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Study of technology maturity assessment in project management

Supervisor

Prof. Alberto De Marco

Co-supervisor

Prof. Clovis Armando Alvarenga Netto

Candidate

Corrado Musci

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Introduction

"It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change"[1]. This sentence wants to point out that only the changing is a winning strategy through time. From the companies' point of view, changing means innovation and it becomes a lasting source of competitive advantage. Moreover, companies are focusing mainly on customer needs: the need for high customization forces companies to adopt different organizational and production models. In this contest, the companies are project oriented[2] ignoring the project standardization and the economies of scale. Thought the project oriented, a competitive advantage has been created using the development of innovative and differentiated projects. Considering the innovative point of view, the time-cost-quality approach is nowadays used to define the features key. However, the conception of project itself needs to change to better represent the innovative aspect of the projects. For these reasons, the gap is the lack of an effective methodology for project evaluation.

The literature review demonstrates that few attempts were made to define a new methodology for fulfil this gap. However, this is still a challenge because the methodologies have same weakness basically related to them indicators. Furthermore, another limitation of these methodologies is the lack of meaningful case studies datasets to test and validate them.

This Master's degree thesis aims to provide a model to estimate the maturity and innovation goodness of the project. This qualitative assessment model is based on previous knowledge and particularly on the "Technology Readiness Assessment" made and improved by NASA and focus on the technical aspects. The main challenge is to identify of the most effective indicators and to validate the new methodology on real case study.

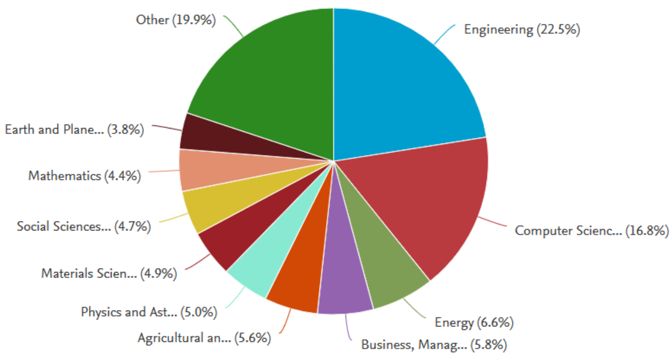

Figure 1 Distribution of articles on technological maturity (10330 results on www.scopus.com)

The literature on technological maturity is very various and embraces multiple sectors. Over time, many studies and many variations of the original model have arisen. In this work, there are some examples as food

[1] *Leon C. Megginson,* Civilisation Past and Present, *1963.*

[2] A Project Oriented Organization can be defined as an organization that: defines "Management by Projects" as an organizational strategy; applies temporary organizations for the performance of complex processes; manages a project portfolio of different project types; has specific permanent organization structures to provide integrative functions; applies the "New Management Paradigm"; has an explicit project management culture; perceives itself as being project-oriented.

for thought and with a view to developing some indicators that correct the gaps. The work evaluates these models and reworking leads a new model that should solve the issues encountered.

This thesis is composed by four chapters. The first chapter summarizes the strategic, economic and financial analysis. It is a necessary step in order to evaluate the project sector and how to exploit this in order to take advantages. After that, some indicators are presented to numerically evaluate the profitability of a project in a comparative perspective. The second chapter regards the Technology Readiness Assessment (TRA) that identifies its purpose and analyze the process. In details, this analysis is based on the Technology Readiness Level (TRL) which is the core of this work. The third chapter identifies the main issues of the TRA and the TRL. It studies the TRL state of the art and propose some changes for a more effective model. Indeed, it propose a customized model to solve the gaps of the previous models. A GUI application has been designed based on the new model and the various mockups have been implemented.

The fourth chapter proposes a study case to demonstrate the differences between the new and the existing methodology. The study case is the “Radiometer Atmospheric CubeSat Experiment” that is a technological mission of NASA / JPL and UTA with the goal of proving the technology of the microwave radiometer.

In conclusion, the thesis studies the Technological Maturity and the possible practical solutions for its assessment. The main result of this thesis is the development of customized TRL that compared with the existing methodologies introduces new indicators for the project assessment.

1. Strategic and Economic Analysis

1.1 The evaluation path of a project

In general, a company deals with several projects. These projects are organized in Project Portfolios. A portfolio is a collection of projects belonging to the same sector of application. Therefore, companies don't own unlimited resources and must prioritize some projects according to predetermined criteria. Assuming that, companies adopt a top-down approach to solve this optimization problem. First, they choose which portfolios they want to distribute their resources to. In this context, it would be better to carry out a careful analysis of the portfolios sector. This is indispensable in order to understand the strengths and weaknesses of the sector, whether it is advantageous to act in that sector or how to take advantage of its peculiarities. It is, therefore, necessary to carry out a strategic analysis and nowadays several tools are available for this purpose.

After carrying out an accurate strategic analysis of the sector with the choice of the portfolios, the individual Business Case of the projects is built in order to define the possible value created. In this context, the analysis of some economic and financial indicators evaluates profitability and financial sustainability of the project.

1.2 Strategic Analysis

Michael Porter[3] asserts that strategy is how a company differs from others to achieve goals, create a competitive advantage and make itself "unique". After identifying the long-term objectives, an analysis of the sector in which it operates is needed to understand its peculiarities, strengths, and weaknesses: knowing about the sector in which the company operates allow to adopt an efficient strategy that creates a lasting and sustainable competitive advantage.

SWOT analysis and Porter's Forces analysis are the most used techniques for carrying out an accurate sector analysis.

1.2.1 SWOT Analysis

SWOT analysis, attributed to Albert Humphrey[4], is a tool used in the strategic analysis phase to evaluate the Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) in a company in order to pursue strategic objectives: it is an essential strategic planning tool. It is used both in business and in university settings. There is a direct proportionality between the strategic value that each of these elements have and its importance; thus, every element of the SWOT analysis is fundamental to realize a complete analysis and even a little simplification has been taken carefully.

The strengths and the weaknesses concern the organization defined as internal environment made by production capacity, production system technology, qualified personnel. The threats and the opportunities, on the other hand, concerns the external environment of the organization represented by the main macroeconomic, social, political and cultural variables. Internal and external factors have been analysed with two different tools. For the internal factors PRIMO-F method is generally adopted while for the external factors PEST analysis is the main framework. The PRIMO-F model was developed from some work of Durham University Business School. Their research show how business growth model evaluates business

[3] Michael Eugene Porter is an american academic known for his theories on economics, business strategy, and social causes. He is the Bishop William Lawrence University Professor at Harvard Business School, and he was one of the founders of the consulting firm The Monitor Group and FSG, a social impact consultancy.

[4] Albert S. Humphrey was an American business and management consultant who specialized in organizational management and cultural change. Initially earning degrees in chemical engineering in Illinois, he eventually moved to London. Humphrey developed the SWOT analysis technique while working for the Stanford Research Institute.

performances by analysing several factors. The work proves that an effective organization needed to fulfil the following equation:

$$Organizational\ Growth\ Effectiveness = Perfomance\ to\ date * Potential\ for\ the\ future$$

Performance to date	Potential for the future
Finance	Resources
Marketing	People
Operations	Innovation and Ideas

Table 1 Elements of Organizational Growth Effectiveness

According to this, the growth effectiveness is given by the product between the first type of factors, in the first column of Table 1, and the second, in the second column. The result of this analysis allows to identify only the initial competitive advantage that a company has towards its competitors. However, this doesn't allow to make any inferences about the future. Furthermore, model weaknesses include a possible subjective assessment depending on the analysts' specialization and the difficulty of distinguishing the factors category. The PRIMO-F model is a simplification of this model. There are a lot of situations where it is difficult to discriminate the elements of one and the other category and it is difficult to apply daily.

Figure 2 PRIMO-F elements

As shown in, PRIMO-F model (Figure 2) focuses on potential for the following aspects:

- **People (P)** are analysed based on their managerial experience (e.g. product development, use of external agents, moving sites) their leadership (e.g. owner manager age, education and training) and the controls (e.g. ability to use information, planning and monitoring adequacy, how performance is assessed).
- **Resources (R)** are analysed on availability, utilization and appropriateness (fit for purpose).
- **Innovation & Ideas (I)** are evaluated based on their number, level of development or market testing and how creative they are.
- **Marketing (M)** is based, for a specific field, on effort, focus and effectiveness of actions.
- **Operations (O)** specify what are the systems in place, the equipment and the productivity.
- **Finance (F)** is about the cashflow, access to finance and management.

The PEST, also known as PESTAL analysis, deals with external evaluation and inspects in detail the following factors:

- **Politics (P)** concerns the set of trends that politicians pursue in a given historical moment and which influence the business of a given sector. Possible variables are the adoption of stricter or more incentive rules for a given sector, political stability and regulation of national or international markets.
- **Economy (E)** assesses the sector profitability based on the costs changing for raw materials or labour, the revenues increasing or decreasing depending on the presence of markets for substitute or complementary goods.
- **Social (S)** aspect concerns the society in which a particular business it is immersed, the ethical rules and its behaviours. Furthermore, to evaluate this aspect, it has also been considered the demography (i.e. the composition of the population) and the existing or potential needs of society.
- **Technology (T)** can cause major changes inside the industry. The introduction of new technologies can crucially increase the productivity and the costs reduction. The willingness of workers to adapt to new technology or the presence of already skilled labour is also important for a faster change process.

- **Environmental (A)** impact of a business is also fundamental because the companies can produce harmful waste, can determine economic problems and disincentivize the business even from an ethical point of view. On the other hand, businesses with a positive impact on the environment is incentivized (for examples through renewable energy).
- **Legal (L)** aspect is linked to the current legal system and the opportunity or threats it offers.

After the use of these techniques (PRIMO-F and PESTAL), it is possible to identify the elements of the SWOT analysis. The SWOT has several sequential phases:

1. Defining the objectives;
2. Defining the quadrants of the SWOT matrix: the strengths of the organization that facilitate the achievement of the objectives; the weaknesses of the organization which disadvantage the achievement of the objectives; the opportunities that are the external factors useful for the pursuit of the objectives; threats or external factors that could slow down or even endanger the set objectives.
3. Verifying goals to be realistic.

SWOT	***Useful Quality for achieving the objectives***	***Harmful qualities for achieving the objectives***
Internal environment	Strengths (S)	Weaknesses (W),
External environment	Opportunities (O)	Threats (T)

Table 2 SWOT model

If the objectives are not realistic SWOT analysis could also assess how internal or external forces can be exploited to achieve other objectives. Theoretically, because of the multidisciplinary of analysis, it requires a number of different figures such as an engineer, a lawyer and a manager.

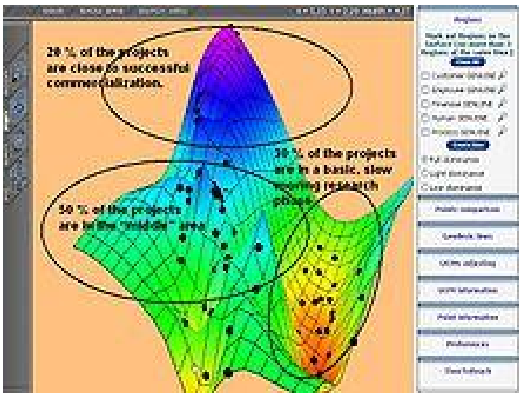

Figure 3 Example of SWOT-landscape analysis

A variant of the SWOT analysis is the SWOT-landscape analysis (Figure 3). This analysis involves the study of different projects requested through forecasts and statistical inferences. The projects are evaluated and classified according to whether there are opportunities or risks.

Generally, SWOT analysis use must be carefully made and constantly integrated with other tools and with economic and financial attention in order to have a vision of the sector being analysed.

1.2.2 Porter's Five Forces Analysis

Porter realized that observing the work of other companies is a necessary but not enough to gain a competitive advantage to them. In fact, he recommends to the companies to evaluate the sector in which they operate and proposes a model for this purpose.

Porter's "5 Forces model" (Figure 4) assesses that the profitability of a sector is a result of 5 competitive factors which affect with the actions taken by a company and can facilitate its operations.

These forces can be classified into:

- **Three sources of horizontal competition**: Threat of Substitution, Threat of New Entry, and Competitive Rivalry;
- **Two sources of vertical competition**: Supplier Power and Buyer Power.

The five Forces are:

1. Threat of Substitution: substitute goods are goods that satisfy the same need but in a different way. An example of a good substitute is an innovative technology capable of carrying out the work previously performed by the labour force. The presence or absence of substitute goods affects the price elasticity of the good: in the presence of many substitute goods, the demand for the good will be very elastic. Among the factors that influence this force are the inclination of the consumer to replace the good and the price-performance ratio of the substitutes and the complexity of the need. In fact, greater is the complexity of the asset, bigger is the difficulty of distinguishing the differences between performance and costs.
2. The threat of new entries: if the sector profitability is high, it will attract more and more companies until theoretically the condition of perfect competition. The ease of access impacts the possibility of entering a new business and depends on the presence of the barriers to entry. The absence of entry barriers determines the sector can be defined as "contestable industry". In this case, the threat of the entrants is enough for the company to maintain a competitive price in order to keep out other companies. Sometimes competitors used a hit-and-run strategy to damage the company's goal. Otherwise, the presence of entry barriers creates a competitive advantage for the company and can preserve its profitability which will be higher than the average.
   The main barriers to entry are:
   - High capital requirement: the need to make huge investments in Research and Development structures.
   - Economies of Scale: the capital-intensive sectors paid by relatively low unit costs only if distributed on a high productivity scale. New entrants have a limited production scale and they have to face higher unit costs.
   - Absolute cost advantage: in some cases, the cost advantage may not depend on the size but on the purchase of cheap raw materials and learning economies[5].
   - Product differentiation: if the brand of a company is recognized by the consumer, it will benefit from a loyalty of the consumer. The new entrants spend a lot on advertising to cover this gap.
   - Access to distribution channels: having a solid and efficient distribution network is fundamental for the sale of consumer goods. The construction of this network often involves huge costs and time.
   - Legal barriers: the need for patent licenses, patents, or compliance with environmental requirements, especially for new entrants.
   - Retaliation: companies adopt aggressive strategies towards new entrants in order to discourage them. An example would be the sudden drop in prices or the increase in advertising campaigns.
3. Competitive rivalry: the competition is between companies already established in a specific sector. This competition is influenced by the following factors:
   - Concentration of sector: it depends on the number of sellers and the distribution of market shares among them. In more concentrated markets, price discretion is greater and price alignment is easier both by collusion and more typically by a "parallelism" of price decisions. Greater is the number of companies, more difficult is the possibility of coordination and greater is the chance that the price will drop.

[5] Learning Economies are based on the know-how picked up through experience. They depend from becoming a true specialist in a certain field.

- Diversity of competitors: the proximity between cost structures and objectives of companies determines a greater probability of collusion.
- Product differentiation: lower is differentiation between products of companies, greater is competition of price and lower is the profitability.
- Barrier on exit: they are the costs to be incurred in the event of leaving the sector. They are often related to production capacity or worker protection.

4. Buyer Power: it depends on two factors:
    - Price sensitivity: it depends on several factors including product quality. So greater is the product quality, lower is price sensitivity; competition between buyers and differentiation of the company cause how a buyer chooses the company.
    - The relative bargaining power: the ability to bargain or not of the buyers. It depends both on the cost generated by the lack of a transaction for the parties involved and on the experience of each "player". Other possible factors could be the concentration of suppliers and the symmetry of information.
5. Supplier Power: suppliers are those from whom a company buys raw materials for the input of its production process. It mirrors the "Buyer Power". Suppliers of complex components keep great bargaining power.

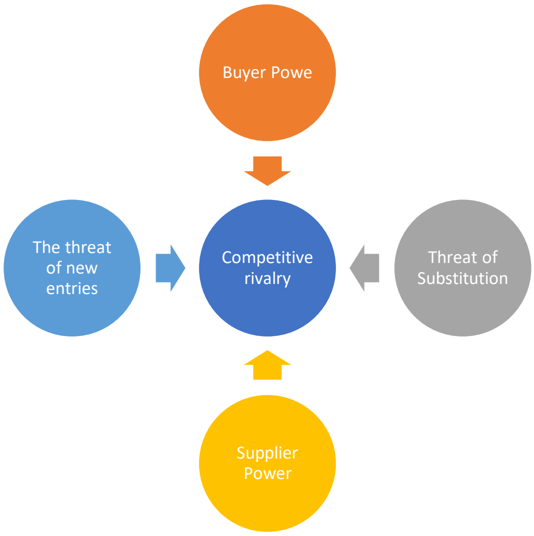

Figure 4 Porter's 5 forces analysis

The Porter's 5 forces analysis allows to evaluate what influence a certain sector but also what are the possible countermeasures to improve the structure of it. Players' trends need to be examined and through these forecasts, it is possible to decide the necessary actions to create competitive advantage. Indeed, a sixth Porter force could be identified. The relationships between two good can be classified in these two types: two goods are substitutes (already analysed by Porter) or two goods are complementary. Complementary goods have an effect contrary to substitute goods: they increase the value of them sector. This kind of products have little value individually and customers appreciate them together.

1.2.3 Key Success Factors

With an accurate analysis of the sector, the company must identify what are the factors that allow to satisfy the customer's needs and to survive the competition through the key success factors. It is necessary that the company doesn't see the consumer needs as an adversity able to erode its profitability through its buyer power but as an opportunity to increase it. Therefore, the company has to identify who is the customer, the product user and their needs and preferences. For example, if consumers choose new smartphones based on their quality, the company has to focus on innovation and the ability to make a good impression on the customer and user. To survive the competition, on the other hand, the main success factors can be identified through the analysis of profitability. It is possible to use Porter's forces analysis in a specular way rather than company sector for the company itself. In this way it will be possible to make a distinction among the driving factors of the company and those instead of improving.

1.3 Economic and Financial Analysis

It is necessary to evaluate a project in economic and financial sustainability terms in order to have a translation of the objectives and profitability also in strictly monetary terms.

The most used measure to evaluate economic profit is **Economic Value Added**:

$$EVA = ROI - WACC$$

As we note from the formula, EVA depends strictly on two other indicators: ROI and WACC.

$$ROI = \frac{NOPAT}{Net\ Invested\ Capital}$$

Return on Investment or ROI represents the profitability of operating activities compared to total investments. The numerator of ROI is Net Operating Profit After Taxes. It is the available income for the stakeholders and for the holders of the debt. The adjective "Operating" refers to the typical activity of the company and excludes all operations that do not belong to this area. The divisor, on the other hand, is the total of assets, net of depreciation and provisions. Already through the exclusive ROI benchmark of the analysed project compared to others, the first assessments can be made.

If the ROI does not meet expectations, we can analyse the sources that determine it in order to take corrective actions. The ROI, in fact, can be broken down by identifying the "value drivers".

$$ROI = \frac{NOPAT}{Revenue} * \frac{Revenue}{Net\ Invested\ Capital} = ROS * Turnover$$

- ROS, return on sales, represents the average operating result per unit of revenue. This ratio expresses the company's profitability in relation to the remunerative capacity of the revenue stream.
- Capital Turnover: represents the speed with which this production cycle is repeated, degree of exploitation of the plants.

However, it is necessary comparing ROI with the weighted average cost of capital or WACC, which indicates the lenders' rate of return. It is extended as the weighted average between the "cost" of risk capital and debt capital. Greater is the risk of the project, greater is the level of return expected by the lenders and the WACC will be higher.

$$WACC = K_e * \frac{E}{E+D} + K_d * \frac{D}{E+D} * (1-t)$$

- kd * (1-t) = cost of debt net of taxation (i.e. interest rate net of tax deductibility of interest expense);
- D = debt value;
- E = value of Equity;
- ke = cost of equity;

In general, three possible scenarios can be prefigured:

- EVA> 0, the company makes extra profits that can be used for business growth.
- EVA = 0: the company manages to remunerate the debt and the equity holders.
- EVA <0: the company cannot even remunerate the cost of capital.

This measure has several advantages: first, it is a measure of performance of projects for managers; secondly, it allows easier comparison between the different projects of the company.

2. Technology Readiness Assessment

2.1 Purpose and Background

Projects developing or using new technologies have a baseline[6] that often runs the risk of ill-defined according to traditional Project Management criteria. Indeed, the new technologies development is a complex process that provides different activities such as the research, the actual application in the operational environment and the integration with existing technologies. How much an innovation project is developed, complete and ready to use is the definition of the technology maturity. More the technology maturity is high than less the technology risks are. In 2008 GAO showed how many technologies of the "Future Combat Systems" program didn't achieve the planned maturity; the ill-definition of the scheduling and costs were the main causes for their cancellation (Case Study 1 of **APPENDIX I**).Therefore, the complete assessment of new technology maturity can be a relevant component: GAO[7] discovered that when program managers are supported with the disciplined processes and readily available information, there is a reduction in technological risks. In this context, a starting point could be the Technology Readiness Assessment (TRA).

"A TRA is a systematic, metric-based process and accompanying report that assesses the maturity of certain technologies [called Critical Technology Elements (CTEs)] used in systems"[8].

If TRA development is correct then TRA can be complementary to the existing management program, the monitoring and the control practices. TRA could be an integral part of an engineering systems because it provides evidence that technical development is unfolding as desired and technologies are mature enough to move on the next phase. TRA is a relevant and an important decision support tool. It is a common language tool that supports the link inside the organization and consolidates the commitments made by the interested parties. It is a tool to reduce the technical and the cost risks associated with the introduction of new technologies. Moreover, it can be customized according to the intended purpose.

From the technical point of view, TRA performs three different functions:

- <u>Identifying the deficiencies</u> during test phases; demonstrates the current readiness level and provides the steps needed for their resolution;
- <u>Identifying the technologies</u> with highest risk and provides the essential resources for their development;
- <u>Increasing transparency</u> in management decisions for identifying immature technologies that increase project risk.

TRA uses the Technology Readiness Level scale that was developed by Stan Sadin [9]at NASA during the 1970s. In this period, it was adopted for assessing different projects such as the Jupiter Orbiter spacecraft design and different Air Force development programs. The TRL was composed of seven levels[10] :

- Level 1 – Basic Principles Observed and Reported.
- Level 2 – Potential Application Validated.

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[6] *The project's baseline is used to measure how performance deviates from the plan. Your performance measurement would only be meaningful if you had an accurate baseline. A project's baseline is defined as the original scope, cost and schedule.*

[7] *The U.S. Government Accountability Office (GAO) is an independent, nonpartisan agency that works for Congress. Often called the "congressional watchdog," GAO examines how taxpayer dollars are spent and provides Congress and federal agencies with objective, reliable information to help the government save money and work more efficiently.*

[8] *[2003 DoD Technology Readiness Assessment Deskbook (updated July 2009)]*

[9] Stan Sadin is a NASA researcher.

[10] Sadin, Stanley R.; Povinelli, Frederick P.; Rosen, Robert (October 1, 1988). *"The NASA technology push towards future space mission systems, presented at the IAF, International Astronautical Congress, 39th, Bangalore, India, Oct. 8-15, 1988".*

- Level 3 – Proof-of-Concept Demonstrated, Analytically and/or Experimentally.
- Level 4 – Component and/or Breadboard Laboratory Validated.
- Level 5 – Component and/or Breadboard Validated in Simulated or Realspace Environment.
- Level 6 – System Adequacy Validated in Simulated Environment.
- Level 7 – System Adequacy Validated in Space.

In 1995, a John C. Mankins'[11] article discussed the TRL and improved the evaluation of descriptions of each level of the TRL and it added two other levels.

- Level 8 - Actual system completed and "flight qualified" through test and demonstration (ground or space).
- TRL 9 - Actual system "flight-proven" through successful mission operations.

In 1999, the GAO recommended the DoD[12] to adopt the TRL and in 2001 the Deputy Secretary of Défense for Science and Technology published a memorandum approving the TRL in the main programs. Later time, the DoD developed a "DoD Technology Readiness Assessment" as a guide for performing the TRAs using the TRL scale. TRL levels are recognized as reliable assessing to the maturity of both commercial and military technologies.

Concrete instances found that projects with higher technological maturity are more likely to succeed while immature technologies often result as increased costs and planned delays (As shown in the Table 3 below).

Product development			
Product development and associated technologies	TRL at program initiation	Cost growth	Schedule delay
Comanche helicopter			
Engine	5		
Rotor	5		
Forward looking infrared	3		
Helmet mounted display	3		
Integrated avionics	3	101 percent[a]	120 percent[a]
Brilliant Anti-Armor submunition			
Acoustic sensor	2		
Infrared seeker	3		
Warhead	3		
Inertial measurement unit	3		
Data processors	3	88 percent	62 percent
Hughes HS-702 satellite			
Solar cell array	6	None	None
Ford Jaguar automobile			
Adaptive cruise control	8		
Voice activated controls	8	None	None

Table 3 Cost and Schedule Experiences for Products with Mature and Immature Technologies (GAO/NSIAD-99-161)

[11] John C. Mankins was a NASA physicist. He published the first detailed definitions of the TRLs in 1995 that discussed NASA's use of TRLs, he proposed expanded descriptions for each TRL and promoted the use of the scale by the US Department of Défense in the late 1990s.

[12] The United States Department of Défense (DoD) is an executive branch department of the federal government charged with coordinating and supervising all agencies and functions of the government directly related to national security and the United States Armed Forces.

Over the years this evaluation metric has become increasingly important and nowadays, different organizations such as the European Space Agency (ESA) or the European Commission use the TRL in many fields.

2.2 Technology Readiness Assessment Process

The TRL scale assigns a value to a specific technology according to the technology maturity level. However, an assessment is not an isolated value without any purpose but the TRA consists of multiple lower-level assessments. In fact, TRA is a complex process that ensures that CTEs work as planned.

Multiple organizations such as commercial industries, agencies and universities agree on four key characteristics that a successful TRA must have:

- Credibility: all the activities such as the planning, execution, and reporting of the TRA must be performed by experts with knowledge in accordance with their role.
- Objectiveness: all evaluations and decisions must be based on objective and impartial data.
- Reliability: TRA is composed by disciplined and coherent processes that can be used in order to be repeatable.
- Usefulness: all stakeholders must be able to use the information provided by the TRA. In this way, the TRA suggestions can be implemented in a timely manner.

These characteristics are not inevitably correlated but together they define the TRA quality. The frequency where the multiple level assessments that compose the TRA mustn't be performed is a specific and sorted way and there is not an optimal number of mandatory assessments.

The TRA process model consists of three consecutive phases:

1. Identifying the Critical Technology Elements (CTEs). An element is defined as *critical* if it is fundamental in achieving the operational system requirements. In addition, its technology or application should be new or developed in an area with great technological risk.
2. Evaluating CTEs with Technology Readiness Level (TRL). The TRL scale ranges from 1 (basic principle observed) through 9 (a total system used successfully in project operations). It does not indicate the quality of the technology implementation but only its maturity level. This phase generates the TRA Report.
3. Developing a Technology Maturation Plan (TMP): identifies the activities necessary to bring immature CTEs to the desired TRL.

2.2.1 Model for Identifying CTEs

A standardized CTEs identification process is important because it allows to give credibility to CTEs list. For this reason, the CTE possible lack or an incorrect assessment of its technological development current state could compromise the performance of the system, the program schedule and its project costs. On the other hand, the identification of too many CTEs could disperse the resources which instead could be used on the CTEs they need. The CTEs identification process consists of four consecutive steps: choosing an appropriate method to identify the possible CTEs; using criteria to establish an initial CTEs list; redefining the list through the collaboration of the technical team and the governance organization; repeating the process when it is necessary.

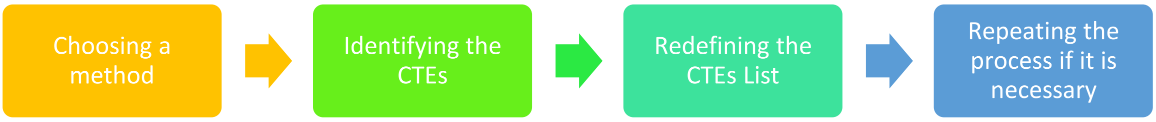

Figure 5 Process of Identifying CTEs

In the first step, the assessment team defines the identification method. Generally, two instruments can be used: the Work Breakdown Structure (Figure 6) or System Flow Diagram (Figure 7).

The use of the Work Breakdown Structure (WBS) is provided in many cases by The Défense Acquisition Guidebook[13] in order to identify CTEs.

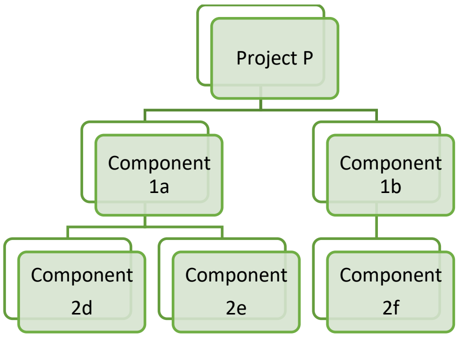

Figure 6 WBS example

The Work Breakdown Structure (WBS) defines the elements that make the project and their implementation. It is the equivalent of a product bill of material. Generally, it is a multi-level structure according to which an element of level n-1 composes the level n elements. The structure is defined in a tree and the intersection of the activities between two branches is zero. There are several logics of decomposition of a WBS:

- FUNCTIONAL: the elements of the project are broken down by function and each one it is individually testable independently of the others;
- SPACE: the breakdown structure is in according to the location of the project elements;
- PHYSICS: breakdown structure based on constituent parts.

The WBS must fully represent the whole project and it is a fundamental element for a successful acquisition of the project components. The WBS is used because it is often already available, evolves with the system, provides all the technologies and reflects the system performance. In the early project stages, the WBS is not available so the System Flow Diagram can be used. A System Flow Diagram is a graphical representation of the activities execution of which the system is composed.

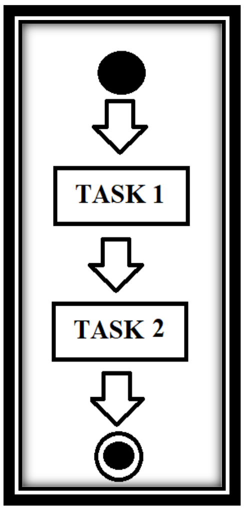

Figure 7 System Flow Diagram Example

[13] *The Défense Acquisition Guidebook (DAG) is a text developed to aid in the understanding and implementation of United States Department of Defense Acquisition practices under the DoD Directive 5000 series.*

Set 1 – Criteria	YES	NO
1. Does the technology directly impact a functional requirement of the process or facility?		
2. Do limitations in the understanding of the technology result in a potential schedule risk, i.e., the technology may not be ready for insertion when required?		
3. Do limitations in the understanding of the technology result in a potential cost risk; i.e., the technology may cause significant cost overruns?		
4. Do limitations in the understanding of the technology impact the safety of the design?		
5. Are there uncertainties in the definition of the end state requirements for this technology?		

Table 4 Criticality Criteria (Source: Technology Readiness Assessment Guide of USDE)

In the second step, the CTEs criteria are defined. Typically, the CTEs criteria are expressed in questions and they are divided into two categories: criticality criteria (Table 4) and the new criteria (Table 5). This model does not represent a definitive criteria form, but it can be used as a starting point.

Set 2 – Criteria	YES	NO
1. Is technology new or novel?		
2. Is the technology modified?		
3. Have the potential hazards of the technology been assessed?		
4. Has the technology been repackaged so a new relevant environment is realized?		
5. Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability?		

Table 5 New Criteria (Source: Technology Readiness Assessment Guide of USDE)

In the third step, the CTEs list is validated by resolving any possible internal disagreements and providing adequate documentation. A good practice could be to develop stable criteria and application methods including internal communication documentation. The most common problem in this phase, occurs in the changes made but not communicated by the various section that deals with the project.

For the fourth step, the TRA team repeats the determination process if necessary. Indeed, during the technology development, some decisions could modify the design, the purpose of the project and consequently, the CTEs can be changed. Furthermore, some immature alternative technologies could be adopted unexpectedly. Obviously, every change must be documented and motivated.

These activities should be performed by the program manager and the program office technical staff. These activities need to be supervised by the independent team of technical experts. All those who perform these evaluations should be aware of the CTE identification in the context of the TRA, the WBS concept, the difference between hardware and software, the affordability and the role that the environment has for identifying CTEs.

2.2.2 Model of TRL Assessment

The most widespread tool for assessing technological maturity is the Technology Readiness Level (TRL) scale. The TRL scale indicates achievement of the technological maturity budgeted objectives of the CTEs and can be related to the program risk.

The TRL includes knowledge such as:

- new technologies basic research;
- development of multiple possible applications for the same technology both in a laboratory environment and in a realistic environment;
- final system launch.

The TRL presents the opportunity to identify the gap between the technologies' maturity and the project requirements. Therefore, TRL can recognize the risk of the unknown on the technology. The TRL assessment should be conducted by an independent expert team and it is fundamental for the project development. Furthermore, it allows taking tests on CTEs to promptly highlight the dangers and to ensure that safety is designed for avoiding a possible cost increasing.

The TRL scale has different functions including:

- **Communication** - The TRL is the means by which programs, projects, decision-makers and engineers can communicate with the same framework. It provides a common understanding of the level of technological maturity because different interpretations sometimes can lead to misunderstandings. TRL is also used for communicating different technological maturity of multiple technologies, their progress and status. Common and conditional understanding is vital for both inside and outside NASA. Examples include technology roadmaps, life-cycle design reviews, technology selection/portfolio meetings and workshops.
- **Set a target/success criterion** - TRL is used as a target and/or success criterion during development. TRL can be used to designate acceptable minimum maturity levels. It is also used in research and technological development projects to establish the starting and the ending points for that project. It can be used also as entry and success criteria for technological demonstration missions. Examples include proposals, opportunities announcement and requests for information.
- **Project planning development** - TRL is used as a tool for the Project Manager for establishing which additional tests, maturation pace and additional loyalty levels are required.
- **Proposal development** - TRL is required to evaluate the technology maturity plans of the system and the subsystem during the development, the solicitation and the revision of the proposal. Examples include SMD, Game-Changing Development (GCD) program and innovative NASA concepts (NIAC).
- **Technology selection** - TRL is used to help to identify sufficiently mature technologies that meet the mission requirements. Program Managers and Project Managers also use the TRL during their evaluation of alternatives in order to identify the candidate technologies.
- **Infusion readiness indicator** - Technology developers use TRL to indicate to Project Managers that their technology has the maturity required for the infusion.
- **Portfolio management** - The TRL scale provides data to understand and communicate the spectrum of ongoing Research and Development (R&D) activities within a technology development portfolio. It helps to facilitate a balanced portfolio among the TRLs and helps to make investment decisions. Examples include investments in the OCTs, investments in the space technology mission (STMD) and investments in advanced exploration systems (AES).

- **Cost estimation** - The TRL is used as input for cost estimation models. For more accurate estimates, the models should also include risk measures like AD2[14]. Examples include cost models of the Independent Program Assessment Office (IPAO).
- **Risk indicator -** The establishment of TRL helps in assessing the risk of that project. It informs the Project Manager of the risk level of specific technologies and helps in the decision-making process on produce that technology or if it is better to buy from external suppliers.

A summary overview of the technology maturing model adopted from NASA and DoD is showed in Table 6.

DEFINITION	LEVEL	DESCRIPTION	DOCUMENTATION
BASIC PRINCIPLES OBSERVED AND REPORTED	TRL 1	The first step is to identify the basic principles of technology. This corresponds to the research and development (R&D) phase.	Researches identifying the basic technical principles. Researches references to who, where, when.
TECHNOLOGY CONCEPT AND/OR APPLICATION FORMULATED	TRL 2	The second phase consists in seeking evidence to support the hypothesized principles.	Publications providing analysis to support the concept.
ANALYTICAL AND EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF OF CONCEPT	TRL 3	The third phase involves analytical studies in the laboratory to measure the parameters of interest and compare them with the analytical forecasts.	Test results performed in the laboratory. References to who and when these tests were performed.
COMPONENT AND/OR BREADBOARD VALIDATION IN A LABORATORY ENVIRONMENT	TRL 4	Identifying the components integrated into the technology to evaluate how they will work together. Breadboard tests are also carried out and the deviations are assessed.	System concepts that have been considered. The results from testing laboratory-scale breadboards. References to who did this work and when.
COMPONENT AND/OR BREADBOARD VALIDATION IN A RELEVANT ENVIRONMENT	TRL 5	The basic technological components are integrated into a system of good "Loyalty". Tests are performed in a simulation environment. The forecasts are compared to expectations and the consecutive evaluations are processed.	Test results to highlight technological differences in the relevant environment and simulated environment.

[14] AD2 is a risk methodology proposed in 2002. It focus on the issues with the development and the incorporation of new technologies into a space system.

SYSTEM/SUBSYSTEM MODEL OR PROTOTYPE DEMONSTRATION IN A RELEVANT ENVIRONMENT	TRL 6	The System model or prototype is defined at high "Loyalty" and the final configuration is started in terms of performance, weight, and volume. Tests are carried out to identify any deviations from the expectations.	Test results that highlight the differences between the prototype and the desired configuration.
SYSTEM PROTOTYPE DEMONSTRATION IN AN OPERATIONAL ENVIRONMENT	TRL 7	In this level the prototype is more complex and defined. More advanced and developed compared with the previous level. It is ready to be tested in an operational environment.	Results from testing a prototype system in an operational environment. Specify it there are any problems.
ACTUAL SYSTEM COMPLETED AND QUALIFIED THROUGH TEST AND DEMONSTRATION	TRL 8	Represents the end of the true level of development. Final configurations are made. A conformity assessment is performed with the respect to the operational requirements.	Results of testing the system in its final configuration in the operational (Limited range) environment.
ACTUAL SYSTEM PROVEN THROUGH SUCCESSFUL MISSION OPERATIONS	TRL 9	Technology presents itself actual application.	Final reports.

Table 6 TRL Description

The Table 7 is often used by the DoD and clarifies even better the relationship between technology development and the development environment.

The fidelity includes four different values:

- Identical System - the project meets all the requirements.
- Similar System - the project meets almost all the requirements.
- Pieces System - part of the project meets the requirements.
- Paper System - the existence of the project on paper.

The environment includes four different values:

- Operational (Full Range) - the full range of actual waste.
- Operational (Limited Range) - the limited range of actual waste.
- Relevant - simulation environment and limited range of actual waste.
- Simulated - simulation environment.

TRL	Fidelity	Environment
TRL 1	Paper	N/A
TRL 2	Paper	N/A
TRL 3	Pieces	Simulated
TRL 4	Pieces	Simulated
TRL 5	Similar	Relevant
TRL 6	Similar	Relevant
TRL 7	Similar	Relevant
TRL 8	Identical	Operational (Limited Range)
TRL 9	Identical	Operational (Full Range)

Table 7 Relationship between technology development and development environment

In order to give for the actual context a more detailed explanation of the terminology used in the Table 8 are proposed some definitions of the terms foreseen in the definition of the TRL scale.

TERM	Definition
Breadboard	Integrated components that provide a representation of a system/subsystem and can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble the final system/subsystem in function only.
High Fidelity	Addresses form fit and function. A high-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.
Low Fidelity	A representative of the component or system that has limited ability to provide anything but first-order information about the end product. Low-fidelity assessments are used to provide trend analysis.
Model	A functional form of a system, generally reduced in scale, with operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.
Operational Environment	An environment that addresses all the operational and specifications requirements of the final system in order to include platform/packaging.
Prototype	A physical or virtual model used to evaluate the technical or manufacturing feasibility of a particular technology, process, concept, item or system.
Relevant Environment	A testing environment that simulates the key aspects of the operational environment.
Simulated Operational Environment	A real environment that can simulate all the operational and specifications requirements of the final system. Used to

	determine whether a developmental system meets the operational requirements and specifications of the final system.

Table 8 Additional Definitions of TRL (Source: Défense Acquisition Guidebook)

The assessment requires the following steps:

- Describing the technology and functions that should be performed. Writing the history and status of the technology (this description may include drawings and photographs).
- Describing the environment in which the technology is demonstrated: make a summary of the simulation analysis between the environment already demonstrated and the operational environment. Tests need to be performed with many repetitions to get meaningful statistics.
- Applying the TRL criteria and assigning a readiness level value to the technology.
- Presenting paper references, data and facts to support this assessment. The information must relate where possible when and where the texts were executed and who performed them.
- Describing in detail each CTEs.
- Indicating the evaluation of the audit team and if this technological maturity is enough to proceed for the next step.

The US Air Force Research Laboratory developed a tool for the TRL assessment named TRL Calculator. This is a Microsoft Excel spreadsheet application that shows, by answering some standard questions, the TRL level of the project. It is an excellent tool because it makes the evaluation process standard and repeatable. The TRLs are documented in the TRA Report.

The TRA report (as shown in Figure 8) is the document that describes the TRA assessment process and explains the TRL assessment for each CTE. It highlights the most important parts of all the documentation used for the evaluation. The fulfilment of this report is coordinated by the TRA review team leader. It provides:

- A description of the technology or system through a WBS or a flow diagram to identify the CTEs.
- A score for each CTE.
- A final report documenting the findings of the assessment review team.

2.2.3 Technology Maturation Plan

The Technology Maturation Plan (TMP) is a document for planning the technological development of the still immature CTEs in order to achieve the desired TRL. The results of the DoD and NASA show CTEs with a TRL level lower than 6 as potential causes of excessive discrepancies between the baseline and the possible corrective actions. They are therefore sources of risk both for the scheduling and for the cost of the project. The TRA is very useful to highlight possible shortcomings in the TMP and induce changes through corrective actions. This summary includes the TRLs for each CTE as documented in the last available TRA. In addition, all the activities that determined the current state of the art should be documented. Furthermore, the TMP describes the approach used in the technological development activities carried out, including the incomplete TRL assessment, risk assessments and value engineering. The objectives and success criteria should also be reported as well as a schedule and should be provided the budget for achieving them. Obviously, the schedule and the budget must incorporate the development of the activities for each planned CTE and the major decision points.

A brief summarization for the TMP can be represented as following:

- Key Technology Addressed.
- Objective.
- Current State of the Art.

- Technology Development Approach.
- Scope.
- Schedule.
- Budget.

EXECUTIVE SUMMARY

Briefly state who requested the Technology Readiness Assessment (TRA), what organization was responsible for conducting the TRA, what technology was assessed. Provide a summary table of the critical technologies and corresponding Technology Readiness Levels (TRL) determined during the review.

INTRODUCTION

Background

Provide project/program overview and background information (i.e., general description of the program and the technology system, including the critical technologies to be assessed).

Purpose and Scope of the TRA

Provide an explanation of why the TRA was conducted (i.e. program management's review for maturing technologies, TRA required for a decision point, etc.), and scope of the assessment. Reference applicable decision memos and planning documents.

TRA Process

Provide an overview, and plan of actions and milestones to conduct the TRA. Reference planning documents.

RESULTS

Provide the following for each critical technology assessed:

• Technology Reviewed: Provide a detailed description of the technology that was assessed. The level of detail can vary depending on the phase of development, design characteristics, and scope of review. Organizations should strive to provide a sufficient amount of information to facilitate an understanding of the technology assessed.

• Function: Describe the functions of the critical technologies.

• Relationship to Other Systems: Describe how the critical technologies interface with other systems.

• Development History and Status: Summarize pertinent development activities that have occurred to date on the critical technology.

• Relevant Environment: Describe relevant parameters inherent to the critical technology or the function it performs as it relates to the intended operational environment.

• Comparison of the Relevant Environment and the Demonstrated Environment

Describe differences and similarities between the environment in which the critical technology has been tested and the intended environment when fully operational. The demonstrated environment must correspond to the identified relevant environment for the TRL to be justified.

• Technology Readiness Level Determination

State the TRL determined for the critical technology and provide the basis justification for the TRL.

• Operational Requirement: Describe the required/traceable system functional performance and enabling features for the critical technology elements.

ATTACHMENTS

Include the following planning documents:

• TRA Plan
• Supporting documentation for identification of critical technologies
• Completed tables: TRL Questions for critical technologies
• List of support documentation for TRL determination
• TRL Summary table
• Lessons Learned
• Team biographies

Figure 8 Template Of TRA assessment (Source: GAO analysis of agency documents - GAO-16-410G)

1.0 INTRODUCTION

• Purpose of the Project

Provide a brief summary of the project's mission, status, technology(s) being deployed, etc.

• Purpose of the TMP

Describe the objectives and content of this TMP and relate it to the status of the project and any upcoming CDs.

2.0 TECHNOLOGY ASSESSMENTS OF THE PROJECT

• Summary of the Previous TIPRs

Summarize any previous TIPRs or other technical assessments that may have contributed to the need for a TRA and this TMP.

• Summary of Previous TRA(s)

Describe the results of previous TRAs with particular emphasis on the latest TRA that is driving this TMP. Include the definition of TRLs as used in the TRA. Discuss the CTEs that were determined for the project.

• Technology Heritage

Summarize the previous technology development activities that brought the technology to its current state of readiness. Include discussions of any full-scale plant deployments of the technology in similar applications.

• Current Project Activities and Technology Maturation

Describe ongoing technology development activities (if any) that were initiated prior to this TMP. Completion of these activities should define the starting point for this TMP.

• Management of Technology Maturity

Indicate the DOE and contractor organizations that will be responsible for managing the activities described in this TMP. Include a brief discussion of key roles and responsibilities.

3.0 TECHNOLOGY MATURATION PLAN

• Development of Technology Maturation Requirements

Describe the approach used in defining the required technology development activities that will be conducted as described in this TMP. These could include evaluating incomplete criteria in the TRL Calculator, risk assessments, and value engineering.

• Life-Cycle Benefit

Briefly discuss life-cycle benefits to the project that will result from successful completion of the TMP technology development activities.

• Specific TMPs for each CTE will be described following the format below for each CTE that was defined in the latest TRA.

− CTE A

- Key Technology Addressed (Describe the function that the CTE carries out in the project.)
- Current State of Art (Describe in one paragraph the current status of the CTE including the specific TRL assigned in the latest TRA.)
- Technology Development Approach (In paragraph form, describe how the needed technology development work to reach TRL 6 will be performed. This could include the performing organization, location, simulant versus actual waste, etc.)
- Scope (Provide a list of the key steps to be taken in performing the work. Include a table that gives milestones, performance targets, TRL achieved at milestones and a rough order of magnitude cost of development.)

− CTE B

- Key Technology Addressed
- Objective
- Current State of Art
- Technology Development Approach
- Scope

− CTE C (etc., as needed)

4.0 TECHNOLOGY MATURITY SCHEDULE

Provide and briefly discuss a high-level schedule of the major technology development activities for each CTE. Any major decision points such as proceeding with versus abandoning the current technology, selection of a back-up technology, etc. should be included. Detailed schedules should be given in test plans or used for status meetings during implementation.

5.0 SUMMARY TECHNOLOGY MATURITY BUDGET

Present the rough order of magnitude costs to reach TRL 6 for each major technology development activity for all CTEs in the project. Include the total technology maturation costs.

6.0 REFER

Figure 9 Template of TMP

3. Customized TRA

3.1 Limits and inappropriate uses of TRL

This purpose of this chapter is to describe the TRL issues in order to provide some correctives changes. In addition, it has been proposed a new possible solution that solves the TRLs gaps and increases their application opportunities. Over time, the TRA and the TRL have become widespread, but some gaps have undermined the TRL credibility as a generic technological maturity indicator. Some of these limits, as shown in Figure 10 are:

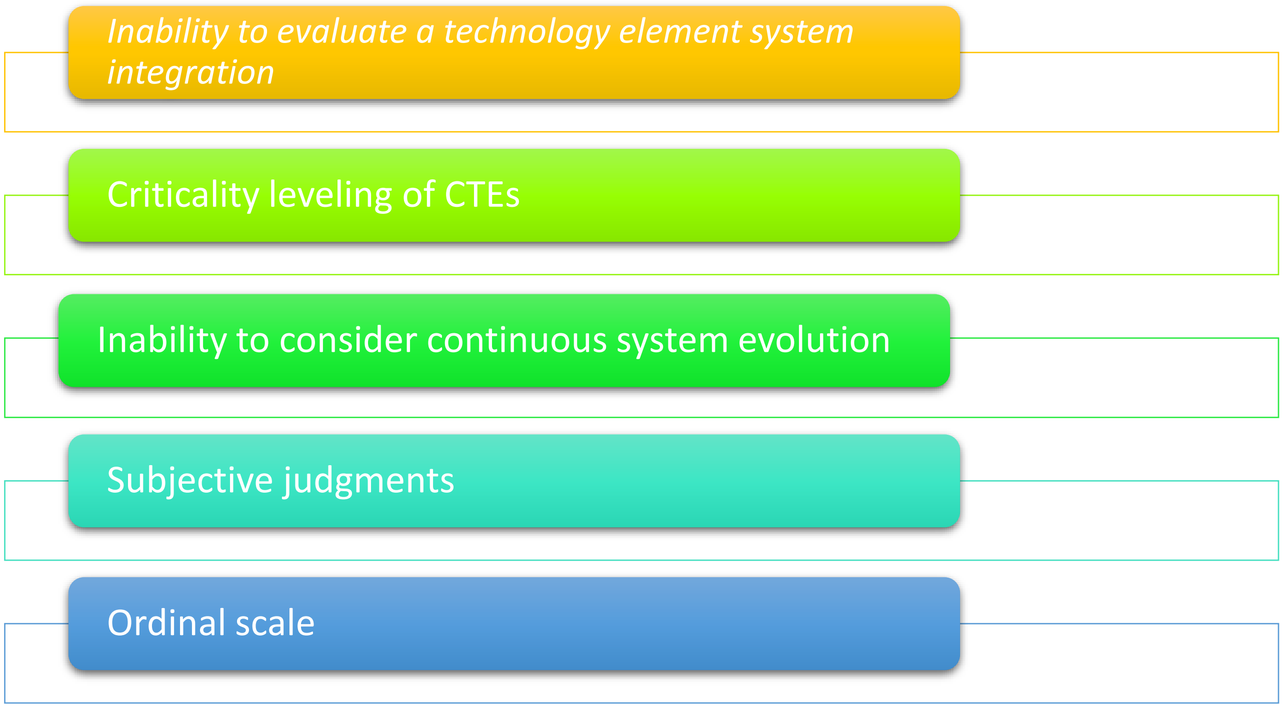

Figure 10 Limits of Technology Readiness Level

- **Inability to evaluate a technology element system integration**: the TRL scale exclusively evaluates the individual technology maturity and doesn't analyse its integration within a system. Indeed, a system itself is more complex than the sum of singles components evaluated individually. Its quality, however, also depends on the connections among the components and how they are integrated.
- **Criticality levelling of CTEs**: all CTEs have the same criticality level. There isn't a scale so it's not possible to measure how much they impact on the system. This can implicate a possible incorrect resources distribution.
- **Inability to consider continuous system evolution**: TRL does not consider the continuous updates or changes of a given technology. It does not foresee further levels after having verified the technological maturity (TRL 9).
- **Subjective judgments**: there is not a specific way to define a technology assessment that deeply depends on subjectivity of its process. This evaluation could be distorted depending on the assessor pursued interests. Different companies have different environment, working moods, purposes, goals and missions. These differences determine many perspectives in the TRA conduction. For example, in the project proposal, a specific actor could present a particularly optimistic evaluation to attract funds and stakeholders (Case Study 2 of **APPENDIX I**).
- **Ordinal scale**: the efforts required to move from one TRL level to the next, do not increase linearly or progressively because it's an ordinal scale and not an interval o ratio scale.

The TRL scale also lends itself to inappropriate uses that do not provide a correct assessment, and which helps in a greater understanding of its shortcomings. A brief list of inappropriate uses is listed below:

- **Evaluation based exclusively on the TRL scale**. It does not provide itself a complete technological maturity picture of an element because it does not consider many relevant aspects. TRL scale, however, combined with other factors, can be more effective.
- **Self-assessments/Marketing tool**. The estimates can be altered for multiple reasons. For example, they can be overestimated for easier approval of the analysed project.

3.2 Other methodologies based on TRL

For all the limitations described other methodologies based on TRL have been developed. Some of these are: Manufacturing Readiness Levels (MRL)[15], Systems Readiness Level (SRL)[16], Innovation readiness level (IRL)[17], Logistics readiness level and Product Readiness Level (PRL)[18].
For the thesis purposes, three indicators have been investigated as they are the basis of the news proposed parameters: PRL, SRL and IRL.

3.2.1 Product Readiness Level

The Product Readiness Level is a Technology Readiness Level extension and has the purpose of evaluating the product development process. Nowadays, in increasingly competitive globalized markets, it is necessary to assess the technology readiness. Indeed, if misidentified, can lead to bad performance in terms of quality or functionality and important commercial implications. This model attempts to solve the problems related some limits of the TRA-TRL and specifically to the inability to consider continuous evolution of the system, the inability to evaluate a technology element system integration and the Criticality levelling of CTEs.

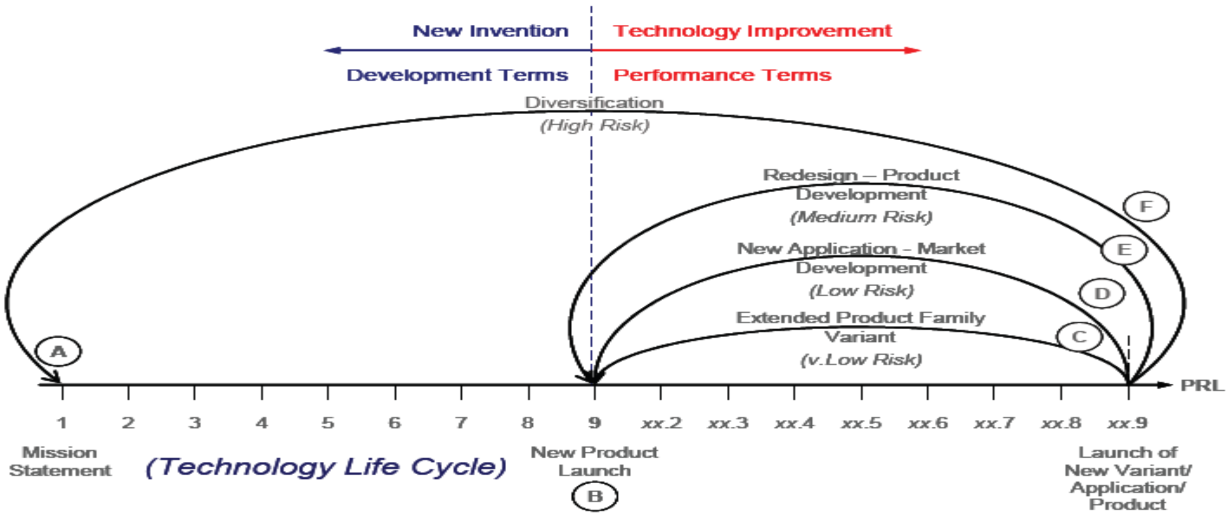

Figure 11 The Technology Product Lifecycle Model. Source: A Methodology for evaluating Technology Readiness during product Development (Hicks at all. 2009)

When a new technology achieves its maximum maturity level (Level 9), the TRL scale fails to capture all the subsequent updates or diversifications. In this context, the Product Readiness Level bases its development on a Technology lifecycle model (as shown in the Figure 11) which was built from existing business models. The Figure 11 can be divided into two parts: "New Invention" and "Technology improvement".

[15] Morgan, 2007.
[16] Sauser B., et al., 2006
[17] Lee, et al., 2011
[18] Hicks, et al., 2009

The technological level of "New Invention" products is measured through the standard TRL scale; the measurement for the "Technology improvement" section provides the introduction of new levels in order to measure the natural cycle of technological development. The two sections are divided by "Product launch". The product obtained the necessary technological maturity and for this reason it is ready for the market. All the subsequent categories instead represent increasingly differentiated variants of the product. For every category is associated a strategic risk that is proportional to the original product changes.

The category with the lowest risk is "Extended Product Family" which includes all products belonging to common technology and which is exploited in the same area.

Subsequently, the "New Application-Market" provides the use of the product or its related products in new application fields. Thus, introduces a greater strategic risk since it provides products that deviate greatly from the original one.

The "Redesign Product" category provides deeply changes in the article structure and its functionality has been made to improve the quality of the original user experience.

The "Diversification" category foresees the change of the original technology and the study of a new one. In fact, in this case, it is necessary to start from level 1 of the TRL scale.

Representing these new categories, the PRL introduced two new levels:

TRL	Definition
10.2	The enhancement of an existing element or the introduction of a 'sustaining technology' to an already operational component, sub-system or system is conceived. Commencement of applied research.
10.3	Feasibility and key benefits of enhancement or introduction initially validated through active R&D (Physical validation and analytical study of technology in appropriate context)
10.4	Low-fidelity validation of new 'feature' in a laboratory environment. Technological implementation now focussed on meeting project requirements.
10.5	Validation of new 'feature' in a relevant environment. Test 'set-up' to be of higher fidelity than at TRL 4 (Basic integration of new 'feature' with established components required for a sub-system or system).
10.6	High-fidelity 'alpha' prototype of (Or incorporating) new 'feature' demonstrated in a relevant environment.
10.7	'Beta' prototype (Of appropriate or full-scale) demonstrated in operational environment (New element must be fully integrated with established components for a sub-system or system).
10.8	New 'feature' qualified to relevant project requirements and/or regulatory standards.
10.9	Revised and certified component, sub-system or system proven to all governing meet requirements through 'real world' operation.
11.2	The enhancement of an existing element or the introduction of a 'sustaining technology' to an already operational component, sub-system or system is conceived. Commencement of applied research.
11.3	*Continue TRL progressions as before…*

Figure 12 Extended Technology Readiness Level. Source: A Methodology for evaluating Technology Readiness during product Development (Hicks at all. 2009)

In order to obviate the problems of inability to evaluate multiple technologies and the Criticality levelling of CTEs, the PRL introduces a criticality scale consisting of 3 levels in order to weigh the CTEs in a complex product through their criticality (as shown in Figure 13).

Criticality Value	Definition
3	Technology is 'enabling' to the core functionality of the product. No work-around or substitution possible.
2	Technology fulfils a vital role in the product's core functionality. However, a work-around may be possible using substitute technologies that will incur an acceptable penalty.
1	Technology is 'enhancing' to the product's performance, cost, etc. Several alternative technologies exist that could be substituted and incur a minimal penalty.

Figure 13 Criticality Definition (Hicks at all. 2009)

Therefore, after evaluating the criticality of the single CTEs, the PRL expects to calculate a new index that is based both on the TRL and on the criticality scale introduced: $TRL_{PRO.}$

The TRL_{PRO} has been computed as follow:

$$TRL_{PRO} = \frac{\sum(TRL * Criticality)}{\sum Criticality}$$

Through this formula it is possible to assess different types of products. Both products provide a high TRL for core elements and many elements are not very critical with a low TRL level and vice versa. This general indicator could get the ambiguity of understanding of two different products but represented by the same value. Therefore, it is good to perform in-depth analyses on the index composition and never perform superficial analyses.

In order to be clearer about the concept expressed since now an example is exploited. There are two products with four technologies T_1, T_2, T_3, T_4, but the criticality level and the TRL level of each technology are different for the two products (as shown in Table 9).

PRODUCT COMPONENT	T1	T2	T3	T4
PRODUCT_1 TRL	5	5	9	9
PRODUCT_2 TRL	9	9	5	7
PRODUCT_1 CRITICALITY	1	2	3	3
PRODUCT_2 CRITICALITY	1	2	3	3

Table 9 Example of Data for PRL

The two TRL can be computed in the following way:

$$TRL_{PRO1} = \frac{1*5+2*5*3*9+3*9}{1+2+3+3} = 7.6 \quad TRL_{PRO2} = \frac{1*9+2*9*3*5+3*7}{1+2+3+3} = 7.6$$

Despite the two indices have the same value, the two products are different. In the first scenario the two core elements have a TRL equal to 9 and this means that the product in the main functionalities is mature. In the second case, instead, the core elements have respectively a TRL equal to 5 and 7 and the product, at least in its main functions, is still substantially immature. The two indexes have the same value because in the second case, the two less critical elements have a TRL level of 9. Thus, on average, the final product has the same TRL_{Pro} value of the product of the first scenario.

Contextualizing the TRL_{Pro} related with "Ulrich and Eppinger's product development processes"[19] and "key business functions"[20], a new framework is designed. This model has the purpose to identify the production process bottlenecks through the communication and collaboration of the business functions suggested in the Table 10.

PRL	TRL_{PROD}	Marketing	Manufacturing	Other Functions	Development Phase
1	2	• Target market identified.	-	• Business goals of development effort defined.	*Mission Statement*
2	3	• Market segments defined. • Lead users & their needs identified. • Competing products analysed.	• Manufacturing cost estimated. • Production feasibility assessed.	• Single concept selected for further development. • Project justified economically. • IPR issues investigated.	*Concept Development*
3	4	• Plan for product options and extended product family formulated.	• Make-or-Buy analysis performed. • Key suppliers identified. • Final assembly scheme designed.	• Support Make-or-Buy analysis. • Potential service issues identified.	*System-Level Design*
4	5	• Marketing plan developed.	• Standard parts identified. • Production processes defined. • Tooling designed. • Long lead-time tooling procured. • Quality assurance processes defined.	• Control documentation issued.	*Detail Design*
5	6	• Promotion and launch materials developed. • Field-testing facilitated.	• Supplier 'ramp-up' facilitated. • Fabrication and assembly processes refined. • Commence work force training. • Quality assurance processes refined.	• Sales plan finalised. • Regulatory approval / certification obtained.	*Testing and Refinement*
6	7				
7	8				
8	9	• Early 'production ramp-up' products placed with preferred customers.	• Work force training completed. • Operation of entire production system commenced.	-	*Production Ramp-Up*
9	9	*Product Promotion*	*Full Production*	*Active Service & Support Infrastructure*	*Product Launch*

Table 10 Product Readiness Levels and the product development process (Hicks at all. 2009)

3.2.2 System Readiness Level

The System Readiness Level (SRL) aims to assess the system technological maturity according to the DoD's Phases of Development for the Life Cycle Management Framework. The SRL is based both on the TRL scale for the individual technologies evaluation and on a new scale named Integration Readiness Level (IRL) for the evaluation of the connections between them. This index tries to resolve in a different way than the PRL, the TRL limitation to exclusively assess individual technologies that, as Smith's studies demonstrate, may have architectural inequalities in the integration.

The IRL is defined "as a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (TRLs)"[21].

The goal is to describe the technology integration maturity considering standards, interaction, quality, compatibility between technologies with different levels of technological maturity. The TRL scale assesses the risk of technological development. On the other hand, IRL assesses the integration risk. The IRL is based

[19] It is a set of procedures for making a product and for selling it to the market.
[20] These are key processes or operations that guarantee the proper functioning of the company such as financial, production, office, marketing, operations, and legal.
[21] Sauser B., et al., 2006

on the Open System Interconnect, model used for computer network structures descriptions that use different technologies (Description of OSI model in **APPENDIX II**).

Generalizing this model, new levels have been defined[22]:

1. An ***interface*** (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterization of the relationship.
2. There is some level of specificity to characterize the ***interaction*** (i.e. ability to influence) between technologies through their interface.
3. There is ***compatibility*** (i.e. common language) between technologies to orderly and efficiently integrate and interact.
4. There is sufficient detail in the ***quality and assurance*** of the integration between technologies.
5. There is sufficient ***control*** between technologies necessary to establish, manage, and terminate the integration.
6. The integrating technologies can ***accept, translate, and structure information*** for its intended application.
7. The integration of technologies has been ***verified and validated*** with sufficient detail to be actionable.

The SRL index synthesizes TRL index and IRL index and assigns a single value to the system. This value ranges from 5 to 1 and all the indices are defined in the Table 11.

SRL	**Name**	**Definition**
5	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	*Production & Development*	Achieve operational capability that satisfies mission needs.
3	*System Development & Demonstration*	Develop the system; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	*Concept Refinement*	Refine initial concept. Develop system/technology development strategy.

Table 11 System Readiness Level (Sauser B., et al., 2006)

In order to obtain SRL, after defining the IRL, the dynamic relationships between TRL and IRL have been studied. In details, all possible variations of a system made by two technologies (TRL1-IRL-TRL2) have been analysed. For the latter case, the system included 567 variations because TRL scale has nine levels and the IRL scale has seven. However, some of these possibilities have excessively low levels of TRL and IRL (immature integration), so it was considered a sample of 26 TRL-IRL-TRL systems. Through an online survey, the 26 systems were assessed in terms of SRL by sector experts that technically motivated their decision.

The results are represented in Figure 14 where it is possible to identify the following correspondences:

- Systems 1-1-1 correspond to an SRL 1 with 100% probability;
- systems 4-2-4 correspond to an SRL 2 with 100% probability;

[22] Sauser B., et al., 2006

- systems 7-7-7 correspond to an SRL 3 with a 90% probability;
- systems 8-7-8 correspond to an SRL 4 with 80% probability;
- systems 9-7-9 correspond to an SRL 5 with 100% probability;

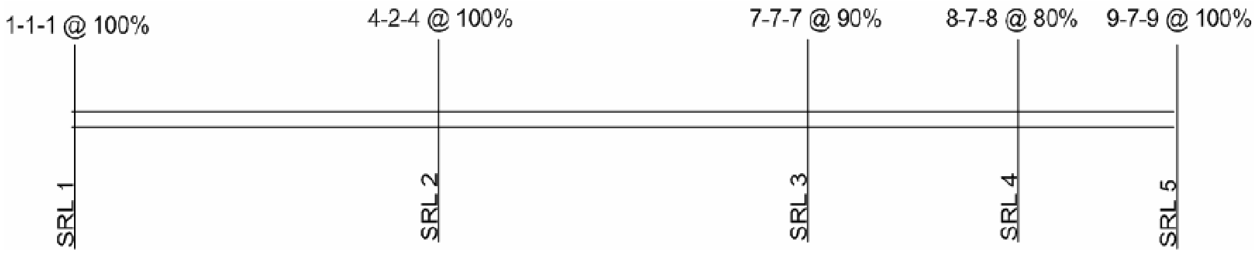

Figure 14 Probability distribution of System Readiness Level

3.2.3 Innovation Readiness Level

The Innovation Readiness Level framework is a tool for managing the innovation process and establishes the generic activities characterizing the innovation lifecycle. Managers can use it in order to evaluate the key elements management of innovation in the business context. This framework is the result of a more complex study presented in the "An Approach for developing concept of Innovation Readiness Levels"[23] which provides the tool and the evidence of its operation through the contribution of several case studies. The model presented is developed on the others previously defined and on those such as the life cycle assessment described by the S curve[24].
The model is defined of the six C, since the phases of which it is characterized are all called with words who's initial is a C, defined as:

1. Concept: the basic of the scientific principles of innovation and the related experiments have been carried out (equivalent to TRL 1-3).
2. Components: a prototype has been developed whose components have been validated (equivalent to TRL 4-6).
3. Completion: Technological development has been completed and the final system functionality has been proven in the field (equivalent to TRL 7-9).
4. Chasm: in the IRL framework, the term charm refers to the unexpected events and difficulties that a new technology encounters when it enters a market for the first time.
5. Competition: involves the absence of growth and innovation. The market is defined as mature and only the companies can consolidate their position to win competition.
6. Changeover/Closedown: In the market decline phase, there are two options. *Changeover* refers to new technologies built based on an existing innovation or to the change for the business model to develop competitive advantage. On the other hand, *closedown* means the innovation has come to obsolescence and exits.

Furthermore, each phase is characterized by five key aspects which are:

- Technology is the set of infrastructure, knowledge and products needed to satisfy human needs by changing nature through a production process (design, production, repair). Concrete examples are computers, planes and cell phones.
- Market is the company function assigned to the customer-supplier relationship. Market represent all the situations where consumers, having the necessary resources, buy the product with regulation imposed by law.

[23] Ming-Chang Lee, et al., 2011.
[24] The S-Curve Pattern of Innovation highlights the fact that as an industry, product, or business model evolves over time, the profits generated by it gradually rise until the maturity stage.

- Organization implements innovation and provides a maturity measure necessary to develop technologies.
- In the partnership, the partners share the business risk and therefore company losses or profits.
- Risk management is essential in the innovation context. There are different types of innovation-related risks, i.e. technological, market and organizational issues.

3.3 Customized TRA

3.3.1 Scope

Customized TRA is a new TRA variant that aims to improve itself and extend its use field. Originally, the TRA was designed by NASA for the technological risk assessment of aerospace projects. The thesis purpose is to generalize the model for analysing any type of project. Since now, all the analysing developed are not used and able to fulfil all the project type. For this reason, this work provides an advanced and complex solution for every project. With this point of view, the project is a system made up of various elements. Its evaluation is the average of the assessments of the individual components.

Anyway, the three main problems that have been addressed are:

- the inability to evaluate a technology element system integration;
- the criticality levelling of CTEs;
- inability to consider continuous system evolution.

These gaps mainly depend on the model of the TRA process and on the criticality concept proposed within it. Indeed, the TRA process model is a linear model that provides static assessments that cannot be updated over time. To solve this problem, a cyclical system or a degree of freedom could be adopted to consider future changes of a mature system (TRL 9). As the PRL presents, technological innovations can often be non-radical. For this reason, it's not possible to use the cyclic system because reached the maximum maturity all the other modification cannot be radical as explained in the PRL. With these prerequisites another parameter has been introduced in the TRA evaluation which adds a degree of freedom to the assessment. Furthermore, the TRA criticality concept is incapable of providing a scale of values to be assigned and it basically reflects a binary scale. All this makes inefficient the Technology Readiness Assessment because it evaluates the projects as black boxes and it is unable to adapt to continuous changes.

In order to solve these problems by making the necessary changes, the Customized TRA was created.

3.3.2 Model

Before describing the proposed model in detail, it is necessary to clarify that an important assumption has been made. As described above (3.1 Limits and inappropriate uses of TRL) the TRL scale is an ordinal scale. However, based on the literature, the TRL scale was considered as an interval scale.

The problems encountered concern the first two phases of the Technology Readiness Assessment Process:

1. Identifying the Critical Technology Elements;
2. Evaluating the Critical Technology Elements with Technology Readiness Level.

The critical elements identification strictly depends on the criticality concept. Unlike TRA, this model provides two types of criticality: technological criticality and functional criticality.

Technological criticality is the innovation degree of the element assessed.
"Final Report of the NASA Technology Readiness Assessment (TRA) Study Team"[25] defines three different categories of technological elements. Initially, the TRL scale was applied exclusively for the evaluation of new

[25] HQ Office of the Chief Engineer/Steven Hirshorn and HQ Office of the Chief Technologist/Sharon Jefferies, 2016.

technologies, but over time its use has been extended to a much wider spectrum of technological innovations. The three categories represented are:

- The “New Technology” is a new performance or function whose application, adaptation and integration is needed for new demonstrations. It has never been used operationally and is not an “Engineering” or an “Heritage” element.
- The “Engineering Technology” is a performance or a function whose application is in the original intention and whose development requires existing components or techniques. It is not an “New technology” element or “Heritage” element.
- The “Heritage Technology” is a performance or a function whose application doesn’t provide any change. Indeed, it is used in the application environments with none adverse than before and its manufacturing doesn’t provide any changes.

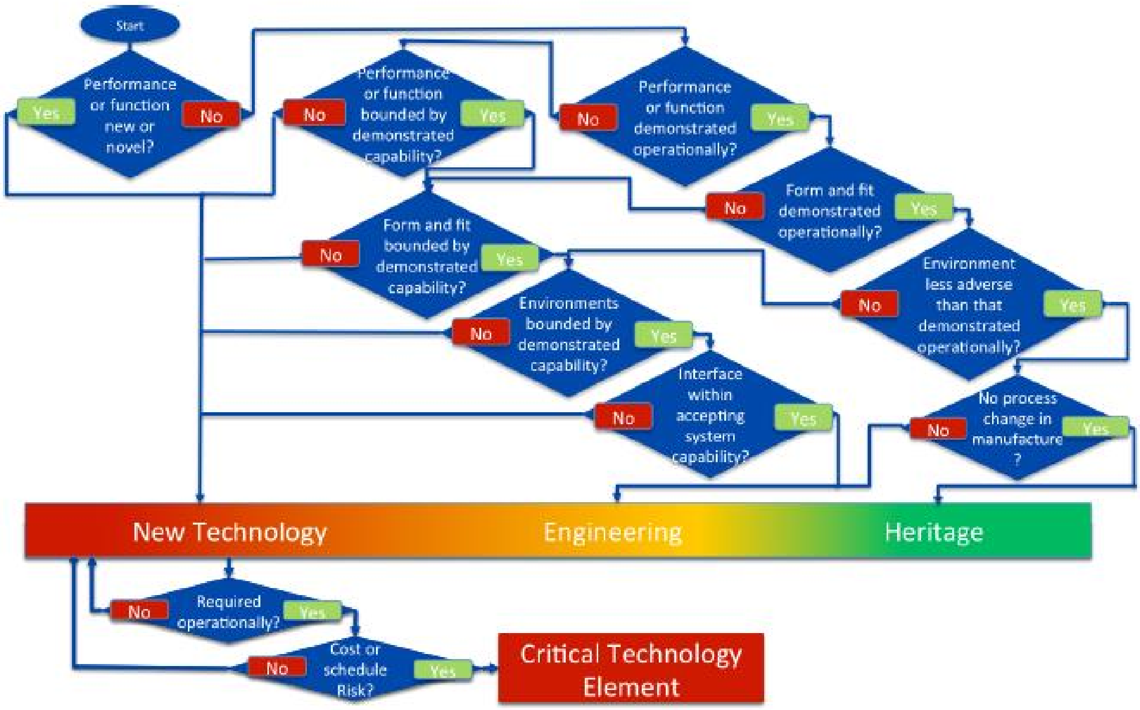

Figure 15 Flowchart for identifying of CTEs

The Figure 15 shows that an ex-ante decision-making process is needed in order to classify an element as "New Technology", "Engineering" or "Heritage". This method identifies only a "New Technology" type elements as critical element and simply it doesn't consider the others. In this case, the absence of modularity of the criticality could lead to an inefficient resource’s allocation. As shown in the Figure 15, an "Engineering" component is more critical than a "Heritage" component, so it needs more resources. For this reason, it must be made evident even ex-post. To avoid this information loss, in the customized TRL these categories are associated with a scale as follows:

- The "Heritage" category is assigned the minimum value "1" which indicates minimum criticality;
- The category "Engineering" is assigned the value "2" which indicates intermediate criticality;
- The "New Technology" category is assigned the value "3" which indicates maximum criticality.

The values were assigned in according to the NASA definitions.

In order to understand these three categories, the use of the television has been taken as example. If the television is based on a new technology never used (that requires some tests) and whose production process still must be developed, the television will be classified as "New technology". If, on the other hand, a TV component is simply modified because there is a new supplier for some of its components, then this technology will be classified as "Engineering". Finally, if the television is not modified in any component and will be used in the same previous operating environment then it will be classified as "Heritage".

Functional criticality identifies the operational importance of the component within the system. Therefore, a system is not a black box anymore, but it is composed by many components. In the system, main and secondary components can be identified through a specific scale. This idea is like the same expressed by the Product Readiness Level. Indeed, there are three levels of functional criticality with different values how it was done for technological criticality:

- “Satellite”: a component that performs a secondary and irrelevant function for the purpose of delivering the system main function. It has been assigned the minimum value "1" which indicates minimum criticality;
- “Intermediate”: a component that performs a secondary but relevant function for the purpose of delivering the system main function. It has been assigned the value "2" which indicates intermediate Criticality.
- “Core”: a component that performs the main function and therefore relevant for the purpose of delivering the correct system function. It has been assigned the value "3" which indicates maximum criticality.

In order to understand the meaning of the functional criticality, it possible to consider the smartphone as a system example. For sake of simplicity, this smartphone has three components and two main functions. The components are camera, volume capsule and screen while the functions are "calls" and "messaging". In this system the camera is classified as a satellite component because if the camera is broken, the smartphone can continue to perform its main functions; the breakdown of a volume capsule, on the other hand, invalidates a main functionality of the smartphone, i.e. calls, but it is still usable; finally, the screen breaking makes the smartphone unusable and it will no longer be able to provide any functions.

Therefore, the component criticality is the combination of technological criticality and functional criticality. The criticality is the weight of the component in the system. By distinguishing these two types of critical issues, it is possible to identify the reasons why a component is critical. it can be critical because of its innovative character or because of its function within the system. NASA suggested that the innovative nature of a component implies a technological risk; in the new model, technological and functional criticality they have been distinguished and one does not entail the other one.

Assigning to the single categories presented a numerical value allows to represent multiple scenarios and to "**l**evelling" the criticality.

Analytically, the criticality was computed as product of the two criticality types:

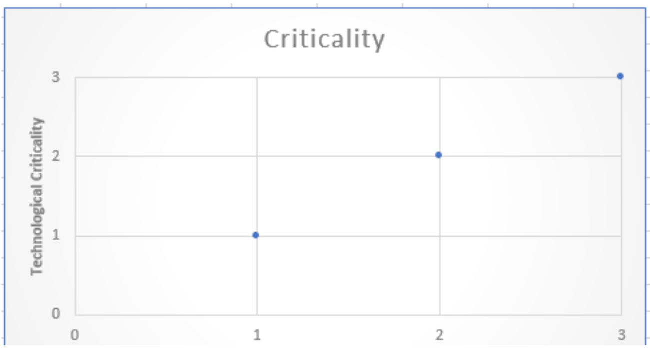

Figure 16 Criticality chart

$$Criticality = \boldsymbol{Funtional_c} * \textbf{Technological}_c$$

Figure 16 shows the criticality as the area identified by the Functional and Technological criticality.

The possible "Criticality" values can be classified into three ranges:

- If the criticality value rages from 1 to 3 where the component is not very critical either because it has a low functional criticality value or because it has a low technological criticality value;
- If the criticality value is 4 or 5, the component has an intermediate criticality level;
- If the criticality value rages 6 to 9, the component is defined as critical.

The evaluating of CTEs considers also the concepts of the criticality. It is calculated for each component and impacts on the general level of the system. So, a System $TRL_{costumized}$ has been defined. This indicator is the weighted average, respect to the criticality, of the individual components TRL level and it is computed as follows:

$$STRL_{costumized} = \frac{\sum TRLcostumized}{\sum criticality} \quad \text{where} \quad TRLcostumized_i = TRL_i * Criticality_i$$

This indicator allows considering both the degree of maturity of the product and its innovation level. In the TRA these concepts were linked and the assessment was necessarily static. With this work it is possible to perform multiple evaluations at the time. This is possible thanks to the distinction between the two different criticality types and through the introduction of a scale for technological criticality.

In order to evaluate the individual system components, the use of the Integration Level indicator has been included. Indeed, the Integration Level allows to verify the "robustness" of the system (paragraph 4.2.2). In the System Readiness Level, the Integration Readiness Level is used together with the Technology Readiness Level. However, its application was limited as it concerned systems consisting of just two elements. In this case, the IRL constitutes an evaluation and it is therefore used for the exclusive purpose of evaluating the individual connections. It is no longer needed to study the n-component systems and to avoid any probabilistic errors for the determination of another higher-level index (SRL). Indeed, with this methodology the two indicators will remain conceptually separate. In this context, the IRL evaluates the integration of every single element of the system considering all its related elements.

In order to evaluate the integration of the components using IRL, follows these steps:

1. Create a table whose rows represent the pairs of each connection between CTEs.
2. Evaluate these connections in order to verify and validate the integration of the components in the product according to IRL.
3. Calculate the average of the IRLs of the connections in order to synthesize the result. This new indicator is named System Integration Readiness Level (SIRL).

Connections	Integration Level
(A,B)	6
(A,D)	7
(A,C)	4
(B,D)	5
(C,D)	3

Table 12 Example of IRL Analysis Table

is a graphical view of a simple system of four components. Each component is already evaluated through the $TRL_{costumized}$ and the connection between them is evaluated through the IRL.

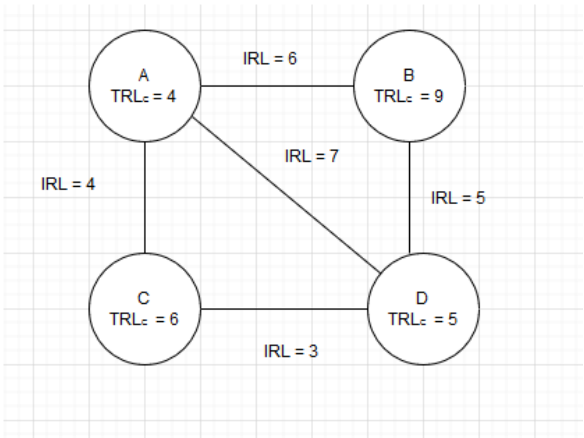

Figure 17 Example of a system

3.3.3 Best practices and standardization process

The customized TRA aims to reduce subjective evaluations to a minimum but, generally, it bases on qualitative indicators. For these reasons, it is not possible to establish specific tests to check the TRL or IRL levels. It needs to be supported by appropriate technical documentation. Anyway, some good practices that each organisation should adopt are listed below:

- Create teams, dividing them by type of component (for example: mechanical, electronic, software components), so that they can increasingly specialize.
- Provide for external audit teams in order to mitigate any teams' opportunisms (example: a project that you want to do necessarily).
- Since these are innovative projects, adopt an Agile methodology. At the base of the Agile Approach, there is a continuous interaction with the "costumer" as who defines the goals with continuous project changes. Particularly, it highlights the results rather than the process. This is called adaptive planning. While the traditional approach is based on the parameters of time, cost and purpose, the agile approach turns to the strength of teamwork and collaboration with the customer: everything is possible thanks to high flexibility.
- Development of software for improving the component development environment and for collecting data on the project components and the progress of the projects. There are many other benefits and are covered in the next section.

3.3.4 Software advantages and example

In the time, many tools are developed in order to evaluate the TRL of technologies. For example, the US Air Force Research Laboratory developed the TRL Calculator that is basically a Microsoft Excel spreadsheet (2.2.2 Model of TRL Assessment). However, this kind of tool often meets some problems and it could be inefficient to manage the complex process of evaluation. For these reasons, the software model is proposed. It has the application logic described, a graphical interface and a shared company database. This design of the software has several advantages.

Some advantages of a graphical interface are:

- Learning curve: software with a graphic interface, allows user-friendly use and therefore does not require specific training. Furthermore, it leads to faster learning. It also allows to view the results and therefore more secure data management.
- Multitasking: software allows the execution of additional tasks and the following multitasking and productivity.

Some advantages of a database are:

- Effective data collection: it allows to make inferences about the future, which improves the planning and the scheduling of future activities. In addition, the data collection in a database permits checking the redundancy of the data. The redundancy determines several disadvantages such as greater use of memory and the changes of the information must be performed several times.
- Atomicity of operations: the sequence of operations on the data allows the DBMS to keep it consistent with the reality.
- Concurrent access to data: A DBMS allows simultaneous access to users without generating anomalies.
- Permission management: users' access to data is partial and depends on the permissions granted.

For the purposes of this thesis, the mock-ups of a GUI are realized in order to highlight the previous instance.

The GUI consists of eight different frames: Login, Register Account, Welcome Page, Projects Details, Project Details, Calculator IRL, Component Details, Calculator TRL.

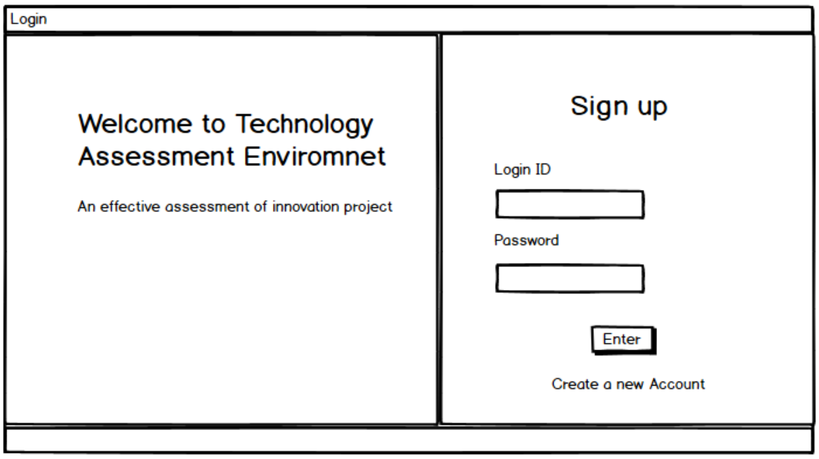

Figure 18 GUI Login example

The first page (Figure 18) is dedicated to the login into the software. It consists of a descriptive part and another one dedicated to insert the fields necessary for the actual login. Below, there is a link to create a new user. The login is necessary to guarantee the management of permissions between different users.

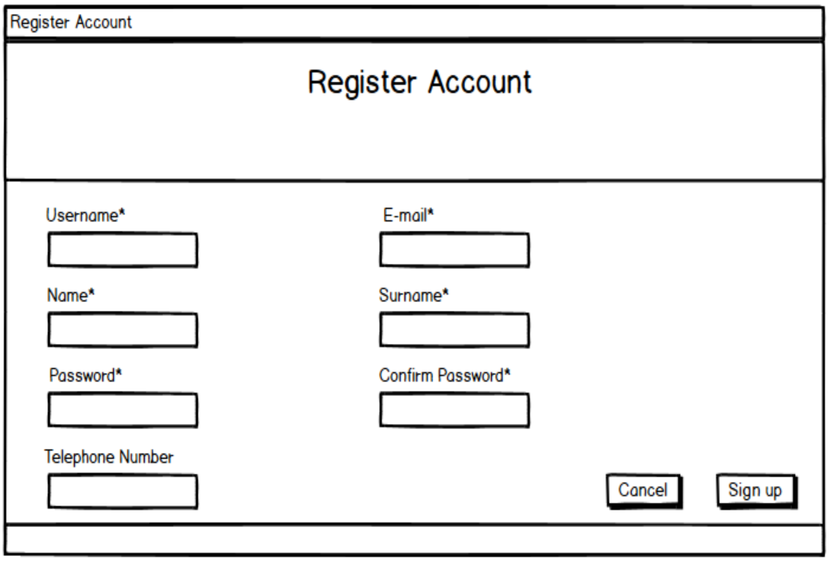

Figure 19 GUI Register Account example

The "Register Account" page, on the other hand, is dedicated to user registration. It is divided into two sections. The top contains the page header while the content section contains the different fields for information introduction. It provides seven fields: username, e-mail, name, surname, password, Confirm password and Telephone Number. They are all mandatory except the Telephone Number. Through this page, it is possible to record a user in the database. In this way, only registered users can access the software data.

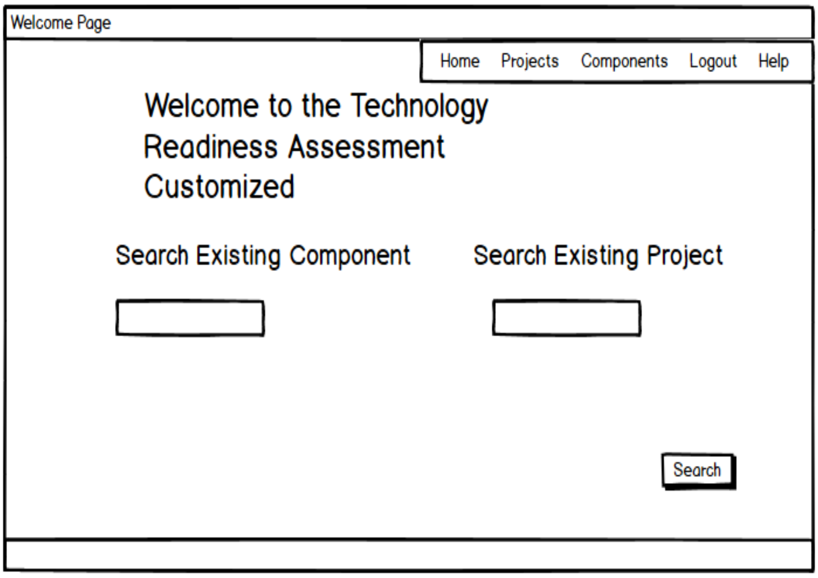

Figure 20 GUI HomePage example

The "Welcome Page" represents the GUI Homepage. This first page (Figure 20) is dedicated to the login into the software. It consists of a descriptive part and another one dedicated to insert the fields necessary for the actual login. Below, there is a link to create a new user. The login is necessary to guarantee the management of permissions between different users.

The header of the page has a menu which permits the navigation in the software. It has the home button to return to this page; the Projects button to directly access the projects in the database; the Components button makes possible the access to all the components of the different projects in the database. This menu is available on all the following pages. Within this page, it is possible the search for projects or components of existing projects. In addition, it permits access to relevant pages to create new ones.

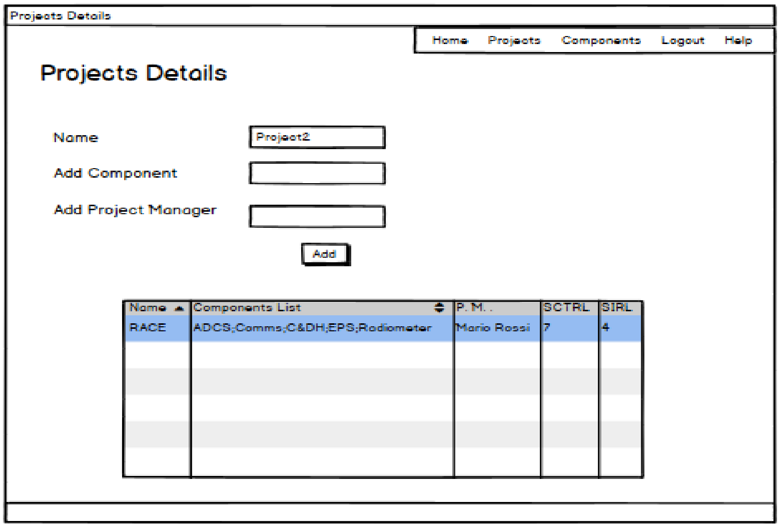

Figure 21 GUI Projects Details example

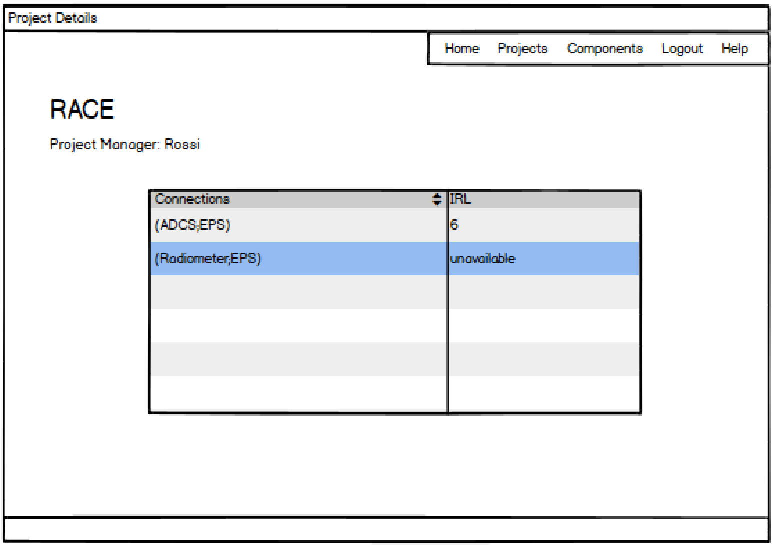

Figure 22 GUI Project Details example

Figure 21 shows "Projects Details" page. It is necessary to clarify that a component can once be a project. It has been assumed that a name, a list of components and a Project Manager have to be assigned for each project. Through this organization of the data, many types of researches are available. In addition, there are specific search bars for the projects and for the components each of which has an identifier. The projects are listed in a table and are associated with the list of components and the PM. The $STRL_{costumized}$ and SIRL fields contain the current value of the evaluation of the whole project. If the field is "unavailable" it means that at that moment the index calculation procedure is in progress and therefore not available.

By selecting a project, it is possible to access its page (Figure 22). This page shows all the specifications of the project and may have different views. In the specific case, it is a view showing a table with all the possible connections between the components of the project and the relative IRL value according to the modeling proposed in the previous paragraph. If the field is "unavailable" it means that at that moment the index calculation procedure is in progress and therefore not available.

By selecting the IRL value in the table, it will open the page "Calculator IRL" (Figure 23). With this page it is possible to evaluate the IRL of a selected connection. At the end of the procedure, the software evaluates the IRL level of the connection and it assigns the value.

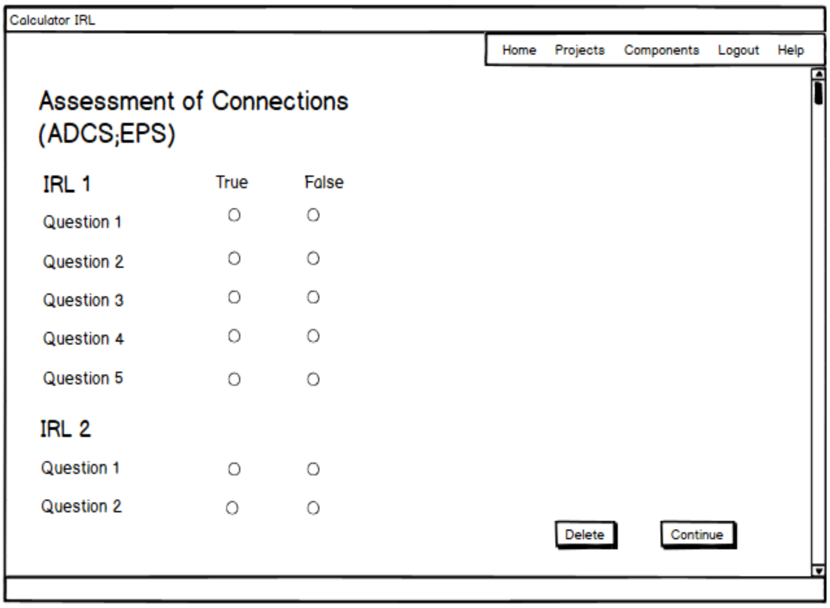

Figure 23 GUI Calculator IRL example

Figure 24 describes the "Component Details" page. It has been assumed that each component must be assigned a name, type, technological criticality, functional criticality and TRL level. Below, there is a table that permits to access and search for the components in the database. The identifier is managed by the DBMS.

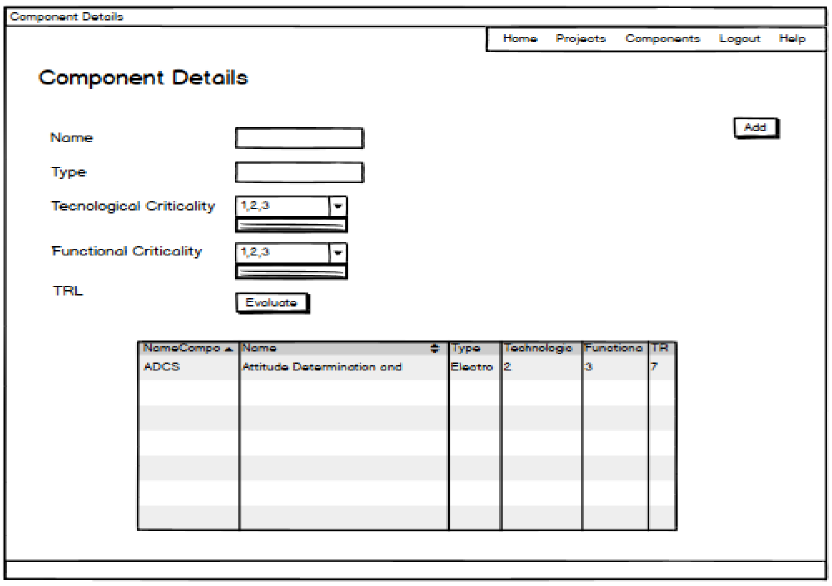

Figure 24 GUI Component Details

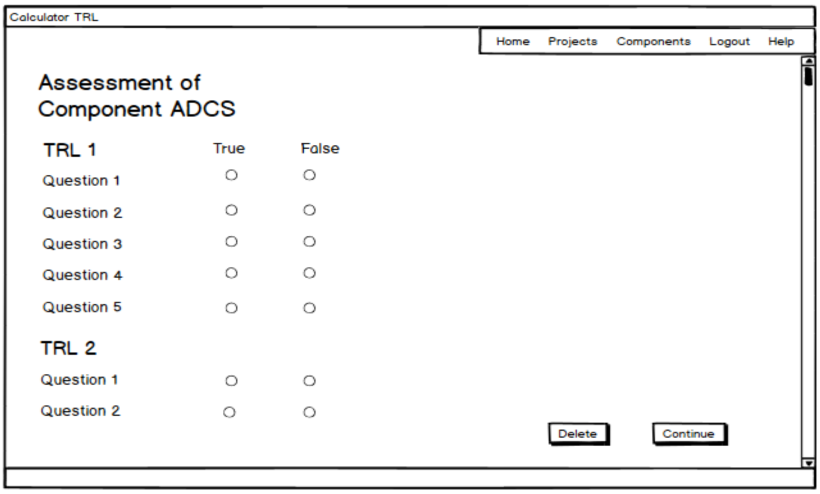

Figure 25 GUI Calculator TRL

Through the evaluate button it is possible to reach the "Calculator TRL" page (Figure 25) through which it is possible to evaluate the TRL of a selected component. At the end of the procedure, the software evaluates the TRL level of the component and it assigns the value.

4. Study case

4.1 Case study: Radiometer Atmospheric CubeSat Experiment

In order to understand the news indicators and to analyse any differences with the existing methodology, an application case is proposed. Particularly, the case study described is the Radiometer Atmospheric CubeSat Experiment "RACE". It was a technological mission of NASA / JPL[26] and UTA[27] with the goal of demonstrating the technology of the microwave radiometer on a CubeSat[28] 3U platform. This radiometer measures the path of liquid water and the water vapour. In fact, there are important on a global scale as they allow to understand the water cycle. In turn, this one is fundamental for the energy balance of the Earth and for understanding climatic weather processes. The radiometer had a frequency of 183 GHz which allows studying different layers of the atmosphere both vertically and horizontally.

The technical objectives of this mission were:

- To advance the technology of the 35 nm indium phosphide receiver subsystem of the radiometer instrument.
- To advance the technology of a 183 GHz water vapor radiometer CubeSat system.
- To reduce the risk for future users of the technology.
- To enhance the hands-on training for the RACE project team members within the Phaeton Program platform.
- To explore possibilities for smaller missions with distributed risks.

The RACE brings the TRL of the receiver from 4 to 6 and the CubeSat radiometric system from 4 to 7. A radiometer inside the CubeSat allows to switch from traditional large-scale missions with high costs and risks to smaller and more distributed missions. RACE provides assistance in the development of critical technologies that improve NASA's exploratory and scientific discovery mission SDL (Satellite Design Laboratory) at the UTA built and subsequently tested CubeSat.

4.1.1 RACE Design

Figure 26 shows the functional bill of material of the CubeSat used in the RACE mission. It composed by five sub-systems:

- Attitude Determination and Control System (ADCS): Attitude Determination and Control Systems (ADCS) is the subsystem of a satellite structure dedicated to the determination of the satellite, as well as the position. In order to determine its orientation and position, a combination of sensors is used to calculate a reliable estimate of its coordinates;
- Comms: The term Comms is an abbreviation for "Communication". Indeed, this section is dedicated to the reception or sending of data collected by the radiometer. In particular, it covers an UHF antenna and a UHF radio (band ranging from 300 MHz to 3 GHz);
- C&DH: it means Command & Data-handling Systems and is generally composed by a Pic Processor and memory. It has many functions such as the management of all forms of data on the spacecraft, of the commands sent from Earth, collection of solar power and charging of the batteries, of information about all subsystems and payloads and of the preparation of data for transmission to Earth;
- EPS: The Electrical Power subsystem (EPS) is the equipment to supply the electrical energy, power generation and control, power conversion and distribution.

[26] The Jet Propulsion Laboratory (JPL) is a federally funded research and development center and NASA field center.
[27] University of Texas, Austin.
[28] A CubeSat is a type of miniaturized satellite for space research that is made up of multiples of 10 cm × 10 cm × 10 cm cubic units.

- Radiometer: The radiometer system is composed by 3 major blocks: an antenna for receiving the signal and for determining the coarse frequencies of observation; the radiometer front-end that has the internal calibration system and the amplifier chain; the diplexer block contains the waveguide splitter, additional amplifiers, filters and detectors.

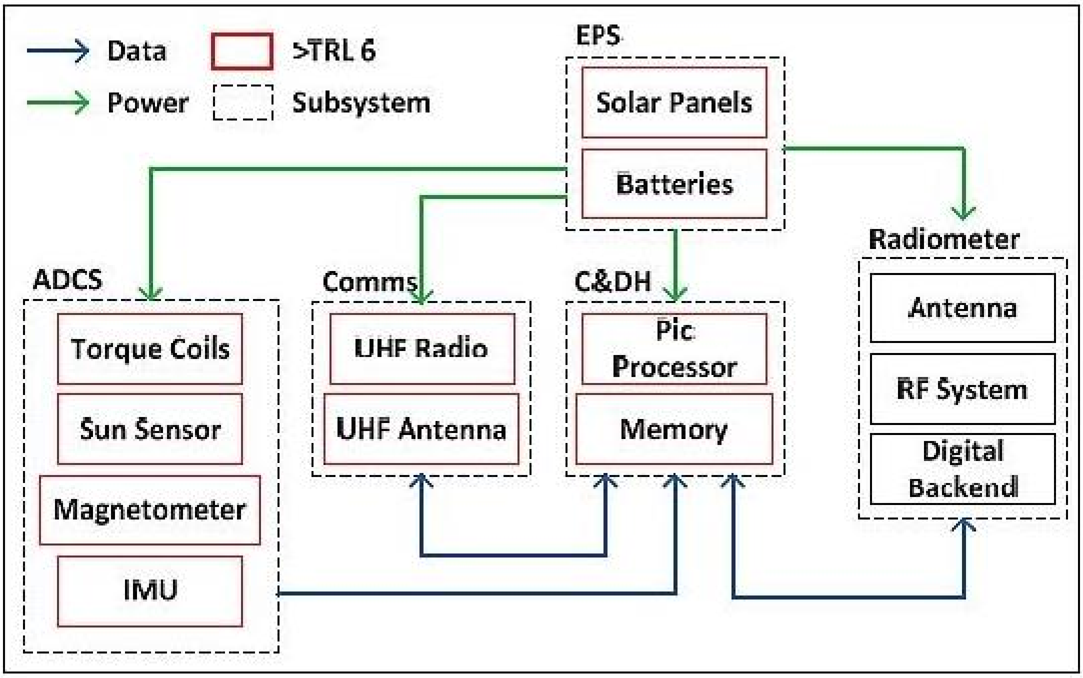

Figure 26 Bill of Material of CubeSat in the RACE mission

Figure 26 shows that many components have a TRL greater than 6. In the RACE mission, the changes to the CubeSat consisted of adding four solar panels, replacing the radio by inserting a UHFL3 cadet radio and adding an ADCS active. Given the high TRL of the system, these changes should not have been a problem.

4.2 Results and Discussion

This case study allows to understand the main following advantages of the introduction of new parameters:

- Functional Criticality and Technological Criticality improve the description of system components and allow to allocate project resources with more precision.
- Technology upgrades can be considered properly according to the criticality.
- System component can be evaluated both individually and as a system.

The TRL assessment of the functional components of the "RACE" system is shown Table 13. The TRL scores of each subsystem were greater than 6. It is possible to notice that the only exception is the score of Radiometer. Indeed, the latter was assessed with a TRL greater than 4. The values shown in the table are approximations. The TRL estimation is the result of the existing methodology as shown in 4.1.1 RACE Design.

	TRL
ADCS	7
COMMS	7
CDH	7
EPS	7
Radiometer	5

Table 13 Data Analysis with the previous TRL scale.

This assessment does not consider many introduced concepts such as the degree of innovation of the components or their functional criticality within the system. In this paragraph, it is shown an application example of the $STRL_{costumized}$ to point out the improvement made on the methodology.

	Criticality				*TRL*
	Functional Criticality	Technological Criticality	Criticality	TRL	
ADCS	3	2	6	7	42
COMMS	3	2	6	7	42
CDH	3	1	3	7	21
EPS	3	2	6	7	42
Radiometer	3	3	9	5	45
$STRL_{costumized}$					6

Table 14 Data Analysis with the $STRL_{costumized}$

The $STRL_{costumized}$ assessment is shown in the Table 14. In addition to the TRL value, three values have been considered for the Criticality assessment. In detail, Functional Criticality and Technological Criticality have been defined. According to the definition (3.3.2 Model), the Criticality represents the product between Functional Criticality and Technological Criticality.

According to the description of the subsystems (4.1.1 RACE Design) and the Functional Criticality definition and scale (3.3.2 Model), for this parameter, the following values have been assigned:

- ADCS: the value 3 has been assigned to this subsystem. In fact, without this component, CubeSat is no longer able to control its payload. Indeed, at the first anomalous event, the entire system is compressed or easily compromised.
- COMMS: the value 3 has been assigned to this subsystem. As communication component is essential in order to deliver to send and to receiver data.
- C&DH: the value 3 has been assigned to this subsystem. This subsystem is a fundamental functional component because it manages spacecraft data.
- EPS: the value 3 has been assigned to this subsystem. The Electrical Power Subsystem stores and delivers energy for the entire system. Therefore, it is not possible to operate without it also because the system has not a support energy system.
- Radiometer: the value 3 has been assigned to this subsystem. This subsystem has the function of collecting and measuring data. It is fundamental in the execution of the function of the entire system.

All the subsystem, in this specific case study, are “core” components because they are all fundament for the correct work of the entire system. In general, it is possible that a system is made up of all equally functionally critical components.

As reported for the Functional Criticality, the Technological Criticality is described in 3.3.2 Model. In accordance with the description of the subsystems, the following values have been assigned:

- ADCS: this subsystem was added for the first time within the CubeSat previous version. Its original function has been retained. However, a new engineering process was needed to integrate this component in the pre-existing CubeSat. For these reasons, the value 2 has been assigned.
- COMMS: this subsystem has already been implemented previously within the CubeSat.
  In the CubeSat 3U, a UHFL3 cadet radio was integrated within the COMMs. Therefore, as for the ADCS, a new engineering process was required and the value 2 has been entered.
- C&DH: this subsystem has already been used in previous missions and has been adopted in this mission with the same function. It is therefore of the "Heritage" type and the value 1 was assigned.

- EPS: this subsystem has already been implemented previously within the CubeSat. However, four solar panels have been added. Due to this improvement, a new engineering process was needed and value 2 has been entered.
- Radiometer: this subsystem was a new component for CubeSat spacecraft. The radiometer is a new technology never tested in space[29]. It is possible to consider it as "New Technology" type and the value 3 has been assigned.

The Technological criticality values of the individual subsystems show that they have a very high value except C&DH which is, on the other hand, not very critical.

The $TRL_{costumized}$ is estimated according to the $STRL_{costumized}$ methodology (3.3.2 Model). The whole system also has an $STRL_{costumized}$ level of around 6.

The CubeSat Technology maturity is lower than the value provided to the traditional evaluation. Due to the introduction of different weights for each component, it is possible to evaluate the critical aspects of them and highlight the differences among them. In the traditional methodology, indeed, all subsystems had the same weight by default.

The technological maturity of the system strongly depends to the Radiometer maturity because this component as New Technology needs more effort during the project process. Indeed, the weight of the Radiometer assumed a greater percentage compared with previous evaluation. This evidence allows to positively evaluate the Customized TRA because it allows to effectively estimate the most critical components of the system. The difference between the TRL and $STRL_{costumized}$ results is even more evident if functional criticality of subsystem is different.

According to these observations, it is evident that the proposed methodology can effectively evaluate all the possible scenarios in real case systems.

The methodology presented in this work considers also the IRL (3.3.2 Model). However, RACE project does not report enough information to perform this analysis. Indeed, the project description reports exclusively only the connections between the subsystems. Any details are not provided about technical information. The combination of the $STRL_{costumized}$ and IRL index is innovative aspects studied in this thesis and it still remain a challenge without a dataset.

[29] *Boon Lim*, et al. Jet Propulsion Laboratory. Development of the radiometer atmospheric CubeSat experiment payload.

Conclusion

In this era, innovation is one of the main sources of competitive advantage. A correct methodology is fundamental for evaluating innovative aspect. The state of the art points out the ineffectiveness of existing techniques. Thus, the aim of this thesis was the improvement of the existing methodologies for the assessment of innovative projects. The NASA methodology was focused only on the technological maturity instead of the innovation. Thus, an effort for splitting the technology maturity and innovation has been made from the further methodologies. Looking for all of the advantages of the existing methodologies the challenge of this work was to point out innovative aspects in a standardized way.

To reach this goal, Technology Readiness Assessment has been chosen for supporting the activities of Project Assessment. After the description of the Technology Readiness Assessment, an analysis of its main critical issues was carried out and the main variants that have been developed over time have been highlighted.

Based on existing literature, a new variant of the Technology Readiness Assessment has been proposed with the aim of solving its main problems. In particular, the following have been resolved:

- the inability to evaluate a technology element system integration;
- the criticality levelling of CTEs;
- inability to consider continuous system evolution.

The new variant has been called as "TRA customized" and has provided for the introduction of new concepts. First, TRA customized approach is different from the TRA because in this case it is possible to evaluate also single system component instead of the whole system. Indeed, the analysis involves the study of each individual component. The component is assessed not only by the existing TRL index but also through the concepts of functional criticality, technological criticality and integration between components.

Through the introduction of these new concepts, it was possible to achieve the following results:

- Assessment of multiple technologies system;
- Improvement of classification for components trough criticality levels;
- Storage of system upgrades.

Highlighting the best practices that can be adopted in this process, the use of software that manages the analysis process was proposed. Indeed, a well-structured software introduces important advantages in the realization and management of the procedure such as learning curve or data collection. In details, the interface design was structured in eight mock-ups.

Finally, a RACE project was proposed as case study in order to understand the differences between the new methodology and state of art. Due to the lack of meaningful datasets, as mentioned before, the validation of the methodology is still a challenge. In this case, the analysis on the RACE project tested the validation methodology and showed promising results of the methodology developed.

Future development could be summarized into three main points:

- Development of a complete dataset of case studies to validate the procedure.
- Implementation of the software based on the GUI proposed in this thesis.
- Investigate the TRA customized applications in different field. The model is tested in aerospace projects field. However, it could be applied not only in technological fields but also for development project. Smart cities for example required innovative solutions for a programmatic growth so this methodology could be an efficient tool for innovation assessment.

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APPENDIX I

Case Study 1: Immature Technologies Increase Risk, from *DOD,* GAO-08- 408
Before its cancellation in 2011, the Future Combat Systems—comprised of 14 weapon systems and an advanced information network—was the centrepiece of the Army's effort to transition to a lighter, more agile and more capable combat force. In March 2008, GAO has shown that 42 out of the program's 44 critical technologies had not reached maturity halfway through its development schedule and budget at five years and $12 billion in spending. Major technical challenges, the Army's acquisition strategy and the cost of the program, as well as insufficient oversight and review, all contributed to its subsequent cancellation.
GAO*, Défense Acquisitions: 2009 Is a Critical Juncture for the Army's Future Combat System,* GAO-08-408 (Washington, D.C.: March 7, 2008).

Case Study 2: Space Programs Often Underestimate Costs, from *DOD*, GAO-07-96
Costs for DOD space acquisitions have been consistently underestimated over the past several decades—sometimes by billions of dollars. In 2006, GAO has shown that cost growth in DOD space programs was largely caused by initiating programs before determining whether requirements were achievable within available resources. Unrealistic cost estimates resulted in shifting funds to and from programs, which also exacerbated agency wide space acquisition problems. For example, on the National Polar-orbiting Operational Environmental Satellite System program, DOD and the Department of Commerce committed to the development and production of satellites before the technology was mature—only 1 of 14criticaltechnologies was mature at program initiation and 1 technology was found to be less mature after the contractor conducted more verification testing. The combination of optimistic cost estimates with immature technology resulted in cost increases and schedule delays. GAO recommended that DOD, among other things, require officials to document and justify the differences between program cost estimates and independent cost estimates and develop a centralized database of realistic and credible data for cost estimators. GAO also recommended that, to better ensure investment decisions for space programs, estimates could be updated as major events occur within a program that might have a material impact on cost, such as budget reductions, integration problems and hardware and software quality problems.

GAO, *Space Acquisitions: DOD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems*, GAO-07-96 (Washington, D.C.: Nov. 17, 2006).

APPENDIX II

OSI Model

7	Application	High-level APIs, including resource sharing, remote file access
6	Presentation	Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
5	Session	Managing communication sessions, i.e., continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
4	Transport	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
3	Network	Structuring and managing a multi-node network, including addressing, routing and traffic control
2	Data Link	Reliable transmission of data frames between two nodes connected by a physical layer
1	Physical	Transmission and reception of raw bit streams over a physical medium

“The OSI Model's Seven Layers Defined and Functions Explained". *Microsoft Support*. (28 /12/2014)