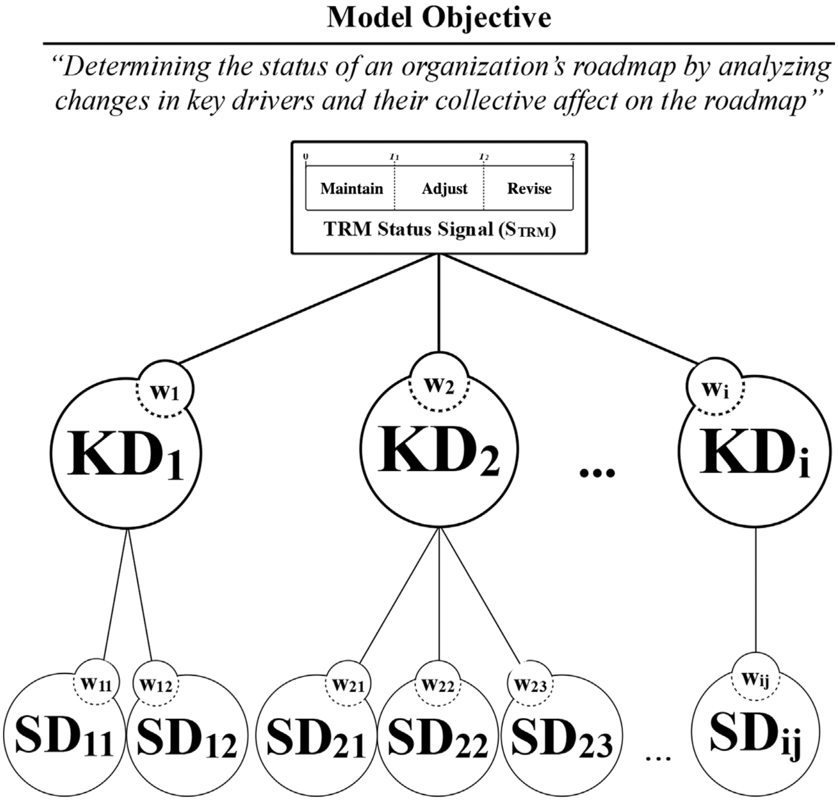


Fig. 6. Hierarchical Structure of an Evaluation Model.

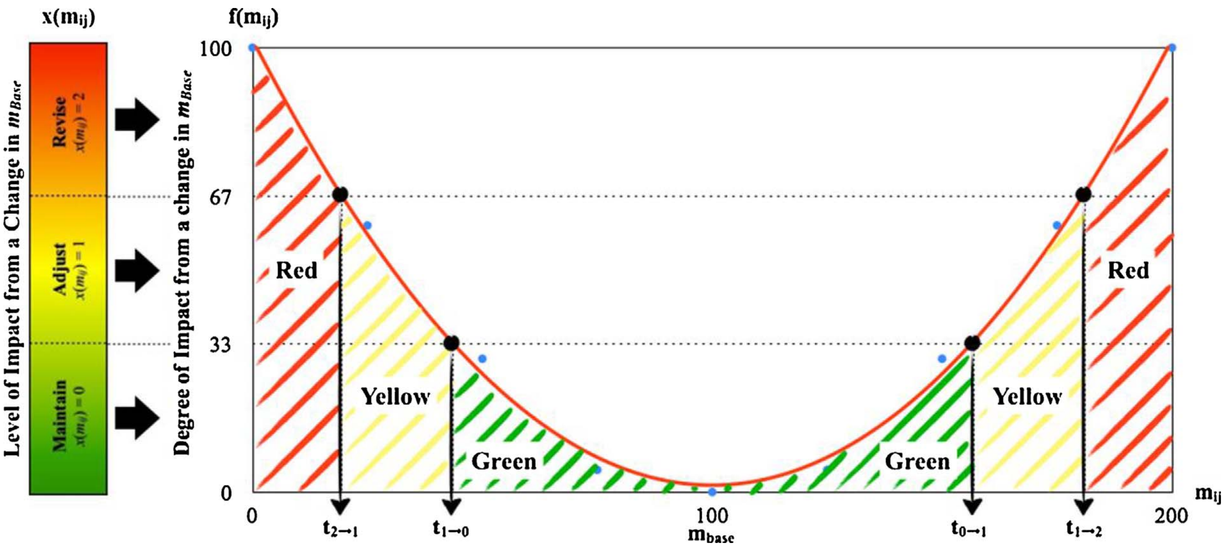
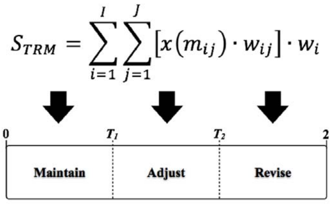


Fig. 7. Generic Pattern of a perception curve on the tolerance interval for a Sub-Driver Measurement.



$$S_{TRM} = \sum_{i=1}^{I} \sum_{j=1}^{J}[x(m_{ij}) \cdot w_{ij}] \cdot w_i \tag{1}$$

where:

w_i:Relative importance of key driver (i) with respect to the objective.

w_{ij}:Relative importance of sub-driver (j) associated with key driver (i).

m_{ij}:Measurement value of sub-driver (j) associated with key driver (i).

$x(m_{ij})$:A signal representing an integer value ($x(m_{ij})$ = [0,1, 2]) to indicate the level of impact from a change in the measurement value m_{ij} on a roadmap for the sub-driver (j) under key driver (i).

$x(m_{ij})$ = 0: Changes in m_{ij} have little or no impact.

$x(m_{ij})$ = 1: Changes in m_{ij} have a moderate impact

$x(m_{ij})$ = 2: Changes in m_{ij} have a major impact

$S_{KD_i} = \sum_{j=1}^{J} x(m_{ij}) \cdot w_{ij}$:A collective signal ($S_{KDi}$) indicating the status of measurement values for all sub-criteria j (i.e. sub-driver (SD_j)) under the criterion i (i.e. key driver (KD_i)).

S_{KDi}: Key driver status signal

$S_{TRM} = \sum_{i=1}^{I} \sum_{j=1}^{J} [x(m_{ij}) \cdot w_{ij}] \cdot w_i$: A collective signal indicating the overall status of a roadmap.

S_{TRM}: TRM status signal

3.3.1.3. Model measurement and operation. During the model construction process, a team of experts determines a unit of measurement for each sub-driver and a source of information to obtain the measurement value (m_{ij}). The team also defines a baseline value (m_{base}) for each sub-driver measurement. The m_{base} value reflects the status quo of a sub-driver at the time when the roadmap was developed. A roadmap can be maintained in its present state as long as there is no change in the baseline values. Any change in the baseline value reflects a deviation from the strategic plan represented by a current roadmap. For example, an organization needs to adjust or revise their strategy when a negative change in their sub-drivers threatens their overall strategic plan. On the other hand, a positive change can offer an unexpected opportunity and an organization should prepare itself to exploit this windfall by adjusting or revising their strategic plan. Once m_{ij} deviates from m_{base} the level of impact for that change is determined. According to the evaluation model an integer value $x(m_{ij})$ = [0,1, 2] is assigned to m_{ij}. The integer value $x(m_{ij})$ reflects the level of impact from a change in m_{base} and is determined by predefined tolerance intervals. The collective results on the impact of changes from all drivers accounted with the relative importance of each sub-driver are calculated to represent the status signal of a roadmap (S_{TRM}) as shown in Eq. (1).

3.3.2. Assessing the impacts on the changes of internal factors

This section presents the conceptual framework using technology readiness level (TRL) to construct and operate an evaluation model that can assess the impact of changes from internal factors; particularly from the technology development progress. As aforementioned, the changes in technology development progress either delay or ahead of the desired progress can impact the timing of strategic targets specified on a roadmap. The objective of the model is to *determine the status of the organization's roadmap by analyzing the impact of changes in technology development progress on the roadmap*.

3.3.2.1. Development of an evaluation model. The development of one product can be broken down into the level of systems and technology components. The status of product development at any given time is depended on the completion of technology components of each system. Therefore the status of product development specified on a roadmap is determined as an aggregate on the development progress of all technology components. Fig. 8 shows the hierarchical structure of systems and technology components required for the completion of product development specified on a roadmap.

Level 1–Model Objective: The top level of the evaluation model represents the overall objective of the model, which is to analyze the effect of changes in technology development progress on an organization's roadmap to determine its current status.

Level 2–Systems: This level represents all systems required as a part of the targeted product. The development of these systems is set to complete within the specified timeline on a roadmap.

Level 3–Technology components: This level represents technology components needed to be developed as a part of each system specified at Level 2.

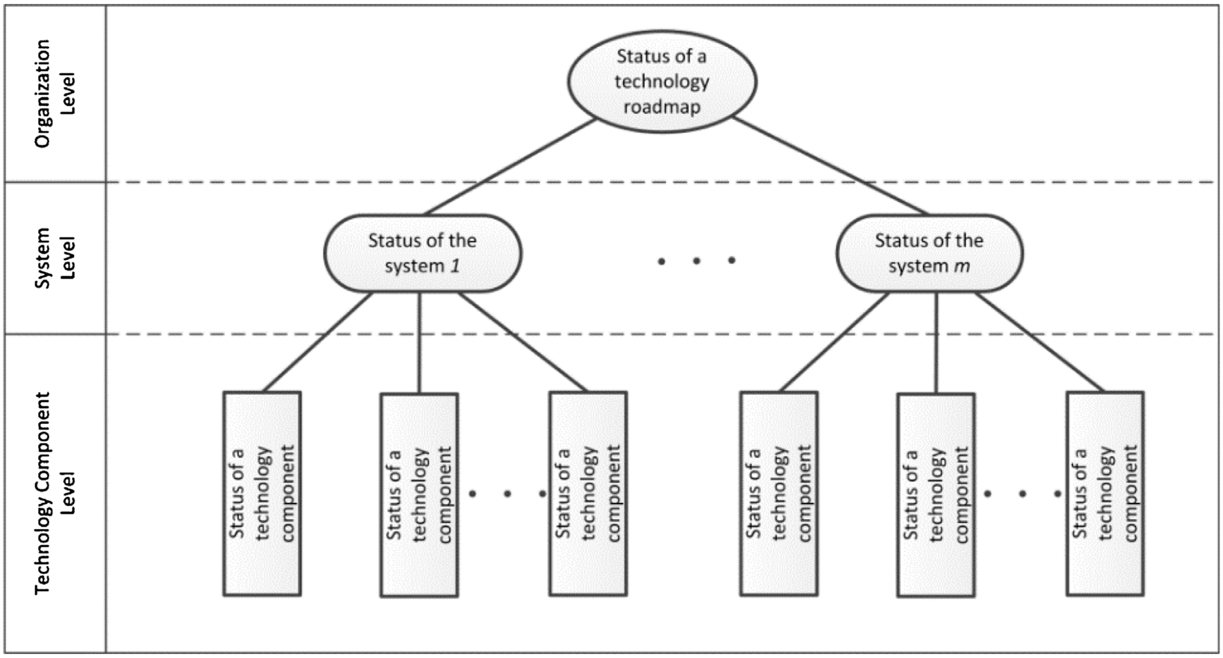


Fig. 8. Hierarchical structure of an evaluation model for assessing TRM status signal.

The development of each technology component is not always equally important. The level of technology readiness of some technology components may be close to the desired level as targeted on a roadmap. In this case, the development of these components may not so critical comparing to the development of some other technology components in which more development are needed to be done before meeting the desired level.

3.3.2.2. Computational model. A unit of measurement on the actual development progress for each technology component is considered in TRL scales. TRL concept was introduced by National Aeronautics and Space Administration (NASA) in mid 1970s and widely adopted by industry over the past 10 years (Mankins, 2009). The TRL scales range from 1 to 9. TRL1 is the level of pure research which the basic principles are observed and reported while the TRL9 is the level that an actual system is successfully operated. Fig. 9a provides the overview of the technology readiness level scales. There is a tool that can be used to measure Technology Readiness Levels called 'TRL calculator'. It is designed in the form of Microsoft Excel Spreadsheet and can be used to evaluate the development of both software and hardware technology. The calculator would provide sets of questions for the user and employ the answer gained to calculate the result on the level of TRL (Altunok and Cakmak, 2010; Nolte et al., 2003; Technology Readiness Assessment Guide, 2011). Fig. 9b provides the example of TRL calculator.

As aforementioned, the TRL calculator is applied as a tool to measure the actual development progress of a technology component at current milestone. The level of importance on the development of each technology component is taken into account to consolidate the actual development progress of all technology components in order to calculate the actual development progress for a system. The actual development progress of a system gives management the overview on the status of the development progress of a system at current milestone.

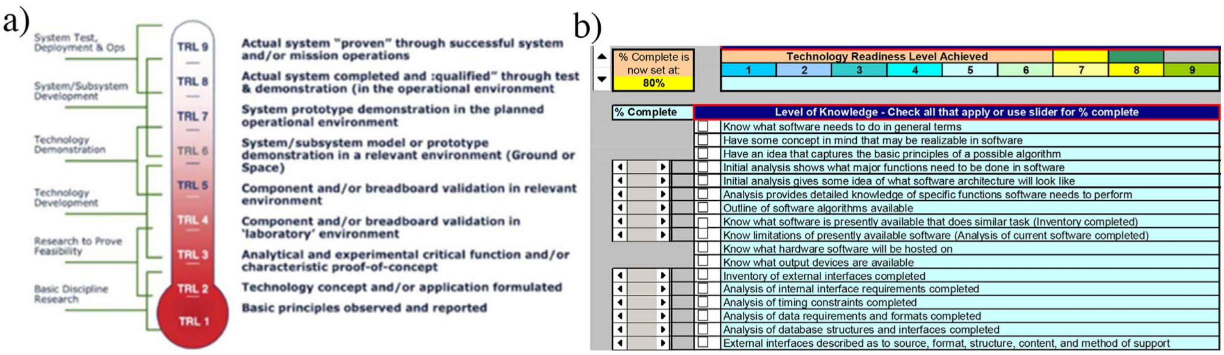


Fig. 9. (a) Tahe overview of the TRL scale (Mankins, 2009); (b): Example of TRL calculator (Nolte et al., 2003).

The desired development progress of each technology component at different milestone is pre-identified during the planning stage. To calculate the desired development progress for a system, the desired development progress of all technology components are consolidated with the consideration of the level of importance on the development of those technology components to the completion of the system. The desired development progress of a system gives management the overview on the progress projection of a system at each milestone.

Changes in the development progress of a system are calculated based on the deviation between the actual and desired development progress of a system at the time of assessment. The degree of impacts from changes is pre-determined to reflect how much the management can tolerate to changes in development progress before considering to adjust or revise status of a roadmap. There are four equations which would be used in the computational part of the evaluation model to assess the TRM status signal. The four equations are shown below;

1. Equation to compute the progress (actual and desired development progress) of the system *i* (TRL_i).
2. Equation to compute the changes in development progress of the system *i* (ΔTRL_i).
3. Equation to compute the development status of the system *i* (S_i).
4. Equation to compute the status of a technology roadmap (S_{TRM}).

To calculate the development progress (actual/desired development progress) of a system by using TRL scales, the development progress of all technology components are consolidated with the consideration of the level of importance on the development of those technology components to the completion of a system. Therefore, the level of technology readiness on the development progress of the system *i* (TRL_i) can be computed from:

$$TRL_i = \sum_{j=1}^{N_i} w_{i,j} \cdot trl_{i,j} \tag{2}$$

Where:

i = index of systems

j = index of technology components

$trl_{i,j}$ = the level of technology readiness on the development progress of technology component *j* belong to the system *i*

N_i = the number of technology components belong to the system *i*

$w_{i,j}$ = the relative importance on the development of technology component *j* with respect to the completion of system *i*

The Eq. (2) is used at the *model development stage* to construct a *progress projection curve* for a system by consolidating the progress projection curve of all technology components with the consideration of the level of importance on the development of those technology components to the completion of the system. The progress projection curve for a system represents the projection on the development progress of a system at different milestone.

In addition, Eq. (2) will also be applied at the *model operation stage* to evaluate the actual level of technology readiness on the development progress of a system by consolidating the actual level of technology readiness on the development progress of all technology components with the consideration of the level of importance on the development of those technology components to the completion of the system.

In brief, Eq. (2) can be applied for the computation of the desired development progress for a system at the model development (planning) stage as well as the actual development progress for a system at the model operation (monitoring) stage. Therefore, the desired progress and actual progress on the development of a system *i* which represented by TRL can be computed from Eq. (2.1) and (2.2) respectively.

$$desired\ TRL_i = \sum_{j=1}^{N_i} w_{i,j} \cdot desired\ trl_{i,j} \tag{2.1}$$

$$actual\ TRL_i = \sum_{j=1}^{N_i} w_{i,j} \cdot actual\ trl_{i,j} \tag{2.2}$$

Where:

i = index of systems

j = index of technology components

$desired\ TRL_i$ = the desired level of technology readiness on the development progress of system *i*

$desired\ trl_{i,j}$ = the desired level of technology readiness on the development progress of technology component *j* belong to the system *i*.

$actual\ TRL_i$ = the actual level of technology readiness on the development progress of system *i*

$actual\ trl_{i,j}$ = the actual level of technology readiness on the development progress of technology component *j* belong to the system *i*

N_i = the number of technology components belong to the system *i*

$w_{i,j}$ = the relative importance on the development of technology component *j* with respect to the completion of system *i*

To determine the changes in development progress of a system, the difference between the actual development progress and desired development progress of the system at the measuring milestone is considered. The comparison between the actual progress($actualTRL_i$) and the desired progress ($desiredTRL_i$) reveals whether the current development progress of a system *i* is delayed or ahead of the strategic timeline identified on the technology roadmap by how far. The changes in development progress of the system *i* (ΔTRL_i)can be computed from:

$$\Delta TRL_i = \text{actual } TRL_i - \text{desired } TRL_i; \tag{3}$$

Where:

$actual\ TRL_i$ = the actual level of technology readiness on the development progress of system *i*

$desired\ TRL_i$ = the desired level of technology readiness on the development progress of system *i*

Note that the ΔTRL_i with negative values indicate that the current development progress of the system *i* is *less than* the desired development progress which means that the development of the system *i* is currently delayed. While the ΔTRL_i with positive values indicate the current development progress of the system is *more than* the desired development progress which means that the development of the system *i* is currently ahead of the targeted timeline. Eq. (3) is used at the *model operation stage* to determine the level of changes in development progress of a system at current milestone. The the development status of the system *i* (S_i) would be represented by integer value as following;

Maintain Status (green signal) = 0

Adjust Status (yellow signal) = 1

Revise Status (red signal) = 2

The development **status of the system *i* (S_i)** can be computed from:

$$S_i(\Delta TRL_i) = \begin{Bmatrix} 0, & \text{if} -c \le \Delta TRL_i \le a; \\ 1, & \text{if} -d \le \Delta TRL_i < -c, \text{ or } a < \Delta TRL_i \le b; \\ 2, & \text{if} -2 \le \Delta TRL_i < -d, \text{ or } b < \Delta TRL_i \le 2; \end{Bmatrix} \tag{4}$$

Where ΔTRL_i is the changes in development progress of system *i*, and $S_i = 0$ indicates a “maintain” status, $S_i = 1$ indicates an “adjust” status and $S_i = 2$ indicates a “revise” status. While *a, b,* $-c$ and *-d* are the points of tolerance intervals (Fig. 10) which represents how much an organization can tolerate to changes in development progress before the development status is changed to adjust or revise status.

Since a targeted product identified on a technology roadmap can be comprised of more than one system, status of a technology roadmap (S_{TRM}) is derived from the development status of the system (S_i, i = 1,2,…,m) which has *maximum* integer value of the development status. This is because all systems are part of the targeted product. The maximum integer value on the development status of a system reflects the most severe development situation of the targeted product for the management to be aware of. However, the management can also track back to understand the development status of any system belong to the targeted product if they are interested to.

With the rationale previously explained, the **status of a technology roadmap (S_{TRM})** can therefore be computed from:

$$S_{TRM} = \max(s_1, s_2, \dots, s_m); \tag{5}$$

Where:

s1, s2, …, sm are the statuses of the system 1, 2,…, m respectively.

m = The number of systems belong to the targeted product

Note that Eq. (5) would be applied in the final step of *model operation stage* in order to determine the current status of a technology roadmap once the development status of all systems have already been determined.

3.3.2.3. Model measurement and operation. Technology manager is collaborated with technology development team to monitor the actual development progress of each technology component. The technology developers use the TRL calculator to assess the actual development progress of a technology component. Experts of an organization then determine the level of importance on the development of each technology component to the completion of a system.

To assess the changes in technology development progress at a system level, the difference between the actual and desired development progress of a system is calculated. For example, the desired development progress of a system should achieve TRL7 at current milestone; however, the actual development progress of a system at current milestone is only at TRL 6. The development progress of a system is currently delayed by 1 level of TRL. Therefore, the changes in development progress would indicate not only whether the current development progress is delay or ahead of the desired plan but also by how far. Once the changes in development progress of a system are determined, the impact of changes on the status of a roadmap is then needed to be evaluated. The experts of an organization would determine the *tolerance intervals* which represent how much an organization can tolerate to changes in

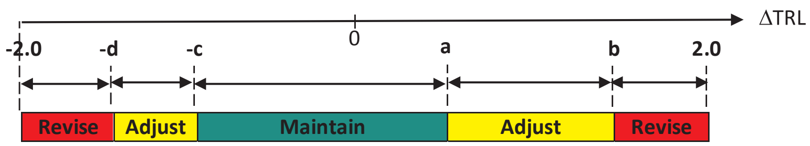


Fig. 10. Tolerance intervals indicating how much an organization can tolerate to changes in development progress.

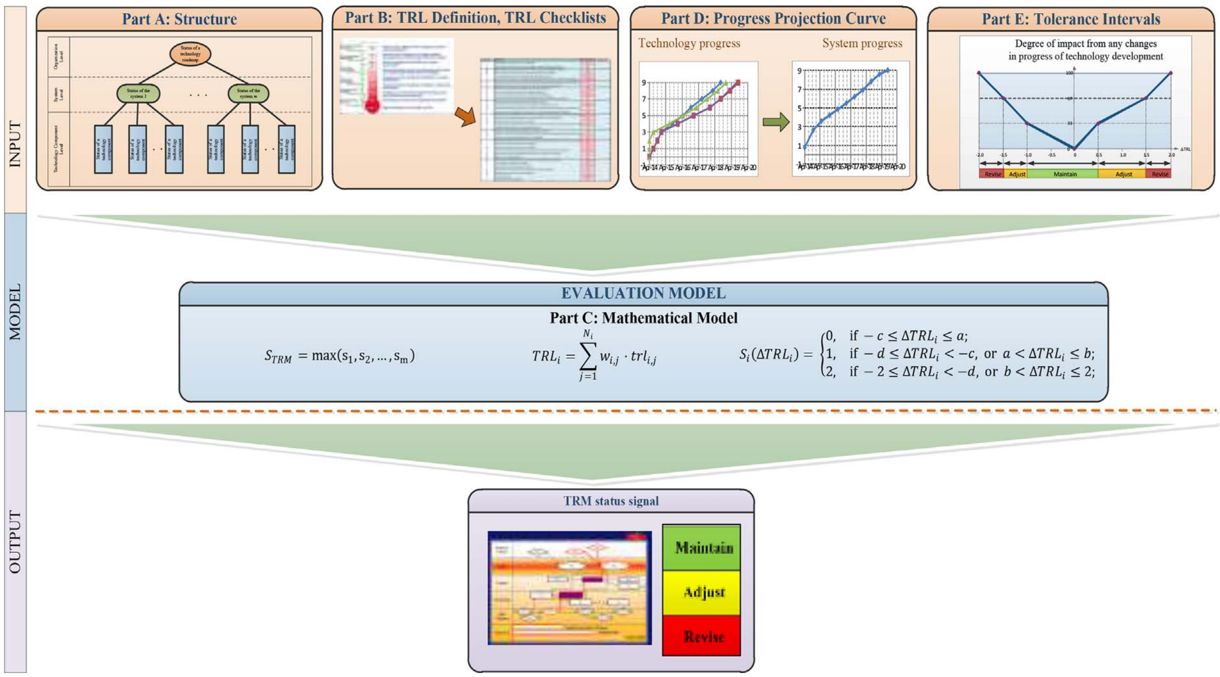


Fig. 11. Evaluation model to determine the current status of a technology roadmap with the consideration of the impacts of changes in technology development progress (i.e., internal factor).

development progress before the status is changed to adjust or revise status. The tolerance intervals are separated into three intervals of *maintain (green)*, *adjust (yellow)* and *revise (red)* interval. If the changes in development progress are little and occur within the maintain (green) tolerance interval, the changes may not affect the roadmap. Therefore, the roadmap can probably stay as it is. However, if the changes are significant and go beyond the maintain (green) tolerance interval, then the roadmap requires the updating to reflect the changing situation. Failure to update the roadmap at the appropriate time could result in inefficient management of resources and budget and affect the company's competitiveness in the market. Fig. 11 demonstrates the evaluation model to determine the current status of a technology roadmap with the consideration of the impacts of changes in technology development progress.

4. An illustrative example

With an aging population that continues to grow while economic growth in many countries gets slower, the situation has demanded for more supports to keep elders age-well and being able to live independently longer at home while try to reduce the burden of caretakers and control healthcare costs. One of major ongoing development is the assistive robotic technologies.

For the organization presented as a case example in this section, the company's roadmap has been set in 2017 to guide the future development of its fully automated assistive robotics. The key drivers impacting the future development are identified as the increase of elderly population, the shortage of caregivers, the government policy on financial support for elders and tax incentives for manufacturers, the availability and affordability of new technologies like energy storage and sensor, etc. The results on trend analysis of these key drivers present that the suitable timing for launching the fully automated assistive robotics is in 2021. To complete in time, the development of key technology components should be planned as shown in the roadmap (Fig. 12).

Assuming that today is at the end of 2018, the trends of each key drivers get reassessed and the development status of key technology components also get reported according to the pre-defined level of technology readiness (TRL). The results show that the progression of some drivers has reached the target sooner than the initial projection. For example, in 2017 at the time we developed this roadmap, we anticipated that the cost of energy storage would reduce from 400 Euro/Wh in 2018 to 200 Euro/Wh in 2020 but now we observe that the cost of energy storage has fallen faster which it is expected to be 200 Euro/Wh in 2019 (one year sooner than the initial plan). While the progression of some drivers seems to be slower than the initial projection. For example, in 2017 we anticipated that the government will launch a special financial packages in 2019 supporting elders and also offer 10% tax reduction incentive to assistive robotic developers and manufacturers. But due to economic slowdown, there is a clear signal that the government would continue to increase the monthly allowance for elders but it may be slightly lower than expected. While the tax incentive plan would be postponed for another 2 years. For the development status of key technology components, the report shows the development progress of rechargeable battery, composite material, sensor, and software has achieved the targeted TRLs while the development progress of motor&drive, 3D printed part, and micro-controller has lagged behind the targeted TRLs.

With the abovementioned circumstance, it leads to the question for the management to decide whether their initial roadmap in

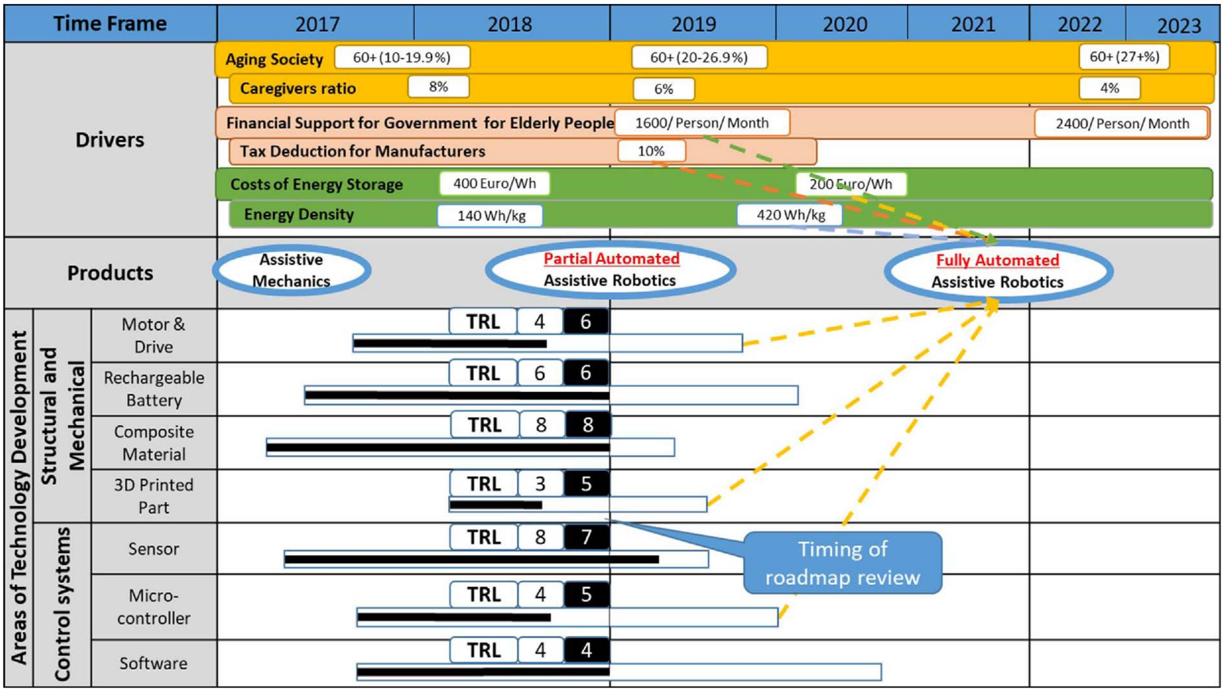


Fig. 12. A case company's roadmap on the development of fully automated assistive robotics.

2017 is still valid. Should the target for launching the fully automated assistive robotics initially set for 2021 be adjusted or totally revised?

4.1. Computational demonstration

The following calculation (Table 2) represents the impact of changes on external drivers causing S_{TRM} to signal "Adjusted" recommendation to the initial roadmap.

The following calculation tables represent the impact of changes on technology development progress from the structural and mechanical systems causing S_{TRM} to signal "Adjusted" recommendation to the initial roadmap (Table 3) as well as "Maintain" recommendation from the control systems (Table 4). Taking the development progress of both systems into consideration, the status of overall recommendation should reflect from the most severe case. Therefore, the TRM status (S_{TRM}) signals "Adjusted" recommendation to the initial roadmap.

By evaluating the impacts of changes from both external and internal environment as shown above, it indicates that the changes are significant enough. Therefore, the initial roadmap set in 2017 must be adjusted. The management should call the meeting as earliest as possible to update their roadmap with the tendency to launch the fully automated assistive robotics sooner due to the faster development of market opportunity in this area. In the meantime, the management needs to call the immediate meeting with key technology development teams to discuss major issues causing the development progress to be lower than the targeted TRLs. The solutions or remedies must be concluded in the meeting with the clear plan for monitoring their effectiveness.

Table 2
Calculation on the impact of changes from external drivers .

Description	Weight w(i)	Tolerance Limits					Actual	Calculation	
		$t_{2\to1}$	$t_{1\to0}$	m(base)	$t_{0\to1}$	$t_{1\to2}$	m(i)	x[m(i)]	w(i) * x[m(i)]
Aging Society	0.10	10	15	20	25	30	20	0	0
Caregivers ratio	0.10	8	7	6	5	4	6	0	0
Financial Support	0.25	1200	1400	1600	1800	2000	1400	1	0.25
Tax Deduction	0.20	0	5	10	12	14	0	2	0.40
Costs of Energy Storage	0.20	400	350	300	250	200	250	1	0.20
Energy Density	0.15	100	150	200	300	400	250	0	0
Sum	1.00								0.85
							TRM Status Signal		Adjusted

Table 3
Calculation on the impact of technology development progress: *Structural and mechanical systems* .

Technology Components	weight	Desired TRL	Actual TRL	Difference
Motor & Drive	0.20	6	4	
Rechargeable Battery	0.30	6	6	
Composite Material	0.35	8	8	
3D Printed Part	0.15	5	3	
	1.00	6.55	5.85	−0.70 Adjusted

Table 4
Calculation on the impact of technology development progress: *Control systems*.

Technology Components	weight	Desired TRL	Actual TRL	Difference
Sensor	0.35	7	8	
Micro-controller	0.50	5	4	
Software	0.15	4	4	
	1.00	5.55	5.4	−0.15 Maintain

5. Conclusion

Since a roadmap represents a case at the time of developing it, it does not reflect the *changing situation* happening after the finish of the roadmap development. From time to time, the changes from any of the components/factors, which are identified on a roadmap, may occasionally occur. Thus, it is highly important for management to ensure that a roadmap is kept up-to-date along with the changing situation. Otherwise, a roadmap can eventually become obsolete. Without a clear process to identify the current status of a roadmap, management sometime find that it is quite a big challenge to keep the roadmapping process alive.

This paper therefore attempts to address the challenge of maintaining the technology roadmap by determining the current status of a roadmap. Under the constant changing situation, the consideration of the impacts of changes from *both* internal and external factors of an organization on a technology roadmap is therefore taken into account. The previously mentioned conceptual framework of this paper indicates the common steps used for evaluating the impacts of changes from both external factor (i.e., key drivers) and internal factor (i.e., technology development) on current status of a roadmap.

Through the operation of the conceptual framework, the TRM status signal is therefore generated in the final step. The generated TRM status signals would help an organization to make a clearer or even better decision whether the current technology roadmap is still usable. If the generated TRM status signal suggests that the technology roadmap is not up-to-date, management can then be aware of the current status of a technology roadmap. As such, management can make a decision to amend the technology roadmap in line with the occurring changes from any of the factors at the appropriate point of time. As a result, the technology roadmapping implementation can become successful and management can still maintain the competitive edge of the organization.

References

Altunok, T., Cakmak, T., 2010. A technology readiness levels (TRLs) calculator software for systems engineering and technology management tool. Adv. Eng. Software 41 (5), 769–778.
Brown, R., O'Hare, S., 2001. The use of technology roadmapping as an enabler of knowledge management. Paper Presented at the IEE Seminar on Managing Knowledge for Competitive Advantage.
Cosner, R.R., Hynds, E.J., Fusfeld, A.R., Loweth, C.V., Scouten, C., Albright, R., 2007. Integrating roadmapping into technical planning. Res.-Technol. Manage. 50 (6), 31–48.
Dissel, M., Phaal, R., Farrukh, C., Probert, D., 2006. Value roadmapping: a structured approach for early stage technology investment decisions. Paper Presented at the 2006 Technology Management for the Global Future-PICMET 2006 Conference.
Farrukh, C., Phaal, R., Probert, D., 2001. Industrial practice in technology planning-implications for a useful tool catalogue for technology management. Paper Presented at the Management of Engineering and Technology, 2001. PICMET 2001. Portland International Conference.
Fleury, A.L., Hunt, F., Spinola, M., Probert, D., 2006. Customizing the technology roadmapping technique for software companies. Paper Presented at the Technology Management for the Global Future, PICMET 2006. Portland International Conference.
Garcia, M.L., Bray, O.H., 1997. Fundamentals of Technology Roadmapping (Unlimited Release No. SAND97-0665). Strategic Business Development Department, Sandia National Laboratories, Albuquerque, NM.
Gerdsri, N., Vatananan, R.S., Dansamasatid, S., 2009. Dealing with the dynamics of technology roadmapping implementation: a case study. Technol. Forecasting Social Change 76 (1), 50–60.
Gerdsri, N., Assakul, P., Vatananan, R.S., 2010. An activity guideline for technology roadmapping implementation. Technol. Anal. Strategic Manage. 22 (2), 229–242.
Gerdsri, N., Kongthon, A., Vatananan, R.S., 2013. Mapping the knowledge evolution and professional network in the field of technology roadmapping: a bibliometric analysis. Technol. Anal. Strategic Manage. 25 (4), 403–422.
Gerdsri, N., 2007. An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies. Int. J. Innovation Technol. Manage. 4 (02), 121–135.
Gerdsri, N., 2013. Implementing Technology Roadmapping in an Organization Technology Roadmapping for Strategy and Innovation. Springer, pp. 191–210.
Groenveld, P., 1997. Roadmapping integrates business and technology. Res. Technol. Manage. 40 (5), 48.
Groenveld, P., 2007. Roadmapping integrates business and technology. Res.-Technol. Manage. 50 (6), 49–58.

Holmes, C., Ferrill, M., 2008. A Process for the update and review of operation and technology roadmaps. Int. J. Innovation Technol. Manage. 5 (2), 247–258.
Kappel, T.A., 2001. Perspectives on roadmaps: how organizations talk about the future. J. Product Innovation Manage. 18 (1), 39–50.
Kerr, C., Phaal, R., Probert, D., 2012. Addressing the cognitive and social influence inhibitors during the ideation stages of technology roadmapping workshops. Int. J. Innovation Technol. Manage. 9 (06).
Kostoff, R.N., Schaller, R.R., 2001. Science and technology roadmaps. IEEE Trans. Eng. Manage. 48 (2), 132–143.
Lee, S., Park, Y., 2005. Customization of technology roadmaps according to roadmapping purposes: overall process and detailed modules. Technol. Forecasting Social Change 72 (5), 567–583.
Li, M., Kameoka, A., 2003. Creating added value from roadmapping process: a knowledge-creating perspective. Paper Presented at the Engineering Management Conference, 2003. IEMC 2003. Managing Technologically Driven Organizations: The Human Side of Innovation and Change.
Mankins, J.C., 2009. Technology readiness assessments: a retrospective. Acta Astronaut. 65 (9), 1216–1223.
McCarthy, R.C., 2003. Linking technological change to business needs. Res.-Technol. Manag. 46 (2), 47–52.
McMillan, A., 2003. Roadmapping-agent of change. Res. Technol. Manage. 46 (2), 40–47.
Nauda, A., Hall, D.L., 1991. Strategic Technology Planning-developing Roadmaps for Competitive Advantage. the New International Language, Paper presented at the Technology Management.
Nolte, W.L., Kennedy, B.C., Dziegiel, R.J., 2003. Technology readiness level calculator. Paper Presented at the NDIA Systems Engineering Conference.
Phaal, R., Muller, G., 2009. An architectural framework for roadmapping: towards visual strategy. Technol. Forecasting Social Change 76 (1), 39–49.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2001a. Characterisation of technology roadmaps: purpose and format. In: Paper Presented at the Portland International Center for Management of Engineering and Technology (PICMET). Portland, OR, July 29 – August 2.
Phaal, R., Farrukh, C., Probert, D., 2001b. T-plan: the Fast Start to Technology Roadmapping: Planning Your Route to Success. University of Cambridge.
Phaal, R., Farrukh, C., Mitchell, R., Probert, D., 2003a. Starting-up roadmapping fast. Res.- Technol. Manage. 46 (2), 52–59.
Phaal, R., Farrukh, C.J.P., Mills, J.F., Probert, D.R., 2003b. Customizing the technology roadmapping approach. Paper Presented at the Portland International Center for Management of Engineering and Technology. (PICMET).
Phaal, R., Farrukh, C.J., Probert, D.R., 2004a. Technology roadmapping, A planning framework for evolution and revolution. Technol. Forecast. Social Change 71 (1), 5–26.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2004b. Customizing roadmapping. Res. Technol. Manage. 47 (2), 26–37.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2005. Developing a technology roadmapping system. In: Paper Presented at the Portland International Center for Management of Engineering and Technology (PICMET). Portland, OR., July 31 – August 4.
Phaal, R., Farrukh, C.J., Probert, D.R., 2007. Strategic roadmapping: a workshop-based approach for identifying and exploring strategic issues and opportunities. Eng. Manage. J. 19 (1), 3–12.
Rinne, M., Gerdsri, N., 2003. Technology roadmaps: unlocking the potential of a field. In: Paper Presented at the Portland International Center for Management of Engineering and Technology (PICMET). Portland, OR, July 20–24.
Strauss, J.D., Radnor, M., 2004. Roadmapping for dynamic and uncertain environments. Res. Technol. Manage. 47 (2), 51–57.
Technology Readiness Assessment Guide. U.S. Department of Energy, Washington, D.C.
Vatananan, R., Gerdsri, N., 2012. The current state of technology roadmapping (TRM) research and practice. Int. J. Innovation Technol. Manage. 9 (04), 1–20.
Vojak, B.A., Chambers, F.A., 2004. Roadmapping disruptive technical threats and opportunities in complex, technology-based subsystems: the SAILS methodology. Technol. Forecasting Social Change 71 (1), 121–139.
Waddell, D., Sohal, A.S., 1998. Resistance: a constructive tool for change management. Manage. Decis. 36 (8), 543–548.
Wells, R., Phaal, R., Farrukh, C., Probert, D., 2004. Technology roadmapping for a service organization. Res.-Technol. Manage. 47 (2), 46–51.