R&D project selection incorporating risk management

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R&D project selection is a critical decision in organizations engaged in scientific research and technology development. Resource limitations impede these organizations from engaging in every project, so careful consideration should be taken in the selection process to ensure that the most promising projects are selected. The different types of R&D reflect different technology readiness levels, and can serve multiple purposes: build new or nurture internal competences, develop new conceptual models, test prototypes, develop technological systems and thus become platforms for developing new products. Given their diverse nature, the different types of R&D projects should be addressed separately in the selection process, and compared to each other using appropriate criteria. R&D projects can also present uncertainty and risk, since they aim at developing solutions with a degree of novelty. Current R&D project selection methodologies, although addressing risk and uncertainty, do not take into consideration different perspectives on risk, driven by the readiness levels of technologies and the scale of R&D projects, therefore not contributing to a homogenization of organizational policies towards risk management. Furthermore, project selection methodologies provide no means for risk assessments made in the selection stage to be used in later stages of project life cycle, for risk management and control purposes. In order to address these issues, a new R&D project selection methodology that fills these gaps is proposed. The proposed methodology is applied in the industrial partner of this study.

Keywords: R&D, project management, selection, risk

1 Introduction

In line with the technology strategy guidelines of organizations, a number of strategic R&D projects proposals are generated. Due to resources constraints, organizations often use selection techniques in order to focus on the most promising projects.

This set of R&D projects can be of various types, depending on the strategic objectives defined by the organization: competence building and nurturing, expansion of technologies portfolio for future applications, increase of sales from launching newly developed products or existing products with improved technologies, etc. (Chiesa, 2001, Tidd *et al.*, 2005). Therefore, careful consideration should be taken regarding strategic objectives in different types of R&D projects during the selection process.

Furthermore, the project selection process, which is performed in the early stages of projects life cycle, is clouded by uncertainties, either originated from incomplete knowledge about the current shape of the market and the status of scientific and technological development and/or from questions about which trajectories science and technology will follow (Wang *et al.*, 2010). Risk and uncertainty are thus pervasive throughout all stages of the projects' life cycle. Decisions made at an early stage may also undergo several changes throughout the projects' execution. As such, the incorporation of uncertainty in the project selection process, as well as a risk control mechanism able to assist managers in dealing with uncertainty during the execution of the selected projects, is therefore required.

The strategic nature and irreversibility of this type of investments has stimulated the development of numerous R&D project selection methodologies. Although risk and uncertainty has been incorporated in many of proposed methodologies, the incorporation of risk assessment and control mechanisms early on the projects' life cycle based on a defined organizational policy towards risk has not been explored. Taking into account this research gap, this study presents a new project selection methodology that aims at addressing these issues, through the combination of various existing tools and techniques. This methodology is applied in the industrial partner of the study.

This study is structured as follows: section 2 provides a literature review on themes related to R&D project selection and risk management practices; in sections 3 and 4 the development of a new methodology is described; the application of the methodology in the industrial partner is presented in section ; and section 6 presents the final discussions and conclusions of this study.

2 Literature review

This section is divided into two parts. The first presents a review on R&D project selection methods, with emphasis on the methods that incorporate risk and uncertainty. The second part presents, with greater detail, risk management tools and practices in projects

2.1 R&D project selection

Executing every single candidate project generated from the strategic guidelines of the organization is limited by the availability of resources. Investment in the development of innovative technologies and products is widely recognized as one of the main sources for obtaining competitive advantages for organizations. Therefore, selection is a critical activity, because it enables organizations to focus their efforts on projects that have more chances to succeed.

R&D project selection theme is, clearly, a subset of the project selection problem. And, as expected, both problems share many traits. Notwithstanding this, some peculiarities of R&D projects are discussed later in this section.

The topic of project selection or project portfolio selection – addressing the selection of a group of projects from available projects and projects currently under execution - has been discussed for decades. Its applicability extends beyond the borders of projects, including *technologies selection* (Iamratanakul *et al*., 2008, Shakhsi-Niaei *et al*., 2011), *technology acquisition mode* (Lee *et al*., 2009) and its corresponding mode in projects, *project execution mode*. In a review on project portfolio selection, Archer and Ghasmzadeh identified eleven propositions that should be addressed in the development of an integrated methodology for project selection (Archer and Ghasemzadeh, 1999). Among such propositions are:

- consideration of internal and external business factors prior to project selection to build strategic directions and focus;
- organization into a number of stages to allow decision makers to move logically towards an integrated approach to project selection;

- avoid unnecessary data;
- use of common measures, i.e., techniques and indicators that are applicable to the type of projects under consideration, to ensure that project are compared equitably during selection;
- allow reviews or re-evaluations at milestones or gates of current projects at the same time new projects are under consideration for selection;
- screening should be used before selection, if necessary (i.e., too many projects);
- projects dependencies should be considered in selection;
- consider the time-dependent nature of project resource consumption, i.e., resource competition between projects to be selected and projects under execution;
- enable controlling mechanisms that provide decision makers with feedback on the consequences of changes and adjustments made on projects;
- should be adaptable to group decision support environments and thus reflect overall objectives of the organization.

Several project selection methods and techniques have been proposed in literature. Traditional approaches were based on quantitative and economic tools, such as discounted cash flow, net present value, return on investment (ROI) and payback period (Liberatore, 1987). These methods have been criticized for providing one-dimensional approach to project selection (Shakhsi-Niaei *et al*., 2011), thus leading to a myopic decision process (Pinches, 1982). Recent publications have emphasized the importance of including non-financial criteria into project selection (Meade and Presley, 2002, Martinez et al., 2011) in order to cover organizational, managerial, political, social, environmental and other dimensions (Lopes and Flavell, 1998). In this domain, subjective (and qualitative) criteria, which relies on managers' experience, knowledge and intuition (Tan *et al*., 2011) have been largely applied.

Operations Research field has contributed substantially to project management (and thus selection) through mathematical modeling of complex decision problems (Tavares, 2002). Despite its undeniable contribution, some approaches have become so mathematically intricate that necessitate the support of an expert decision analyst to be used in practice (Henriksen and Traynor, 1999). Advances in computer technology and improvements in the sophistication of models developed by academics have not yet found wide acceptance by managers (Liberatore and Titus, 1983, Fahrni and Spätig, 1990, Shane and Ulrich, 2004).

Nevertheless, and due to the great interest in the area and wide range applicability, a great variety of methods exist in literature and authors have attempted to cluster or classify them according to their nature. One of the first classifications is proposed by Baker and Freeland (Baker and Freeland, 1975). According to their classification, there are three types of R&D project selection methods: *comparative approaches*, methods where managers are supposed to compare project proposals against each other (examples include Q-sort, ranking, rating, paired comparisons, standard gambles and others); *scoring models*, methods based on a relatively small number of decision criteria used to assess the desirability of each alternative project proposal; and *benefit contribution models*, where projects are evaluated according to their contributions to a number of objectives or systems' requirements, examples of such methods include economic return, cost/benefit, risk analysis and relevance trees.

More recent classifications include the numerous methods applied to the R&D project selection problem in the last four decades. According to Henriksen and Traynor, there are eight categories, which are classified according to their underlying theory (Henriksen and Traynor, 1999): *unstructured peer review*; *scoring*; *mathematical programming* (integer programming (IP), linear programming (LP), nonlinear programming (NLP), goal programming (GP) and dynamic programming (DP)); *economic models* (internal rate of return (IRR), net present value (NPV), return on investment (ROI), cost-benefit analysis and option pricing theory); *decision analysis* (multi attribute utility theory (MAUT), decision trees, risk analysis, and the analytic hierarchy process (AHP)); *interactive models* (Delphi method, Q-sort, behavioral decision aids (BDA), and decentralized hierarchical modeling (DHM); *artificial intelligence (AI)* (expert systems and fuzzy sets); and *portfolio optimization*.

In another study, Iamratanakul *et al.* classifies project portfolio selection in six dimensions: *benefit measurement methods, mathematical programming approaches, simulation and heuristics models, cognitive emulation approaches, real options, and ad hoc models* (Iamratanakul *et al.*, 2008). In a brief critical review, the authors argue that one methodology does not fit all project selection requirements since each methodology has it owns advantages and disadvantages. The techniques used in each dimension are portrayed in Figure 1.

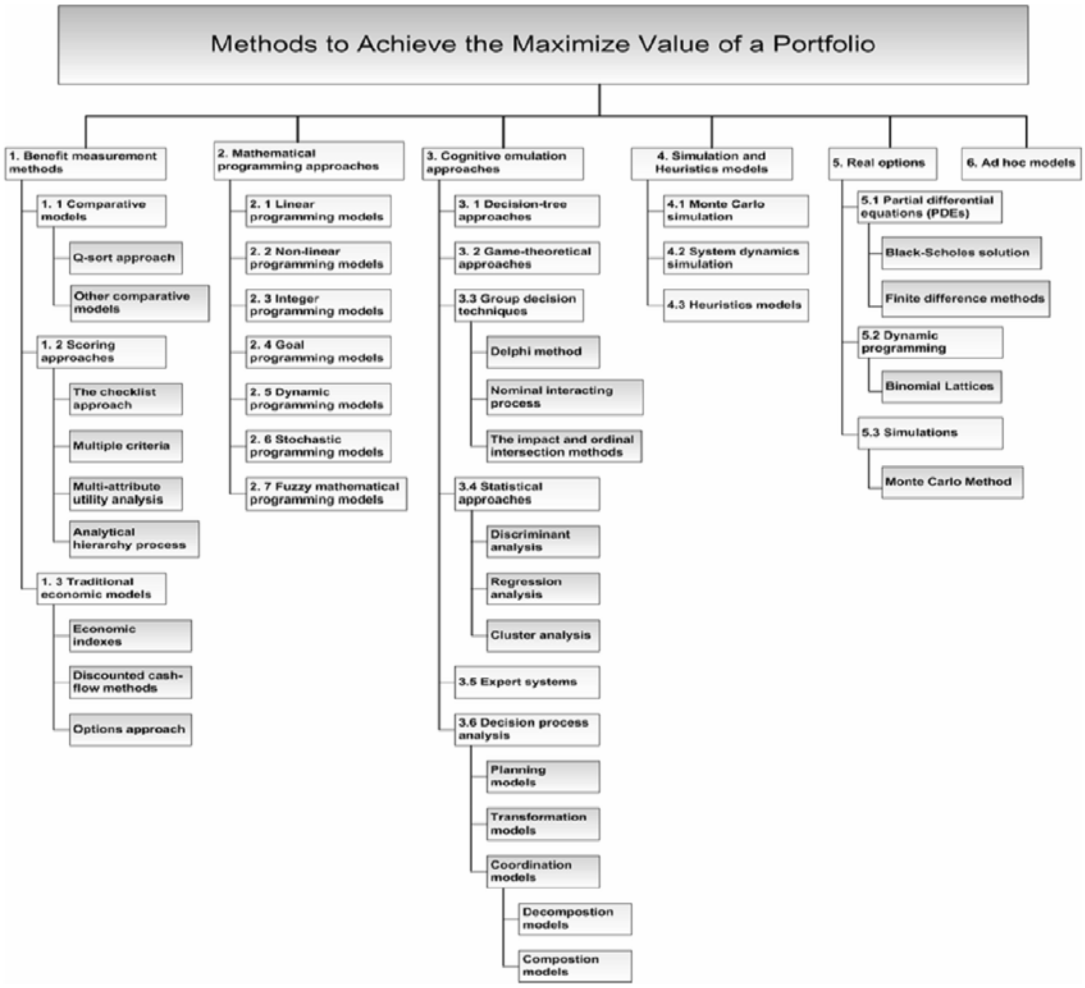


Figure 1 - A classification of project portfolio selection methods. Source: (Iamratanakul *et al.*, 2008)

Verbano and Nosella adds another class of methods to Henriksen and Traynor's classification: *strategic models*, methods that use subjective input to take into account multiple strategic aspects in R&D project selection, like the Boston Consulting Group matrix and strategic buckets (Verbano and Nosella, 2010). In this same publication, and based on an extensive review of previous studies on project selection methods, a set of aspects is identified, that needs to be considered during R&D project selection. This complements the propositions of Archer and Ghasmzadeh: evaluation of both economic (quantitative) and strategic (qualitative) aspects; strategic coherence within a project portfolio and interdependency analysis; risk and uncertainty analysis and evaluation of method implementation characteristics.

Among such aspects, uncertainty and risk are frequently cited as factors to be considered in the project selection process (Fahrni and Spätig, 1990, Henriksen and Traynor, 1999, Ghasemzadeh and Archer, 2000, Poh *et al*., 2001). The development of new technologies and products are subjected to uncertainties and risks concerning the achievement of technical and market goals. Therefore, risk should be managed throughout all the R&D project stages in order to improve success rates (Wang *et al*., 2010). Supporting this perspective, Chiesa argues that projects should be evaluated according to their characteristics of relevance (or benefit) and risk (Chiesa, 2001). Given the importance of the theme, a number of project selection methodologies incorporating uncertainty and risk are reviewed next.

A considerable number of project selection methods that incorporate risk belong to the class of complex optimization models: Heidenberger presents a mixed integer linear programming (MILP) model for dynamic project selection and funding problems under risk, with multiple resources with different qualifications (Heidenberger, 1996); Medaglia *et al.* propose an evolutionary method named stochastic parameter space investigation (PSI) to address the project selection problem with partial funds, multiple (stochastic) objectives, project interdependencies and resource constraints (Medaglia *et al*., 2007); Solak *et al.* present a multistage stochastic integer model with endogenous uncertainty for dynamic optimization of project portfolios over a planning period (Solak *et al*., 2010); a stochastic optimization model for project portfolio selection is proposed by Gutjahr and Froeschl, which considers uncertainties about real efforts for the work packages contained in the projects (Gutjahr and Froeschl, 2013).

Other studies use stand-alone methods that address the dynamic nature of environmental factors that influence R&D project selection decision process. Fox and Baker use simulations on a number of selected variables, which are included in two models: the profitability and project generation models (Fox and Baker, 1985). The outputs of these two models feed a third one, the decision model, where projects are selected according to their expected contribution to profitability. A dynamic multi attribute utility decision model based on simulations made on three project attributes (technological risk, market risk and economic benefits) is proposed by Zhong el al. (Zhong *et al*., 2010). A Data Envelopment Analysis (DEA) model is presented by Ghapanchi *et al.* that take into account project interactions and uncertainties, modeled as fuzzy variables (Ghapanchi *et al*., 2012)**.**

More complex frameworks that combine different methods have also been applied. For example, Gabriel *et al.* argue that project selection under uncertainty should incorporate multiple criteria and probabilistic components. As such, they propose a multiobjective optimization model that maximizes projects ranks (modeled previously via Analytic hierarchy process - AHP, a multiple criteria method) and minimizes cost distributions, modeled with Monte Carlo simulations (Gabriel *et al*., 2006). Another example is provided by Shakhsi-Niani *et al.*, that uses another multiple criteria method, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) method (Brans and Vincke, 1985), embedded into a Monte Carlo simulation framework to rank projects under uncertainty, to analyze the probabilities of achieving different ranks in each project and the impact of these uncertainties in the final ranking (Shakhsi-Niaei *et al*., 2011).

The consideration of strategic factors in conjunction with economic factors has been largely addressed via multiple criteria and scoring methods. Liberatore presents an AHP model that links the mission, objectives and strategy of business with criteria used to select R&D projects (Liberatore, 1988). Henrikssen and Traynor propose a simple scoring method that accounts with tradeoffs among evaluation criteria through a value index algorithm that produces a measure of project value (Henriksen and Traynor, 1999). Meade and Presley applies a more generic version of the AHP, the Analytic Network Process, that considers interrelationships among decision levels and attributes (Meade and Presley, 2002). Unlike Henrikssen and Traynor's scoring model that uses the same criteria, but with different relative importance for different categories of R&D, Lawson *et al.* proposes a scoring model that considers different criteria for different types of R&D (Lawson *et al*., 2006), namely basic research, applied research and experimental development.

The need to consider different R&D project types in the selection process is supported by many authors (Mitchell, 1990, Coldrick *et al*., 2005, Tidd *et al*., 2005, Lawson *et al*., 2006, Verbano and Nosella, 2010). According to the Frascati Manual, a document published by the Organization for Economic Co-operation and Development (OECD) that provides the guidelines for collecting statistics about research and development, there are three types of R&D projects (OECD, 2002):

- **Basic research:** *"experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular or use in view"* (OECD, 2002, p.77);
- **Applied research:** *"original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective*" (OECD, 2002, p. 78);
- **Advanced technology or experimental development:** *"systematic work, drawing on knowledge gained from research and practical experience, that is directed to producing new materials, products and devices; to installing new processes, systems and services; or to improving substantially those already produced or installed"* (OECD, 2002, p. 79).

Criteria should be used according to the expected objectives of each project type: early stage or basic research comprise projects aimed for *knowledge building* (Tidd *et al*., 2005) into areas that can generate future opportunities or threats. Applied research and advanced technology or experimental development is aimed at testing the feasibility of early prototypes and versions of technological systems. At this point, possible applications can be envisioned and thus, market analysis start to play an important role.

Extending beyond this classification, there is another project type, related to *business investments* in new products, services and processes, with success criteria depending on meeting the needs of target groups of users (Tidd *et al*., 2005). In this study, emphasis is given to *product development* projects.

Selection criteria for basic research are subjective in nature, while later stages of development require more pragmatic approaches, more related to expected economic benefits. Therefore, greater preference has been given to scoring and multiple criteria methods, which take into consideration qualitative factors, in earlier stages. More quantitative methods are preferred as market and economic factors become more critical in later stages, although strategic factors should not be ignored in any way (Chiesa, 2001).

Perceptions of uncertainty and risk also differ in each type of R&D project: as suggested by Anderson and Nolte, the technology readiness levels (TRL) or maturation rate of a technology drives the focus of risk management activities (Anderson and Nolte, 2005). TRL is a scale developed in the mid-1970s by the National Aeronautics and Space Administration (NASA) to allow a more effective assessment and communication regarding the maturity of new technologies (Mankins, 2009). This scale is closely related to the well know classifications of basic research, applied and technology development, as depicted in Figure 2.

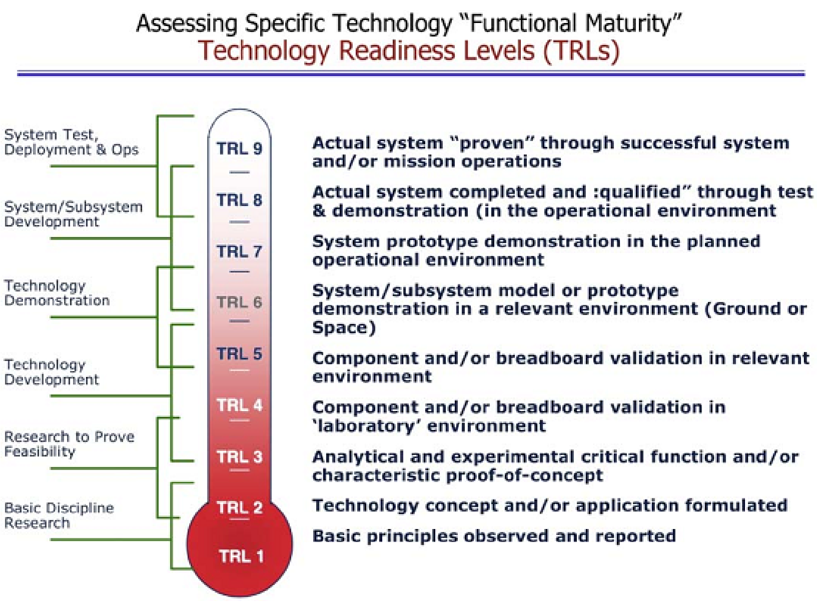


Figure 2 - Overview of the technology readiness level scale. Source: (Mankins, 2009)

Perceptions of risk and uncertainty change depending on the magnitude of projects (Tidd *et al.*, 2005). Basic research projects are reasonably low budget projects, and *"often treated as necessary overhead expense"* (Tidd *et al.*, 2005, p.222). Applied research and technology development projects require greater investments in the development and feasibility tests of prototypes and technological systems. Product development projects require investments of an even greater order of magnitude, which includes the industrialization and commercialization of products. As the investments levels increase, the perception of risk changes accordingly, since the impact of not achieving expected technical and market goals increases.

The various R&D project selection methods reviewed in this section, despite addressing critical aspects of risk, uncertainty and interdependency of projects, somehow ignore the integration of risk assessment control mechanisms, which could be based on a defined organizational policy towards risk. If such integration could be achieved, one could provide feedback information to managers on the consequences of adjustments performed in projects and promote a greater homogenization of risk perspectives in the organization. This could allow continuous re-evaluations, and consider the impact of selecting new projects in ongoing projects, mentioned by Archer and Ghasmzadeh as a critical requirement for effective project selection methodologies (Archer and Ghasemzadeh, 1999). These approaches not only include evaluations performed at early stages of projects, but also continuous evaluations throughout the lifecycle of projects at key points, milestones or gate reviews (Cooper, 1990). The integration of front end activities of projects or “ideation” into portfolio management is mentioned by Heising as an important factor for sustainable success (Heising, 2012).

Among the various methods for projects’ continuous evaluations are *risk management processes*. This type of process also has advantages over others that use deterministic criteria or indicators, because it recognizes uncertainty as intrinsic to achieving technical goals and to rapidly changing environments. In fact, considering risks in the earlier stages of the project life cycle provide managers with more time to act upon risks (Institute, 2008). None of the reviewed methods present a comprehensive methodology, which incorporates a risk management process early on project selection stage, that enables different risk perspectives to be incorporated, and a controlling mechanism that provides feedback information with respect to changes in risk throughout the execution of the project. The methodology presented in this study aims at addressing these gaps.

Prior to presenting the steps that led to the development of the methodology, project risk management processes are reviewed in the following section.

2.2 Risk management processes

The execution of a project aimed at delivering something new, either a theoretical or experimental development, a practical application of a concept, a prototype, entire technological systems or products is inevitably subjected to a certain degree of risks. Every type of R&D project and product development project is exposed to risks related to not achieving specified project goals (duration, budget and quality, namely). In the specific case of product development projects, because of the dynamic business environments, there is also the risk of not addressing changing customers' needs, or market risk as mentioned by Unger and Eppinger (Unger and Eppinger, 2009).

Although the concepts of risk and uncertainty are often used interchangeably, they are not synonymous. The researcher adopts the view according to which risk involves situations where the probability of a particular outcome is known, and uncertainty occurs in situations when the probability is not known (Horne, 1966). Furthermore, it is considered that while uncertainty may not necessarily result in undesirable consequences, risk, on the other hand, is always negative and is manifested in an unsatisfactory consequence (Lefley, 1997). Recently, a number of authors are suggesting the incorporation of uncertainty management processes in order to improve project management performance (Ward and Chapman, 2003, Atkinson *et al*., 2006, Perminova *et al*., 2008). They argue that current risk management processes have solely focused on managing threats originated from risk, and a more balanced approach to opportunity and threat management, via uncertainty management, would support organizations in restricting negative impacts from threats and to leverage positive impacts originated from opportunities. Despite being a topic of recognized relevance to project management, uncertainty management processes are still in their infancy. Therefore, this study is focused in risk management processes, without completely ignoring the role of uncertainty in projects though.

Project *risk management processes* are defined by the Project Management Institute's (PMI) standard *Guide to the Project Management Body of Knowledge* as the process of conducting risk management planning, identification, analysis, response planning, and monitoring and control on a project (Institute, 2008). Its objectives are to increase the probability and impact of positive events, and to decrease the probability and impact of negative events in the project. The adequacy of company-wide education on the concepts of risk management, risk register and risk management plans, and maturity of an organization's processes for assigning ownership of risks, are among the success factors in project management (Cooke-Davies, 2002). An empirical research conducted on 176 firms suggests that the integration of risk management into project portfolio management as having positive impact in risk coping capacity and portfolio success (Teller and Kock, 2013). Another survey with 84 project managers from the software and high-tech sectors also revealed that risk management contributes to meeting project schedules, budget and planned objectives and achieving customer satisfaction (Raz and Michael, 2001). The importance of project risk management is also supported by the fact that it belongs to the nine knowledge areas of PMI's Project Management Body of Knowledge (PMBOK).

Risks can jeopardize the successful completion of a project, and is formally defined as the likelihood of an event along with its negative consequence (INCOSE, 2006). There are four main categories of risk, which are closely related to each other, as portrayed in Figure 3.

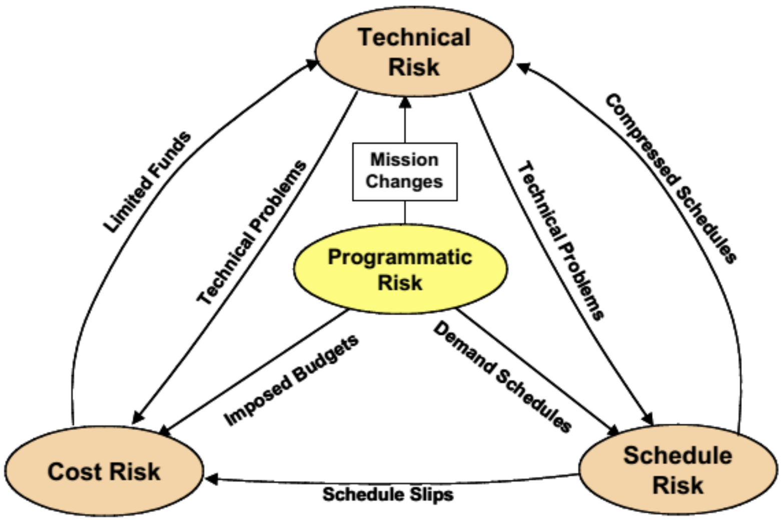


Figure 3 - Relationships between risk categories. Source: (INCOSE, 2006)

Technical or performance risk is defined as the possibility that a technical or performance requirement or output of a project may not be achieved; *cost risk* is the possibility that available budget or funds set for a project will be exceeded; *schedule* *risk* is the possibility that a project will fail to meet scheduled milestones and duration. *Programmatic risk* is produced by events that are beyond the control of the project manager, normally from decisions made by people with higher level of authority, for example the reduction in project priority, delayed authorizations and funds, and many others. As such, programmatic risks can be a source of risk in any of the other three categories of risk.

Other forms of risk may exist, for example, risks involved in the collaboration with project partners, such as the inadequacy of complementary competences, lack of coordination and others. Any of these risks are expected to increase technical/performance, cost and schedule risks. A comprehensive categorization of project risks is, thus, unfeasible, but these four categories are useful for project planning and controlling purposes (Unger and Eppinger, 2009).

The PMBOK identifies six core activities in the risk management process:

- *Plan risk management:* the process which defines how to conduct risk management activities for a project, ensuring visibility of the risk management process, sufficient time and resources and an agreed approach for evaluating risks;
- *Identify risks:* determination and documentation of the risks that may affect the project. It is an iterative process since new risks may evolve or become known along the execution of the project;
- *Perform qualitative risk analysis:* the process where risks are prioritized for further analysis or action, using their relative probability or likelihood of occurrence and their impact on project objectives;
- *Perform quantitative risk analysis:* the process of numerically analyzing the effect of identified risks on overall project performance and objectives, related to a quantitative approach for decision-making in the presence of uncertainty;
- *Plan risk responses:* the process of developing options and courses of actions to leverage on opportunities and reduce threats to project objectives, which follows the qualitative and quantitative risk analysis (if used). The process also includes the designation of one person (the “risk response owner”) to take responsibility for each agreed-to and funded risk response;

- *Monitor and control risks:* the process of implementing risk response plans, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating the risk process effectiveness throughout the project.

These processes interact with each other and with the other nine knowledge areas of PMBOK. A more recent international standard provides additional contributions to this area: the ISO 31000 *"Risk management – Principles and guidelines"* (Standardization, 2009a). Despite having many similarities with the process from PMBOK, the ISO 31000 standard observes the risk management process in isolation, thus providing an easier to understand approach. The process is constituted of seven activities. These activities and their relationship structure in ISO 31000 are portrayed in Figure 4. Tools and techniques for each activity of the sub process named *risk assessment*, are identified in another document from the same family of standards, the *Risk management – Risk assessment techniques* (Standardization, 2009b).

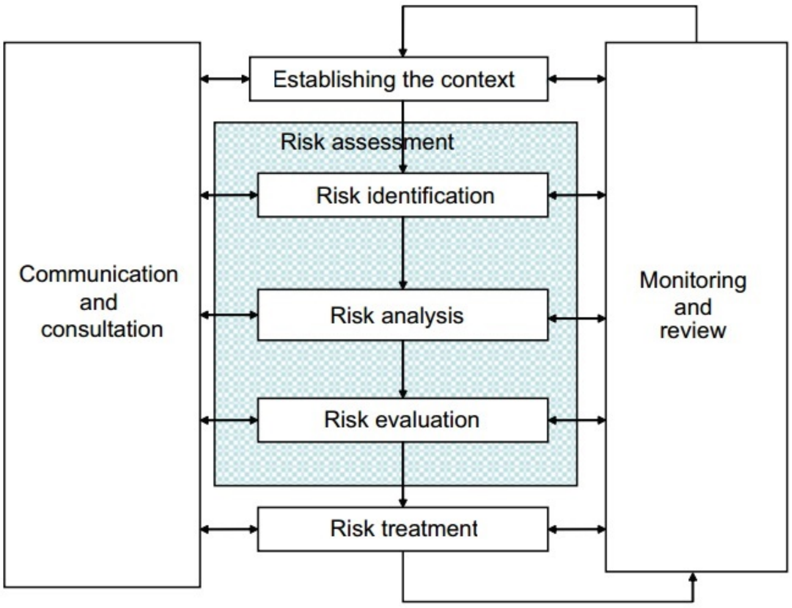


Figure 4 - Risk Management process. Source: (Standardization, 2009a)

Different and various tools have been used for each phase of the risk management process. Table 1 presents the risk management processes in ISO31000 and PMBOK, the tools recommended for each activity.

Table 1 - Risk management tools in PMBOK and ISO 31000. Sources: (Standardization, 2009b) (Institute, 2008)

Tools	PMBOK						ISO 31000		
	PRM	IR	PQlRA	PQnRA	PRR	MCR	RI	RA	RE
Planning meeting and analysis	X								
Documentation reviews		X							
Brainstorming, Delphi technique, Interviewing,		X					X		
Root cause analysis		X						X	X
Checklists analysis		X					X		
Assumptions analysis		X							
Cause and effect diagrams		X					X	X	
System or process flow charts, influence diagrams, SWOT analysis		X							
Expert judgment		X	X	X	X				
Risk probability and impact assessment, Risk data quality assessment, Risk categorization, Risk urgency assessment			X						
Probability and impact matrix			X				X	X	X
Probability distributions, Sensitivity analysis, Expected monetary value analysis				X					
Modeling and simulation				X					X
Strategies for negative risks or threats (avoid, transfer, mitigate, accept), Strategies for positive risks or opportunities (exploit, share, enhance, accept), Contingent response strategies					X				
Risk assessment, Risk audits, Variance and trend analysis, Technical performance measurement, Reserve analysis and Status meeting						X			
Primary hazard analysis, Sneak circuit analysis							X		
Hazard and operability studies (HAZOP), Hazard Analysis and Critical Control Points (HACCP), Environmental risk assessment, Structure "What if?" (SWIFT), Scenario analysis, Business impact analysis, Failure mode effect analysis, Layer protection analysis (LOPA), Cost/benefit analysis, Multi-criteria decision analysis (MCDA), Risk indices, FN curves, Reliability centered maintenance, Fault tree analysis, Human reliability analysis							X	X	X
Event tree analysis, Markov analysis							X	X	
Decision tree, Bow tie analysis, Bayesian statistics and Bayes Nets								X	X

Legend: PRM – Plan Risk Management, IR – Identify Risks, PQlR – Perform Qualitative Risk Analysis, PQnR – Perform Quantitative Risk Analysis, PRR – Plan Risk Responses, MCR – Monitor and Control Risks, RI – Risk Identification, RA – Risk Analysis, RE – Risk Evaluation.

The risk management process described in PMBOK and ISO 31000 share some common activities, namely regarding the identification of risks, the treatment of risks or risk response actions and monitoring and review. Other activities have no corresponding activity in the other risk management process. In PMBOK process, the *plan risk management* activity addresses how risk will be managed internally, using for this purpose a series of documents from other areas of the PMBOK system, defining the set of tools to be used, data sources, roles and responsibilities, risk categories, budgeting and timing for the risk management process. On the other hand, *establishing the context* activity from ISO 31000, although also addressing how risk will be managed in the organization, deals with this process in a broader sense, considering internal (capabilities, information flows, values, culture, etc.) and external (cultural, political, legal, regulatory and other drivers) parameters relevant to the organization, and the definition of risk criteria in the process, such as risk acceptance thresholds, nature and types of impacts, the way probabilities are to be expressed and others.

Risk analysis activity in ISO 31000 is also a broader process, that considers quantitative, semi-quantitative and qualitative analyses. Quantitative and qualitative analysis in PMBOK are placed separately, but objectives and purposes are the same as in ISO31000. The *communication and consultation* activity is a continuous activity in the ISO31000 that deals with the development of a communication plan, and is related to all other activities in the process, while in PMBOK the development of a communication management plan is one of the inputs of the risk management process.

Table 2 - Risk management processes and selected examples from the literature.

PMBOK	**ISO 31000**	**Selected examples from the literature**
-	Establishing the Context	
Plan Risk Management	-	-
Identify Risks	Risk Identification	
Perform Qualitative Risk Analysis	Risk Analysis	(Cagno *et al.*, 2007)
Perform Quantitative Risk Analysis		(Browning, 1998, Wang *et al.*, 2010, Dey, 2010)
-	Risk Evaluation	
Plan Risk Responses	Risk treatment	(Ben-David and Raz, 2001) (Seyedhoseini *et al.*, 2009)
Monitor and Control Risks	Monitoring and review	(Kujawski and Angelis, 2010)

As this literature analysis clarifies, risk assessment is a central issue in project management. Table 2 presents a number of publications that propose methods for each of the activities portrayed in both risk management processes. Significantly no reviewed methodology was found which assesses risk in the context of different types of R&D projects, in the project selection stage, and that provides a link between these early assessments and risk control and monitoring activities throughout the execution of the project. It is the researcher’s understanding that such a methodology can provide valuable assistance to project managers in three areas:

1. *consideration of different types of R&D:* R&D projects types are characterized not only by different scopes and objectives, but also by different orders of magnitude with respect to the duration, cost and quality perspective. For example, a 1% cost overrun in a basic research project is not the same as a 1% cost overrun in the Product Development project, given the different levels of investment of each project (much higher in Product Development projects). A risk assessment that takes into account risk perspectives in different types of R&D thus provides a more equitable comparison between projects;
2. *risk assessment in project selection:* the sooner the risk assessment is made, more time project managers will have to develop appropriate risk response plans and mitigate their effect. Furthermore, risk identification and analysis made in the project selection phase enables risk to be also considered one of the selection criteria;
3. *risk monitoring and control system:* linking risk assessments to a control system enables risk monitoring and control throughout the execution of a project. It also allows managers to assess how accurate risk estimates made at an early stage of the projects life cycle (the project selection phase) were, and thus they can “calibrate" their risk analyses in future projects.

The following section presents the steps taken in the development of a new methodology that aims to address these gaps.

3 Methodology development

In this section, the building blocks of a new methodology for R&D project selection that incorporates risk assessment, management and control are presented. This new methodology incorporates a considerable number of tools, and in order to speed up the calculations and facilitate its implementation in real settings, software written in VBA language for Microsoft Excel® was developed.

The new methodology, in addition to incorporating risk, shall meet the critical requirements for an integrated project selection methodology, proposed by Archer and Ghasemzadeh, and Verbano and Nosella (Archer and Ghasemzadeh, 1999, Verbano and Nosella, 2010), which were described earlier in the literature review section. In order to remind the reader, they are summarized below:

- ensure strategic (qualitative) coherence by acknowledging both internal and external business factors, along with the implications of economic factors (quantitative) in project selection, where appropriate;
- use indicators and criteria that are suitable for the type of R&D project under consideration, to ensure a more equitable comparison during selection;
- organization in a number of stages to enable decision makers with a logical approach for project selection;
- reflect the overall objectives of the organization and perspectives on risk for different types of R&D;
- consider the interdependency between projects;
- reflect the effects on resource competition;
- incorporate risk controlling or re-evaluation mechanisms at milestones or gates of projects.

In order to provide a clear description about the methodology development process, the text that follows is divided into three sections: “Criteria and information requirements” describing the process by which project selection and execution mode criteria is mapped; “Risk assessment and management” providing an understanding of the methods used in incorporating risk assessment and management early in the project selection phase and “

Methodology for R&D projects selection incorporating risk management" presenting an overview of the integrated methodology.

3.1 Criteria and information requirements

The project selection methodology proposed in this study incorporates the three types of R&D projects, as defined previously: basic research, applied research and advanced technology development. A fourth type of project is considered, namely *product development*, related with development, industrialization and launch of new products.

Beyond selection, another important decision of the technology strategy process, with clear implications to R&D projects, is related to deciding on the *technology acquisition mode*. It is argued that this type of decision is entirely relevant to the project selection process, since it is intrinsically related to the characterization of projects (cost, duration, roles and responsibilities, etc.) and, therefore, to the risks involved. Surely, the term "technology acquisition mode" seems more suitable for advanced technology development type of R&D projects. In order to extend its meaning to other types of R&D and to product development, it will be referred hereafter as a *project execution mode*. Thus, the proposed methodology considers, in addition to the project selection decision, the project execution mode decision.

A trend in decision analysis announced four decades ago concerns the transition from "decision models" towards "decision information systems" (Baker and Freeland, 1975). There are two reasons for this, as Baker and Freeland pointed out: models are often incomplete, ignoring important aspects of the R&D environment, which then forces managers to constantly make adjustments to account for the numerous environmental conditions not included in the model. The second reason is related with the decision problem itself, characterized by multiple criteria, many of which are not easily quantifiable. This requires extra attention in information flows that feed project proposals at project selection stage, to enable a more transparent and clear comparison between candidate projects. Nowadays, with the advancement of information technologies, which enable substantial productivity gains in the management of information flows, and the importance of knowledge in innovation performance, this trend becomes even more relevant.

The information requirements for candidate projects were mapped using a review on the criteria used in different models proposed in the literature. Thus, one expects to find the necessary information, whether of quantitative or qualitative nature, to be included in the characterization of the projects, in a project proposal document, in order to make the comparison between projects a more transparent task. The relationship between criteria considered in the methodology and the information contained in the project proposal document is found in Appendix 1

Although some studies do not differentiate criteria according to the type of R&D and product development project (Meade and Presley, 2002, Henriksen and Traynor, 1999), it is understood that only projects of the same type can be compared against each other, using adequate criteria for this purpose, as supported by Tidd (Tidd *et al.*, 2005). Therefore, emphasis was given to publications that used different criteria according to the type of R&D project considered.

A review on decision criteria for mapping information needs in project execution mode decision was also performed. The following sections present an analysis conducted on decision criteria used in project selection and project execution mode.

3.2 Project selection criteria

The purpose of this section is to identify the most frequently mentioned themes used as criteria in decision models for selection of different types of R&D projects and product development. Emphasis was given to publications where criteria were used for each type of R&D involved, and for product development projects. While acknowledging that criteria choice in these publications may take into account intrinsic factors to organizations, it is observed a number of generic themes across these studies, i.e., the criteria do not differ much from study to study. Those generic themes are embedded in the methodology as default or built-in criteria, but flexibility is ensured in the way that managers can delete, add and modify criteria if required. Such flexibility is incorporated in the software developed for this methodology.

Criteria designed for basic and applied research projects are not abundant in literature. However, two publications were found that cite specific criteria to these types of projects.

Table 3 - Review on basic research project selection criteria

Publication, criteria and sub criteria (in parenthesis)
Publication: (Chiesa, 2001) **Criteria:** Strategic relevance (Relation with core technologies of the firm, The range of applicability of the project results, Consistency of the project objectives with business, Relevance of the business(es)); Expected benefits (Potential applications, Creation of a base of knowledge, Impact on other projects); Time and costs (Project duration, Project costs); Resource adequacy (Project leadership, Team feasibility, Access to external source); Soundness (Feasibility, Technical strengths of the project, Peer reviews); Originality (Newness, Patenting); Project definition (Potential benefits, Soundness of the theoretical background, Awareness of the current knowledge, Project programming).
Publication: (Coldrick *et al*., 2005) **Criteria:** Technical (Technical risk to project completion, Technical resource availability); Corporate and strategic (Fit with company business plan, Product range growth potential, Synergy with other products/processes); Regulatory (Risk in obtaining regulatory clearance, Ability to meet likely future regulations).

As can be seen in Table 3, basic research project selection criteria clearly emphasize the contribution of projects to enhance the *knowledge* base of the organization, and the strength of the scientific and theoretical background of the research. Criteria related to market is not mentioned, since it is a very early stage phase of research. To foresee any business application at this stage is almost impossible. Other themes are related to the *capability* of the organization, reflected in the familiarity with the research topic and resources (competences, equipment, etc.) to conduct the research, and *strategy*, namely concerning the fit with the business strategy of the organization, in observable trends and their urgency. *Project development* issues, such as programming or programmatic risks, interdependencies/synergies with other projects, project risks, and duration and costs are also cited.

Applied research aims at testing the applicability of theoretical concepts, through early versions of prototypes, models and devices. Therefore, potential technologies arising from such applications can be evaluated as well as their patentability. Possible benefits from standard setting with other compatible technologies, for example in opening new markets and raising barriers against competitors, should also be included as a criterion (see Table 4).

Table 4 - Review on applied research project selection criteria

Publication, criteria and sub criteria (in parenthesis)
Publication: (Chiesa, 2001) **Criteria:** Strategic relevance (Strategic importance of technological area concerned, Range of applicability of project results, Benefits to the firm's positioning in the business, Relevance of the business(es) where the project results would be utilized); Economic relevance (Revenues, Costs, Return on investment, Probability of commercial success); Time-to-market; Robustness (Normative factors, Technological factors, Economic factors, Indirect factors, Industrial benefits, Environment benefits, Scientific benefits); Resource adequacy (Project leadership, Team specialization, Integration of R&D with other functions, Availability and appropriateness of the equipment); Soundness and originality of idea (Technical feasibility, Originality); Project definition (Clarity of the final objective, Clarity of the intermediate objectives, Market benefits, Patenting); Engineering (Criticality of resources needed in the engineering phase, Constraints to the industrial exploitation, Firm's strength in the technologies used in the exploitation phase, Industrialization experience, Transfer to manufacturing and scale up); Willingness to exploit project.
Publication: (Coldrick *et al*., 2005) **Criteria:** Technical (Technical risk to project completion, Technical resource availability); Corporate and strategic (Fit with company business plan, Product range growth potential, Synergy with other products/processes); Regulatory (Risk in obtaining regulatory clearance, Ability to meet likely future regulations).

Possible applications of such systems can raise interest in a number of markets as well, unlike what happened with basic research projects. At this level, market analysis, which includes knowing the markets size, growth rates, customers' needs and competitive intensity, is still broad, meaning that a wide range of applications can be envisioned. Therefore, market analysis is still more judgmental than pragmatic or quantitative.

As with basic research project selection criteria, themes related to strategy, capability and project development should also be included.

Advanced technology developments projects bring early prototypes and devices to a more mature state, likely to be incorporated in a product. Therefore, rather than assessing potential technologies, as in applied research, in advanced technology development the assessment should focus on potential products. Furthermore, the stage in the life cycle of technology - a process that describes the diffusion process of a technology, normally divided in emerging, mature and in declining technologies - is an important criterion to evaluate the degree of innovativeness of the technology to be developed (see Table 5).

Table 5 - Review on advanced technology development project selection criteria

Publication, criteria and sub criteria (in parenthesis)
Publication: (Chiesa, 2001) **Criteria:** Relevance of the technology (Market potential, Applicability, Customer value creation); Risk associated with the development of the technology (Technical risk, Commercial risk, Financial risk); Appropriability (Secrecy, Accumulated tacit knowledge, Lead times and after-sale service, Learning curve, Complementary assets, Product complexity, Standards, Pioneering radical new products, Strength of patent protection).
Publication: (Coldrick *et al*., 2005) **Criteria:** Technical (Technical risk to project completion, Technical resource availability); Corporate and strategic (Fit with company business plan, Product range growth potential, Synergy with other products/processes); Regulatory (Risk in obtaining regulatory clearance, Ability to meet likely future regulations).
Publication: (Cooper and Robert, 2006) **Criteria:** Business strategy fit (Congruence, Impact); Strategic leverage (Proprietary position, Platform for growth, Durability, Synergy with corporate units); Probability of technical success (Technical gap, Project complexity, Technology skill base, Availability of people and facilities); Probability of commercial success (Market need, Market maturity, Competitive intensity, Commercial applications development skills, Commercial assumptions, Regulatory and political impact); Reward (Contribution to profitability, Payback period, Time to commercial start-up).
Publication: (Shehabuddeen *et al*., 2006) **Criteria:** Technical (Quality, Reliability, Flexibility, Repeatability, Volume); Financial (Capital, Sales, Renewal, Operation); Pressures (Environmental, Regulatory, Standards); Integrability (Compatibility, Impact); Usability (Usefulness, Utilization); Supplier Suitability (Service, Integrity, Partnership); Strategy Alignment (Support, Compatibility); Risk (Operational, Technological, Commercial).
Publication: (Huang *et al*., 2008) **Criteria:** Competitiveness of technology (Proprietary technology, Key of technology, Innovation of technology, Advancement of technology); Relevance of technology (Technological extendibility, Technological connections, Generics of technology); Economic benefit (Technology spillover effects, The potential size of market, Improvement on research capability); Social benefit (Improvements on quality, quality, environmental protection, industrial safety, national image and industrial standards, Coincidence with Science and Technology policy, Benefits for human life, The contributions to the state of knowledge); Quality of technical plan (Content of technical plan, Capability of research team, Reasonableness for research period, Reasonableness for research cost, Environmental and safety consideration); Availability of resource (Technical resource availability, Technical support, Equipment support); Technical risk (Opportunity of technical success, Evidence of scientific feasibility, Specification of technology); Development risk (Risk for development cost, Risk for time cost, Timing for project); Commercial risk (Opportunity of market success, Opportunity of project result implementation).

Table 5 (continued)

Publication, criteria and sub criteria (in parenthesis)
Publication: (Shen *et al*., 2010) **Criteria:** Technological merit (Advancement of technology, Innovation of technology, Key of technology, Proprietary technology, Generics of technology, Technological connections, Technological extendibility); Business effect (Potential return on investment, Effect on existing market share, New market potential, Potential size of market, Timing for technology); Technology development potential (Technical resources availability, Equipment support, Opportunity for technical success); Risk (Commercial risk, Technical risk, Technical difficulties).
Publication: (Davoudpour *et al*., 2012) **Criteria:** Market (Span of applications opened by technology, Potential of commercialization, Supporting national related strategies); Competitiveness (Key of technology, Competitive situation in market, Added value); Technical factors (Position of the technology in its own life-cycle, Threat of substitution technologies, Ability to result in technical know-how, Ability to use international cooperation potentials); Capability (Alignment with organization objective and capability, Value of laboratories, Successful experience accumulated in the field, Registered patents, Value of equipment); Environmental factors (Impact on environmental factors and energy consumption improvement).

Along with these factors and since the maturation rate of the technology is higher, considerations about the market are even more important at this stage, as the range of possible applications is narrowed when compared to applied research. Project development issues such as estimated cost and duration becomes critical given the larger scale of investment. Interdependencies/synergies with other projects and programmatic risks should also be considered.

Product development projects aims at bringing technological innovations to the market, in the form of new products. As such, considerations about the product to be developed should be included as criterion, namely the degree of product differentiation and product range growth potential (see Table 6).

Table 6 - Review on product development project selection criteria

Publication, criteria and sub criteria (in parenthesis)
Publication: (Liberatore, 1988) **Criteria:** Manufacturing (Capability, Factory/equipment); Technical (Probability of success, Costs, Time, Resources); Market/distribution (Potential, Capability, Trends); Financial (Profit, Capital investment, Unit cost).
Publication: (Henig and Katz, 1996) **Criteria:** Size of existing market; Competition; Competitive advantage; Patentability; Efficacy; Capability of development; Production; Cost of development; Time to completion; Toxicity.

Table 6 (continued)

Publication, criteria and sub criteria (in parenthesis)
Publication: (Calantone *et al*., 1999) **Criteria:** Fit with core marketing competences (The product matches the desired entry timing needed by our target segments, The product will be priced at or below price points for our target segments, The product fits with our logistics and distribution strengths, The products fits with channels of distribution where we have strength, The product fits with current product lines, The product fits our sales force coverage, training, and compensation plans.); Fit with firm's core technological competences (The product gives the customer a differential advantage or benefit, The manufacturing speed will match demands, The product is designed for quality needed by target segments, The product uses materials of high quality and low rejection, The product fits with our best manufacturing technology, The product allows us to use the very best suppliers); Total dollar risk profile of the project (Total dollar payoffs in net present value, Total dollar costs in net present value); Overall management uncertainty about project's outcomes (Percentage of loss that cannot be addressed by research, Research and intelligence mitigated uncertainty).
Publication: (Oh *et al*., 2012) **Criteria:** Financial contribution (Net present value, Cost, Revenue, Sales, Quantity); Strategic importance (Fit with key initiatives and priorities, Innovation related to market, Core competence development); Commercial potential (Base net present value, Gross profit margin, Use base growth, Proof of concept, Product, process and clinical development, Intellectual property); Commercial risk (Competitive positioning at launch, Customer preference, Operational leverage).

Considerations about the technology(/ies) to be incorporated in the product design should not be ignored. Patentability and benefits from standards setting might have greater importance than in previous R&D projects, so as to ensure that the full business potential of the product can ben grasped. The stage of technology(/ies) life cycle should also receive greater attention if the objective is to develop a product with a high degree of innovativeness, i.e., consisting of emerging technologies.

The market(s) where the product will be launched are known at this stage. The timing of introduction in the market is an important criterion, so managers can assess whether the expected timing for launching the product is appropriate, since customers' needs may change over time.

Product development involves considerable investments, not only in the development of the product itself, but in industrialization, logistics and distribution networks and in promotional efforts, such as in fairs and exhibitions. Thus, it requires more rigorous quantitative criteria, mostly related to the economic benefits of such project, which can be done using metrics such as net present value (NPV), payback period and internal rate of return (IRR). As with the other types of R&D projects, strategic issues and project development should be included as criteria. The capability of the organization should not only emphasize the resources and competences to develop the product, but also include the adequacy of complementary assets (Teece, 1986), i.e., the necessary infrastructure and capabilities to support the production and commercialization of products, such as appropriate manufacturing equipment, distribution channels, after-sales services and others.

A recurrent theme in criteria used in the various publications analyzed is associated with the risks involved in the project, which further reinforces the need to consider the risk as early as in the project selection stage. As mentioned earlier, risk assessments can be done either qualitatively, through the description of possible risk events that may cause an impact on the project, and quantitatively, through a number of tools that were described in Table 1. Both approaches are adopted in the proposed methodology. Qualitative risk events are described as part of project proposal document. The quantitative risk assessment of the methodology is described in the following section.

Based on the ideas mentioned throughout this section, the proposed methodology includes the following default criteria and sub criteria (in parentheses) for R&D project and product development selection:

- **Basic research:** Capability (familiarity with research topic, resources and competences to conduct research); Strategy (strategy fit, observable trends, urgency); Knowledge creation (learning effects on the organization's knowledge base, scientific background, research originality); Project Development (interdependencies with other projects, estimated cost, estimated duration, cost risk, schedule risk, performance risk, research risks).

- **Applied research:** Capability (familiarity with research topic, resources and competences to conduct research); Strategy (strategy fit, observable trends, urgency); Technology (potential technologies, patentability/design protection, benefits from standard setting); Market (market size, market growth, clear market needs, competitive intensity); Project Development (interdependencies with other projects, estimated cost, estimated duration, cost risk, schedule risk, performance risk, research risks).

- **Advanced technology development:** Capability (familiarity with technology, resources and competences to conduct development); Strategy (strategy fit, observable trends, urgency); Technology (potential products, patentability/design protection, benefits from standard setting, Stage in technology life cycle); Market (market size, market growth, clear market needs, competitive intensity); Project Development (interdependencies with other projects, estimated cost, estimated duration, cost risk, schedule risk, performance risk, technology development risks).

- **Product development:** Capability (familiarity with product, resources and competences to conduct development, complementary assets); Strategy (strategy fit, observable trends, urgency); technology (patentability/design protection, benefits from standard setting, stages in technologies life cycles); Product (product differentiation, product range growth potential); Market (market size, market growth, clear market needs, competitive intensity, timing of introduction); Project Development (interdependencies with other projects, economic attractiveness, estimated cost, estimated duration, cost risk, schedule risk, performance risk, product development risks).

3.3 Execution mode criteria

The criteria reviewed in this section are based on studies that have proposed decision models for the selection of technology acquisition mode. Studies that propose criteria for selection of R&D project execution mode are very scarce. Emphasis has been given to the motivations of organizations in deciding to engage in collaborations and in outsourcing R&D services (Martinez-Noya *et al.*, 2012, Cruz-Cázares *et al.*, 2013), such as the desire to share development costs, seek new knowledge and reduce technical uncertainties. In addition to this, some project execution modes are more common in certain types of R&D than in others. For example, companies often outsource activities to universities and research institutes in basic research projects, as they may not have such scientific competences internally. On the other hand, collaborative and outsource forms are more rare in product development projects, due to complexities involved in managing communication channels, how to share revenues and others (Bruce *et al*., 1995). Collaborations and outsourcing in product development are seldom focused in specific activities with partners with which organizations have long standing relationships.

Notwithstanding this, it is found that criteria for the technology acquisition mode decision can be easily applicable to the project execution mode, and thus, they are reviewed in this section. In the proposed methodology, the execution mode decision precede the project selection decision, so it is assumed that collaborators or "outsources" are already identified by the time of the decision making process and included in the project proposal document.

According to Chiesa, there are many technology acquisition modes available to organizations: license-in, research contract funding, joint ventures, mergers, patent purchase, alliances, internal development and others (Chiesa, 2001). In order to simplify this process and extend the scope of this decision to acknowledge project execution mode decision, the methodology incorporates three generic forms: internal *development, external acquisition* (acquiring technology through purchasing patents or licenses, etc.) *or outsource* (the activities that constitute the project) and *collaboration*. This simplification was also adopted in a multi criteria model proposed by Lee *et al.*, for the problem of selecting technology acquisition modes (Lee *et al*., 2009).

Three publications that propose criteria for the technology acquisition mode decision are reviewed in this section and portrayed in Table 7. This table reads as follows: the greater value for the criterion, the greater the preference for the corresponding execution mode column, translated into a higher number of plus signs (+) or asterisks (*).

A number of criteria can be identified from analyzing Table 7. Familiarity with the research topic, technology or product may favor the internal development mode in order to take advantage on accumulated knowledge generated internally. Resources and competences that the organization possesses and that are related to knowledge areas of the project will favor the internal development mode, since technical risk associated with the project will be reduced. Collaborations may still be interesting to further reduce development duration and technical risk.

Table 7 - Technology acquisition mode decision criteria. Source: (Lee et al., 2009, Cho and Yu, 2000, Chiesa, 2001)

Reference	**Criteria**	**Sub criteria**	**Internal development**	**Cooperate**	**External acquisition/Outsource**
(Cho and Yu, 2000)	Firm	Technical position	Positive relationship	Positive relationship	Negative relationship
		Research manpower	Negative relationship	Positive relationship	Negative relationship
		R&D experience	Positive relationship	Positive relationship	Negative relationship
		History of in-house R&D	Positive relationship	No relationship	Negative relationship
		History of R&D cooperation	Negative relationship	Positive relationship	No relationship
	Technology	Level of technology	No relationship	No relationship	No relationship
		Technology development stage	No relationship	No relationship	No relationship
		Developing cost	Negative relationship	No relationship	Positive relationship
		Need for standardization	Negative relationship	Positive relationship	Negative relationship
		Possibility of commercial success	No relationship	No relationship	No relationship
	External Environment	Market size	No relationship	No relationship	No relationship
		Extent of competition	Positive relationship	Negative relationship	No relationship
		Appropriability regime	No relationship	No relationship	No relationship
		Government. support system	No relationship	No relationship	No relationship
(Chiesa, 2001)	Quality of external sources	-	*	**	***
	Development time	-	*	**	***
	Appropriability	-	***	**	*
	Learning	-	**	***	*
	Development costs	-	*	**	?
	Technical risk	-	*	**	***
(Lee *et al.*, 2009)	Capability	Technological position	++	+	
		R&D resources	++	+	
		R&D manpower	++	+	
		R&D experience	+		
		Firm size	++	+	
		Complementary asset	+		
	Strategy	Fit with business strategy	++	+	
		Fit with technology strategy	++	+	

Table 7 (continued)

Reference	Criteria	Sub criteria	Internal development	Cooperate	External acquisition/Outsource
(Lee *et al*., 2009)	Strategy	Acquisition urgency		+	++
		Importance to a firm	++	+	
	Technology	Stage in technology life cycle	0/+	0/+	++
		Development cost		+	
		Technological readiness	++	+	
		Easiness to imitate			+
	Market	Commercial uncertainty	+	+/++	
		Market size	+	++	
		Competitive intensity	+	0/+	0/+
	Environment	Appropriability regime	0/++	+	
		Availability of external source			+
		Quality of external technology		+	++
		Dynamism		+	++

Environmental factors also play an important role in defining the most suitable execution mode. A high level of expertise of project partners or technology suppliers favors the collaboration and external acquisition/outsource as opposed to internal development. The difference between collaboration and external acquisition/outsource modes will depend upon the expertise level of the external agents under consideration in each alternative. Past and positive experiences with external agents will favor the external acquisition/outsource and collaboration development modes. The difference between collaboration and external acquisition development modes will also depend upon past experiences with the external agents under consideration in each alternative. The existence and magnitude of stimulus for external acquisition/outsource or collaboration, of any nature (financial, equipment sharing, etc.), favor these development modes. Finally, if the outcome of the research is aimed at being proprietary, the appropriation of the benefits to be generated by the project is affected by the execution mode. Normally, collaborations and external acquisition/outsource modes reduce appropriability since the results of the project will be shared. Developing it internally, on the other hand, ensures that the results of the project will benefit the organization.

The aforementioned project development criteria also influence execution mode decision. Collaborations normally reduce the costs to the organization since resources are shared. On the other hand, this reduction may not be entirely satisfactory if the duration and resources to set up the collaboration are significant. Costs of external acquisition/outsource are highly dependent upon the terms and conditions of the contract. Collaborating in a project normally reduces the project duration, and is normally faster than internal development if the time to set up is not too long. Still, of all the three development modes, external acquisition/outsource is the one that contributes more to shorter project duration. Interdependencies with other projects favor the internal development since the resources allocated and knowledge generated by the project remain in-house, thus ensuring a better development of the other projects. Each development mode may have different risks, and a careful analysis on the risks list is necessary to determine the most appropriate development mode.

In basic research projects, collaborations normally contribute to a greater and faster accumulation of knowledge, while in external acquisition/outsource there is none or reduced sharing of experiences. Notwithstanding this, the knowledge to be assimilated is also dependent on the expertise and openness of partner(s). The originality of the research arises interest in the project, and may favor the internal development mode, but collaborations and outsourcing (normally to research institutions) may be preferred if the organization does not possess internal competences to execute the project.

In the remaining types of R&D and product development projects, technological and market factors influence the decision to whether develop internally, to collaborate, to acquire technology externally or outsource project activities. Patentability and design protection of the technology or product to be developed favors internal development mode, because it ensures that knowledge generated during the development remains in-house. Collaboration is an intermediate alternative due to a partial loss of control over the technology, and external acquisition or outsourcing of activities seems to be the least viable alternative. Benefits can be reaped by launching compatible technologies, in accessing a wider portion of the market. In these cases, collaborations may be an interesting solution to boost technology diffusion by setting standard technologies. External acquisition or outsourcing may also be desirable, at the expense of losing some technical knowledge. The internal development of technologies positioned in later stages of their life cycle may not be interesting from a business point of view, since the useful time period for the commercialization of the technology before its decline is reduced. Cooperation is a way to reduce this risk by sharing resources and costs. Even if the technology or product proves to have some economic viability, external acquisition made by purchasing a patent, for example, seems to be the best alternative to reduce the time to market and thus ensure a longer time period for technology and product commercialization.

Organizations may engage in collaboration in order to achieve greater market share that, by themselves alone, would be difficult to achieve. But, on the other hand, such collaboration may present risks of deterioration if the scope and responsibilities of each party are not well defined. The preference for internal development and collaboration will depend on these factors. External acquisition and outsourcing activities are the least recommended development modes, as the technical know-how lost by not building skills and competences internally may hamper the commercialization of the technology or product. In highly competitive business environments, the value of the intellectual property generated by the development of a new technology or product is high, so organizations tend to favor internal development. Collaborations can be interesting but presents risks with respect to the lack of clarity in the delineation of the relevant property rights. External acquisition or outsourcing activities appear to be less suitable for development under these circumstances. Finally, a clear knowledge about market needs may favor internal development mode because the organization has greater control over the definition of product and technologies specifications. Collaborations, external acquisition or outsourcing activities do not present any apparent benefits, unless valuable market information is shared.

In the case of product development projects, organizations that possess complementary assets (manufacturing technology, distribution channels accessibility, after sales capability and others) may prefer internal development mode in order to take advantage of these internal capabilities. A highly differentiated product may favor internal development mode, since the knowledge involved in developing the product is of strategic nature and supports the creation of a distinguishable market position for the organization. If the organization possesses compatible or complementary products in its portfolio, potential for product range growth is high, and therefore internal development may be preferred.

The criteria and sub criteria (in parenthesis) for selecting project execution mode in each type of R&D and product development projects in the proposed methodology are summarized below:

- **Basic research:** Capability (familiarity with research topic, resources and competences to conduct research); Environment (Expertise level of collaborators or suppliers, incentives and stimulus for collaboration or outsourcing, experience with potential collaborators, appropriability regime); Knowledge creation (learning effects on the organization's knowledge base, research originality); Project Development (interdependencies with other projects, estimated cost, estimated duration, development mode risks).

- **Applied research:** Capability (familiarity with research topic, resources and competences to conduct research); Environment (expertise level of collaborators or suppliers, incentives and stimulus for collaboration or outsourcing, experience with collaborators or suppliers, appropriability regime); Technology (potential technologies, patentability/design protection, benefits from standard setting); Market (market size, market growth, clear market needs, competitive intensity); Project Development (interdependencies with other projects, estimated cost, estimated duration, development mode risks).

- **Advanced technology development:** Capability (familiarity with technology, resources and competences to conduct development); Environment (expertise level of collaborators or suppliers, incentives and stimulus for collaboration or outsourcing, experience with collaborators or suppliers, appropriability regime); Technology (patentability/design protection, benefits from standard setting, stage in technology life cycle); Market (market size, market growth, clear market needs, competitive intensity); Project Development (interdependencies with other projects, estimated cost, estimated duration, development mode risks).

- **Product development:** Capability (familiarity with product, resources and competences to conduct development, complementary assets); Environment (expertise level of collaborators or suppliers, incentives and stimulus for collaboration or outsourcing, experience with collaborators or suppliers, appropriability regime); Technology (patentability/design protection, benefits from standard setting, stage in technology life cycle); Product (product differentiation, product range growth potential); Market (market size, market growth, clear market needs, competitive intensity); Project Development (interdependencies with other projects, estimated cost, estimated duration, development mode risks).

3.4 Multi criteria method

The AHP is a popular multi criteria method with applicability in a wide range of situations. A comparative study places the AHP among the top R&D project selection methodologies (Poh *et al*., 2001). AHP is transparent, easy to understand method, and is also capable of handling both quantitative and qualitative criteria. For such advantages, the AHP is the multi criteria method used in the methodology proposed in this study, for execution mode and project selection.

The AHP is a structured decision making process developed by Thomas Saaty in the 1970s, and is based on mathematics and psychology. Its fundamental reasoning relies on the basis that humans are better at comparing successive pairs of alternatives than a high number of alternatives at once. In this way, AHP differs from scoring models, since weights are not based on arbitrary scales, but on ratio scales from human judgments, i.e., on the mathematical synthesis of numerous human judgements about a decision problem.

The process starts with the definition of a goal. In the case of the proposed methodology, the goals are “select the best project execution mode” and “select the best project”. Once the decision alternatives are settled (execution modes and projects), then a number of criteria and related sub criteria (if necessary) is derived for evaluating the alternatives with respect to the goal. A hierarchical structure can be used to represent the problem, such as the one in Figure 5.

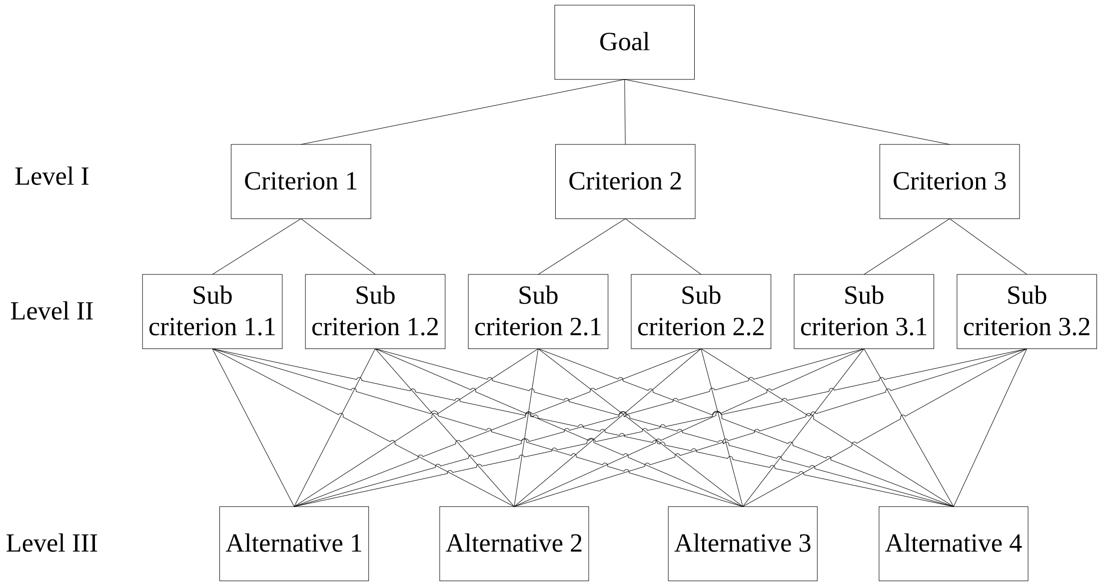


Figure 5 - The structure of an AHP hierarchy

Then, priorities are calculated for criteria, sub criteria and alternatives of the decision hierarchy, through a series of pairwise comparisons at each level, using the judgmental scales described in Table 8. Observing the decision hierarchy above, the process starts with pairwise comparisons made between criteria depicted at level I, with respect to the goal, resulting in priority values for each criterion. Then, at level II, pairwise comparisons are made between sub criteria, with respect to their contribution to their related criterion, resulting in priority values for each sub criterion. Finally, at the lowest level of the hierarchy, pairwise comparisons between alternatives are performed, with respect to their performance in each sub criterion, resulting again in priority values for the alternatives. The synthesis of these priorities into an overall priority value for each alternative provides a ranking of the best alternatives of the decision problem.

The pairwise comparisons are performed on matrix of judgements, and consistency ratios are calculated throughout the process to ensure consistency in the decision analysis.

Table 8 - The fundamental scale of absolute numbers. Source: (Saaty, 2008)

Intensity of importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

3.5 Risk assessment and management

This section presents the risk assessment and management mechanism that is incorporated in the novel project selection methodology.

As mentioned previously, the technology readiness level, which can be easily translated into the three types of R&D, is an important driver for risk management activities (Anderson and Nolte, 2005). This suggests that different risk perspectives should be addressed as the technology follows a path of maturation, from early research and prototypes until incorporation into a product for commercialization. The approach to risk assessment and management proposed in this study follows these ideas.

The technology readiness level influence risk in a number of ways. An important one has to do with a trade-off between uncertainty and impact, with obvious implications to risk. For example, basic research projects are highly uncertain with regard to achieving technical objectives set for the project, since work is primarily undertaken on theoretical concepts. On the other hand, and as basic research tend to be inexpensive projects, the financial impact of failing technical objectives of the project is reduced.

The transition from basic research to applied research and then advanced technology development is made through the development of devices and prototyping to test the feasibility of technological solutions in real-world conditions. Greater knowledge about the technology is acquired throughout these phases, which then reduces technical risk, but greater investments are also made, which means that not achieving project goals may cause severe financial losses. In product development projects, investments are even higher, since it involves industrialization and the development of an infrastructure to support the commercialization of the product. Even though technical risk is supposedly lower in product development, since technologies are already proven feasible (or at least they should be), risk exists in the form of setting product specifications or attributes that have low value from the perspective of customers.

Project budget and duration definitely influence technical risk in the way that less funds or resources and shorter duration diminishes the probability of achieving expected project goals. Projects need to be delivered under constraints of budget, duration and scope. A change in one of these constraints has inevitable implications in the other two. These three constraints represent what is known as project management triangle, and are often used as measures to project execution. Project scope is usually defined as statements and quantifiable goals. Thus, project scope can also be understood as "quality" or "performance" when considering the quantified objectives of the project.

Although there are several classifications of risk, the most commonly used in project risk management relates to technical risk, cost risk and schedule risk, as portrayed previously in Figure 3. The term “performance risk” will be used hereafter, to include not only technical, but also other types of objectives, if quantifiable in some sort of way. Thus, the concept of risk used in this study is related to the probability and impact of failing targets outlined in terms of performance, cost and duration of projects.

There are two sources of risk: one produced by uncertainty about how much time a project will take and how much will it cost to reach specified goals (Brigham, 1975) and the other produced by risk events that may increase or decrease project duration, cost and performance. Some examples of such events include delays in equipment delivery from suppliers, which increases schedule risk, raw materials price volatility, which can both increase and reduce the cost risk and also volatility in product demand, which can both increase also reduce performance risk.

A class of such risk events is a source of programmatic risks, as defined previously. These events are usually caused by higher levels of authority, in the context of scientific and technological development programs, and can be a source of risk in performance, cost and schedule risk. Modeling the influence of all possible events in the three categories of events is a task of extreme complexity, and prone to produce unreliable results, especially in early stages of the project life cycle such as project selection. However, they definitely cannot be ignored and should be identified as early as possible so managers have more time to prepare and implement risk response plans. In the proposed methodology, managers have the opportunity to introduce, in text format, the events that can be source of risk in the project, and describe their likelihood of occurrence and impact.

Each individual has different perspectives on risk (Lefley, 1997). The different perspectives of decision-makers in an organization towards risk tend to make the process even more difficult to manage. A new approach capable of homogenizing the organizational policy with regard to managing risk in projects is also proposed in the methodology.

The modeling of the schedule, cost and performance risk requires proposals to include project tasks planning and resources to be allocated. Although it considerably increases the amount of information required, it is justified given the strategic nature of projects to be under consideration in the selection process. Realistically, such a procedure would not be necessary for projects of lesser importance to the organization.

The tools and techniques used for modeling schedule, cost and performance risk in different R&D and product development projects are presented next.

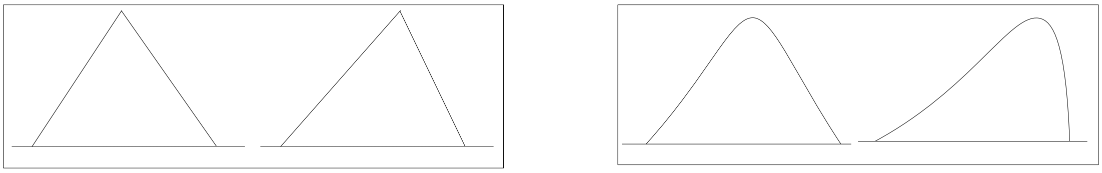
3.5.1 Schedule and cost risk

Among the various existing methods[1], Gantt diagram is chosen to represent project planning in the methodology, due to its simplicity in use and wide popularity. Gantt diagrams are a type of bar chart that illustrates project tasks, their durations and precedence networks. In the software written for the methodology, users are able to introduce tasks codes, descriptions, durations and precedent tasks (see Appendix 2 to visualize the forms). Concurrent or parallel tasks in project are also enabled by introducing start dates for tasks, i.e., without any precedent tasks.

Uncertainty is modelled through the introduction of three estimates for tasks durations - pessimistic, most likely and optimistic – and Monte Carlo simulation. Monte Carlo simulation is a computerized mathematical technique used to estimate the probability of certain outcomes by running multiple trial runs, called simulations, based on random variations of key parameters within statistical constraints. Many statistical distributions can be used in Monte Carlo simulation, the most commonly used in project management are the triangular and beta distributions, since they can be easily modelled using three estimates, an approximation to pessimistic, most likely and optimistic values commonly used by managers. Only beta distribution has been implemented in the software, but additional distributions can be incorporated in the future with few modifications. This difference between shapes of triangular and beta distributions can be visualized in Figure 6.

Once project tasks, their three estimates for durations and precedent tasks are inserted, resources needed to conduct the project are allocated. Resources are of two types: human and machinery or equipment, and are drawn from a resource pool database, which contain their operating costs (monetary units/day). Resources are then allocated to each task, along with the time fraction (in percentage of total time) dedication to the task.

[1] Some examples include: Graphical Evaluation and Review Technique (GERT), Design and Structure Matrix (DSM), Activity-on-Arc diagram and Icam DEFinition for Function Modeling (IEDF0) diagram.

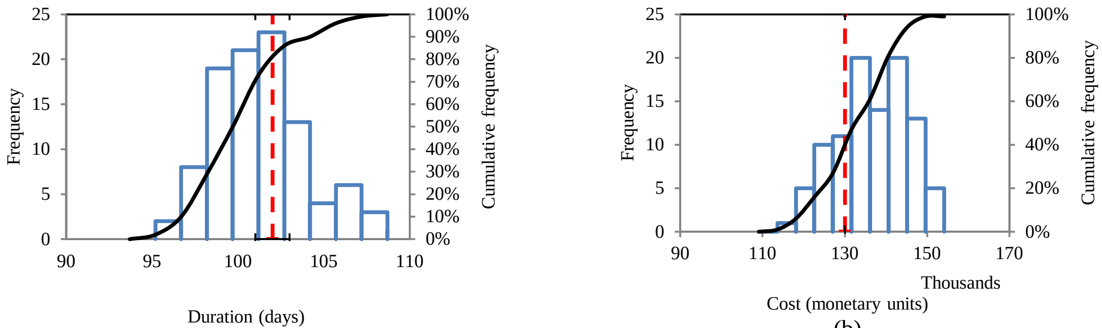


(a) (b)

Figure 6 - Shapes of triangular (a) and beta (b) distributions

Cost items, such as purchases of specific software, equipment and patent applications, are inserted for each task, where appropriate. As with task durations, three estimates are used for cost items. Beta distribution is used as well.

Running a Monte Carlo simulation with the inserted parameters provides distributions of project duration and cost, as depicted in Figure 7.



(a) (b)

Figure 7 - Project duration (a) and cost (b) distributions from a Monte Carlo simulation

Project target duration and cost, as represented in the dashed lines in the charts above (102 days and 130000 monetary units), determine the probabilistic component of schedule and cost risk. In other words, the probability of failing target duration and cost can be calculated. The cumulative frequency curve depicted in the charts above provides an estimation of the probability of project schedule and cost overrun. The simulation results at the right of (or greater than) the target represent unacceptable outcomes of project duration and cost. Then, the point where cumulative frequency curve crosses the target provides the estimates for schedule and cost overrun. In the example above, schedule overrun is estimated at 19% for cost overrun is estimated at 59%.

As mentioned throughout this study, individuals and organizations have different perspectives on risk. These perspectives are also highly influenced, among other factors, by the maturation rate of a technology (Anderson and Nolte, 2005). This suggests that impact suffered from failing project targets have different interpretations depending on the type of R&D involved. As such, an impact function should be used in order to translate organizational policy towards risk. The impact component of risk is modelled using the *utility based loss function* proposed by Ben-Asher (Ben-Asher, 2008).

Utility theory is frequently used in decision analysis and is essentially based on the idea that products, policies, outcomes, etc. can be evaluated in terms of utility or value to their users, customers, recipients, managers, etc.(Keeney and Raiffa, 1993, Browning, 1998). Utility theory also provides a systematic methodology for elicitation and quantification of relative utility or preference for objects or attributes.

Utility is commonly measured on an ascending scale of preference from zero to one. The utility based loss function proposed by Ben-Asher is an inversion of this scale. A value of 1 is assigned to the worst expected impact $U(X_{worst})$ and a value 0 to no impact, $U(X_{best})$. Impact is understood as the difference between actual project's duration and cost and their respective targets. The utility based loss function is constructed by asking managers or the risk management board the following question: "*if you have 50:50 chance of having a schedule/cost overrun of [maximum expected impact introduced] days/monetary units or no overrun, or having a certain schedule/cost overrun of [a high impact value, but lower than the maximum expected impact] days/monetary units, what would you prefer?*". Answer options are "*take the chance (choose the lottery)*"," *the certain amount*" or "*indifferent*". Successive questions are made, by alternatively changing the certain amount with low and high impact values to reduce the range, until managers or the risk management board are indifferent. This method of elicitation is known as *certainty equivalent method*. The indifference point, $U(X_{indifferent})$ has utility value of 0.5. Then, the utility based loss function can be constructed using the functional approximation method, which is essentially solving a system of linear equations, as described by Neufville (Neufville, 1990). A hypothetical example, for the sole purpose of illustration, is described below:

Utility based loss function – $U(X) = a + bX^c$

Worst expected impact (X_{worst}) = 200 days

Indifference point (X_i) = 110 days

$U(110) = 0.5$

$U(0) = 0 = a + b(0)^c$, then a = 0

$U(110) = 0.5 = a + b(110)^c$

$U(200) = 1 = a + b(200)^c$

Solving the system of linear equations, b = 0.002148 and c = 1.159425

Utility based loss function – $U(X) = 0.002148(X)^{1.159425}$

The impact component can be calculated as the utility of the difference between duration or cost outcomes that are greater than the target, and the target. Finally, the formal formula for schedule and cost risk can be written as follows. Only schedule risk is described in equation (1), since a similar equation applies for cost risk.

Schedule risk - $$R_{schedule} = \int_{T_s}^{\infty} f(S_0)[U(S_0 - T_s)]dS_0 \quad (1)$$

where,

T_s – target schedule

$f(S_0)$ – probability density function of duration outcomes, from Monte Carlo simulation

S_0 – duration outcome (from simulation)

$U(S_0 - T_s)$ – utility value of the difference between the duration outcome and the target duration

The discrete form of the risk equation is calculated in the software application: a spreadsheet containing the random samples for duration/cost, and a second column for the impact. If the random sample is lower than target, then the impact is zero. A third column is a multiplication of each random sample and respective impact. The sum of this column provides an approximation for the schedule and cost risk, when it is the case.

The software application of the methodology also provides a Program Evaluation Research Technique (PERT) analysis. PERT analysis enables the identification of the minimum duration of the project, or the set of tasks that, if delayed, delays the completion of the entire project. These tasks are part of the critical path of the project. Since uncertainty is considered, many critical paths may exist. The software identifies every possible critical path in the project, and calculates their corresponding probability of occurrence.

3.5.2 Performance risk in basic research, applied research and advanced technology development projects

The calculation of performance risks in basic research, applied research and advanced technology development projects borrows the ideas proposed by Browning *et al.* (Browning *et al*., 2002).

Projects are characterized by a number of quantifiable goals, which can be research objectives, technical specifications in prototypes and entire technological systems, depending on the type of R&D. These project goals will be mentioned as *performance measures* hereafter. Additionally, these goals are of three types: large is better (LIB), when greater values for project goals are more desirable, small is better (SIB), when lower values for project goals are preferred, and nominal is best (NIB), when values near a nominal value are desired.

As with schedule and cost, uncertainty is considered with three estimates, worst case value (WCV), most likely value (MLV) and best case value (BCV), and modeled with a beta distribution. Thus the probability component of performance risk is calculated using Monte Carlo simulation, as previously described. Random samples, when below the target in LIB performance, do add to risk. The opposite works for SIB performance measures. In NIB performance measures, any deviation, greater or lower than the nominal, add to risk.

The impact component of performance risk is calculated using individual utility curves for each project goal. The development of utility curves for each performance measure starts with the definition of a range of possible values, which tend to be equal to the range defined for the three estimates, i.e., the range between the pessimistic and optimistic value. Within this range, a utility curve is built, representing different degrees of preference to each performance measure. Hypothetical examples are given in Figure 8. Such information should represent preference levels of customers, designers, engineers, and others, depending on the situation and the type of R&D. This information must be gathered through customer surveys or defined internally, through staff meetings with the team of engineers, managers and designers, and should be available to all people involved in the projects.

The next step concerns the consideration of possible interactions, relationships and trade-offs between performance measures. When performance measures are considered independent from each other, it means that a lower value for a performance measure can be counterbalanced by a greater value in another performance measure. When this is observed, the method for performance risk evaluation is the *single attribute utility method*. On the other hand, this trade off may not exist, and all performance measures must be considered together to define the global utility of the system. Observing the hypothetical performance measures of Figure 8, this means, for example, that a lower performance in processing speed (a lower value) cannot be counterbalanced by a better performance for set-up time (a lower value) and tolerance (closer to nominal value). When this is observed, the method for performance risk evaluation is the *multi attribute utility method*. Both methods are incorporated into the software developed for the methodology, and it is the responsibility of the project team to define which type of relationship exists in the performance measures of the project. These methods are described below.

The single attribute utility method suggests different weights for each performance measure, in a way that a lower value achieved in performance measure, can be counterbalanced by a higher value in another performance measure assigned with a high weight. Thus, different weights, that should sum up to one, are assigned to each performance measure in order to characterize different degrees of importance to the global performance of the project.

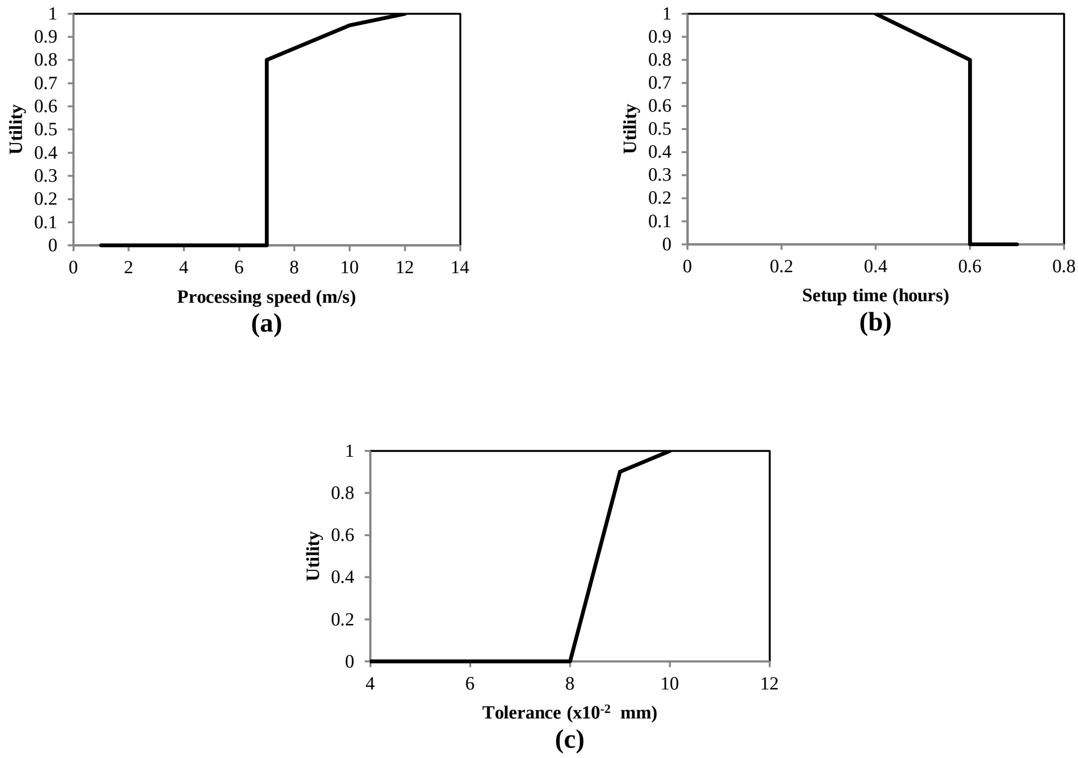


Figure 8 - Utility curves for performance measures: large is better (a), small is better (b) and nominal is best (c)

The single attribute utility method suggests different weights for each performance measure, in a way that a lower value achieved in performance measure, can be counterbalanced by a higher value in another performance measure assigned with a high weight. Thus, different weights, that should sum up to one, are assigned to each performance measure in order to characterize different degrees of importance to the global performance of the project.

The continuous and discrete forms for calculating performance risk for each performance measure are similar to schedule and cost risk, as described previously. The utility of each performance measures and their target is defined by the utility curve built previously for each performance measure. The global performance risk is the weighted average of all performance risk for each performance measure.

Performance risk (LIB)
$$R_{PM} = \int_{-\infty}^{T_{PM}} f(P_0)\left[U(T_p) - U(PM_0)\right]dP_0 \quad (2)$$

Performance risk (SIB)
$$R_{PM} = \int_{T_{PM}}^{\infty} f(P_0)\left[U(PM_0) - U(T_p)\right]dP_0 \quad (3)$$

Performance risk (NIB)
$$R_{PM} = \int_{-\infty}^{\infty} f(P_0)\left|U(PM_0) - U(T_p)\right|dP_0 \quad (4)$$

where,

T_{PM} – target performance measure

$f(PM_0)$ – probability density function of duration outcomes, from Monte Carlo simulation

$U(PM_0)$ – utility of performance measure outcome

$U(T_{PM})$ – utility of target performance measure

Global performance (GP) risk (single attribute utility method)
$$R_{GP} = \sum_{i} w_i R_{PM,i} \quad (5)$$

where,

w_i – weight of the *i*th performance measure

The multi attribute utility method, on the other hand, requires additional transformations to account for the relationships between every performance measure. The global performance utility with *i* number of performance measures is a composite measure given by equation (6):

$$U(GP) = \frac{\prod(Kk_i U(PM_i) + 1) - 1}{K} \quad (6)$$

The normalizing factor, K, determines consistency and is determined such that U(GP) = 0 when all $U(PM_i) = 0$ and U(GP) = 1 when all $U(PM_i) = 1$. The scaling factors, k_i, are the multi attribute utility of the best level of its performance measure i, when all other performance measures PMj, $j \neq i$, are on their worst levels. The procedure for estimating the scaling factor for each attribute suggested by Richard de Neufville (Neufville, 1990) involves asking a series of questions for each performance measure PM_i, similar to the ones used for the estimation of the utility based loss function. When an indifference point is reached, that is the scaling factor for the respective performance measure. Such procedure is implemented in the software.

The normalizing factor K is calculated when all scaling factors k_i are known, using equation (7):

$$\mathrm{K} + 1 = \prod (\mathrm{Kk}_i + 1) \tag{7}$$

Solving for K involves trial and error or the Newton's method. Once all parameters are calculated, the multi attribute utilities can be calculated. The equation and the discrete procedure for calculating performance risk are similar to the ones previously described. The difference is in the number of simulations required: whereas in single attribute utility method simulations of each performance measure results in simulations of utilities for each of them, which are then weighted using the weights assigned for each performance measure, in the multi attribute utility simulations result into an overall utility value for the project performance.

Although the tools described in this section represent methods for assessing project performance, some performance measures may be difficult to quantify in the proposed manner, depending on the type of R&D under consideration. This is the case, for example, of basic research projects. While still at a very early stage of technological development, basic research projects' performance measures tend to be more qualitative in nature, related to the acquisition of new knowledge, and not to technical specifications, which is only possible in more advanced types of R&D. Likert scales of preference can be used for this purpose, but may represent inadequate simplifications. In addition, and a common practice in many projects, the definition of technical specifications of technologies and products are usually made in later tasks of the project life cycle, normally in the design stages, when enough knowledge about such systems has been acquired. Therefore, analysis of performance in project selection stage only makes sense if technical specifications are, somehow, already known.

3.5.3 Performance risk in product development projects

The method proposed for calculating performance risk in product development projects differs from the one used in the other types of R&D. The justification of product development projects is fundamentally linked with market and economic objectives, that is, to market share, demand units, sales revenues, profitability and other economic indicators. As such, it is highly desirable for performance measures of product development projects to be linked to these sorts of indicators.

This view is also supported by Browning *et al.*, which is then the basis for the calculation of risks for the methodology proposed in this study (Browning *et al*., 2002). In Browning *et al.*'s proposal, the same equation applied for performance risk in basic research, applied research and advanced technology development is also applied to product development, but, in this case, is multiplied by a normalizing constant *K*, for converting units of utility to more intuitive measures of value, such as number of units likely to be purchased. While recognizing the need to connect the performance of a product development project to market objectives, Browning *et al.* does not propose any model or mechanism to support this conversion.

Thus, the challenge relies in linking the performance measure of product development to a *demand model*, capable of estimating products units likely to be purchased. Existing demand models, such as Discrete Choice Models, are heavily based on statistical methods derived from extensive customers' surveys, which may be infeasible to be performed in such an early stage as the project selection stage. Performing surveys can be costlier given the number of projects under consideration and prone to poor results due to the uncertainty about product future specifications. The *product value methodology* proposed by Harry Cook provides a reasonable method for addressing demand in new products (Cook, 1997). Although developed in the context of the automobile industry, it has also been applied in the printing industry (Suh *et al*., 2010) and in the construction equipment (Bush, 1998, Freeman, 2000, Herington, 2000), demonstrating its applicability in other industries. The approach described below follows the ideas proposed by Suh *et al.* in estimating the demand of product with a new technology infused (Suh *et al.*, 2010).

The product value methodology is based on the S-model used for explaining the diffusion of technologies and new products over their life cycle. Cook's proposition is that the value of a product has the same units as price, and is larger than the price if there is demand for the product, and is also proportional to demand. Using the S-model based on market equilibrium, the demand of a product is an analytical function of *N* competing products' prices and values (Cook and Wu, 2001):

$$\mathrm{D_i} = \mathrm{f_i}(\mathrm{V_1}, \mathrm{V_1}, \dots, \mathrm{V_{N;}}\, \mathrm{P_1}, \mathrm{P_2}, \dots, \mathrm{P_N}) \tag{8}$$

where

D_i – demand for the *i*th product

N – number of competing products

V_i – value of the *i*th product

P_i – price of the *i*th product

The derivations towards the following equations are quite extensive. The interested reader may consult Harry Cook's book *Product Management: Value, Quality, Cost, Price, and Organization* for more details of such derivations. The equations applied in the methodology proposed in this study are described below.

When prices and values of the products change independently from their levels, it follows that demand for each product *i* is provided by the equation (9):

$$D_i = K\left\{V_i - P_i - \frac{1}{N}\sum_{j \neq i}\left[V_j - P_j\right]\right\} \tag{9}$$

The constant *K* is calculated from the following expression:

$$\mathrm{K} \approx \frac{E\overline{D}}{\overline{\mathrm{P}}} \tag{10}$$

where,

E – price elasticity of demand

$\overline{D}$ – average demand in the market segment (units/competitor)

$\overline{P}$ – average price in the market segment (monetary units/unit)

If the demands and prices of competing products in a market segment are known from historical data, the linear set of simultaneous equations represented from equation (9) can be solved, resulting in the following expression:

$$\mathrm{V_i} = \frac{\mathrm{N[D_i + D_T]}}{\mathrm{K[N + 1]}} + \mathrm{P_i} \tag{11}$$

where,

D_T = total demand for the market segment,

The above expression can be understood as “top-down” approach to quantifying value of a product, since it can be derived from market data. Another equation provides a “bottom-up” approach to quantifying product value, based on relevant product attributes. Equation (12) provides the formula for the value of the *i*th product as a function of individual product attributes:

$$\mathrm{V(g_1, g_1, g_1, \ldots, g_j) = V_0 v(g_1) v(g_2) v(g_3) \ldots v(g_j)} \tag{12}$$

where,

V = value of the product with j attributes,

V_0 = average product value for the market segment,

$v(g)$ = normalized value for attribute g.

Each individual product attribute $v(g_i)$ falls within three categories, as with the performance measures from the other types of R&D projects: LIB, SIB and NIB. The normalized value for each product attribute g is given by equation (13):

$$\mathrm{v(g)} = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_0 - g_I)^2}\right]^{\gamma} \tag{13}$$

where,

g_C = critical level for the product attribute, if the attribute value exceeds, falls below or deviates from this value, depending on attribute type (LIB, SIB or NIB), the value of the attribute goes to zero, making the product undesirable,

g_I = ideal level for the product attribute beyond which there is no additional gain in value;

g_0 = market segment average level for the product attribute,

γ = time fraction when the attribute is of importance during the utilization of the product, also the value that controls the slope and shape of the value curve.

In order to determine the demand of a new product, based on the above equations, a *baseline product* needs to be identified first. The baseline product is an existing product in the market, with which the product to be developed in the project is comparable in terms of relevant attributes and their levels. The total demand for products in the market segment where the new product will compete, the number of competitors in the segment, the average market price elasticity, the demand, price and attribute levels of the baseline product must be known, so that the value of the baseline product can be calculated using equation (11).

The product development project target performance measures are the target attributes' levels for the new product. Knowing the target, critical, ideal, market segment average levels and time fraction for each of the new product's attribute, then the value of each individual product attribute can be calculated using equation (13). The new product target attribute levels are assumed to represent incremental improvements from the attribute levels of the baseline product. Thus, introducing the baseline product value as V_0 and the value of each new products' attribute target level (calculated from equation (13)) into equation (12), then the value of the new product when all its attributes are on their target levels is calculated. Knowing the price by which the new product will be sold (P_i), and introducing the product target value (V_i) into equation (11), along with the other parameters (K, N and D_T), yields the target demand (D_i) for the new product.

As with the performance measures in the other R&D types, uncertainty is modelled by introducing three estimates for each of the new products' attributes, i.e., the worst case value (WCV), the most likely value (MLV) and the best case value (BCV), which yields three additional estimates for the new products' value, from equation (12), and three additional estimates for the new products' demands, from equation (11) .

The same calculation can be repeated for each year of the projected product life. For this, forecasts are required concerning the evolution of the total demand for the products in the market segment, the number of competitors, the average price and price elasticity of demand. This results in the forecasted demand for the new product during the product life.

With this information, the performance risk for product development projects can be calculated. As with the other risk measures, Monte Carlo simulation based on the three estimates for each of the new product attribute and the beta distribution is performed, which results in a simulation of the total demand for the new product along its lifetime. Simulation results below the target demand (all of the new product's attributes at their target levels) contribute to the risk measure.

In order to harmonize with the other risk measures, a utility based loss function is also used for the impact component. The utility based loss function is built around the lost units sales. Thus, the worst possible outcome for lost units sales during the projected life of the new product must be provided. The utility based loss function is constructed by asking managers or the risk management board the following question: *"if you have 50:50 chance of having a loss of [worst possible impact introduced] unit sales from the planned target or no loss, or having a certain loss of [a high value, but lower than the worst possible outcome] units sales from the planned target, what would you prefer?"*. The procedure that follows is the same as described for schedule and cost risk.

Finally, the continuous formula for performance risk in product development project is provided by equation (14):

$$R_{PM} = \int_{-\infty}^{T_{PM}} f(P_0)[U(T_{PM} - PM_0)]dP_0 \qquad (14)$$

where,

T_{PM} – target performance measure (target demand)

$f(PM_0)$ – probability density function of demand outcomes, from Monte Carlo simulation

PM_0 –demand outcome

$U(T_{PM} - PM_0)$ – utility of lost units sales from target demand

The discrete form of the risk equation above is calculated in the following manner in the purposely developed software application: a spreadsheet containing the random samples for demand and a second column for the impact, which is the utility of the difference between the target demand and the simulated demand. If the random sample for demand is greater than the target demand, then the impact is zero. A third column is a multiplication of each random sample and respective impact. The sum of this column provides an approximation for the performance risk in product development.

The above information can also be used to assess the economic attractiveness of the new product. The revenues can be calculated by multiplying the demand forecasted by the price for which the product is sold in each year. Providing estimations for the cost of manufacturing the product in each year, and the cost of developing the product at year 0, then a cash-flow analysis for the new product is developed. Establishing a discount and inflation rate, typical investment appraisal indicators such as the net present value (NPV), internal rate of return (IRR), payback period and the annualized present value (ANPV), which is more suitable to compare projects with different durations, can be calculated. Such indicators are calculated in the software, and are included as built in criteria for project selection.

Additionally, a sensitivity analysis can be performed on the new product's attributes. Sensitivity analysis is used to assess how uncertainty impact key parameters from a planned target. Uncertainty is modelled in product attributes, with the three estimates mentioned before. Sensitivity analysis is performed around the target NPV and ANPV, when all the product attributes are at their target levels. By building tornado charts like the ones Figure 9 one can visualize the impact of each product attribute in the target NPV and ANPV (vertical dark line in charts): when a product attribute is in its worst case value (left-hand side of bar, in red), NPV and ANPV deviate negatively from the target value, and when it is in the best case value (right hand side of bar, in blue), NPV and ANPV deviate positively from the target value. For example, among all product attributes in Figure 9, product attribute 1 seems to be the one to have the highest impact in the overall product NPV and ANPV. This provides valuable information to designers and engineers, namely in the prioritization of specific product attributes.

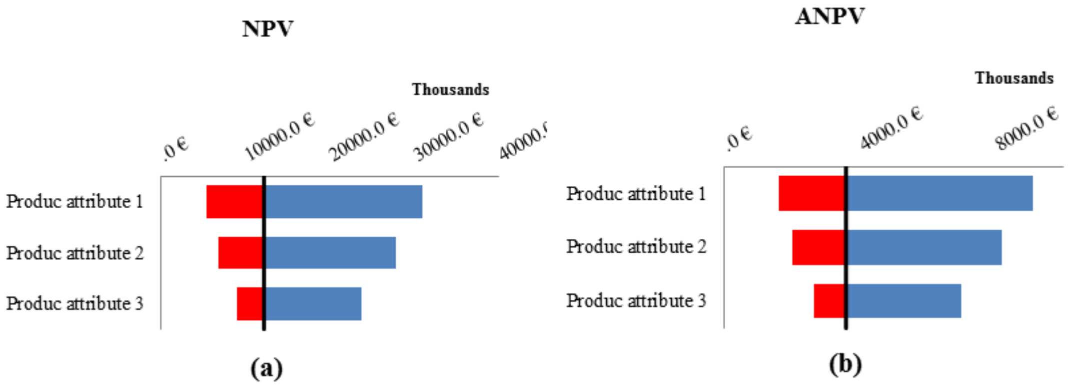


Figure 9 – Sensitivity analysis on NPV (a) and ANPV (b)

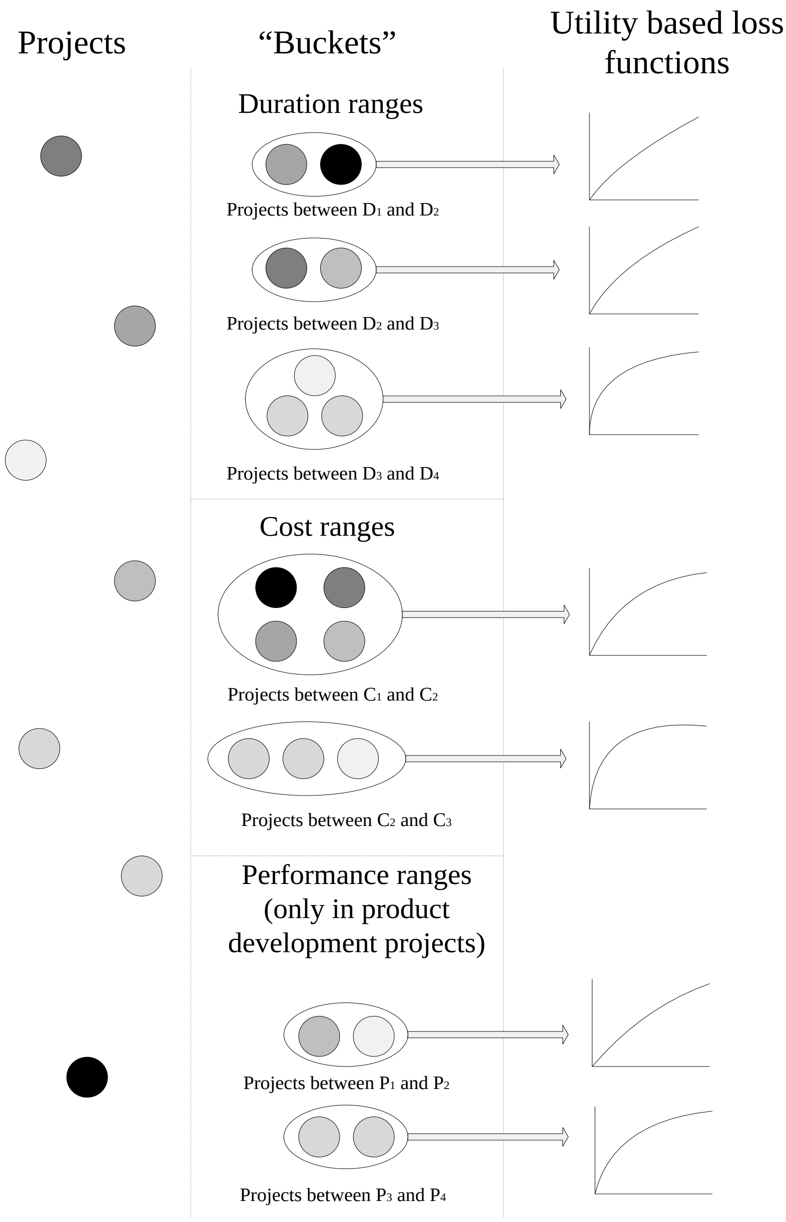
Important to highlight that the product value methodology presented in this section is a theoretical model, only capable of providing rough estimates of performance risk and economic attractiveness of products. A number of its underlying key parameters are also dependent on experience of engineers and managers, such as the manufacturing costs and product selling price. It is highly desirable to update this information in later stages of the project, possibly using statistical methods and customers' surveys. Careful considerations with respect to the quality of data should be taken when using the product value methodology, to ensure a realistic assessment.

4 Methodology for R&D projects selection incorporating risk management

In addition to characterizing different technology readiness levels, different types of R&D projects cover different orders of magnitude, in terms of duration and cost. Adding up to this complexity, there are the numerous perspectives over risk inside an organization. In order to address these issues, the methodology for R&D project selection proposed in this study presents a new approach towards managing risk, which is integrated early on projects’ life cycle.

It is proposed that clustering projects proposals estimations of duration and cost into ranges or “buckets” supports greater homogenization of organizational policies with respect to project risks. This clustering should take into account the types of R&D practiced, their impact on the organization, and project execution modes. Basic research projects are usually inexpensive and short in duration, but as technology matures, projects tend to be costlier and longer. The perspective on risk is inevitably related to the size of the organization: 1 000 000 euros projects, lasting two years, are perceived in different ways by large and small organizations. Projects’ execution modes also determine the clustering of cost and duration ranges, since collaboration involves sharing of resources which is expected to reduce project duration and costs to the organization. Outsourcing involves a third party or parties where duration and cost outcomes become less controlled by the organization. The definition of project ranges should take into account these factors, and be widely discussed and disseminated within the organization.

Once projects duration and cost ranges are defined inside an organization, a single utility based loss function is assigned to each one of them. Figure 10 illustrates this process. Important to notice is that the number of duration and cost ranges may not be the same.



Legend:
Di – duration *i*
Ci – cost *i*
Pi – performance *i*

Figure 10 - Projects clustering into duration, cost and performance (in product development projects) ranges and utility based loss functions

The utility based loss function works as an approximation of the risk perspectives of the organization over the projects' cost and duration ranges, and is then used for the calculation of schedule and cost risk when project planning data is introduced. The mechanism for building the utility based loss function is the following: within each range, the worst possible impact (cost or schedule overruns, where appropriate) is defined, and then questions for elicitation of the utility based loss function are asked, as previously described. An interesting issue, though not tested in a real case, can be expected: as the ranges and worst possible impact increase, utility based loss function tend to be more concave, because increasing cost or schedule overruns will be mapped into higher utility values.

In product development project, performance measures of "total demand for planned product life" are also clustered into ranges and worst possible impacts (loss of units sales) defined. A corresponding utility based loss function is assigned to each one of them.

Projects' duration, cost and performance (in product development) ranges and respective utility based loss function should be stored in a database, so that they can be used in calculating schedule, cost risk and performance risk. A database of the resources available in the organization and their costs should also be created to support project planning. With these two databases created, the process for generating proposals for project selection can be started. The flowchart depicted in Figure 11 illustrates the whole process. The inputs necessary to run the methodology's underlying models can be visualized in the forms developed for the software, in Appendix 2.

The process starts with filling a number of forms for characterization of the project proposals, and is related to the identified criteria for each project type, as described previously. A number of forms are shown below in order to assist the reader in understanding the steps of the methodology. The remaining forms can be seen in Appendix 2.

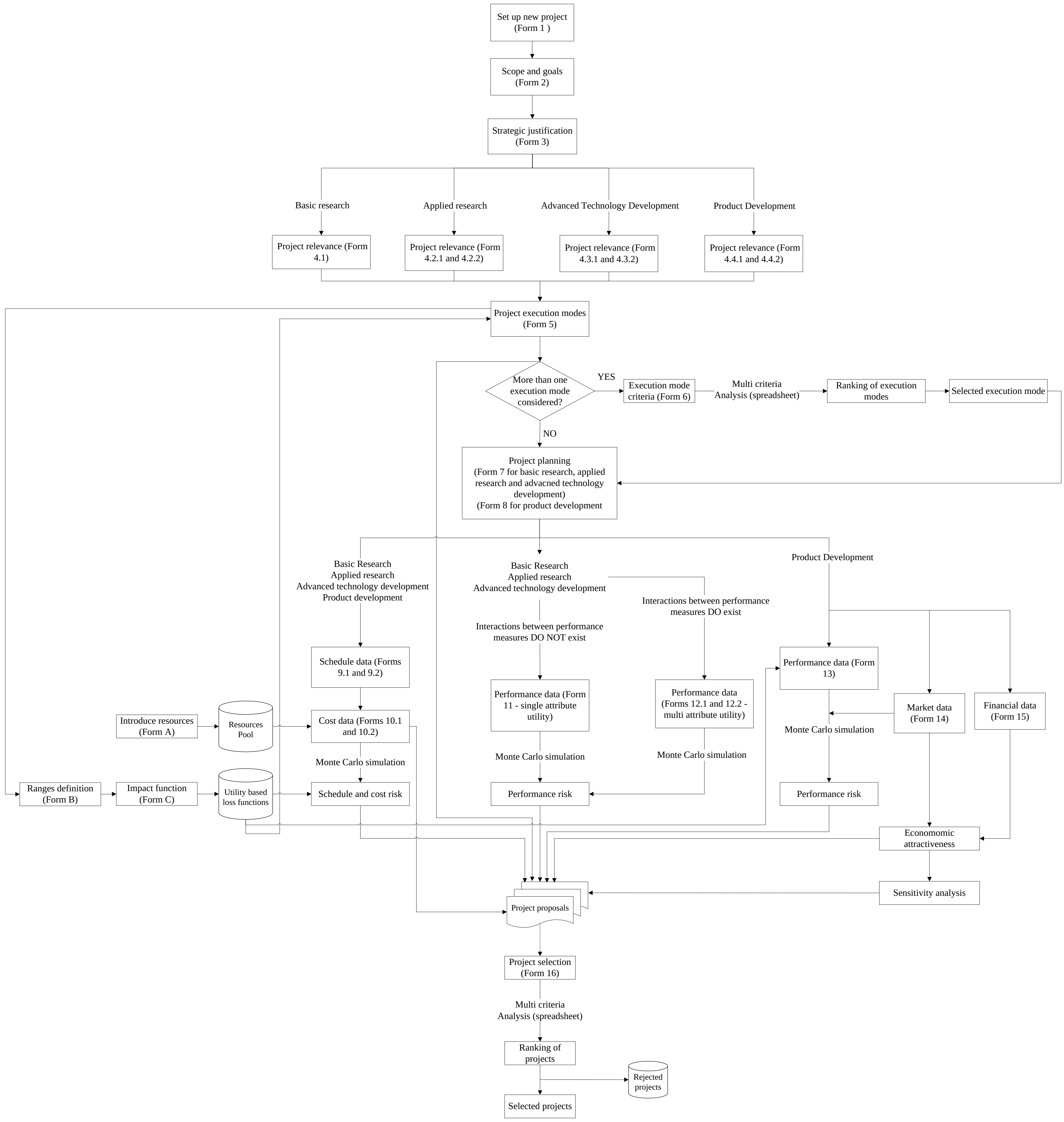


Figure 11 - Methodology for R&D project selection incorporating risk.

Prior to introducing project data, two databases need to be created: one with resources to be assigned to projects and the other containing the utility based loss functions for each defined project ranges. Figure 12 depicts the form where users introduce resource data: resources designation, type (engineer, technician, machine function, etc.) and standard time durations (month and days). The utility based loss functions are introduced via two forms. In the form depicted in Figure 13, the user introduces the range or "bucket designation/name, selects the type of R&D project, and then minimum and maximum value for this range, in terms of schedule, cost and performance (in product development only). For each range, the worst impact expected is introduced. The next form, illustrated in Figure 14, the user is asked a series of questions which define the utility based loss function, following the process described in section 3.5.1. Both these databases are stored as files, and need to be created and uploaded when a new project is introduced.

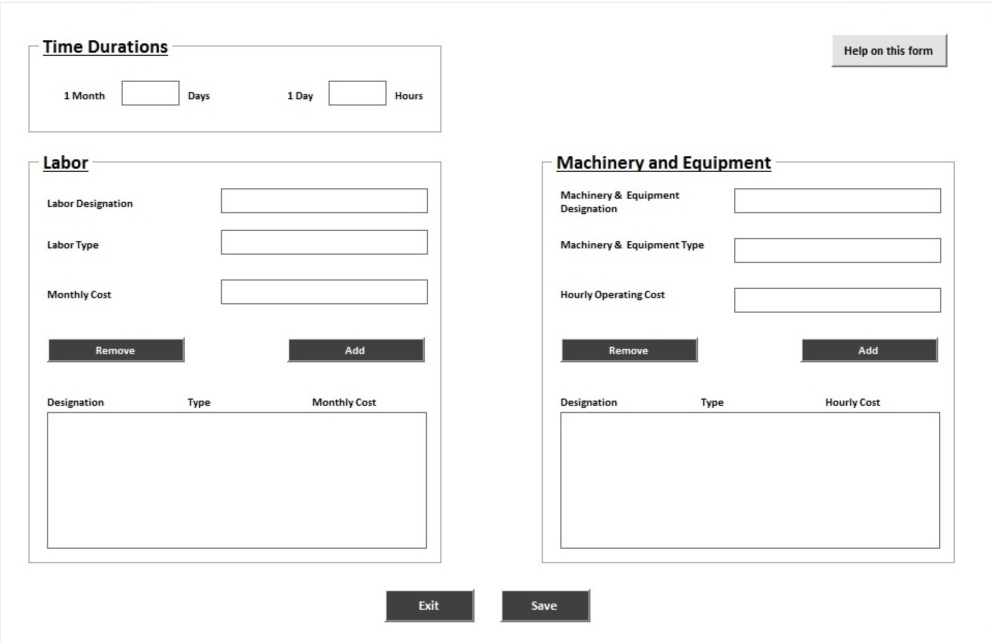


Figure 12 - Resources introduction - Form A

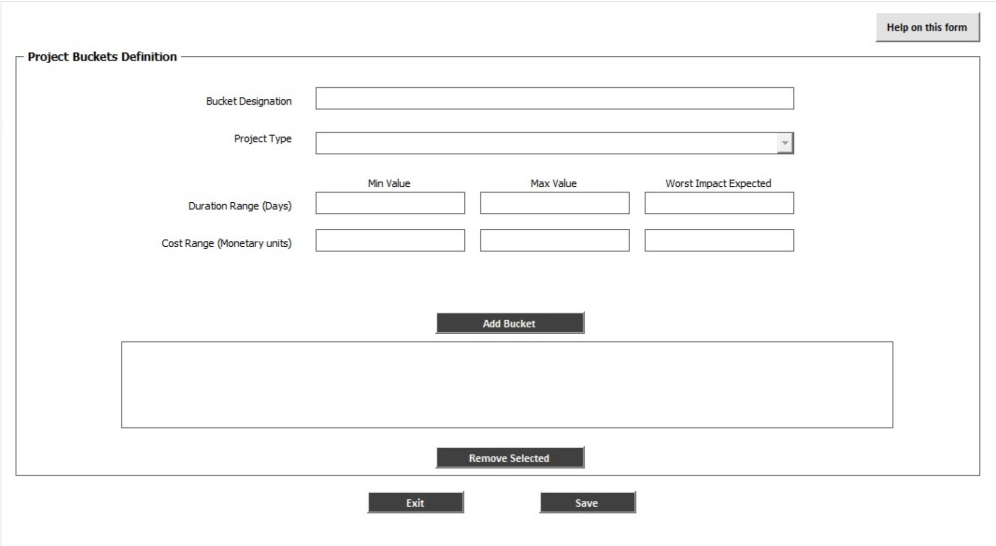


Figure 13 - Project ranges definition – Form B

Figure 14 - Utility based loss function definition - Form C

Having introduced these data, the user can initiate the introduction and characterization of projects. The first form in this process - set up new project, in Figure 15 - involves, among other information, introducing the project type (basic research, applied research, advanced technology development and product development), the execution modes under consideration (internal development, collaboration and external acquisition/outsource) and the paths to the resources and utility based loss function databases, which will be used later in project planning and risk assessment. Additionally, more than one execution mode can be selected if the decision maker is not sure about which is the most appropriate manner for executing the project.

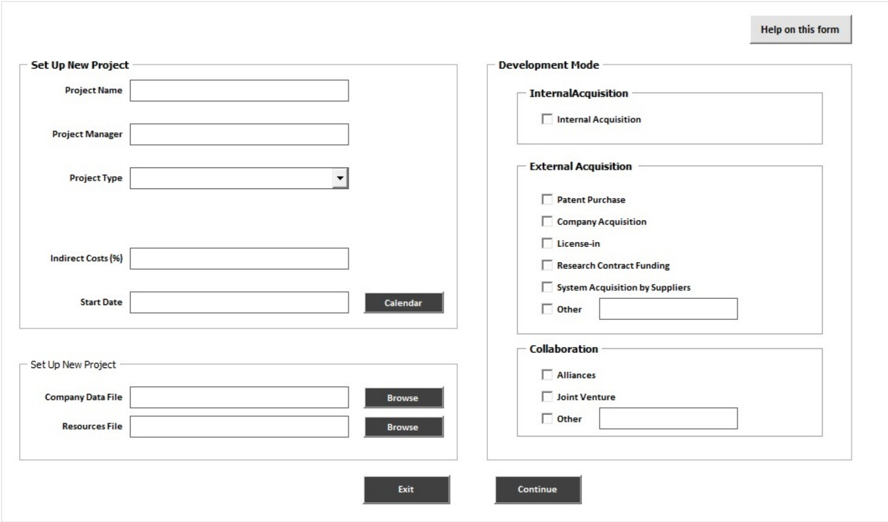


Figure 15 - Set up new project - Form 1

The next two project proposal forms – scope and strategic justification, in Figure 16 and Figure 17, respectively -, which are common to all project types, were designed for the introduction of the scope, goals (performance measures), strategic justification, projected and programmatic risks of the project.

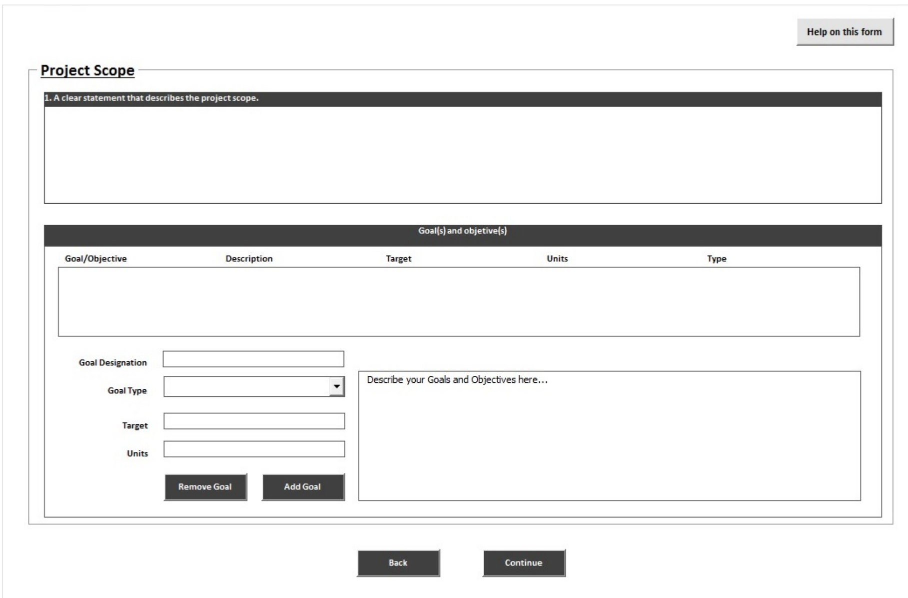


Figure 16 - Scope and goals - Form 2

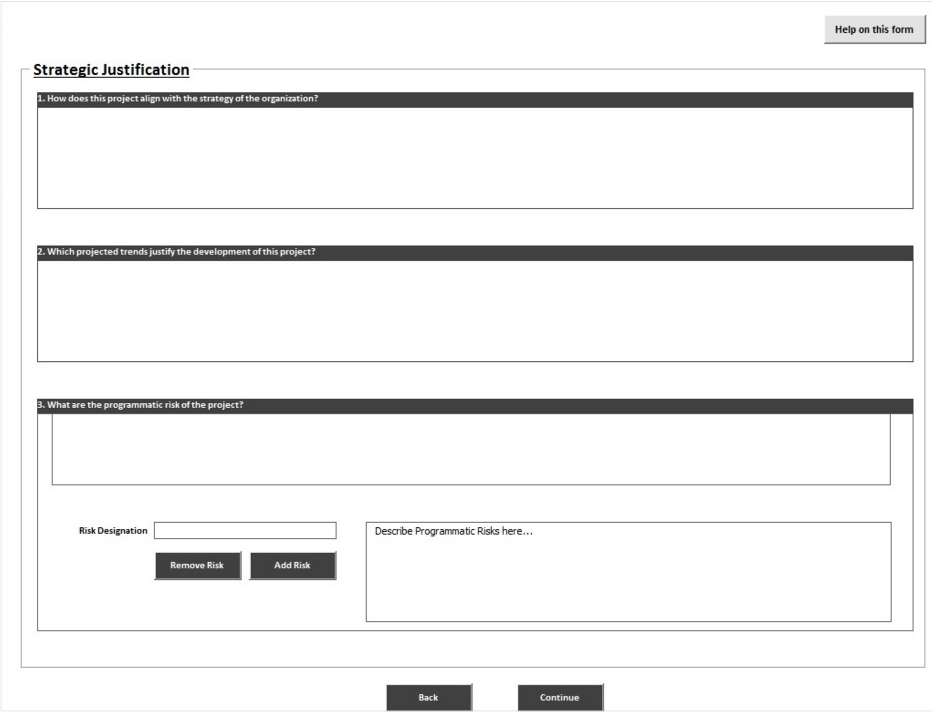


Figure 17 - Strategic justification - Form 3

The fourth form – project relevance - is intrinsic to the project type selected. It is where information about the *relevance* of the project is introduced. For example, in basic research projects, information about how the project will contribute to the knowledge base of the organization, the scientific and theoretical background, interdependencies with other projects and risks related to the research are asked. The project relevance form for basic research projects is shown in Figure 18.

The last form before proceeding to project planning is where information about project execution modes is filled. For each execution mode defined in the first form, information concerning key stakeholders, risks in the execution mode under consideration, assumptions and constraints and required resources (competences, skills, machinery and equipment) is completed. Moreover, and also for each execution mode, “buckets” or duration and cost ranges and their respective impact functions, are selected from the utility based loss function database. In this form, the user can create a new project range and utility based loss function, which is stored in the database – in this case, a spreadsheet file, for the execution mode under consideration.

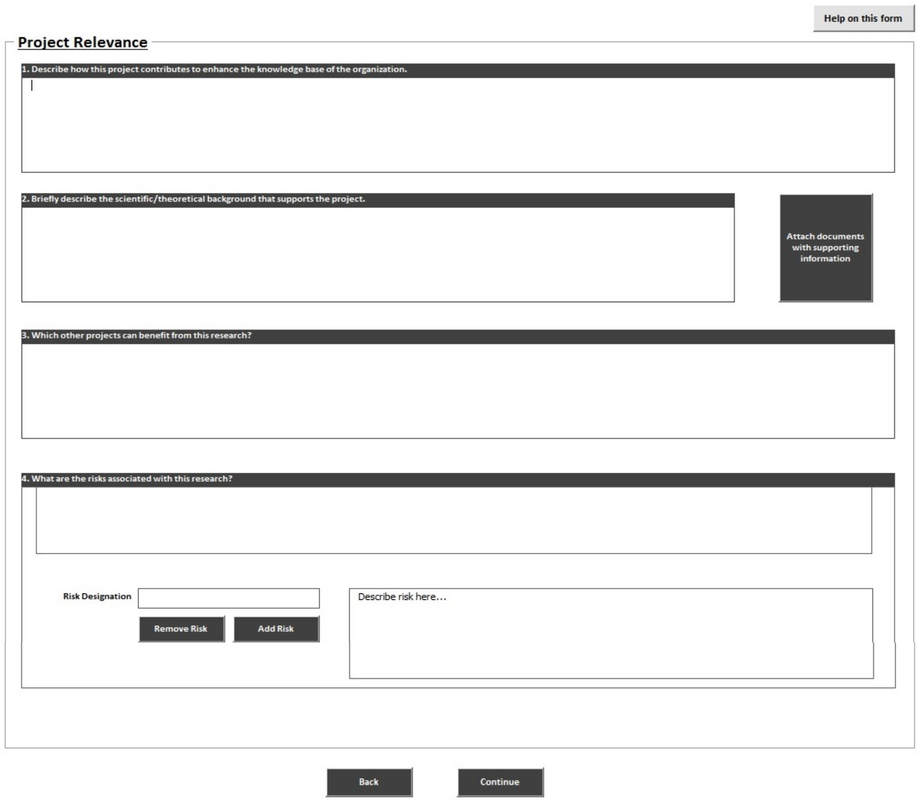


Figure 18 - Project relevance – Form 4.1

If more than one project execution mode has been characterized, a multi criteria analysis based on the AHP is triggered, with built-in criteria for selection of project execution mode, as described previously. Users can delete, change and add new criteria, as shown in the form depicted in Figure 19. Once the multi criteria analysis is performed, a ranking of execution modes is produced. Users can continue with the project execution mode with the highest ranking, or redo the multi criteria analysis if not satisfied with the results.

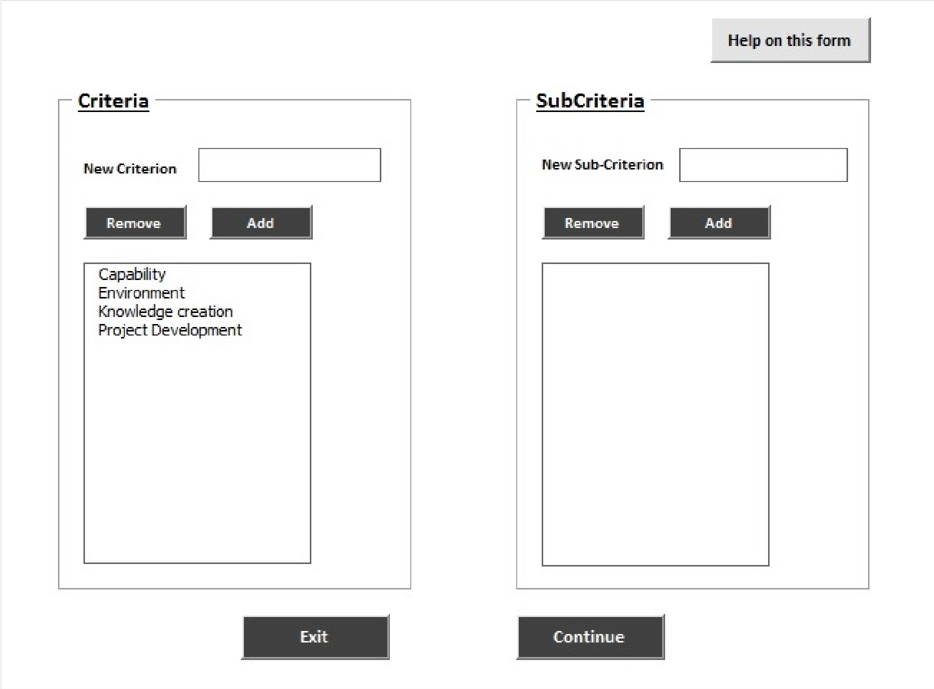


Figure 19 - Execution mode criteria - Form 6

The next stage is related to project planning. The forms for introducing schedule and cost data are the same for all project types. In schedule forms, tasks descriptions, their three duration estimates, precedents and target schedule are filled. In the cost forms, target project cost, human and machinery/ equipment resources are assigned to each task, along with their dedication (in percentage), drawing from the resources database. Then, cost items are filled, with their three estimates if managers are uncertain about their value. Figure 20 presents the form where project tasks and durations are introduced, and Figure 21 presents the form where resources are assigned to project tasks.

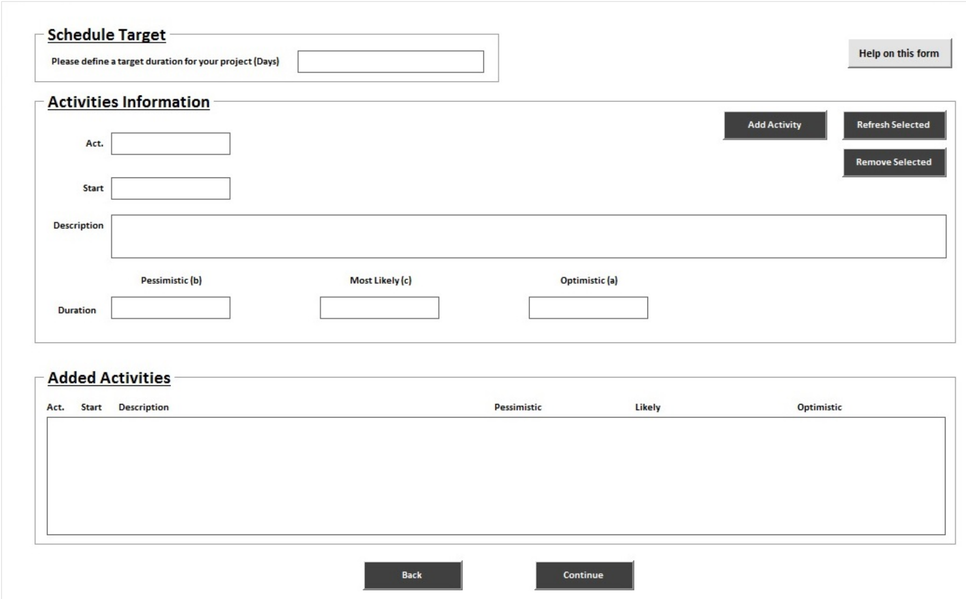


Figure 20 - Schedule data - Form 9.1

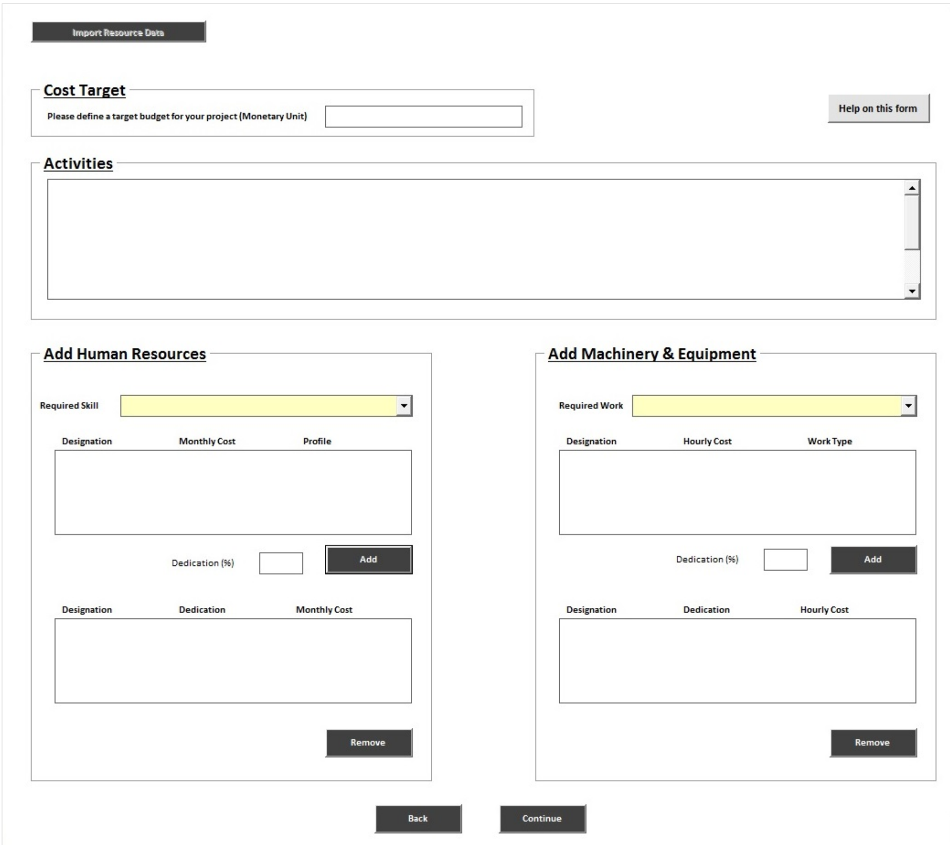


Figure 21 - Cost data - Form 10.1

Performance measures introduced in the second form is retrieved in the performance data forms, and can be edited at this time if desired. Project performance forms are not the same for all project types. In basic research, applied research and advanced technology development projects, managers need to consider whether interactions between performance measures exist or not. If they do not exist, then the single attribute utility method should be used. If interactions exist, then the multi attribute utility method should be used. Figure 22 presents the form for single attribute utility method.

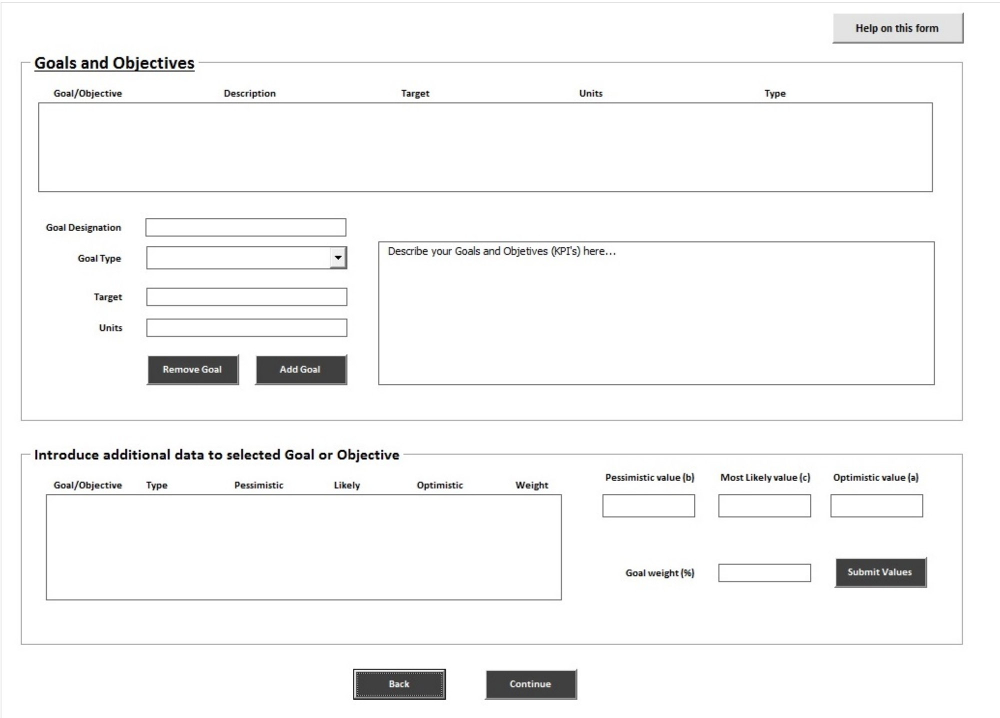


Figure 22 - Performance data – Form 11

The case of product development projects is different. Besides introducing and/or editing performance data, market and financial data should also be introduced, presented in the forms depicted in Figure 23 and Figure 24, respectively. These data feed the product value methodology described previously, which then enables developing an economic attractiveness and sensitivity analysis on product attributes.

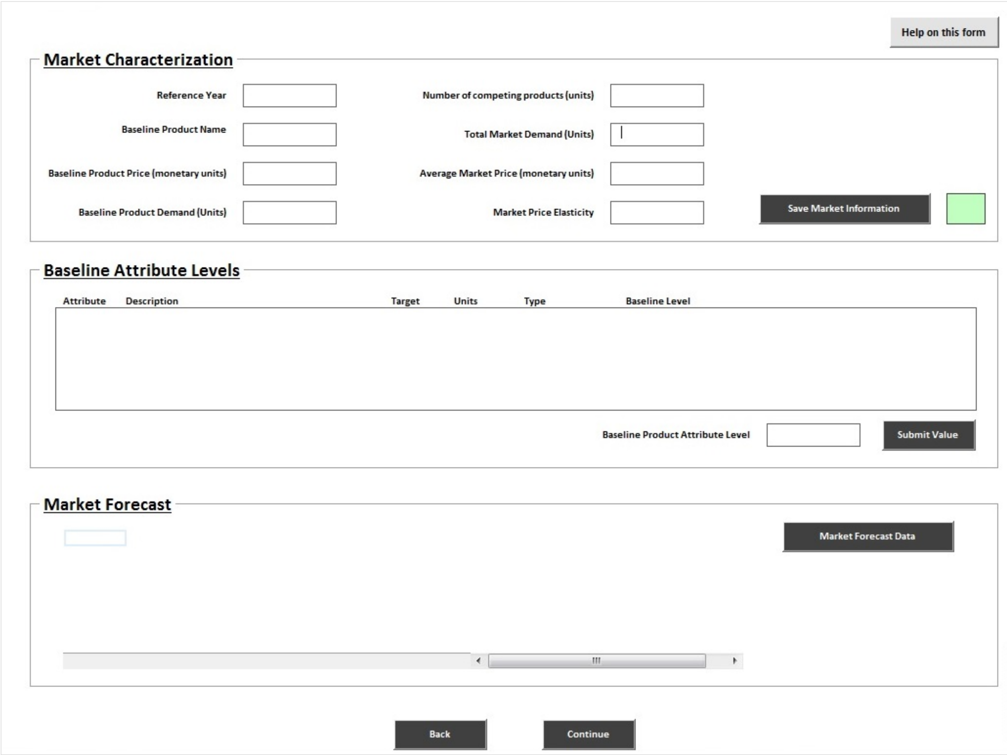


Figure 23 - Market data – Form 14

Figure 24 - Financial data - Form 15

Once schedule, cost and performance data has been filled for a project, Monte Carlo simulation can be run for risk analysis. Managers can decide on the size of the random sample and the bin width. After the simulation is run, schedule, cost and performance risks are calculated.

The final project proposal document includes the information filled in the project characterization forms (scope, strategic justification, relevance and execution mode), the project planning (estimated cost and duration), and the risk analysis (schedule, cost and performance). In product development projects, the proposal document also includes economic attractiveness and sensitivity analysis. Thus, the project proposal document ensures a mix of qualitative and quantitative criteria, a requirement for integrated project selection methodologies (Archer and Ghasemzadeh, 1999, Verbano and Nosella, 2010) and a project characterization framework based on benefits and risks (Chiesa, 2001).

The final project proposal document is stored in a folder, and can be used when the organization engages in the project selection activity. Figure 25 presents the form where projects to be compared are chosen, and selection criteria are defined.

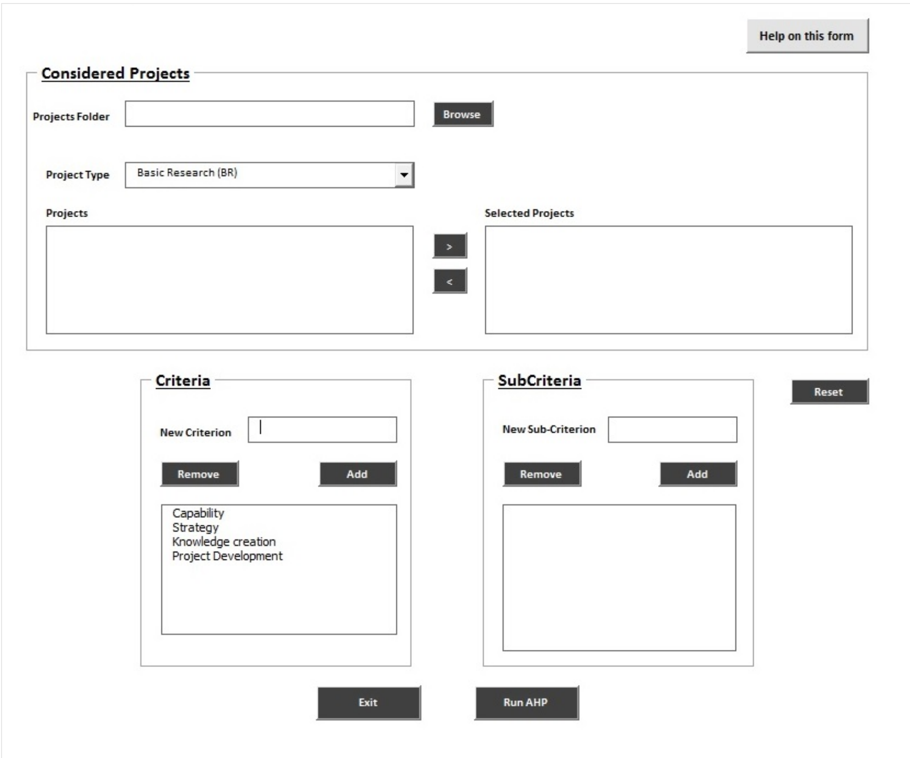


Figure 25 - Project selection - Form 16

In the current stage of development, the software still does not convert the information stored in spreadsheets to a text document, but in the future it is expected that such feature will be enabled. As with the execution mode selection, the AHP is the multi criteria method used for selecting projects. Built-in criteria include the ones described in sub section 3.2, the calculated risk levels and, in the case of product development projects, economic attractiveness of the project, which is based on the investment appraisal indicators (NPV; ANPV; IRR and payback period).

The models and respective tools and metrics used in the proposed methodology are summarized in Table 9.

Table 9 - Summary of models, tools and metrics used in the methodology

Model	Tool(s) or metrics
Schedule risk	Monte Carlo simulation, utility based loss function
Cost risk	Monte Carlo simulation, utility based loss function
Performance risk in basic research, applied research and advanced technology development projects	Monte Carlo simulation, single and multi-attribute utility
Performance risk in product development projects	Monte Carlo simulation, product value methodology, utility based loss function
Economic attractiveness	Net present value, annualized present value, internal rate of return and payback period
Execution mode selection	Analytic hierarchy process
Project selection	Analytic hierarchy process

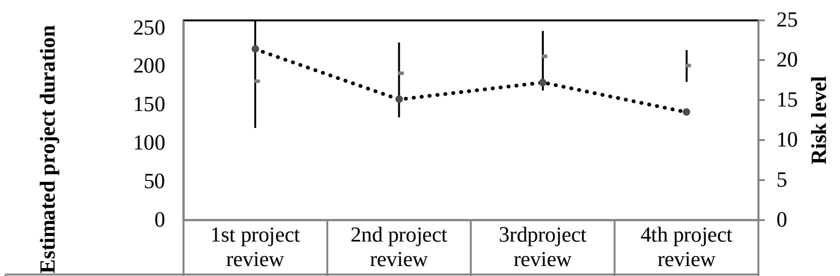
4.1 Risk management and control

Another contribution of this methodology relates to integrating a risk management and control mechanism early on the project selection phase. Once risk levels are calculated, for schedule, cost and performance, the risk levels can be managed throughout the execution of the selected project. Hypothetical examples for schedule, cost and performance are provided in Figure 26, Figure 27 and Figure 28. The example for performance measure shown includes the single attribute utility method. In the multi attribute utility method a composite measure of performance risk is calculated, and no individual risk level for each performance measure can be included in a chart.

In each project review, estimates for the remaining tasks durations, costs and the estimates for performance measures can be updated, as new information is gathered and uncertainty is reduced, which can be observed in the reduction of bar sizes in the charts bellow. This means that the maximum and minimum project's expected duration, cost and performance are reduced as uncertainty is reduced along the project execution. Additionally, new targets for schedule, cost and performance can be set in each project review, and even new performance measures can be added. As a consequence of uncertainty reduction, and/or target changes and/or new performance measures, risk levels change in each project review.

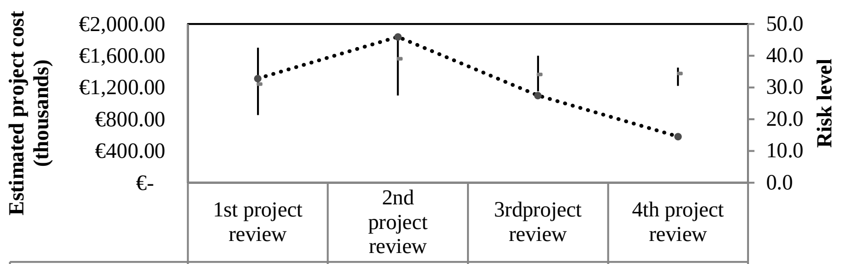
The quantification of risk enables an easier interpretation about the current situation of the project, providing the organization with means for managing risk throughout the life cycle, i.e., in preparing risk response plans and observing their effectiveness in each project review.

The risk management and control mechanism has not been developed for the software, but it can be easily modelled and integrated in future developments.



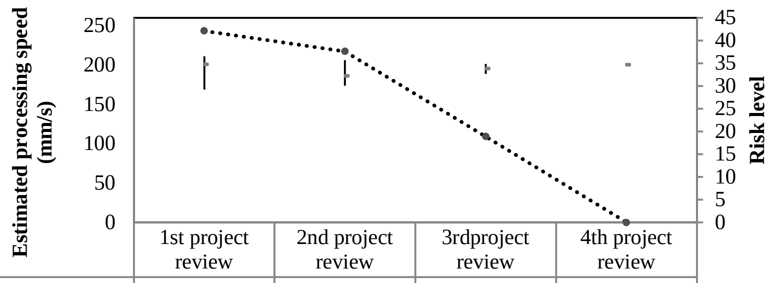
	1st project review	2nd project review	3rdproject review	4th project review
Max	260	230	245	220
Min	121	135	170	181
Average	180.1	190.3	212.7	200.3
Risk level	21.4	15.1	17.2	13.5

Figure 26 - Chart for schedule risk management and tracking



	1st project review	2nd project review	3rdproject review	4th project review
Max	€1,700,000.0	€1,800,000.0	€1,600,000.0	€1,450,000.0
Min	€850,000.00	€1,100,000.0	€1,150,000.0	€1,220,000.0
Average	€1,236,121.0	€1,556,783.0	€1,360,000.0	€1,370,000.0
Risk level	32.8	45.9	27.4	14.5

Figure 27 - Chart for cost risk management and tracking



	1st project review	2nd project review	3rdproject review	4th project review
Max	210	205	200	200
Min	170	175	190	200
Average	200.2	185.6	195.2	200
Risk level	42.1	37.6	18.9	0

Figure 28 - Chart for performance risk management and tracking

4.2 Resource competition

The issue of resource competition is also addressed in the proposed methodology. Resource overload, i.e., when the capacity of a resource is exceeded, happens when resources are working in multiple tasks (from the same project or from many projects) in a determined period of time, and the sum of their dedication to the tasks are over 100%. To better deal with this problem, a simple algorithm that warns managers about the likelihood of resource overload has been developed for the methodology's software.

For each simulation iteration for a project with *N* tasks, and beginning at time t_i=0 of the project, the shortest start or finish time of all tasks in the same simulation iteration, t_{i+1} is searched. Once t_{i+1} is identified, and for the duration range $t_i < d_j < t_{i+1}$, all tasks start and finish times are checked to see if fall inside this duration range. Every task that satisfies this condition is stored in a vector v_k. If the vector contains more than one task, then these tasks overlap within the duration d_j. The dedication of each resource that is shared by these tasks is summed and if it exceeds 100%, then resource overload occurs within the duration d_j.

The procedure is repeated for the next duration d_{j+1} , such that $t_{i+1} < d_{j+1} < t_{i+2}$, and t_{i+2} is the next shortest start or finish time of all tasks in the same simulation iteration, and is greater than t_{i+1}. For each simulation iteration, there are *N*x2 verifications of duration ranges and vectors. In a Monte Carlo simulation with 10000 iterations, there are 10000xNx2 verifications. In order to accelerate this process, the software developed for the methodology only computes average durations, average resource overload and the probability of resource overload, which is taken to be equal to the number resource overload occurrences divided by the number of iterations. Based on this information, managers can decide whether to make change and/or reallocate resources to minimize the chances of resource overload.

Although this mechanism is implemented for resource overloads occurring in single projects, it can be easily extended to multiple and interdependent projects. A faster programming language would then be required. Using the software developed for this study, running a Monte Carlo simulation with 10,000 trials which results in the risk analysis and resource overload verification for a single project, takes approximately two minutes to complete on a computer with a 2.00GHz processor and 4.00 GB of RAM.

5 Methodology application

The methodology proposed for project selection was applied in the industrial partner of the study: a mid-sized manufacturer of sheet metal processing equipment and machinery, including shears, press brakes and laser cutting machines.

A *post mortem* analysis – i.e., conducted after the completion of the projects – was conducted on three product development projects. The three projects were executed in cooperation mode. For confidentiality reasons, they will be denominated Project A, Project B and Project C.

The application of the methodology was performed in three sessions with the CTO of the industrial partner. The software developed for the project selection methodology was used to support the application. In the first session, data and information about the projects were gathered from internal reports and funding applications. The data and information in these documents covered most of the themes in the project characterization forms for product development – forms 1, 2, 3, 4.4.1, 4.4.2 and 5, in Figure 11. Tasks durations and costs described in the projects proposal documents were used as most likely values for project planning. As suggested by the CTO, tasks completion delays and cost overruns were used as the pessimistic values, while the optimistic estimates were around 80% of the tasks durations and costs initially set. The first targets for projects' schedules and costs set were used in this analysis. Additionally, some data about the markets and competitors were available in these documents and fed the demand model. However, not all the necessary data could be gathered for this model, and some assumptions needed to be made, as it will be explained later.

The second session concerned the definition of the utility based functions. First, the projects' ranges in terms of schedule, cost and performance needed to be defined. The CTO provided the minimum and maximum values for each project, which were in line with the reality of the industrial partner. It was assumed a duration of three years for the lifetime of the products to be developed in each project. Then, the CTO proceeded and answered the round of questions to support the definition of the utility based loss functions. Table 10 presents the ranges and the respective worst impact values (WIV), the indifference values and the utility based loss functions for each project. Figure 29 presents the graphic portrayal of the utility based loss functions for Project B.

As it can be observed in Table 10, different projects within the same schedule range may be included in different cost ranges. This is the case of projects B and C, which belong to the same schedule range (792 – 1048 days) but are included in different cost ranges (project B: 1,000,000€ - 2,000,000€ and project C: 500,000€ - 1,000,000€). This can be explained by resource intensive project plans, i.e., the allocation of more resources to specific projects in order to accelerate development duration to meet the desired timing of introduction in the market. Another issue of importance is related to the possibility of the same ranges having different WIV in different projects, such as performance ranges in projects A and B. The reason for this can be explained by the difference in cost magnitude, which is higher in Project B since it belongs to a higher cost range. The execution of a project with a higher development cost can turn the organization more sensitive to likely losses in units sales, characterized by a lower WIV, as is the case of the project B in comparison to project A.

Table 10 - Ranges, indifference values and utility based loss functions for each project

Project	**Ranges and worst impact values (WIV)**			**Indifference value**	**Utility based loss functions**
	Schedule	**Cost**	**Performance (in three years sales)**		
Project A	Min: 528 days Max: 792 days WIV: 528 days (delay)	Min: 500,000€ Max: 1,000,000€ WIV: 200,000€ (cost overrun)	Min: 0 units sales Max: 15 units sales WIV: 6 lost units sales	Schedule: 106 days (delay) Cost: 60,000€ (cost overrun) Performance: 2 lost units sales	Schedule: $U(x) = 0.066783\wedge^{0.431691}$ Cost: $U(x) = 0.000887\wedge^{0.575717}$ Performance: $U(x) = 0.32288\wedge^{0.63093}$
Project B	Min: 792 days Max: 1048 days WIV: 528 days (delay)	Min: 1,000,000€ Max: 2,000,000€ WIV: 300,000€ (cost overrun)	Min: 0 units sales Max: 15 units sales WIV: 3 lost units sales	Schedule: 106 days (delay) Cost: 75,000€ (cost overrun) Performance: 1 lost unit sale	Schedule: $U(x) = 0.066783\wedge^{0.431691}$ Cost: $U(x) = 0.001826\wedge^{0.500}$ Performance: $U(x) = 0.5\wedge^{0.63093}$

Table 10 (continued)

Project	Ranges and worst impact values (WIV)			Indifference value	Utility based loss functions
	Schedule	Cost	Performance (in three years sales)		
Project C	Min: 792 days Max: 1048 days WIV: 528 days (delay)	Min: 500,000€ Max: 1,000,000€ WIV: 200,000€ (cost overrun)	Min: 15 units sales Max: 30 units sales WIV: 15 lost units sales	Schedule: 106 days (delay) Cost: 60,000€ Performance: 6 lost units sales	Schedule: U(x) = $0.066783^{\wedge 0.431691}$ Cost: U(x) = $0.000887^{\wedge 0.575717}$ Performance: U(x) = $0.12892^{\wedge 0.756471}$

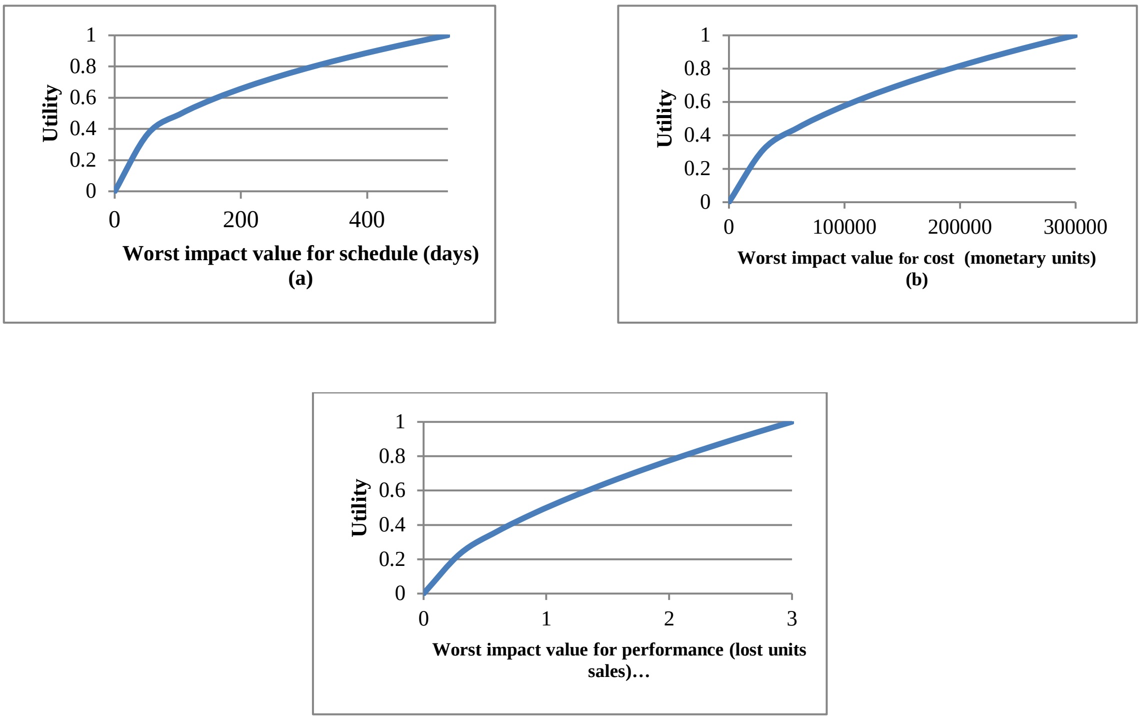


Figure 29 – Schedule (a), cost (b) and performance (c) utility based loss functions for Project B

Having introduced the project characterization data, the project planning, estimates for tasks durations and costs and the utility based functions, the next stage concerned the data introduction in the methodology's demand model. The demand model proposed by Cook (Cook, 1997) is a theoretical model, based on substantial amount of data, such as number of competitors in the segment, price elasticity of demand, average market prices and many others, as described in 3.5.3. Although some data could be collected from projects' documents, several assumptions needed to be made, with support of engineers and other collaborators involved in the projects. As such, the industrial partner was advised to observe the outputs (expected demands for each product, revenues generated and indicators such as NPV, IRR and Payback period) with extreme caution. As mentioned before, project performance analysis may be delegated to later stages of projects' life cycle, when product specifications are established and more market information is collected.

The demand model also required estimates (WCV, MLV and BCV) and target values for each product attribute. For each project, three product attributes were chosen as representative of the products' value. With the assumptions made in the demand model and a products' lifetime of three years, the demand for these years could be estimated; all these, along with the prices and manufacturing costs, served to develop a cash flow analysis. Assuming a 10% discount rate, the NPV, IRR and Payback period (in years) were calculated. Table 11 depicts the target NPV, IRR and Payback period for each project, which were calculated from the target values for each product attribute.

With these inputs, a Monte Carlo simulation with 100 trials was run to perform the risk analysis. Schedule targets for projects A, B and C were 748, 1048 and 1048 days, respectively. Cost targets for projects A, B and C were 720,000€, 1,250,000€ and 825,000€, respectively. Performance targets are based on the target values of each product's attributes. The result of this analysis is a distribution of projects' durations, costs and performances. For the purpose of illustration, Figure 30 depicts the risk analysis charts for project B. The dotted line in these charts represents the target values.

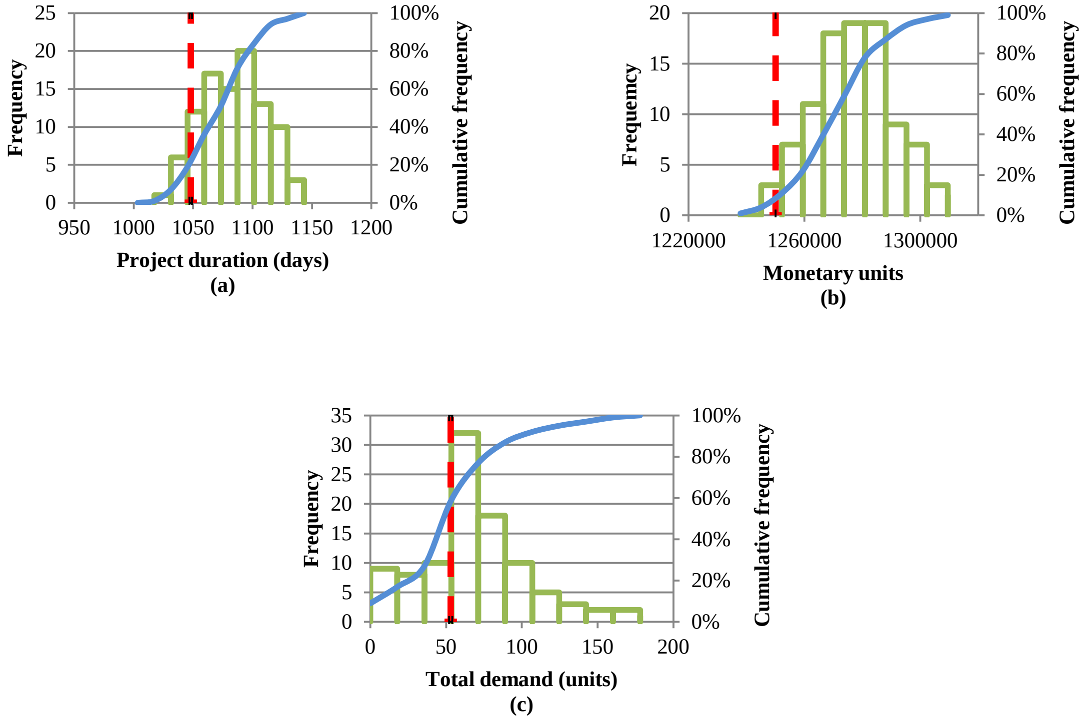


Figure 30 – Distributions of duration, cost and performance for project B

Table 11 - Risk analysis and economic attractiveness indicators for each project

Project	Schedule risk	Cost risk	Performance risk	Target NPV	Target IRR	Target payback period
Project A	6.3	0.8	226.2	705,451.62 €	63%	2.05
Project B	21.7	17.06	191.9	1,913,955.83 €	83%	1.78
Project C	23.54	9.5	226.2	841,149.06 €	70%	1.75

Finally, in the third section the multi criteria selection of the projects was performed. First, the CTO was requested to define the selection criteria to use, from the built in criteria, or adding new ones or changing existing criteria. Figure 31 illustrates the hierarchy model of criteria and sub criteria. Basing the analysis on the characterization of each project and the outputs from the models and the risk analysis, the CTO performed the project selection through pairwise comparisons between criteria, then in sub criteria with respect to corresponding criterion, and then in alternatives with respect to each sub criterion, following the procedure of the AHP method. The most attractive project from this analysis was project C, with a normalized final score of approximately 0.42. The matrices containing the pairwise comparisons can be found in Appendix 3.

The projects considered in this application of the methodology have not yet reached three years after the completion of each project. As such, it was not possible to verify whether the results of the methodology corroborate what the industrial partner has been experiencing with the projects. Overall, the feedback from the CTO was satisfactory, specifically concerning the criteria proposed for select product development projects, which were considered as appropriate for comparing such types of projects. Additionally, the CTO felt that clustering of projects into ranges can contribute to a more rational project management inside the company.

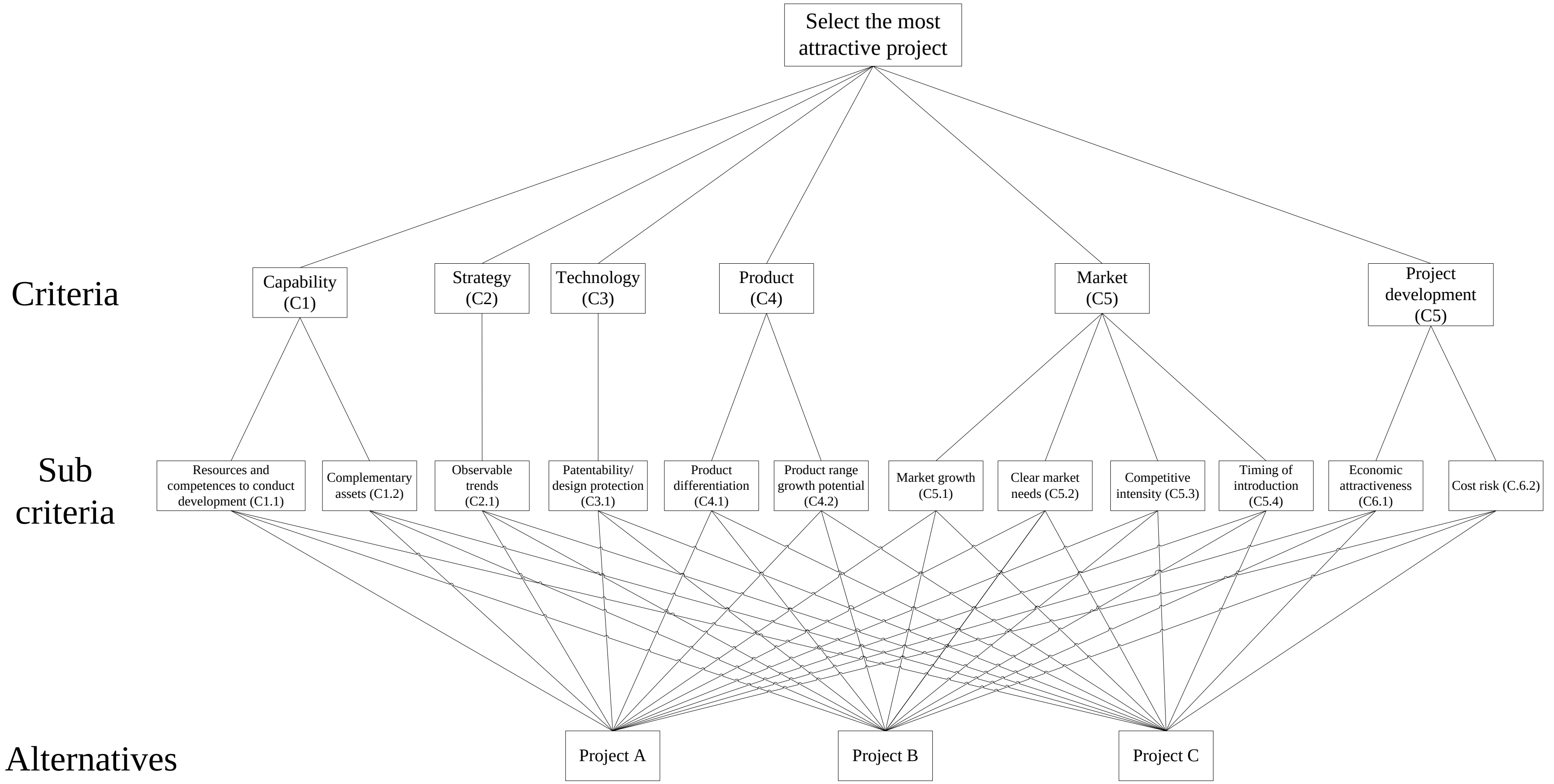


Figure 31 - Criteria and sub criteria hierarchy model used in the project selection

6 Conclusions

This study presents a new methodology for selecting R&D projects that incorporates a risk management mechanism. By combining series of tools, the proposed methodology addresses a number of propositions for an integrated project selection framework.

Several managerial implications are envisioned. The early categorization into different types of R&D and product development projects, in the selection process, allows a more equitable comparison between projects. Managers are also able to observe a logical sequence in the project selection process, which involves the characterization, planning, risk analysis and economic attractiveness (in product development), towards project selection. Both tangible and intangible, positive (benefits) and negative (risks) aspects of projects are covered in the whole selection process.

The integration of risk early in the project life cycle enables more time for managers to mitigate them. The quantification of risks through project buckets and impact functions contributes to greater homogenization and rationalization of organizational policies and practices in risk management. Although risk quantification may be done at a very early stage, and therefore prone to unreliable results, risk levels can be updated throughout the execution of projects as more information is gathered and uncertainty is reduced, through a mechanism of risk management and control. In addition to this, managers are able to calibrate their estimates for future projects.

Despite the listed contributions, some limitations are identified. As with any decision making methodology depending on human judgments, it may suffer from optimism or pessimism bias, leading to unrealistic risk assessments and inadequately selected projects. The extensive data required for the product value methodology may not be readily available in the organization, which then requires the implementation of an active business intelligence system, capable of monitoring competitors new offerings, the market dynamics, and provide more accurate business forecasts.

In highly dynamic environments, the development of utility based loss functions based on ranges or “buckets” may suffer some drawbacks. In such environments, organizations engaging in long duration projects may feel that assumptions made earlier on may not reproduce the “new reality” in times of heavy market turbulence. Financial limitations experienced by the organization in a determined period of time may change the perspective over risk in projects under execution. If this happens, then the utility based loss functions should be revisited. The methodology described does not prescribe metrics that indicate the need to revisit the functions.

A situation that has not been addressed properly by the methodology, with clear implications in risk assessments, concerns the collaboration and outsourcing of specific projects tasks. The methodology assumes uniform cooperation throughout the execution of the project or full outsource of project execution, which may not always hold true. This issue should be taken into account in future development of the methodology.

Future work to be conducted in the methodology is essentially related to incorporating more mechanisms to cover a wider number of situations. Technology valuation methods in monetary terms, such as the cost, income and market approaches, can be incorporated in the methodology to provide a more quantitative value of a technology, thus assisting managers in the decisions involved in what to do with technology once it is developed (license-out, sell patent, develop product, etc.). In the methodology proposed, the value of a technology is not assessed in monetary terms, but qualitatively, through the AHP.

Another valuation method, the real options, considers market uncertainty and can thus be incorporated into the methodology as well. Real options valuation provides a framework for business to have the right, but not the obligation, to undertake certain business initiatives (or options), such as deferring, abandoning, expanding, staging investments in technology, depending on the conditions (favorable or unfavorable) of the market. Real options provides means for dealing with uncertainty, since exercising an option supports the minimization of losses when the environment is not favorable (deferring, abandoning, staging) and leverage gains when is favorable (expanding). Despite the benefits mentioned, the application of real options in businesses is still limited, largely due to its complex mathematical structure, which requires managers to have some background in finance to understand it.

Interdependencies between projects have only been addressed qualitatively in the methodology proposed. The alternatives considered in the multi criteria method integrated in the methodology are restricted to single projects, but future work should be focused to extend such alternatives to include multiple projects, such as entire programs consisting of interdependent projects, concurrent or parallel projects. Including multiple projects as alternatives has, inevitably, implications on how risks are quantified, through the methods described in this study.

Resource competition between the multiple projects and the projects under execution in the organization should be considered as well. Furthermore, and in order to make resources management more efficient, incorporation of optimization algorithms for resource allocation would be highly desirable. The simple mechanism currently integrated in the software, that warns managers about the possibility of resource overloading, can be a starting point for the development of this algorithm.

It is hoped that the proposed methodology for project selection provides a significant contribution towards integrating various practices within an organization. Future work, as mentioned above, could enhance this integration.

7 Acknowledgements

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Appendixes

Appendix 1

Project proposal document template – Basic research

Project Name:
Project Manager:
Project Type: Basic research
Execution Mode:

Tech_IPRS

PROJECT PROPOSAL

PROJECT DETAILS

PROJECT NAME	PROJECT MANAGER	PROJECT TYPE	EXECUTION MODE	START DATE
		Basic research		

SCOPE

(related criteria: Familiarity with research topic)

Goals:

DESIGNATION	TYPE	TARGET	UNITS

STRATEGIC JUSTIFICATION

Strategic alignment:
(related criteria: Strategy fit)

Trends:
(related criteria: Observable trends, Urgency)

Programmatic risks:

RISK DESIGNATION	DESCRIPTION

PROJECT RELEVANCE

Contribution to knowledge base:
(related criteria Learning effects on the organization's knowledge base)

Created on: December 11, 2013 Page 1

Project Name:
Project Manager:
Project Type: Basic research
Execution Mode:

Tech_IPRS

Scientific/theoretical background:
(related criteria Scientific background, Research originality, Familiarity with research topic)

Interdependencies/synergies with other projects:
(related criteria Interdependencies with other projects)

Research risks:
(related criteria research risks)

RISK DESIGNATION	DESCRIPTION

EXECUTION MODE DETAILS

Execution mode:

Estimates:
(related criteria: estimated cost, estimated duration)

COST	DURATION

Stakeholders:
(related criteria Expertise level of collaborators or suppliers, Experience with potential collaborators)

STAKEHOLDER DESIGNATION	DESCRIPTION

Execution mode risks:
(related criteria Execution mode risks)

RISK DESIGNATION	DESCRIPTION

Assumptions and constraints:
(related criteria: Appropriability regime, Incentives and stimulus for collaboration or outsourcing)

ASSUMPTIONS	CONSTRAINTS

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Project Name: Tech_IPRS
Project Manager:
Project Type: Basic research
Execution Mode:

Resources:
(related criteria Familiarity with research topic, Resources and competencies to conduct research)

COMPETENCIES AND SKILLS	MACHINERY AND EQUIPMENT

PROJECT PLANNING

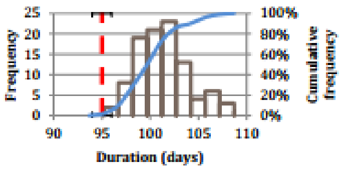
ACTIVITY CODE	DESCRIPTION				ESTIMATES		
					Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)						
	Cost (Monetary units)						
Resources							
Labor	Daily cost	Qty	%dedication		(a)	(b)	(c)
Cost items					(a)	(b)	(c)
					Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)						
	Cost (Monetary units)						
Resources							
Labor	Daily cost	Qty	%dedication		(a)	(b)	(c)
Cost items					(a)	(b)	(c)

INDIRECT COSTS (MONETARY UNITS)	TOTAL PROJECT COSTS (MONETARY UNITS)

PROJECT RISK ANALYSIS

Schedule analysis:
(related criteria: Schedule risk)

Target duration (days)	
Average duration (days)	
Probability of overrunning	
Maximum expect impact (days)	
Schedule risk	



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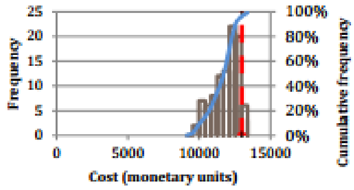
Project Name:
Project Manager:
Project Type: Basic research
Execution Mode:

Tech_IPRS

Cost analysis:
(related criteria: Cost risk)

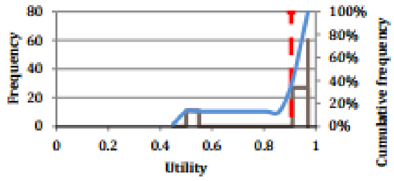
Target duration (Monetary units)	
Average duration (Monetary units)	
Probability of overrunning	
Maximum expected impact (Monetary units)	
Cost risk	



Performance analysis:
(related criteria: Performance risk)

GOAL	TYPE	TARGET	UNITS	WORST CASE VALUE	MOST LIKELY VALUE	BEST CASE VALUE

Probability of failing goal 1 target	
Probability of failing goal 2 target	
Probability of failing goal 3 target	
Performance risk	



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Project proposal document template –Applied research

Project Name:
Project Manager:
Project Type: Applied research
Execution Mode:

Tech_IPRS

PROJECT PROPOSAL

PROJECT DETAILS

PROJECT NAME	PROJECT MANAGER	PROJECT TYPE	EXECUTION MODE	START DATE
		Applied research		

SCOPE

(related criteria: Familiarity with research topic)

Goals:

DESIGNATION	TYPE	TARGET	UNITS

STRATEGIC JUSTIFICATION

Strategic alignment:
(related criteria: Strategy fit)

Trends:
(related criteria: Observable trends, Urgency)

Programmatic risks:

RISK DESIGNATION	DESCRIPTION

PROJECT RELEVANCE

Potential technologies:
(related criteria: Potential technologies)

TECHNOLOGY	DESCRIPTION

Created on: December 11, 2013 Page 1

Project Name:
Project Manager:
Project Type: Applied research
Execution Mode:

R&D_IPRS

Potential markets:
(related criteria: Market size, Market growth, Clear market needs, Competitive intensity)

TECHNOLOGY	MARKET	NEEDS	SIZE	GROWTH RATE	COMPETITION

Protection against imitation:
(related criteria: Patentability/design protection)

Interdependencies/synergies with other projects:
(related criteria Interdependencies with other projects, Benefits from standard setting)

Applicable standards:
(related Patentability/design protection)

STANDARDS	DESCRIPTION

Applicable patents:
(related Patentability/design protection)

PATENT	DESCRIPTION

Research risks:
(related criteria research risks)

RISK DESIGNATION	DESCRIPTION

EXECUTION MODE DETAILS

Execution mode:

Estimates:
(related criteria: estimated cost, estimated duration)

COST	DURATION

Stakeholders:
(related criteria: Expertise level of collaborators or suppliers, Experience with collaborators or suppliers)

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R&D_IPRS

Project Name:
Project Manager:
Project Type: Applied research
Execution Mode:

STAKEHOLDER DESIGNATION	DESCRIPTION

Execution mode risks:
(related criteria: Execution mode risks)

RISK DESIGNATION	DESCRIPTION

Assumptions and constraints:
(related criteria: Incentives and stimulus for collaboration or outsourcing, Appropriability regime)

ASSUMPTIONS	CONSTRAINTS

Resources:
(related criteria: Resources and competencies to conduct research, Familiarity with research topic)

COMPETENCIES AND SKILLS	MACHINERY AND EQUIPMENT

PROJECT PLANNING

ACTIVITY CODE	DESCRIPTION			ESTIMATES		
				Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)					
	Cost (Monetary units)					
Resources						
Labor	Daily cost	Qty	%dedication	(a)	(b)	(c)
Cost items				(a)	(b)	(c)
				Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)					
	Cost (Monetary units)					
Resources						
Labor	Daily cost	Qty	%dedication	(a)	(b)	(c)
Cost items				(a)	(b)	(c)

Indirect costs (monetary units)	Total project costs (monetary units)

Created on:6:54:59 PM / December 11, 2013 Page 3

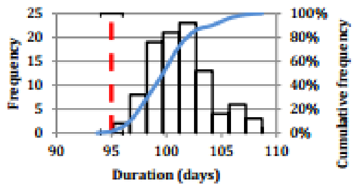
Project Name:
Project Manager:
Project Type: Applied research
Execution Mode:

R&D_IPRS

PROJECT RISK ANALYSIS

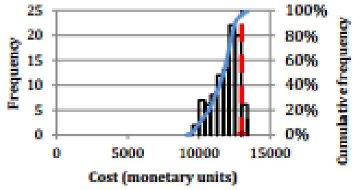
Schedule analysis:
(related criteria: Schedule risk)

Target duration (days)	
Average duration (days)	
Probability of overrunning	
Maximum expect impact (days)	
Schedule risk	



Cost analysis:
(related criteria: Cost risk)

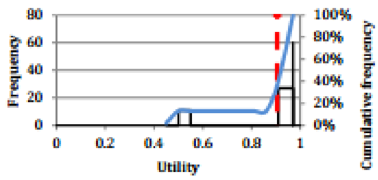
Target duration (Monetary units)	
Average duration (Monetary units)	
Probability of overrunning	
Maximum expected impact (Monetary units)	
Cost risk	



Performance analysis:
(related criteria: Performance risk)

GOAL	TYPE	TARGET	UNITS	WORST CASE VALUE	MOST LIKELY VALUE	BEST CASE VALUE

Probability of failing goal 1 target	
Probability of failing goal 2 target	
Probability of failing goal 3 target	
Performance risk	



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Project proposal document template – Advanced technology development

Project Name:
Project Manager:
Project Type: Advanced technology development
Execution Mode:

Tech_IPRS

PROJECT PROPOSAL

PROJECT DETAILS

PROJECT NAME	PROJECT MANAGER	PROJECT TYPE	EXECUTION MODE	START DATE
		Advanced technology development		

SCOPE

(related criteria: Familiarity with technology)

Goals:

DESIGNATION	TYPE	TARGET	UNITS

STRATEGIC JUSTIFICATION

Strategic alignment:
(related criteria: Strategy fit)

Trends:
(related criteria: Observable trends, Urgency)

Programmatic risks:

RISK DESIGNATION	DESCRIPTION

PROJECT RELEVANCE

Potential products:
(related criteria: potential products)

PRODUCT	DESCRIPTION

Created on: December 11, 2013 Page 1

Project Name:
Project Manager:
Project Type: Advanced technology development
Execution Mode:

Tech_IPRS

Potential markets:
(related criteria: Market size, Market growth, Clear market needs, Competitive intensity)

PRODUCT	MARKET	NEEDS	SIZE	GROWTH RATE	COMPETITION

Stages in technologies life cycles:
(related criteria: Stage in technology life cycle)

TECHNOLOGY	LIFE CYCLE STAGE

Protection against imitation:
(related criteria: Patentability/design protection)

Interdependencies/synergies with other projects:
(related criteria Interdependencies with other projects, Benefits from standard setting)

Applicable standards:
(related Patentability/design protection)

STANDARDS	DESCRIPTION

Applicable patents:
(related Patentability/design protection)

PATENT	DESCRIPTION

Technology risks:
(related technology risks)

RISK DESIGNATION	DESCRIPTION

EXECUTION MODE DETAILS

Execution mode:

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Project Name:
Project Manager:
Project Type: Advanced technology development
Execution Mode:

Tech_IPRS

Estimates:
(related criteria: estimated cost, estimated duration)

COST	DURATION

Stakeholders:
(related criteria: Expertise level of collaborators or suppliers, Experience with collaborators or suppliers)

STAKEHOLDER DESIGNATION	DESCRIPTION

Execution mode risks:
(related criteria: Execution mode risks)

RISK DESIGNATION	DESCRIPTION

Assumptions and constraints:
(related criteria: Incentives and stimulus for collaboration or outsourcing, Appropriability regime)

ASSUMPTIONS	CONSTRAINTS

Resources:
(related criteria: Resources and competencies to conduct development, Familiarity with technology)

COMPETENCIES AND SKILLS	MACHINERY AND EQUIPMENT

PROJECT PLANNING

ACTIVITY CODE	DESCRIPTION			ESTIMATES		
				Pessimistic value (a)	**Most likely value (b)**	**Optimistic value (c)**
	Duration (days)					
	Cost (Monetary units)					
Resources						
Labor	**Daily cost**	**Qty**	**%dedication**	**(a)**	**(b)**	**(c)**
Cost items				**(a)**	**(b)**	**(c)**
				Pessimistic value (a)	**Most likely value (b)**	**Optimistic value (c)**
	Duration (days)					
	Cost (Monetary units)					
Resources						

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Project Name: Tech_IPRS
Project Manager:
Project Type: Advanced technology development
Execution Mode:

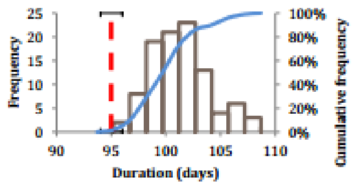
Labor	Daily cost	Qty	%dedication	(a)	(b)	(c)
Cost items				(a)	(b)	(c)

INDIRECT COSTS (MONETARY UNITS)	TOTAL PROJECT COSTS (MONETARY UNITS)

PROJECT RISK ANALYSIS

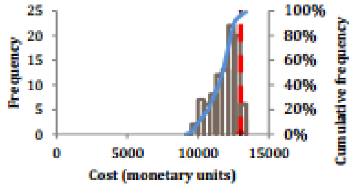
Schedule analysis:
(related criteria: Schedule risk)

Target duration (days)	
Average duration (days)	
Probability of overrunning	
Maximum expect impact (days)	
Schedule risk	



Cost analysis:
(related criteria: Cost risk)

Target duration (Monetary units)	
Average duration (Monetary units)	
Probability of overrunning	
Maximum expected impact (Monetary units)	
Cost risk	

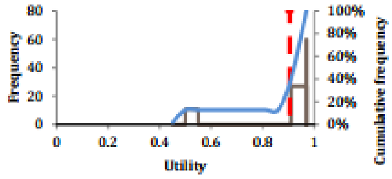


Project Name: Tech_IPRS
Project Manager:
Project Type: Advanced technology development
Execution Mode:

Performance analysis:
(related criteria: Performance risk)

GOAL	TYPE	TARGET	UNITS	WORST CASE VALUE	MOST LIKELY VALUE	BEST CASE VALUE

Probability of failing goal 1 target	
Probability of failing goal 2 target	
Probability of failing goal 3 target	
Performance risk	



Project proposal document template – Product development

Project Name:
Project Manager:
Project Type: Product development
Execution Mode:

Tech_IPRS

PROJECT PROPOSAL

PROJECT DETAILS

PROJECT NAME	PROJECT MANAGER	PROJECT TYPE	EXECUTION MODE	START DATE
		Product development		

SCOPE STATEMENT

(related criteria: Familiarity with product)

Product attributes:

DESIGNATION	TYPE	TARGET	UNITS

STRATEGIC JUSTIFICATION

Strategic alignment:
(related criteria: Strategy fit)

Trends:
(related criteria: Observable trends, Urgency)

Programmatic risks:

RISK DESIGNATION	DESCRIPTION

PROJECT RELEVANCE

Potential markets:
(related criteria: Market size, Market growth, Clear market needs, Competitive intensity)

MARKET	NEEDS	SIZE	GROWTH RATE	COMPETITTION

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Project Name:
Project Manager:
Project Type: Product development
Execution Mode:

Tech_IPRS

Product differentiation:
(related criteria: Product differentiation)

Product growth range:
(related criteria: Product range growth potential)

Adequacy of time of introduction:
(related criteria: Timing of introduction)

Stages in technologies life cycles:
(related criteria: Stage in technology life cycle)

TECHNOLOGY	LIFE CYCLE STAGE

Protection against imitation:
(related criteria: Patentability/design protection)

Interdependencies/synergies with other projects:
(related criteria Interdependencies with other projects, Benefits from standard setting)

Applicable standards:
(related Patentability/design protection)

STANDARDS	DESCRIPTION

Applicable patents:
(related Patentability/design protection)

PATENT	DESCRIPTION

Risks:
(related Product development risks)

RISK DESIGNATION	DESCRIPTION

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Project Name:
Project Manager:
Project Type: Product development
Execution Mode:

Tech_IPRS

EXECUTION MODE DETAILS

Execution mode:

Estimates:
(related criteria: estimated cost, estimated duration)

COST	DURATION

Stakeholders:
(related criteria: Expertise level of collaborators or suppliers, Experience with collaborators or suppliers, Complementary assets)

STAKEHOLDER DESIGNATION	DESCRIPTION

Execution mode risks:
(related criteria: Execution mode risks)

RISK DESIGNATION	DESCRIPTION

Assumptions and constraints:
(related criteria: Incentives and stimulus for collaboration or outsourcing, Appropriability regime)

ASSUMPTIONS	CONSTRAINTS

Resources:
(related criteria: Resources and competencies to conduct development, Familiarity with product, Complementary assets)

COMPETENCIES AND SKILLS	MACHINERY AND EQUIPMENT

PROJECT PLANNING

ACTIVITY CODE	DESCRIPTION			ESTIMATES		
				Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)					
	Cost (Monetary units)					
Resources						
Labor	Daily cost	Qty	%dedication	(a)	(b)	(c)

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Project Name: Tech_IPRS
Project Manager:
Project Type: Product development
Execution Mode:

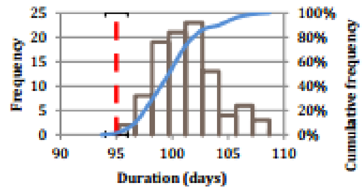
Cost items				(a)	(b)	(c)
				Pessimistic value (a)	Most likely value (b)	Optimistic value (c)
	Duration (days)					
	Cost (Monetary units)					
Resources						
Labor	Daily cost	Qty	%dedication	(a)	(b)	(c)
Cost items				(a)	(b)	(c)

INDIRECT COSTS (MONETARY UNITS)	TOTAL PROJECT COSTS (MONETARY UNITS)

PROJECT RISK ANALYSIS

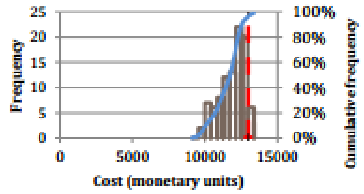
Schedule analysis:
(related criteria: Schedule risk)

Target duration (days)	
Average duration (days)	
Probability of overrunning	
Maximum expect impact (days)	
Schedule risk	



Cost analysis:
(related criteria: Cost risk)

Target duration (Monetary units)	
Average duration (Monetary units)	
Probability of overrunning	
Maximum expected impact (Monetary units)	
Cost risk	



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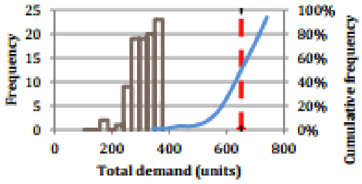
Project Name: Tech_IPRS
Project Manager:
Project Type: Product development
Execution Mode

Performance analysis:
(related criteria: Performance risk)

ATTRIBUTE	TYPE	TARGET	UNITS	WORST CASE VALUE	MOST LIKELY VALUE	BEST CASE VALUE

Average annual target demand (units)	
Average annual demand (units)	
Probability of failing target demand	
Maximum expected impact (lost unit sales)	
Performance risk	



ECONOMIC ATTRACTIVENESS

(related criteria: Economic attractiveness)

	QUARTER	YEAR
EXPECTED PRODUCT LAUNCH		

PRODUCT LIFE (YEARS)	

TARGET DEVELOPMENT DURATION (YEARS)	
Target cost 1st year	
Target cost 2nd year	
Total target cost	

	COST OF PRODUCT SOLD	ASSUMED PRICE POLICY	GROSS MARGIN
Year1			
Year2			
Year3			
Year4			
Year5			

CASH FLOW ANALYSIS

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Project Name:
Project Manager:
Project Type: Product development
Execution Mode

Tech_IPRS

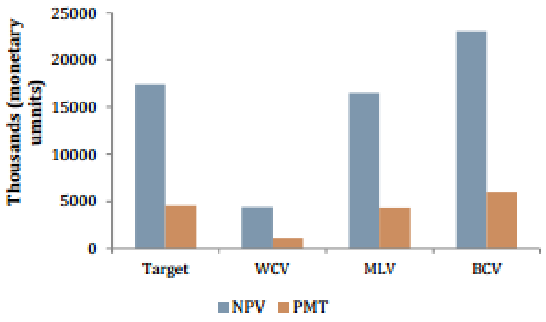
:

	PRODUCT WITH TARGET SPECFICIATION AT TARGET COST AND SCHEDULE	PRODUCT WITH WCV SPECFICIATION AT TARGET COST AND SCHEDULE	PRODUCT WITH MLV SPECFICIATION AT TARGET COST AND SCHEDULE	PRODUCT WITH BCV SPECFICIATION AT TARGET COST AND SCHEDULE
Year0				
Year1				
Year2				
Year3				
Year4				
Year5				

DISCOUNT RATE	

INFLATION RATE	

	NPV	PMT	IRR	PAYBACK (YEARS)
Product with target specification at target cost and schedule				
Product with target specification at target cost and schedule				
Product with target specification at target cost and schedule				



SENSITIVITY ANALYSIS

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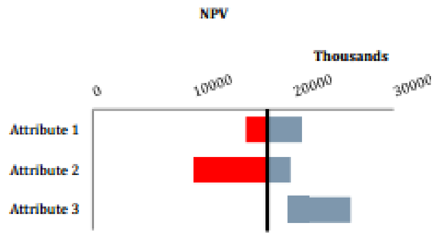
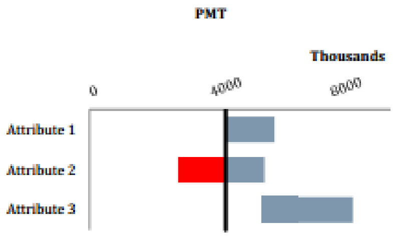
Project Name:
Project Manager:
Project Type: Product development
Execution Mode

Tech_IPRS

	NPV		
	WCV	Target	BCV
Attribute 1 Name			
Attribute 2 Name			
Attribute 3 Name			

	PMT		
	WCV	Target	BCV
Attribute 1 Name			
Attribute 2 Name			
Attribute 3 Name			





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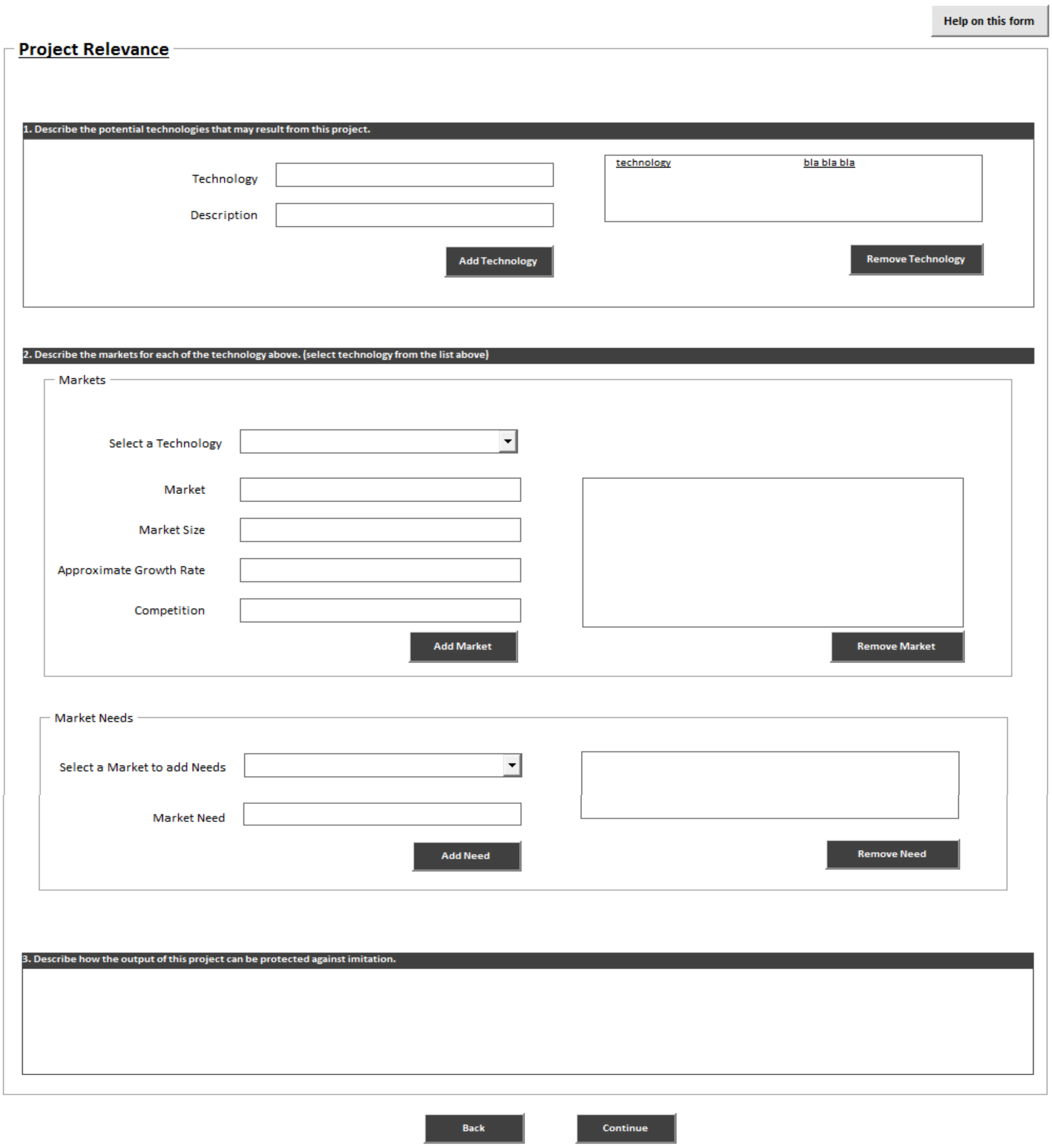
Appendix 2

Project relevance (Form 4.2.1)


Help on this form

Project Relevance

1. Describe the potential technologies that may result from this project.

Technology

Description

technology bla bla bla

Add Technology

Remove Technology

2. Describe the markets for each of the technology above. (select technology from the list above)

Markets

Select a Technology

Market

Market Size

Approximate Growth Rate

Competition

Add Market

Remove Market

Market Needs

Select a Market to add Needs

Market Need

Add Need

Remove Need

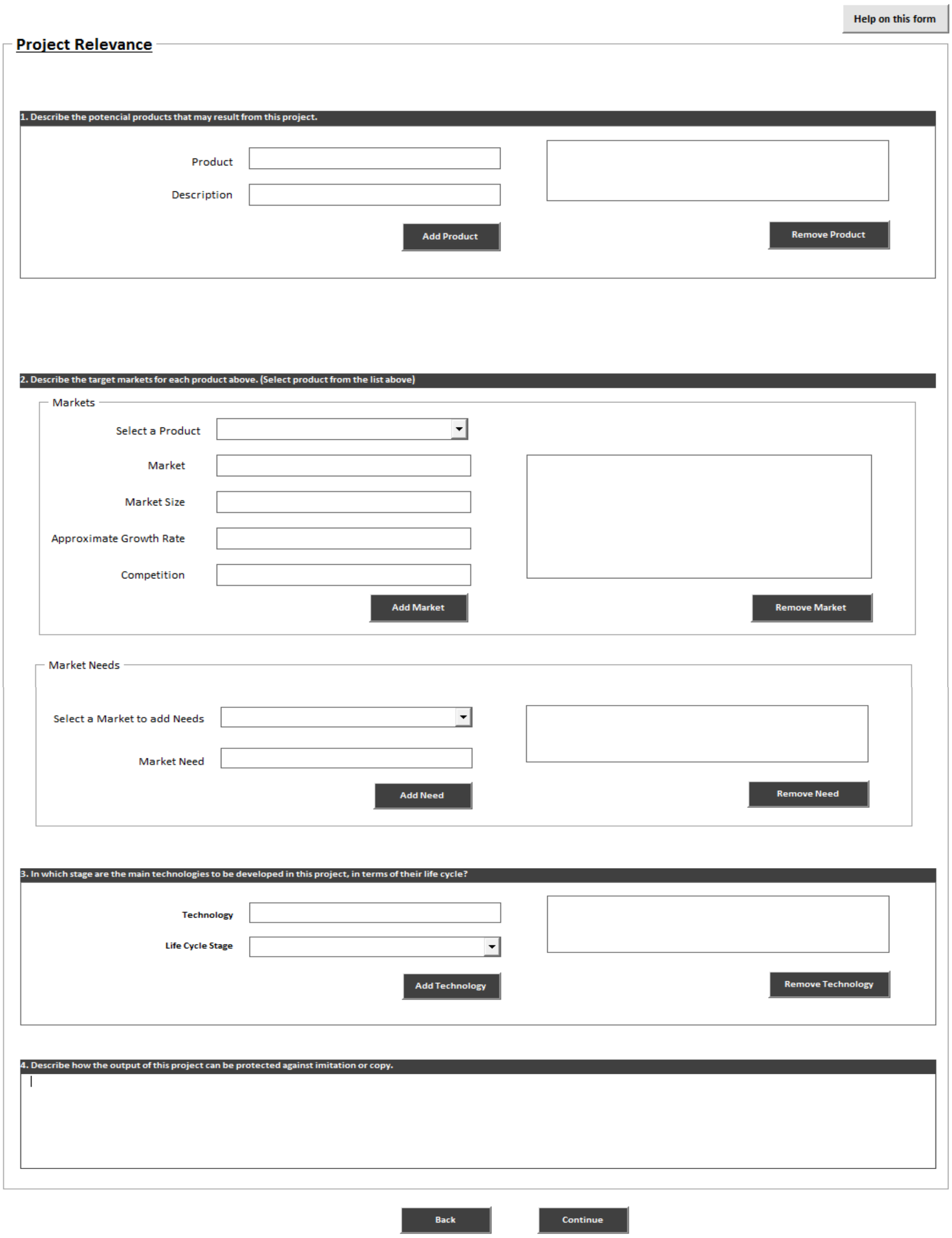
3. Describe how the output of this project can be protected against imitation.

Back

Continue

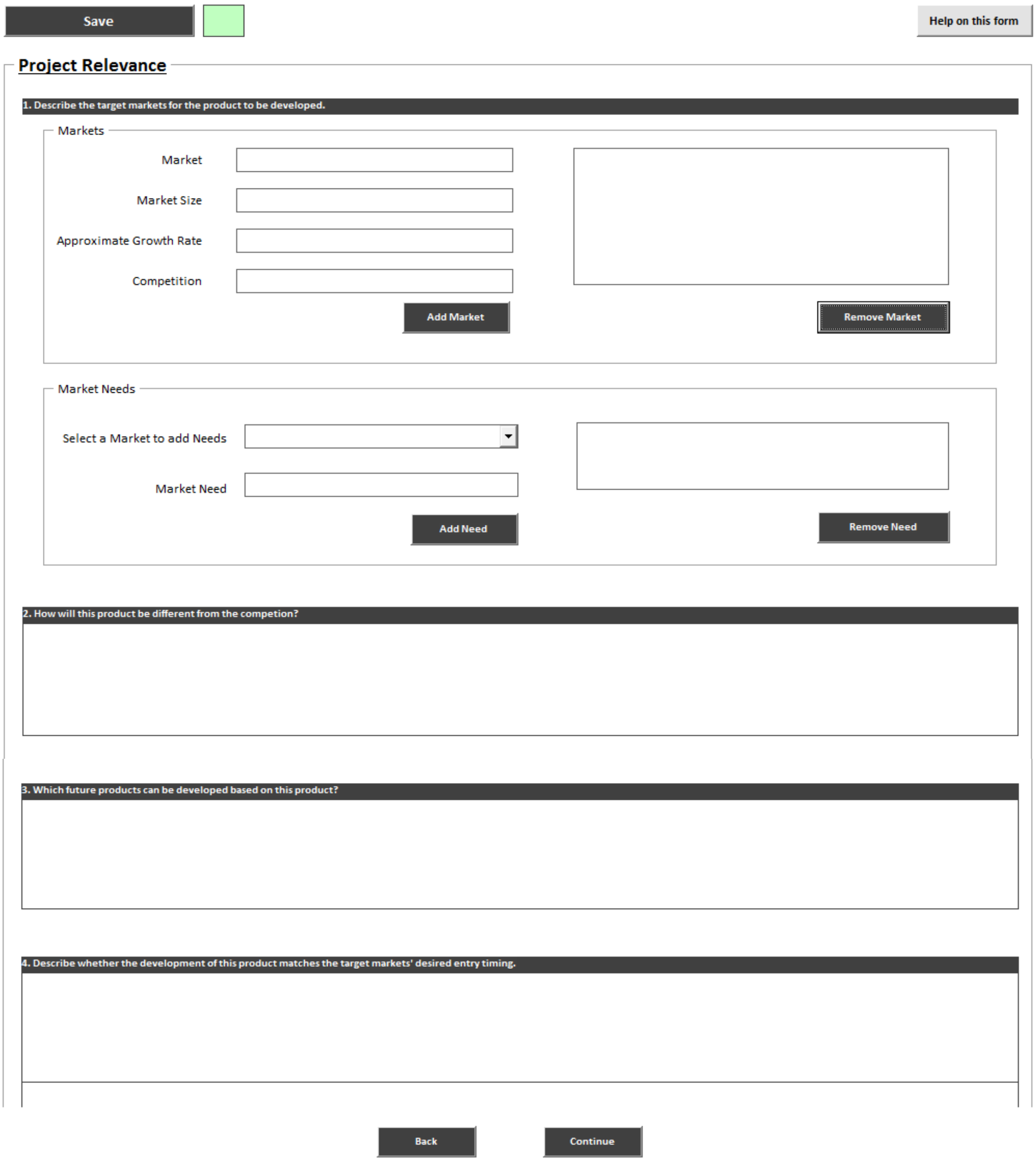
Project relevance (Form 4.2.2)

Project relevance (Form 4.3.1)

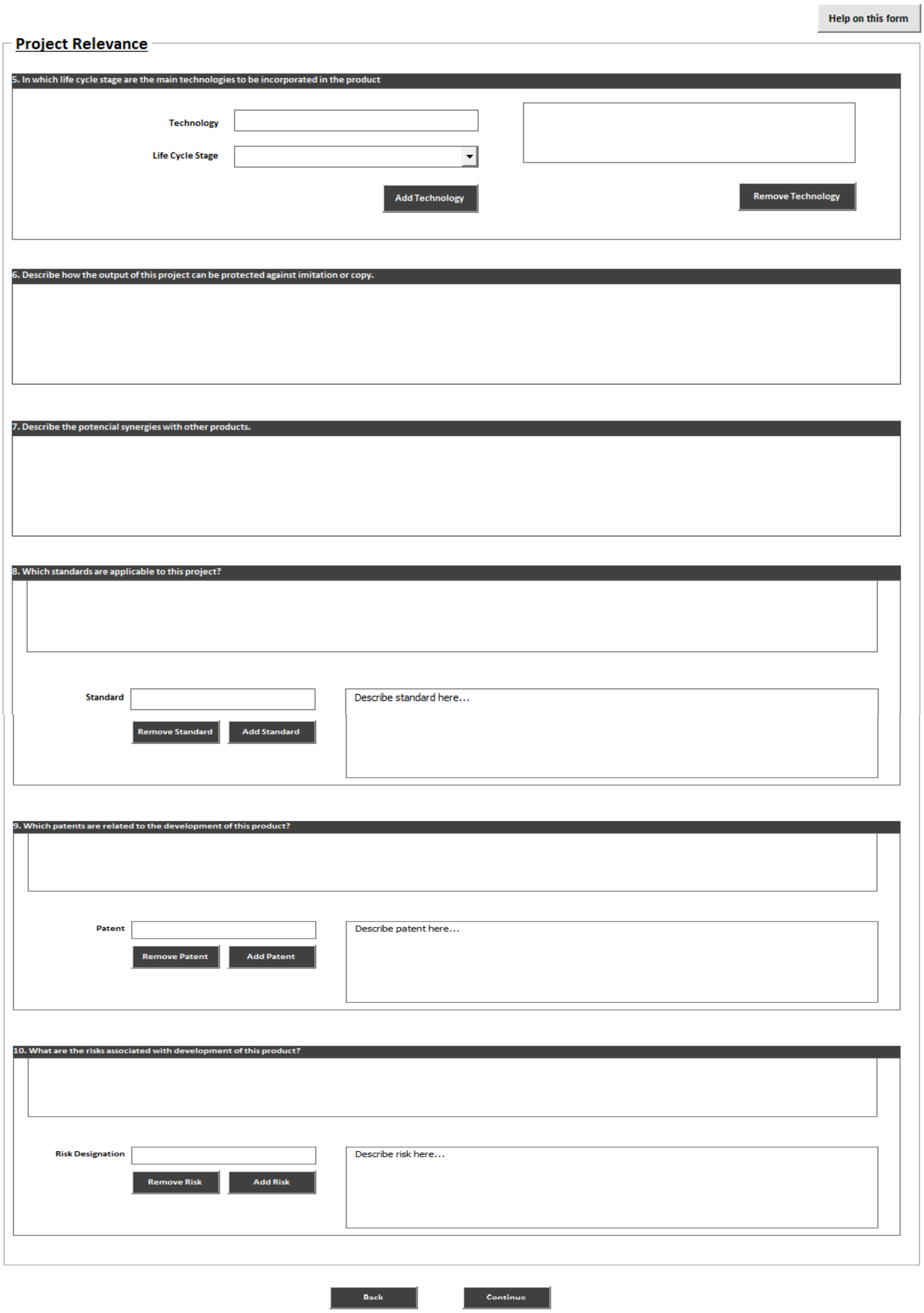


Project relevance (Form 4.3.2)

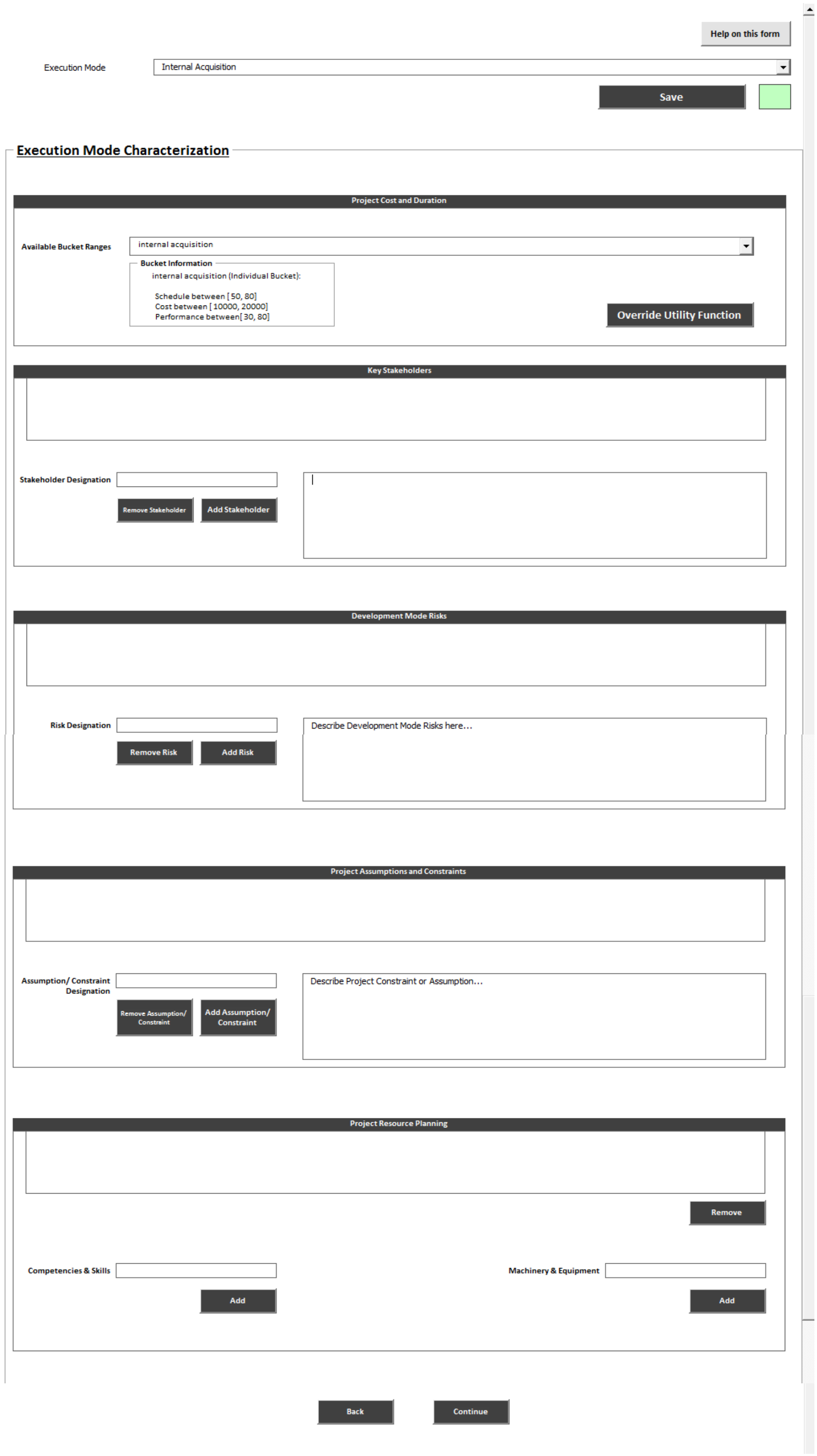
Project relevance (Form 4.4.1)



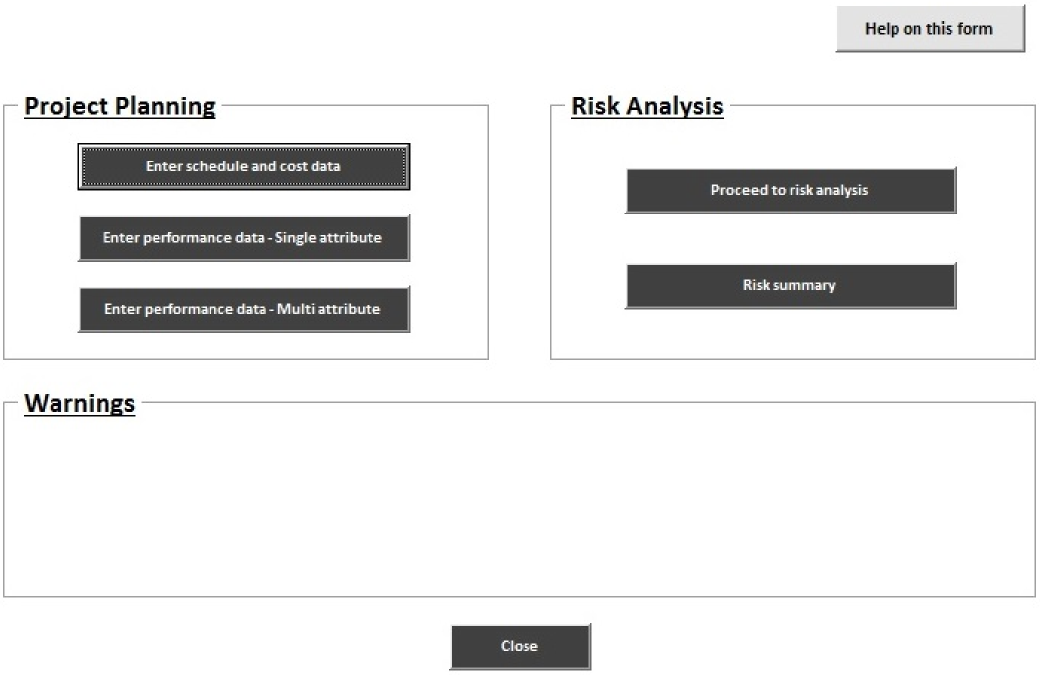
Project relevance (Form 4.4.2)



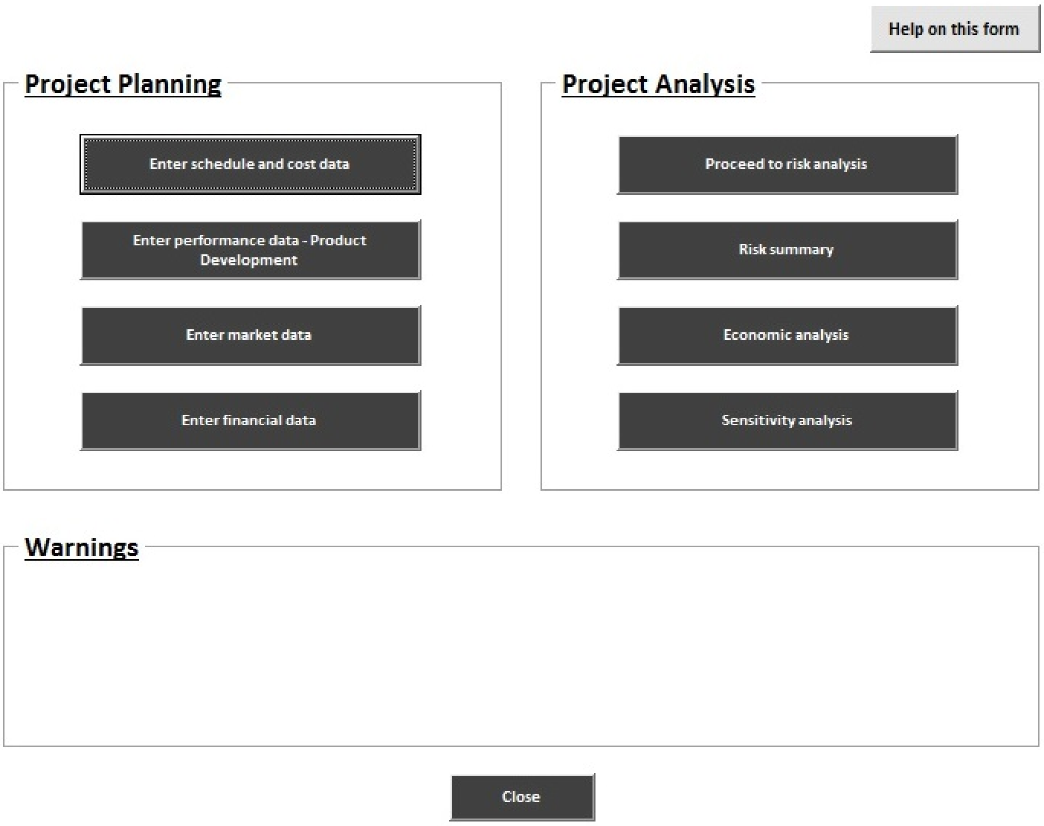
Project execution modes (Form 5)



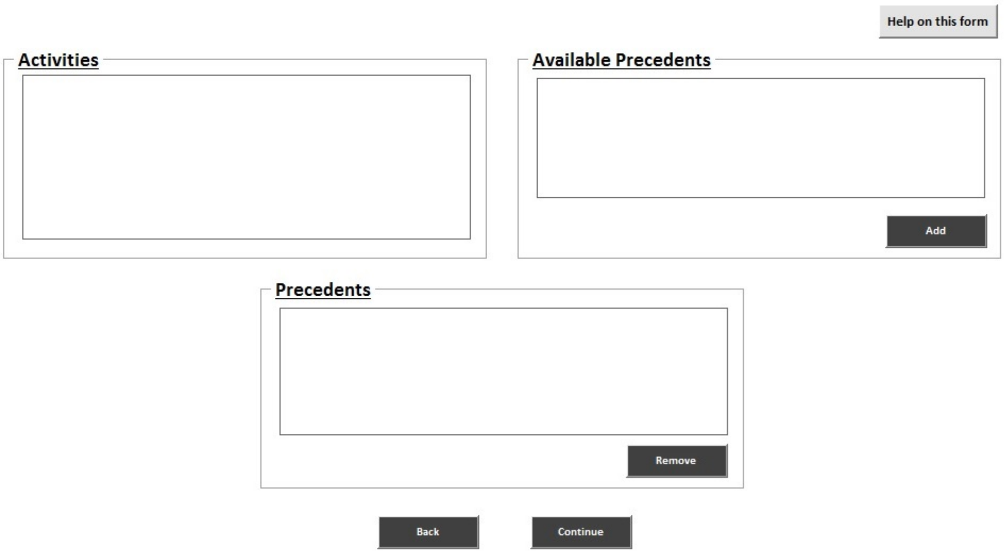
Project planning (Form 7)



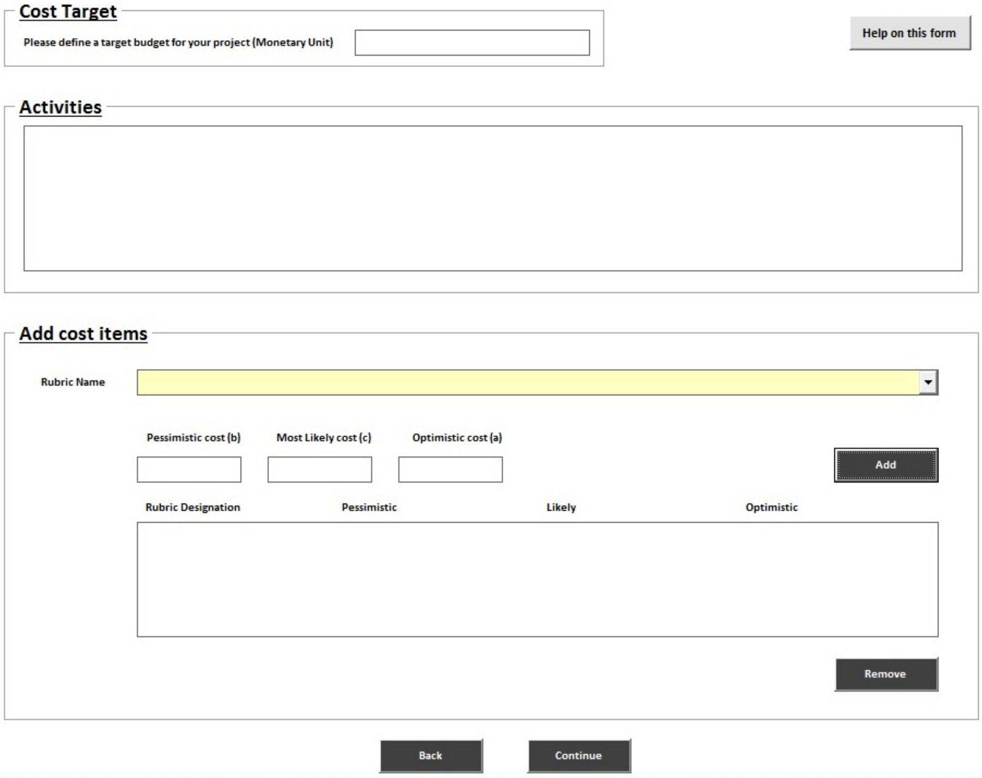
Project planning (Form 8)



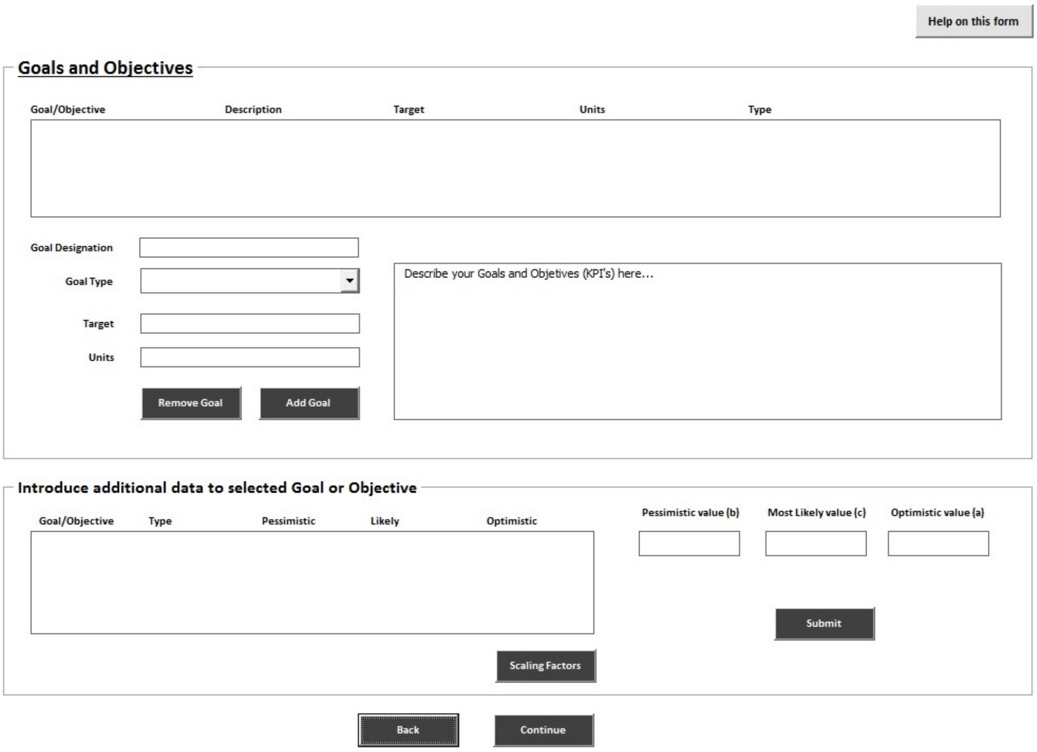
Schedule data (Form 9.2)



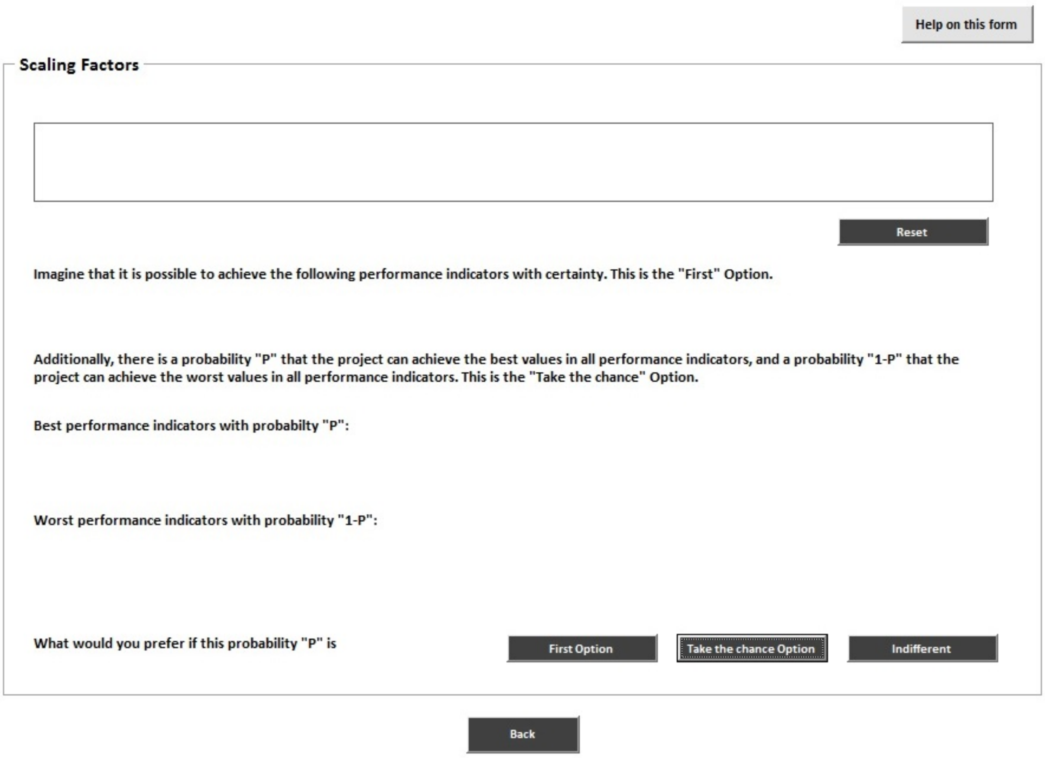
Cost data (Form 10.2)



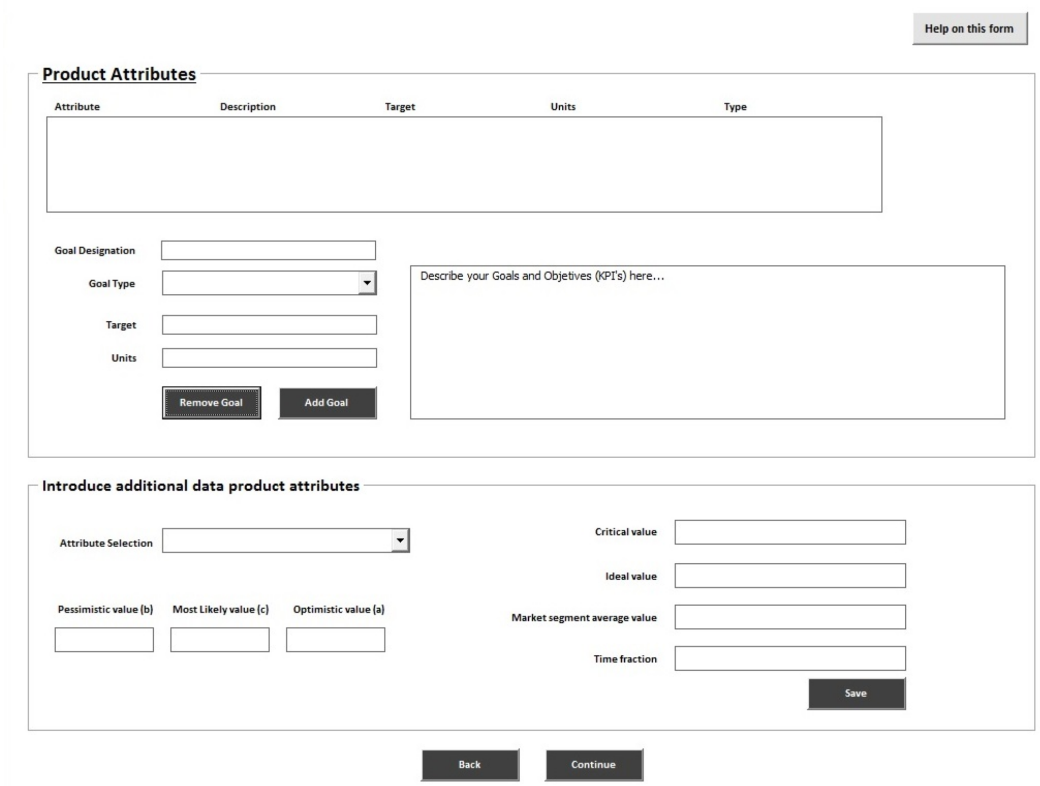
Performance data (Form 12.1)



Performance data (Form 12.2)



Performance data (Form 13)



Appendix 3

Pairwise comparisons - Criteria

Capability	Strategy	Technology	Product	Market	Project Development	Priority vector
1	0.5	0.5	0.5	0.5	3	0.114654952
2	1	2	1	0.5	4	0.214325709
2	0.5	1	0.5	0.5	0.5	0.107162854
2	1	2	1	1	2	0.214325709
2	2	2	1	1	4	0.270033472
0.333333333	0.25	2	0.5	0.25	1	0.079497304

Pairwise comparisons – "Capability" sub criteria

Resources and competences to conduct development	Complementary assets	Priority vector
1	1	0.5
1	1	0.5

Pairwise comparisons – "Product" sub criteria

Product differentiation	Product range growth potential	Priority vector
1	4	0.8
0.25	1	0.2

Pairwise comparisons – "Market" sub criteria

Market growth	Clear market needs	Competitive intensity	Timing of introduction	Priority vector
1	2	2	2	0.390524292
0.5	1	2	2	0.276142375
0.5	0.5	1	2	0.195262146
0.5	0.5	0.5	1	0.138071187

Pairwise comparisons – "Project Development" sub criteria

Economic attractiveness	Cost risk	Priority vector
1	2	0.666666667
0.5	1	0.333333333

Pairwise comparisons – Alternatives versus "Resources and competences to conduct development" sub criterion

Project A	Project B	Project C	Priority vector
1	2	2	0.493385967
0.5	1	0.5	0.195800351
0.5	2	1	0.310813683

Pairwise comparisons – Alternatives versus "Complementary assets" sub criterion

Project A	Project B	Project C	Priority vector
1	9	3	0.671625453
0.111111111	1	0.2	0.062941205
0.333333333	5	1	0.265433342

Pairwise comparisons – Alternatives versus "Observable trends" sub criterion

Project A	Project B	Project C	Priority vector
1	0.333333333	0.333333333	0.142857143
3	1	1	0.428571429
3	1	1	0.428571429

Pairwise comparisons – Alternatives versus "Patentability/design protection" sub criterion

Project A	Project B	Project C	Priority vector
1	1	0.25	0.174371455
1	1	0.333333333	0.19192062
4	3	1	0.633707925

Pairwise comparisons – Alternatives versus "Product differentiation" sub criterion

Project A	Project B	Project C	Priority vector
1	0.333333333	0.333333333	0.139647939
3	1	0.5	0.332515928
3	2	1	0.527836133

Pairwise comparisons – Alternatives versus "Product range growth potential" sub criterion

Project A	Project B	Project C	Priority vector
1	1	1	0.333333333
1	1	1	0.333333333
1	1	1	0.333333333

Pairwise comparisons – Alternatives versus "Market growth" sub criterion

Project A	Project B	Project C	Priority vector
1	2	1	0.4
0.5	1	0.5	0.2
1	2	1	0.4

Pairwise comparisons – Alternatives versus "Clear market needs" sub criterion

Project A	Project B	Project C	Priority vector
1	0.5	0.333333333	0.157055789
2	1	0.333333333	0.249310525
3	3	1	0.593633685

Pairwise comparisons – Alternatives versus "Competitive intensity" sub criterion

Project A	Project B	Project C	Priority vector
1	3	3	0.593633685
0.333333333	1	2	0.249310525
0.333333333	0.5	1	0.157055789

Pairwise comparisons – Alternatives versus "Timing of introduction" sub criterion

Project A	Project B	Project C	Priority vector
1	1	1	0.333333333
1	1	1	0.333333333
1	1	1	0.333333333

Pairwise comparisons – Alternatives versus "Economic attractiveness" sub criterion

Project A	Project B	Project C	Priority vector
1	0.25	0.333333333	0.117220771
4	1	3	0.614410656
3	0.333333333	1	0.268368573

Pairwise comparisons – Alternatives versus “Cost risk” sub criterion

Project A	Project B	Project C	Priority vector
1	5	3	0.636985572
0.2	1	0.333333333	0.104729434
0.333333333	3	1	0.258284994

Alternatives Final and Normalized scores

Project	Final score	Normalized score
Project A	0.555616099	0.272099496
Project B	0.626608468	0.306866285
Project C	0.859734744	0.421034219