TECHNOLOGY READINESS IMPACT ON HIGH-TECH R&D PROJECTS

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In this paper the impact of technology readiness on the activities in an R&D project is discussed. For this, NASA's technology readiness level (TRL) model, initially developed for aerospace is applied to R&D projects. Two case studies from electronics and robotics are presented. Based on this, it is determined that projects can be grouped in four distinct categories, depending on the TRLs of the technologies used in the project. These categories can be used in the future for selecting the best project management approaches, depending on technologies readiness.

In this way, the paper aim is to contribute to the current efforts of finding suitable management approaches, depending on project main characteristics.

Keywords: project classification, technology readiness level, technology uncertainty, project novelty, high-tech projects, R&D projects

1. Introduction

High-tech industries, including areas such as IT, robotics, aeronautics, electronics, etc., are characterized by a sustained rhythm of innovation. The need for innovation is dictated by the markets for such industries, which are very dynamic and competitive, demanding for continuously higher performance at the same or even reduced price.

In R&D projects within high-tech industries, new products are designed, using not only established technologies, but also a substantial amount of new technologies. In fact, in many such projects, new technologies are being developed in parallel to the product design.

From a project management perspective, the higher the amount of technology innovation, the higher is the level of uncertainties of the project. In the past years several studies have shown that for projects with high uncertainty, traditional project management approaches are not well suited [1] - [4]. In order to determine new, better suited project management approaches, it is important first to understand very well the characteristics of such projects, as well as the exact

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impact that the uncertainties related to new technologies have on the projects.

In this paper the characteristics of new technology development, as well as its impact on a project are analyzed. The ultimate goal of this analysis is to help determining a classification of high-tech projects and allow the selection of the best project management approach.

2. Literature review

Traditional project management (TPM) approach [5], requires that project specifications are set at the beginning of the project, within the planning phase. Also, during the same phase, a detailed plan has to be developed. This plan is the essential document for the subsequent project activities. Any change in the project is regarded as an exception and its consequences on the project have to be limited through risk management.

This approach, although very mature and extremely useful for deterministic projects, has been recently questioned by many authors. There have been many discussions on the inability of the traditional methods of project management to deal with modern projects and consequently on the need of "changing" them to better fit these projects [1]-[4], [6]-[8]. IEEE Engineering Management Review had a special issue on *Rethinking Project Management* [1], [2]. Some of the present realities presented in [1], [2] that demand for new project management approaches include the fact that many modern projects have "a fuzzy concept of a goal", the fact that project success is no more the "conformance to the written requirements" but the achievement of the business case. In high-tech R&D projects the "fuzzy concept" and the incomplete requirements that some projects have at their starting point are common and mainly due to the high degree of innovation of those projects.

Therefore, the classical project management style cannot be suitable for all types of high-tech R&D projects. Particularly, it is of limited benefit for projects in which:

- Specifications cannot be almost entirely set at the beginning of the project and will constantly change during the project life cycle;
- Exact effort estimation cannot be achieved, due to the high degree of novelty (at least for that organization) of some of the technologies used/ developed within the project;
- Frequent changes appear due to the new manufacturing technology used in the project or due to the high degree of innovation

This conclusion is well demonstrated and explained in the research works of Shenhar and Dvir [4], [6], [7]. Based on their own research as well as other previous works, the authors introduced a framework using a project classification on four dimensions: (product) novelty, technology, complexity and pace. This is best explained in [4], which summarizes previous works. The technology dimension classifies the projects in terms of how new is the set of technologies used by the project. The newer the technology, the higher is the uncertainty of the project. New technology implies more design cycles and consequently a later design freeze. The authors proposed a classification of projects into several categories, for each of these dimensions [4]. Based on this classification, the authors demonstrated that the traditional approach of project management (TPM) cannot suit each category of projects, and, consequently, different approaches have to be taken depending on the project characteristics. This project classification based on technology is generic, and refers to any type of project, therefore it is not precise enough for the classification of high-tech, R&D projects.

A very detailed classification of technology maturity, or readiness level was developed by NASA and has been used by several US Government agencies [9]-[11]. For instance, Department of Defense (DoD) has used such a classification "as a metric to assess the maturity of a program's technologies before its system development begins"[10]. The main purpose of this classification is to facilitate the acquisition and the investment in development of novel equipment. Based on it, other classifications have been introduced to better describe the maturity of complex systems, where the integration aspects are critical [10], [11].

NASA's technology readiness level (TRL) classification uses 9 levels, starting from new idea and up to successful, proven system based on newly developed technologies [9]. Despite being targeted to aerospace technologies, the paper will show how they can be used for any type of high-tech R&D projects.

3. Technology readiness level and its impact on project

An important factor generating uncertainties in an R&D project is the technology level [4], [8], [12]. The newer and less mature is a technology, the higher is the level of uncertainty it introduces, thus impacting the project management activities.

Based on the technology level, Shenhar and Dvir propose a classification of projects in four categories [4]: super high tech, high tech, medium tech, low tech. The distinction is made by two factors: the novelty/ maturity of the technologies as well as the relative ratio of new versus existing technologies used in the project. Also, there is a very important distinction between new technologies that are available (have been developed recently) and technologies that do not exist and need to be invented or developed.

The paper will analyze in more details the type of new technologies and their effects on project management, with the final goal of improving the criteria for classifying the R&D projects in one of the categories.

A characteristic of many R&D projects is the fact that they do not just use existing technologies to design a new product, but, they develop a technology based on which the product is designed. In other words, if the needed technology does not exist, the product design goes in parallel with the technology development.

To understand this, the following sections investigate in more detail the stages in the development of a new technology. The starting point is the concept of technology readiness level (or maturity). A detailed classification of technology maturity is provided by NASA's Technology Readiness Level [9], [13]. This classification is reproduced in Table1.

Inspecting the NASA definitions and trying to map them to general technologies and R&D projects (outside the aerospace industry), it can be noticed that TRL 4 is a major milestone, separating the concept/ basic idea or principle (TRLs 1-3) from an integrated system (even if with limited features and performance - "low fidelity"). Similarly, TRL 7 is a significant improvement from levels 4-6, since a full prototype is demonstrated in an operational environment.

4. Case studies analysis

To illustrate how NASA's TRLs can be applied to general technologies, two examples are presented and discussed below.

The first one is the flash memory technology [14]- [18]. As it is known, the concept was invented by Masuoka, when working for Toshiba. He worked on the concept of what was to become the first NOR [18] flash memory, for about 4 years (1980-1984). This period involved both analytical, concept work as well as test-chips experiments [14]. It corresponds to TRLs 1-3, until he obtained a proof-of-concept chip, which was an indication that the new technology might work.

Table 1

TRLs Description [9], [13]

Technology Readiness Level (TRL)	**Description**
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption.

	Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively “low fidelity” compared to the eventual system. Examples include integration of “ad hoc” hardware in a laboratory.
5. Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonable realistic supporting elements so that the technology can be tested in a simulated environment. Examples include “high fidelity” laboratory integration of components.
6. System/subsystem model or prototype demonstration in an operation environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system competed and “flight qualified” through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases this TRL represents the end of true system development. Examples include developmental test and evaluation of the system and in its intended weapon system to determine if it meets design specifications.
9. Actual system flight proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last “bug fixing” aspects of true system development. Examples include using the system under operational mission conditions

He then developed and presented a prototype of the new memory at the annual International Electronics Developers Meeting in San Jose, in 1984.

That prototype had the basic functionality of a memory chip, but still incipient performance and would correspond to TRL 5 or 6. As known [14], [15] several companies were interested in the new technology and Intel invested significantly in reproducing the concept and especially in improving the technology to make it more manufacture-able and affordable [16]. In this case, TRLs 5-8 do not differentiate by the environment on which the technology is applied and tested, but by the level of performance, manufacturability, cost (silicon area) and reliability of the different prototypes, which are in this case test-chips. TRL 8 would correspond in this case to technology qualification, the last step before a chip can be released to production in the new technology. Finally, Intel designed a memory product using this technology and introduced it on the market, in 1988. This was the validation of the technology, which meant moving to TRL 9.

In parallel, Toshiba worked on both catching up and on creating a new version of the flash memory, the NAND flash. The prototypes development and testing went on during 1986-1989 and the new technology was announced in 1989. Because of its generic nature, the flash memory technology can be applied in numerous applications and starting with early ‘90s, several companies introduced many new products based on this technology. This included SanDisk, introducing the first compact flash card in 1994, Information Storage Devices introducing the flash-based voice recorder chip in 1992 and Casio introducing QV11 digital camera using flash memory [15]. Since all these products represent applications that are quite different from the original, computer-based flash memory, the companies that developed them went through a suite of prototypes in order to refine the technology, before their final product was released. Of course, this refers to the internal prototypes for testing the successive improvements and does not include the potential prototypes that the companies presented for determining market reaction and finalizing the product specifications. In all these cases, the companies created their own new technologies, evolving from TRL 4 to TRL 9.

Also, in this example it can be noticed that although the initial flash memory was invented in order to answer a clear practical need, i.e. data storage and retention in computers, it has not turned into an actual design project until it had passed the proof-of-concept milestone, which corresponds to TRL 4. Moreover, immediately after, many projects were started by other companies, in order to apply the technology for new applications. This confirms a pattern, which is also mentioned in [4], that most of R&D projects for many industries do not start from the very initial stages of a new technology (TRLs 1-3). This activity of initiating brand new technologies, which has a very high degree of uncertainty, is more commonly carried on either by start-ups or by separate teams in large corporations.

Another example of development of new technologies refers to the design of the Sojourner robot for Mars exploration [19] - [25]. This was part of the Pathfinder mission, which landed on Mars on July 4th, 1997 [19]. There is much literature on Pathfinder, but it is most interesting to look at the robot design, which is a closer example of an R&D project. The robot was required to move on the Mars soil, get pictures and send them to Earth via the lander and pick several rocks [19],[20]. It was controlled from Earth by an operator looking at the received images, but because of the 10-15 mins delay between sending the images and receiving the command, it had to be also autonomous. At that time, robots were at a very incipient stage and only two other robots had unmanned missions on a celestial body, Moon, but they were Soviet [19]. Sojourner, designed by a Jet Propulsion Laboratory team [22],[23] had to employ several new or brand new technologies. A mechanical system, required to ensure movement on a surface with different consistency and pass over obstacles comparable to its size had not been done before, so that technology was very incipient, at TRL 2. Similarly, the autonomous navigation and obstacle avoidance had been tried before to a certain extent indoor, but not on an unknown outdoor environment, so it was at TRL 3-4, whereas the image capturing, compression and transmission was at its infancy, at TRL 4-5. The rover was developed through a series of prototypes called Rocky 1-4, followed by the final Sojourner [23]. The first prototype was very incipient and focused only on developing a first mechanical system able to ensure stability and climbing over rocks about twice its size. It was on a reduced scale and did not have any autonomous control, neither sensors, nor cameras. This was indeed just a proof-of-concept that robots can move on such an adverse terrain. Thus its successful completion advanced the mechanical technology to TRL 5. The first version of the control system was tested on an indoor prototype, advancing this technology to a similar TRL 5. Then Rocky 3 integrated an improved mechanical system, sensors and autonomous control [24]. It was massively tested outdoors on terrains that were as similar as possible to what Mars soil was supposed to be. At that point, the rover was at TRL 6. Rocky 4 was the final fully integrated prototype, equipped with all scientific equipment. It also employed several changes and improvements in the mechanical as well as in the navigation system, as suggested by Rocky 3 testing. At that point, all the new technologies on rover were at TRL 7. This provided the confidence that the rover will be successful. After that point JPL did not need to use another fully integrated prototype, but only partial versions such as Rocky 4.2 (MFEX), in order to test improvements in some subsystems. Finally, the Sojourner rover was designed and constructed from special materials to operate on the adverse climate conditions on Mars and at that point it was at TRL 8. After its successful mission, the new technologies used in rover reached TRL9.

In this example it can be seen how several technologies are developed and refined to work on a single product. This is similar to many R&D projects where the product is built using several technologies, many of which may be new, even brand new, whereas some may be mature technologies. In such cases, the prototypes allow not only the development and testing of each technology, but also of their integration.

As seen also in these two case studies, it can be determined that TRLs 1-3 correspond to technologies that do not exist yet, TRL 9 to well-established, proven technologies, whereas TRLs 4 -8 determine different levels of development, with TRL 7 as a significant milestone.

Based on these examples, it can be understood how the technology readiness level affects the project activities. In an R&D project, the project design is based on one or several technologies.

If all needed technologies have been already developed, before the project start, they are on TRL 9 and they introduce no uncertainty to the project. From a technology impact viewpoint, there are very few changes expected, the project is then deterministic and can be managed in a traditional way.

If (at least some of) the needed technologies are demonstrated, but not finalized, corresponding to TRL 7-8, they will have to be brought to TRL 9, before the actual product design can be completed. This effort may require some (usually low) level of prototyping and project can be approached in a traditional way, but expecting some level of changes due to technology uncertainties.

If there are technologies on TRL 4-6, they have to evolve first to level 7, and only then product design can advance. Clearly, developing them to level 7 requires several prototypes and adjustments, so there is a great amount of changes that one should expect and the project should be approached in an iterative manner. Activities can be difficult to determine, let alone planned, therefore a more Agile approach is better suited.

If technologies are on level 1-3, they have first to be evolved to TRL 4 (corresponding to a proof-of-concept). Of course, during these stages exact activities are very difficult to be determined and the project is extremely iterative.

5. Conclusions

In this paper the way in which the development of new technologies within an R&D project impacts the project is analyzed. For this, the TRL model developed by NASA was applied to R&D projects. Two case studies from electronics and robotics have been presented and analyzed. All this confirmed the conclusion that the less developed the technology, the greater the uncertainty introduced and the more iterative is the project flow. Furthermore, the paper determined that the 9 TRLs can be grouped into four categories, based on the relationship between the technology development and the product design activities. Thus, if technologies are in TRL 1-3, they are too immature to be used in the design of a product and the project focus is to evolve them to TRL 4. In this stage, the project activities are very difficult to be planned and the project is extremely iterative. For technologies in TRL 4-6, the product design can be initiated, but the main focus remains on developing the technologies. The project remains iterative, but short-term activities can be planned. For technologies in TRL 7-8, the product can be designed, in parallel with technologies refinement. The project is now deterministic and hence longer-term plans can be used, but changes to the plan are very probable, due to some uncertainties still associated with the technologies. Finally, for TRL 9, the technologies are mature and products based on them can be planned, while changes to the technologies uncertainties are improbable.

In practice, at project start, the technologies needed in an R&D project can be in any of the above four groups. Therefore, in such a project, the technologies are developed, evolving to TRL 9, in parallel with the product design.

Based on these conclusions, it is possible to use the TRL model to determine the maturity of the technologies needed in a project and then, their impact on the project activities and planning. Consequently, it is possible to study in the future what type of project management approach is best suited for R&D projects, depending on the TRL of the needed technologies, thus advancing the efforts of finding suitable project management approaches based by project characteristics presented in [1]-[3] and especially [4], [6]-[8].

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