Real Options Decision Framework for Research and Development: A Case Study on a Small Canadian High-Technology Start-Up

by

Sally Jamal Mattar

This thesis is submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Engineering Management

Department of Mechanical Engineering
University of Alberta

Abstract

Research and Development (R&D) projects can be both innovative and highly uncertain. Allowing for managerial flexibility and adopting real options methods and incorporating technology readiness level scales to assess the maturity of technologies progressing through development stages, can help managers hedge the unforeseen risks that arise during these stages. Managers can make decisions that avoid the downside and capture the upside of these risks. This methodology is a decision-making framework for research organizations, where potential values of decisions and projects across a portfolio can be evaluated. The proposed framework analyzes the risks as they progress through the technology readiness level scale, and enables R&D management to play active roles in project evaluations and justify continued spending on risky, long term projects that are expected to be of high future value, an area where traditional valuation methods fall short. A case study on a small Canadian technology start-up is used to discuss the importance of adopting the proposed methodology.

Preface

This thesis is original work by Sally Mattar. The case study, which is part of Chapter 4 of the thesis received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Real options analysis application", Pro0073487, July 20, 2017. This work was not published anywhere else and does not contain collaborative work.

Acknowledgements

I would like to thank my supervisor Dr. Lipsett for giving me the opportunity to complete a Masters in Engineering Management. I am grateful for all his support and guidance throughout the course of my degree and I have enjoyed working with him immensely. It was always a pleasure to chat with him and he always had something intelligent and interesting to say. He was a continuous support and without him, this project could not have been completed.

I would also like to thank Dr. Lianne Lefsrud. Ever since taking her class in the Fall semester of 2016, she has been an inspiration and role model, and I aspire to be like her one day. She always offered support and gave valuable advice when needed. She also provided guidance on the structure and organization of this thesis and I am very grateful for all her help.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Thesis Motivation & Business Case

There is a lack of simple tools that can be used to guide and value decision-making processes associated with technology development, and provide managers with the flexibility to make decisions that can capture opportunities during a technology or research and development (R&D) project. There is a need for a streamlined methodology that can aid decision-makers in developing a set of rubrics where a common understanding of how critical risk elements can influence project success for technology and R&D projects at different stages. The methods need to be adapted in order to model how expenditures at early stages of R&D can lead to discoveries that benefit Canada. Researchers, managers, and decision-makers in R&D and technology organizations are challenged with how to evaluate the potential business benefits of early stage projects and assess the value that these technologies will bring to the firm compared to the costs associated with their development [1]. R&D and technology projects need tools that manage risks and allow managers to make decisions accordingly as conditions change and information is gained [2]. This is the motivation behind the research conducted for this thesis as there is a current gap where there are missing tools that reflect the dynamic nature of R&D and can be applied for these long and risky projects. The work conducted during this research will work to fill those gaps by developing a decision-framework that utilizes a structured approach to technology development and evaluation.

Understanding the potential value of a technology is useful for managers that are choosing between projects and trying to understand the benefit of committing financial and human resources to a project, and for the researchers that try to structure these projects to maximize the value of the potential technology [3]. R&D and technology projects can be long and unpredictable making it challenging for managers to forecast the effort required to develop these new technologies [4] and their likelihood of success once pursued. These uncertainties may lead to high risks and could result in project failures [5]. The currently used valuation methods such as discounted cash flow (DCF) and net present value (NPV) are not sufficient tools to use for these projects.

These traditional methods assume there is only one possible route to achieve project goals or targets and place managers in passive roles that assume that initial predictions made and resource commitments established, cannot be changed even if conditions require them to do so [6]. This lack of managerial flexibility could undervalue a project [7] such as R&D or technology developments that have longer horizons and do not have immediate payoffs. Organizations may overlook these projects as they may have negative net present values [8], neglecting the potential future benefit and the opportunity to grow [9]. In addition, organizations who rely exclusively on financial methods to assess projects are less successful at developing new products than those that also considered qualitative aspects [3]. These traditional approaches use standard investment decision-making that solely depends on profit creation which is not useful for R&D firms whose ultimate goal may not be to create profit [10]. For example, some goals may be to create a product improve the environment, as opposed to market and sell to the general public.

For these reasons discussed, a methodology must be developed to overcome these gaps in technology development management and valuation. The details behind the proposed approach and research objectives are discussed in the following section.

1.2 Objective of Thesis

The objective of this research is to develop a framework that allows managers, researchers, and decision-makers to exercise flexibility through decision-making and value their technology investments. The framework will combine the technology readiness level scale (TRL) and a stage-gate approach that will be the logical points where a project's activities, requirements and risks change and should be reassessed. This will support decision-making through a consistent method that will assess a technology's maturity and progress. The framework will utilize a real options (RO) approach by recommending a small number of options to be placed along the TRL scale where managerial decisions can be evaluated through real options analysis (ROA) and encourage management to make evidence-based decisions for technology development and project continuation.

The application of TRLs and the RO method can enable more consistent discussions on how risks change from one phase of a project to another, and the comparative value of different decisions, or different projects across a portfolio. This approach can be valuable for organizations as it can help explore opportunities and justify spending on longer and riskier projects with potentially very high future values to Canada.

"Real options", an extension of financial option theory, refers to a decision pertaining to a tangible asset as opposed to stock. It refers to the ability of managers to exercise flexibility through decisions such as growth, delay, or abandonment of a project as technology, financial, market or other conditions change [11]. This active decision-making method can improve the likelihood of scientific success and the positive commercial benefit to Canada. Real options will allow organizations to establish key decision points during R&D stages for projects across a research program. It is a structured analysis method for determining success factors as a technology progresses through the development stages, and the comparative influence of making early investments in R&D activities that mitigate technical and commercial risk.

By incorporating TRLs into a decision-framework, this can support these decision-making process during development and implementation [12]. It is an approach that works to reduce risk through proof-of-concept and system success [13]. Furthermore, incorporating real options methods into this framework can provide researchers and managers with a tool that allows them to better understand risk. Real options can make up for what traditional methods lack, which is providing flexibility. It allows managers to alter the course of uncertain projects by incorporating strategic options, that increase the overall value of the project [9]. RO can be thought of as guides that allow managers to make decisions at different stages of the project, such as, whether a project should be continued or terminated [9]. The sequence of decision-making during these projects allows for justified decisions of when to undertake an opportunity [14].

The framework will be applied to a small Canadian high-technology start-up that is currently developing autonomous rovers (AR). These ARs allow access to tailings ponds that are otherwise inaccessible using the current measuring equipment. The case study will examine current technological maturity using the TRL scale and the proposed stage-gate approach and identify critical risks that would threaten progress and the ability for the start-up to meet their organizational and project goals. The behaviour of these critical risks and how they are expected to develop and their effects on project goals will be discussed. RO will then be applied to value a range of potential decisions at key stages of the project. These options will be compared and discussed.

The study will also briefly introduce general concepts related to applying this framework to a large government research organization's portfolio. Framework limitations and application challenges will be considered and recommendations for future research will be discussed.

1.3 Thesis Structure

This thesis is organized into five chapters. Following the introduction, Chapter 2 is a literature review that introduces and discusses relevant topics to R&D and technology development, technology readiness levels and assessment methodologies, real options theory and application, and frameworks used in various industries. Chapter 3 establishes the proposed framework and the approach behind how it can be applied to assess decisions and value options. The framework is then applied to a case study in Chapter 4, and potential application to a government research organization's portfolio is also examined. The analysis and results are discussed. To conclude the work, Chapter 5 provides a summary and discusses the limitations of the framework and recommendations for future research.

Chapter 2 Review of the Literature

This chapter reviews the main topics related to the development of the real options decision framework that will be described in Chapter 3.

General concepts of technology development and R&D are discussed, along with the common stages of development discussed in the literature. This conceptualization acts as the baseline for discussing technology readiness levels (TRL), where general activities, common assessment methodologies, challenges and applications in industry are outlined. Common risks in R&D and technology projects are then defined with illustrative examples. This section is a primer for Chapter 3, as these risks will then be mapped along the development stages and TRL scale.

Risk management concepts and tools used in the R&D context are reviewed. Finally, valuation methods are discussed. Traditional valuation methods and financial option theories are introduced. Real option types, application and industry use are discussed. The steps and important considerations for applying real options will be examined, with additional detail provided during its application in Chapter 3 and Chapter 4.

2.1 R&D and Technology Development

R&D and technology projects deliver a combination of new knowledge, new technology or capability, or a platform of technologies [15]. Technology R&D efforts should improve the performance and reliability of a technology and thus contribute to overall technology maturation, while investments made at each stage should result in risks being reduced [16].

Organizational, portfolio and project goals must be properly prioritized in R&D programs [17]. Proper resource allocation is critical in R&D decision-making, where managers must balance many organizational short-term and long-term goals that may be weighted differently by different stakeholders [17]. Firms need to be able to work effectively within financial and resource constraints [18]. Short-term and long-term goals both also need to be considered accordingly [17].

The need to problem solve and quickly adapt to changing conditions in high-technology R&D is magnified by the presence of unforeseen risks associated with technology integration, performance levels, schedule and project budgets [19]. Tools that help assess the impacts of projects and any overlap with other projects include portfolio analysis[1] and development stage-gates[18]. Stage-gate methods employ gates where the technology is assessed against a set of criteria and a "continue/go or stop/kill" decision is made [15]. Stage-gates and development models are discussed in 2.1.1 and 2.1.2.

R&D and technology projects are often compromised when inappropriate tools and processes (or financial criteria) are applied to manage them [15]. Examples of such tools are discussed in 2.4. Because of the uniqueness of such projects, applying traditional methods to manage innovative projects may cause harm, as it could result in terminating a high-profit potential project [15].

2.1.1 R&D and Technology Development

Developing a new technology may pose high risks to an organization as they carry a large amount of technical uncertainty and other unknowns [15]. Uncertainties in R&D are expected as these projects have intensive activities associated with knowledge discovery, problem-solving, overcoming failure, dealing with change and making breakthroughs [19]. New technology developments are unpredictable, and it is – by definition - impossible to schedule a technological breakthrough, which makes it hard to estimate future efforts [4].

R&D projects are separated into development phases, and milestones are set as a method to determine and control project progress [20]. These phases behave as checkpoints where organizational or project goals are realized and progress is assessed [17]. A lack of specific stage-gate decision points with pre-set criteria results in incorrect product concepts, wasted resources, technology failure and excessive spending [21].

---

[1] Portfolio analysis refers to the processes that involve assessing and addressing the uncertainties in projects, allocating and balancing resources among projects while meeting organizational goals.

At the early stages of the project, there is no concrete evidence or knowledge about the potential success of a technology [22], the probability of technical success may be quite low as technological capability has not yet been recognized [23][15]. However, as a technology progresses and more information is obtained, the estimate of success begins to improve [22]. Many organizations have implemented requirements for their R&D and high-technology projects, where specific business plans and commercialization options are laid-out however, the challenge managers face when dealing with these long and highly uncertain projects, is their inability to correctly complete some of the requirements of these processes [15]. For example, envisioning the market landscape and conducting a market and competitor analysis is difficult for a technology that is still at the fundamental research stage, and has not yet been fully defined [15].

During the conceptual phases of R&D, there may be a change in project direction as technology and market information becomes apparent, it is important for managers to have the flexibility to make these changes[2] [17]. Fundamental research phases may be heavily relying on studies, technical literature, preliminary lab studies, economical valuations and patent surveys [18]. The applied phase of R&D typically involves laboratory work that aims at refining the technology's features, and initial assessment of feasibility and potential market for products and services embodying the new technology. The technology should now have a specific potential application or purpose [18]. These early phases develop concepts and ideas, where pattern recognition[3] and future scenario development is valuable [17]. It is important to identify technologies that are feasible and have a potential for market acceptance [24].

---

[2] This is the value in real options. Real options are defined in 2.4. It allows these decisions to be estimated and considered from aspects related to time, costs, resource requirements, etc.

[3] Pattern recognition is the skill needed to be able to spot trends in data (if any) or projects. Recognizing patterns and trend analysis go hand-in-hand, and managers can utilize such skills to improve project planning and resource allocation if they choose to.

During the technology development phase, the focus becomes on design, prototyping, and testing [18][14]. The ultimate goal during the technology development phase is to eventually be able to deliver a product to a user [25]. At this point, the technology must have proven to add economic value [12]. The pilot testing of technology would have moved from laboratory to operational (or relatively operational) environment [26]. This is also where scale-up activities may begin (and continue into the next phase). During the process of scale-up, new information about risks is realized [26]. The scale-up activities are separated into batch sizes, where smaller sizes can be a proof-of concept, and the larger batches test for the effects of larger scale manufacturing on the quality or viability of the technology [26]. There is also an inherent process that occurs during development, which is the "technology transfer". This is where the development process changes from technology and science creation to product creation. Furthermore, there is a transition where the project is transferred from scientific personnel to the commercialization and market experts [27]. Therefore, it is important for management to ensure that functional groups work efficiently with one another [27], and keep a balance of the team and individual responsibilities [17].

The decision to commercialize is usually made when uncertainties from the R&D stages are resolved [14]. The commercialization warrants a shift in tasks as the organization is involved in market positioning and competition [24]. This phase may involve activities that involve manufacturing, process and product launches done through marketing [14]. During the commercialization phase, issues such as the cost of goods sold (COGS), the size of market and sale price may be critical issues [17]. Commercialization of new technologies could include licensing or donating intellectual property that is not active (i.e. dormant) [9]. The commercialization phase brings new technologies to the market and can include activities such as manufacturing, refining the technology and distribution to customers [25]. The lack of commercial skills and a shortage of finances will prevent an organization from being able to move forward with new technologies [28]. Cooper and Kleinschmidt [21] discuss the results from their research where they found that many companies dive far into later stages of development without any consideration for commercialization, only to realize later their expectations of the market are incorrect [21]. This brings up an important concept that should be discussed, technology-push and market-pull technologies. This is discussed in 2.1.3.

Activities in the stages of development are specific to the project but Cohen et al. [29] discuss nine dimensions for basic gate decision criteria that are the framework for identifying issues. The criteria remain the same but the details evolve as a technology progresses from one gate to another[4]. These dimensions for basic gate criteria are as follows [29]:

- Strategic fit: business strategies and needs
- Market and customer: potential breadth of the technology in the market
- Business incentives and risks: key issues and uncertainties
- Technical feasibility and risks: science and technology uncertainties
- Competitive advantage: technology or business benefits over the competition
- Killer variables: that completely stop a project
- Legal and regulatory compliance: health, safety, environmental or operational integrity
- Critical factors for success
- Plan to proceed: plans to achieve goals, milestones and target dates for the next gate.

Hoegl et al. [30] discuss the importance of team dynamics (and coordination) during all the phases of development and emphasize that proper team dynamics in the early conceptual phases of development can ultimately have major effects on performance in the later stages of development [30]. During the different stages of the project, managers can expect to have different views that overall influence the project. Criteria for decision making should be integrated within all developmental phases [18]. Managers or decision-makers can be thought of as gate-keepers during a project where they can stop projects that are not producing according to set standards, but must also be able to spot potential in new ideas, and make changes during the project to capture these opportunities [29].

Metrics must be set by management early-on in order for progress evaluation to be completed at each stage. As the project progresses from conceptual stages all the way to commercialization, information and evaluation metrics change [17].

---

[4] For example, for research, initially the question asked may be whether the research is feasible. Stages after may become about whether the concepts investigated are feasible.

It is also important to note that R&D organizations may not be corporate environments and their goal may not be to maximize revenue[5][10]. It is important to note that the nature of available information changes during technology development. In the initial stages, data can be expected to be of the qualitative nature, while in the later stages of commercialization, managers can expect more quantitative information [17].

Termination phases are often not included in R&D projects, however, reasons for termination or failure of a project should be considered[6] as it could improve and drive the decision-making processes in a project [17]. Figure 4 illustrates how the termination phase relates to other stages of development and how it fits within a model.

2.1.2 Examples of Technology Development Models

Another common tool used by organizations is the stage-gate development method where the technology is assessed against a set of criteria and decisions are made at each gate [15]. Exxon Research and Engineering (ERE)[7] Company uses a stage-gate system where R&D activities begin with fundamental research, applied research development, validation, and concludes with a commercialization stage [29]. ERE then added three new research gates that precede the standard stage-gate process discussed. This addition included identifying opportunities and enabling science and idea growth [29]. Kelm et al. [24] emphasize that regardless of the differences in the theoretical development models in industry, and the specifics behind each phase, there is an overall consensus that the early stages of a technology developed are heavily involved in technical innovation, while the later phases are focused on commercialization [24].

---

[5] An organization may have its own idea of metrics of success. For example, a not-for-profit could aim to only want to have positive societal impact in the public.

[6] This is can be done through risk assessments.

[7] This has now become Exxon-Mobil (EMRE)

Figure 1. ERE Stages of Development Model [Adapted from [29]]

Stage A shown in Figure 1 is where business managers and researchers begin to try to establish a business case and competitive edge for the potential technology, through a detailed plan that sets technical and scientific variables. The plan includes resource requirements as well as plans of action of how these deliverables can be met [29]. Stage B is where the plan from Stage A is executed, and issues related to scientific process and leads to business opportunities are identified [29].

Using the gate-process is a structured method to assess research progress and allows for decisions to made in a timely manner while tracking project progress from both a science and technology aspect, as well as commercialization aspect [29]. At the gate of each stage, risks and uncertainties and other driving factors should be discussed and communicated with key personnel [17]. There are many versions of technology development models in literature that have been adapted for different purposes and industries [17][29][31][32].

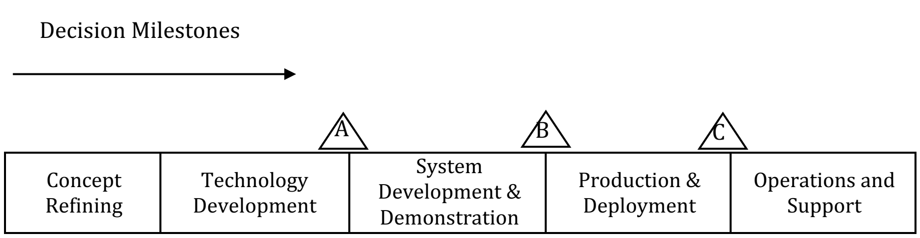


Figure 2. DoD's Technology Stages of Development [Adapted from[33]]

Figure 2 demonstrates the technology development model used by the US Department of Defense (DoD). Their model is comprised of five stages: concept refinement, technology development, system development and demonstration, production and deployment, and operations and support [34][35]. The model identifies three major milestones as logical stops where technology opportunities can be captured [34]. This is shown at technology readiness level (TRL) 4, 6, and 7, and Olechowski et al. suggest that mapping TRLs to stages of development is a useful practice [36]. They argue that it allows expectations to be clear and consistent for all projects [36]. Concepts related to technology readiness levels will be discussed in Section 2.2. The Milestone Decision Authority (MDA) works with stakeholders in order to assess whether there is enough information at each phase, before moving on to the next [34]. A project may start at any stage of the model, however, it is still a requirement that it meet the entrance requirement of any upcoming phases [34].

Lee and Gartner [25] discussed stages of technology development in a simplified model illustrated in Figure 3. There is only one phase of research as opposed to the classic basic and applied research phases and three major gates. This model does not view development as a linear sequential process, instead, it is an iterative process that responds to the market and competition [25]. The potential of whether a technological breakthrough has any commercial viability is done at the first stage with the help of a market specialist [25].

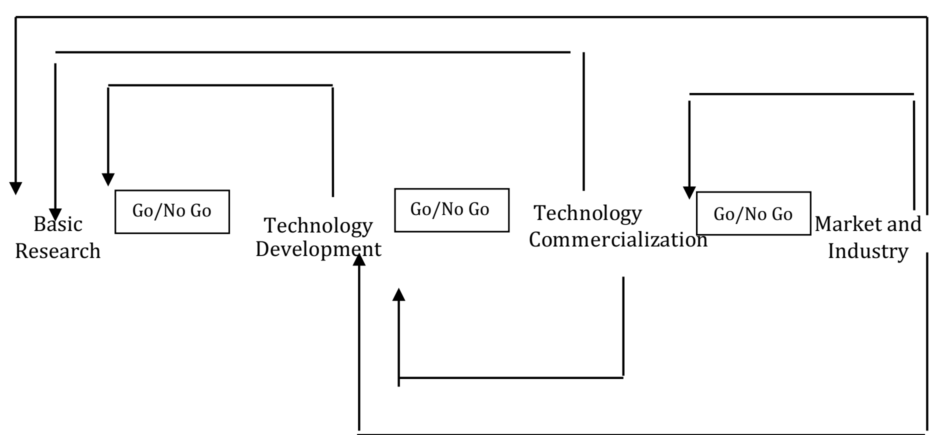


Figure 3. Lee and Gartner's. Development Model [Adapted from [25]]

The stages of technology development model by Tritle et al [17] articulates that a developmental process must be aligned with the vision, values, and goals of a firm. Their model has six stages that are the idea, concept, prototype, development, commercialization and termination. Each phase is a checkpoint and has a deliverable that must be produced [17].

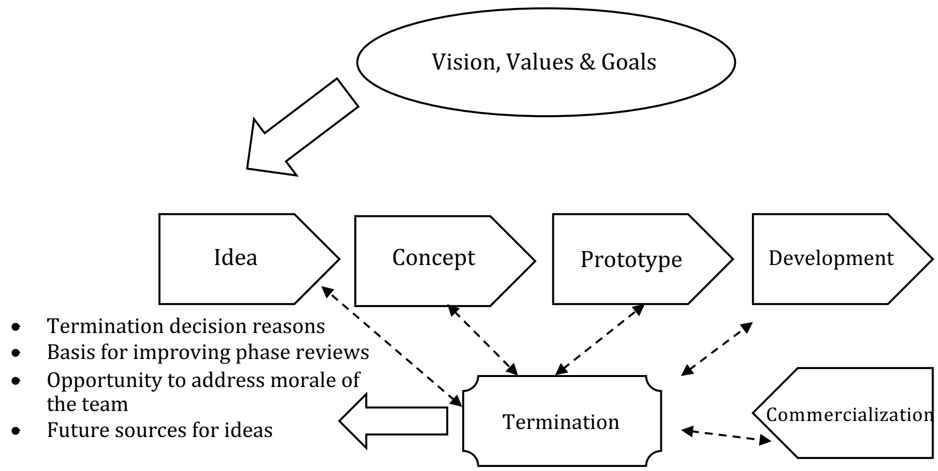


Figure 4. Tritle et al. Stages of Development [Adapted from [17]]

2.1.3 Technology Push – Market Pull

Technology-push projects originate from researchers recognition of a new technological phenomenon, this often causes scientists to become biased as the recognized benefits of a technology override issues of how a scientific or technological phenomenon can meet a market need [37][38].

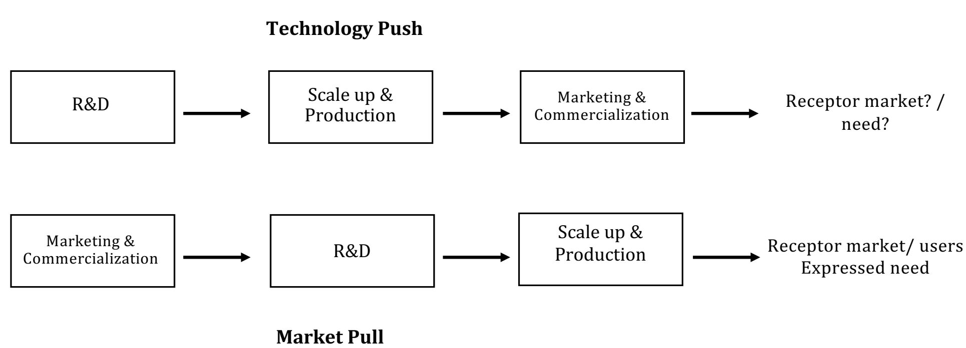


Figure 5. Technology-Push & Market-Pull

The possibilities of these technologies are over-hyped in order to secure initial capital investment, but often there is no identified customer or user need [39]. Wheatcraft argues that the technology-push approach is high risk, and prefers managers and researchers adopt the market-pull approach [39]. Technologies developed with the market-pull or demand-pull approach defined their products features with a market of end users in mind [40]. Market conditions create opportunities for technologies to satisfy unmet market needs [41]. Management's attitude, in general, has an influence on innovation within an organization and the approach taken as they have a critical role in decision-making [38].

2.1.4 Capabilities of a Firm

Capabilities of a firm have a large influence on the financial capital, technical expertise and resource requirements (and availability) [38]. Dynamic capabilities is a topic that has gained popularity over the years [42]. To summarize, it is the ability of an organization to integrate, build and reconfigure their competencies in reaction to fast-paced and dynamics environments [43]. An in-depth review of this topic is outside the scope of the research.

2.2 Technological Maturity

2.2.1 Technology Readiness Levels Overview

The technology readiness level (TRL) scale was first developed by NASA in the early 1970's [36]. The purpose of this scale was to set a standard, and provide a consistent measurement system managers could use to assess technological maturity [16]. This can be validated through demonstrations that increase in fidelity, and in realistic operating environments [44][16]. The TRL scale allows researchers and managers the opportunity to improve risk management, communication of technology development progress, and their deliverables [45]. The original scale developed consisted of seven levels and was later upgraded to nine levels in the 1980's, where NASA then published definitions of each level and their activities [44][46]. By 1999, the U.S Department of Defense (DoD) had adopted this scale for their programs and systems [47] [46]. The scale was then expanded by the DoD to allow the applicability of TRLs to software development projects [48]. The terms "readiness" and "maturity" describe the developmental progress of technology and have been used interchangeably in the literature [34].

With large global companies such as Google, Bombardier, John Deere, BP and Boeing using TRLs, it is the most commonly used scale, utilized across many industries [31][36][49]. Evaluating technology maturity is important as it gives managers insight into some of the risks associated with the technology development stages [46]. Brief descriptions of TRLs are outlined in Table 1. Full descriptions of software and hardware requirements are found in Appendix 1.

Table 1. NASA Technology Readiness Levels [50] [51]

TRL	Description
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Component and/or breadboard validation in a laboratory environment.
5	Component and/or breadboard validation in a relevant environment.
6	System/subsystem model or prototype demonstration in an operational environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and “flight qualified” through tests and demonstration.
9	Actual system “flight proven”.

The purpose of TRLs is to support decision-making processes during development and implementation [12]. The scale ensures a common ground for managers and engineers to assess the status of the technology and ensures risk management is considered during development [12]. It also supports funding programs for development, transfer, and deployment [12]. The TRL scale is also promoted as a gap assessment between current technological maturity, and the required target TRL [52]. Technologies may be considered “low risk” in the engineering and manufacturing development stages when prototypes developed are of consistent quality, and have been proven to work in similar environments as the target operational environment [52]. Technology readiness is a logical approach to systems and works to reduce risk through proof-of–concept and system success [13].

2.2.2 TRLs: Characteristics at Each Level

As shown in Table 1, TRL 1 is the lowest level of maturity where activities might include fundamental research and studying basic properties [30]. The costs during this level could vary depending on the rigor of the research [44]. These related costs are completely dependent on the scientific area of the research conducted and resources required (i.e. white board vs. super computers) [53]. TRL 1 is a common level for universities and research organizations [54][53]. TRL 2 is where the practical application of a technology is identified, but without any experimental proof or proper analysis to support the claim [39]. The costs will still be relatively on the same scale as TRL 1. Any organization may be at TRL 2, however, it is common for universities, entrepreneurs, and small businesses to be in this TRL [53].

At TRL 3, applied research and development begins where the technology is put into context. This level combines analytical and experimental (could be laboratory) methodologies to prove concepts. The specifics behind approaches used are specific to the technology and researchers' discretion. For software, proof of algorithm is necessary, while hardware will require physical validation. Similar to the previous TRLs, costs in TRL 3 can be expected to be unique to the technology being developed [44][53], and because of the increase in costs, it can be expected that some kind of funding would be attained at this point. This could be private sponsorship or government-type funding. At these low TRLs (1 to 3), the technological risk is high which means that lead times are increased and funding opportunities may be scarce. Often technologies at TRL 1-3 may fall into the technology-push category classification, especially during the processes where knowledge is gained without any specific application [39]. During these early stages, managers should begin to consider how the technology or process may be interrelated and the potential risk and other parameters needed for future development [26]. In TRL 4, low-fidelity validation is required and should be developed in a way that is consistent with the requirements of the potential system application, and be able to support the concepts in previous TRLs. The elements of a technology must be integrated to determine that they will all operate with one another and achieve target performance at the levels of a component. Mankins [53] ranks TRL 4 costs as moderate [44], and he describes the cost requirements to be "several times greater" [53] than the previous levels. At TRL 4, the uncertainty is expected to have decreased slightly with the proof of concept and laboratory validation, which is argued to provide greater chances of securing funding sources [53]. TRLs 3-4 should identify activities that prove concepts at a laboratory scale, that are also risk-reducing [26].

TRL 5 requires that elements of a technology be integrated into a component, sub-system or system-level. This may mean that more technologies could be involved in the demonstration. The fidelity of the component tested in this level increases greatly. Costs for R&D incurred in TRL 5 are described as moderate to high [44], where they are two (or more) times greater than that in TRL 4 [44]. The activities completed in this TRL are most likely done by R&D organizations with access to corporate laboratories. Therefore, it is expected that funding required increases due to these increased costs [55]. At TRL 6, the prototype system is tested in a relevant operational environment and proven successful. At this point, maturation is driven by instilling confidence in management (in the technology's future deployment), rather than the R&D. Demonstration may be of the system application and any other technologies that could be integrated. Costs in TRL 6 are expected to be high due to intensive demonstrations of the technology [44]. Almost always, there is a source of funding whether from the government or industry. Pilot-scale testing activities in TRLs 5-6 address risks and expose further information about the concept, and further reduce them[26]. The costs are described to be "two or more times" less than the investment required in TRL 7 [55].

Levels beyond TRL 6 are major maturation steps. In TRL 7, the prototype should be close to, or at the operational scale necessary, with the demonstrations occurring in the relevant operational environments [44]. The purpose of this level is to ensure system engineering, as well as to develop management confidence in concepts related to the market. Costs associated with TRL 7 are described as "very high" [44]. Depending on the scale and fidelity of the system, this could be a large amount of the ultimate system cost, thus would always require formal sponsorship. TRL 8 represents the end of real system development for most elements [55]. This level may include new technologies being integrated into the system. Costs in TRL 8 are specific to the requirements of the system and are classified as "very high" with the magnitude of costs being 5-10 times greater (this is because of full-scale system development) [44] than all the previous TRLs combined, and again, would expect formal funding. TRL 9 is the final level where the system is deployed, and the fixing of system bugs and glitches begins. At TRLs 7-9, researchers and managers should be able to assess customer acceptance and real-world impact as the new product is introduced (or about to be introduced) into the market [26]. This also assumes that customers' acceptance of the technology will be positive, therefore, it is important that the business case is reviewed during this time[26].

It is important to note that reducing risk across TRLs is not done linearly in terms of cost [56]. Mankins [53] noted that the cost to increase from TRL 5 to TRL 6 is more than 4 times the costs of the previous levels, and progressing to TRL 7 comes with even greater costs. He refers to progression past TRL 6 as "the valley of death" [53][56] and discusses the struggle between scientists and managers. With any new technology, reducing risk is a priority for managers so that project budget and project schedules are not affected, while the scientists just want to maximize their advances and discoveries [56]. More on this will be discussed in Chapter 3.

2.2.2 TRL Assessment Methodologies

A technology readiness assessment (TRA) is the process of assessing the maturity level of a technology [31]. This process relies on information during the technology development stages. However, the U.S Government Accountability Office (GOA) suggests that performing a TRA before development begins provides valuable information for management [31]. Mankins [16] states that an important point during development is when management must decide on whether technologies needed as part of a system have all collectively reached the target maturity, risk, and performance level for progress [16]. The assessment of TRLs can be conducted at times that management deems necessary, as a TRA needs to be specific in the context of the technology and the audience that will use it [31]. The ability to conduct a thorough TRA will ultimately depend on the availability of data, reports, and accuracy of it all [31]. In the case of new technology developments, scope is not always available or understood [31].

Because the TRL scale may lack objectivity and rely too much on tacit knowledge, some maturity assessment models and methods have been developed to tackle this issue [34]. These models have not only been used to assess maturity, but to also assess risks so management can better anticipate them in later stages [44][16].

Mankins [44] recommends that a general model to assess a technology should include five categories:

1. A basic research phase where goals and targets are identified.
2. An applied or focused research phase where a specific technology is considered for specific applications.
3. Technology development and prototyping for every identified application (prior to full system development).
4. Full system scale-up and testing.
5. Technology launch and operations.

Mankins also suggests that an assessment should possess the following characteristics [16]:

- Clarity: clear decision-making criteria to determine risks and readiness. Criteria should allow for independent evaluation and verification.
- Transparency: technology risk assessment should be formal and consensus based, where all participants easily understand the assessment processes and results.
- Crispness: decisions made during the assessment should be timely and up to program budget planning requirements.
- Useful in program advocacy: processes used during the assessment should have the basics for advocacy of a result.

The model Mankins [16] introduces is an integrated technology readiness and risk assessment framework (TRRA). This is a quantitative approach [34]. He argues that TRLs fail to address the difficulty in R&D progress, and the effort required to move from a TRL to the next within a set of criteria or requirements. This model builds on another paper by Mankins [57] and describes the "research and development degree of difficulty" ($R\&D^3$) as a measure of the difficulty that is expected during the process of maturation for a technology [55]. The purpose of this is to supplement TRL metrics [57]. It determines the probability of success (or failure) for a given set of technology requirements at different stages of development [16]. The $R\&D^3$ consists of five levels that are described in Table 2. The integrated assessment method developed incorporates another dimension, "the technology need value" (TNV) [16]. The TNV is a weighting factor that is applied relative to the assessment of the importance of technological development (shown in Table 2) [16][55].

The approach assesses the probability of success, identifies the gap between the current TRL and target level and its R&D effort, and then utilizes the TNV to assess the importance of the program. The factors are then applied into a technology risk matrix that assess the technology on a more coherent basis [16].

Table 2. R&D^3 Levels and Descriptions[57] and TNV and Descriptions [16].

R&D^3	**Description**	**TNV**	**Weighting Factor**	**Description**
R&D^3 – I	A very low degree of difficulty is anticipated in achieving research and development objectives for this technology. Probability of Success in "Normal" R&D Effort 99%	TNV 1	40%	Technology effort is not critical at this time to the success of the program. Advances to be achieved are useful for some cost improvements however, the information provided is not needed for decisions until the far term
R&D^3 – II	A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology. Probability of Success in "Normal" R&D Effort 90%	TNV 2	60%	Technology effort is useful to the success of the program. Advances to be achieved would meaningfully improve cost and/or performance however, the information provided is not needed for decisions until the mid to far term
R&D^3 – III	A high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in "Normal" R&D Effort 80%	TNV 3	80%	Technology effort is important to the success of the program. Advances to be achieved are important for performance and/or cost objectives and the information provided is needed for decisions in the near to midterm
R&D^3 – IV	A very high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in "Normal" R&D Effort 50%	TNV 4	100%	Technology effort is very important to the success of the program. Advances to be achieved are enabling for cost goals and/or important for performance for performance objectives and information provided is highly valuable for near term management decisions
R&D^3 – V	The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required. Probability of Success in "Normal" R&D Effort 20%	TNV 5	120%	Technology effort is critically important to the success of the program. Performance advances to be achieved are enabling and the information to be provided is essential for near-term management decisions

Azizian et al. [34] discuss the TRA process used by the DoD for defense acquisition programs. It is a six-step process that is shown in the figure below. The process is started by setting a schedule in order for important milestones to be met [34]. The assessment then continues by identifying the critical elements[8] (CTE) across a Work Breakdown Structure, data is then collected and presented to an audience (experts in technology) that is independent of the team [35]. Reviewers then assess the maturity of CTEs against the metrics that have been decided on and then passed up for approval by the chain of command [34][35]. If not approved, then, they may conduct another TRA [35].

In the case when a component is not at the same TRL as the rest of the technologies, the DoD may do any of the following [35]: restructure the program so that only mature technologies are used; delay the program in order to mature the technology; change the program requirements; not initiate the program and consider another solution.

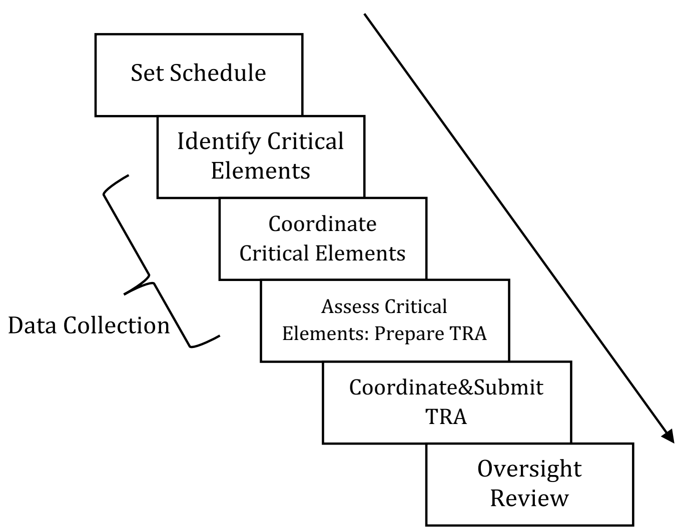


Figure. 6 DoD TRA Process [Adapted from[34]]

---

[8] (CTE) is defined as an element that the system being acquired depends on in order to meet operational requirements [64].

The U.S Government Accountability Office (GOA) drew upon the techniques and practices at NASA and the DoD and produced their own TRA methodology that is often called the “best practice” [58][31]. The published 150 page guide outlines the six steps to implementing this method in detail [31]. These steps are summarized in Appendix 1. Another approach to conducting TRA considers more holistic methods to redraw the boundaries of the problems and examines the rate at which a technology can mature, and larger issues related to technology-life cycles[9], specifically its obsolescence. For more information see [59].

2.2.3 Other TRA Tools and Techniques

Similar to the R&D^3, there are many other maturity assessment tools that have been developed to work or leverage with the TRL scale and provide insight on different aspects of technology development [34]. The advancement degree of difficulty (AD^2) is a qualitative method that is argued to build on the R&D^3 approach and possesses 9 levels that integrate the aspects of cost, schedule, and risk [60]. Another qualitative technique developed, is the Manufacturing Readiness Level (MRL) created by the DoD [61]. It is used to assess the manufacturing maturity of a technology on a scale of 1 to 10 [61][62]. This can be applied during system development of a technology and continues after the technology has been in operation for a few years [62].

The System Readiness Level (SRL) is a quantitative approach that measures the index of maturity on a system-level [63]. SRLs are a function of TRLs (and their maturities) and are expressed based on the Integration Readiness Levels (IRL) [63]. The IRL scale is a 9-point scale that measures maturity and the relationship between the interfaces of other readiness levels and can be used to determine the risk of integration (when used with TRLs) [63][34].

[9] Technology-life cycle has four stages. It starts at the R&D phase and ends in the decline phase where the technology eventually becomes obsolete.

Automated tools to measure maturity are also available, where they quantitatively assess the maturity based on the information fed by the user [34]. The most well-known being the Technology Readiness Level Calculator [58] (and MRL calculator). This is a Microsoft Excel tool that calculates the TRL level as an output at a specific time [58]. The calculator provides no information about risks or the probability of success but can give management a general idea about the risk (as the assumption is the higher the TRL, the lower the overall risk [39]).

2.2.4 Limitations of TRLs

There can be a bias when conducting TRLs where different priorities and metrics for success or levels of acceptable risk can play a factor in which choices are made. This includes optimism, which can affect TRA results. Managers may also be tempted to accept higher risks and immature technologies in hopes of future performance and stakeholder buy-ins [31]. In the case where a technology is not developed at every level[10], the risks related to skipping these levels should be assessed against the cost [39]**.** TRLs alone are not sufficient as an entire framework for technology and risk management. As discussed, many other complementary methodologies have been introduced in order to better identify uncertainties during research and development, to take action upon these uncertainties and to develop long-term technology opportunities based on needs [45][55]. Some other issues identified in literature include improper assessment of methods to integrate two technologies, or an individual component of a system and the measurement of uncertainty during the maturation process [47][46][36]. In addition, the lack of ability to comparatively assess the alternate TRLs on the entire system [47], and failure to consider technology aging (obsolesce) [64].

---

[10] Managers can choose to skip a level; this is called leap-frogging.

Finally, a paper published in 2015 by Olechowski et al. [36] identified a major challenge as the failure to align TRLs with technology development stage-gates. They acknowledge the fact that the aligning is practiced in industry; however, argue that there has been limited discussion about this in the academic world. They argue that the lack of proper mapping done in industry and processes of determining the minimum acceptable TRLs is related to the lack of understanding of the consequences of missed milestones and reaching target TRLs[11].

2.3 Technology Risk Management

2.3.1 Risks in R&D & Technology Development

There is a significant amount of risk that can be expected during a new technology development project [27]. There is a large amount of literature that identifies common risks associated with R&D and high-technology projects. However, there is a weakness in aligning these risks along the stages of development for a technology project and identifying trends of how one risk might affect another. This section highlights the major types and categories of risks on a general level. Chapter 3 will apply the topics summarized in this section and discuss it in a relevant context that builds on the framework in a manner that can be mapped out along technology stages of development and general correlations of how risks may be related. Appendix 1 lists examples of potential risks that may arise during development as outlined by [65].

There is an inherent difference between risk and uncertainty. Risks are described as the degree of which an uncertainty and loss may occur in an event [32]. Therefore risk is a quantified uncertainty and outcome [66]. R&D projects are labeled as "risky" if the probability of a bad outcome is high, the ability to control the risks within time and resource constraints is difficult, and if the potential impact of the consequences is substantial [65]. The high uncertainty in R&D leads to high risks, which may lead to project failure. Improving R&D probability of success requires managers to control risks during all stages of the project [5].

[11] Google and John Deere were the examples discussed.

In general, innovative R&D projects can expect high risks of market and technological uncertainties which ultimately cause project failure [67]. The literature reviewed revealed that individuals had grouped R&D risks according to what was viewed as more dominant or relevant to the projects that were being considered. A summary of the general risk categories from the literature is outlined in Table 3. Critical issues and driving factors can be identified by managers interacting with several functional groups across an organization and other parties (such as customers, suppliers, and experts) [17].

Table 3. Major R&D Risks in Literature

Risk Categories	**Reference**
Technology, market, finance, operations	[65]
Economical, managerial, project management, organizational, quality, market, social, legal political, technical, supplier	[32]
Incompetent management, external risk factors, information technology, lack of marketing, technology development, staff turnover, safety failures, poor strategy	[68]
Strategic, discovery/research, development, commercial, regulatory	[67]
Firm specific risk, competition risk, market risk	[69]
Financial risk, project risk, owner's risk	[70]
Market, technology, environment, organization	[71] [72]
Market, competitive, development, commercialization	[20]
Technology, business, organizational	[73]
Economic, time/schedule, operational, customer, markets	[74]
Technology, market, supplier/process, financial	[75]
Technological, market, financial, institutional/regulatory	[76]

Technology risks can be described as those related to design, platform development, manufacturing technology, IP [65], and technology life-cycles [77], while technical risks are defined as the technical issues that come up with new technologies (such as glitches) [78]. Other examples of technology risk elements include not reducing the technology to practice or failure to demonstrate feasibility [78], or the ability to remain feasible leading to becoming obsolete [69]. Technology and technical risks are important during the early development stages of a technology as they have an influence on milestones and feasibility. Those R&D firms that are able to possess technologies with higher capabilities generally tend to have investors that look for qualities such as a firm's ability to meet technology challenges [24].

Technical uncertainties may create pressure on managers to invest in order to lower the risk [79]. The logic behind this is that delaying investment (i.e. actions and decisions to mitigate these risks) may cause exposure to an increase in competition [79] and delayed market entry (commercialization) could result in significant failure, as competition that possesses the right resources may act quicker and enter the market (competitive risk) [69]. However, aggressively entering a market too early may pose many challenges such as large increases in cost due to the infrastructure needed [79]. Another risk could be competition's response to the new technology launch, as their actions (releasing similar or better products) could destroy a firm's competitive advantage [69]. These competitive risks that could arise are directly related to actions by competitors which can cause varying levels of losses in project opportunities [69].

Manufacturing technology risks are also important, for example, proper scale-up (and the potential for scale-up) [65] is necessary to achieve success in later stages [65]. Figure 7 illustrates the general trend for technology risk[12] as technologies mature across TRLs, as suggested by Batkovsky et al. [12]. The figure depicts an increase in investment in funding requirements as higher TRLs are reached. The actual growth trend as TRLs increase (i.e. linear, exponential, etc.,) is not reflected in Figure 7.

[12] The paper [12] only showed a table that outlined the relative qualitative magnitudes of risk across the TRLs.

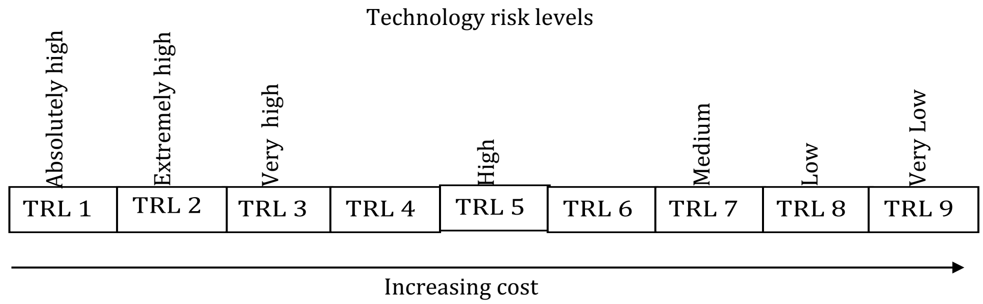


Figure 7. Technology Risk Across TRLs for High Technologies

Market risks can be characterized to be of any or a combination of the following: customer demands, regulatory changes that may influence demand, customer acceptance and adoption, the effect of competitors strategies and the rise of newer and cheaper technologies [65][69]. Wang et al. [20] discuss that when high market uncertainties are present, managers are still at risk to properly match market requirements, even with managerial flexibility. They advise that organizations exercise their efforts to obtain reliable information about the market so that the range of their options to reduce uncertainty can properly be assessed [20]. They also emphasize the importance of maximizing market research capabilities as they argue even with well thought-out technology planning methodologies, a high market uncertainty will reduce any chances of capturing opportunities [20] Often, managers are unsure of the market opportunities for a particular technology [32]. If a firm has access to data on the potential customers, competition, distribution channels and other market information, then this can contribute to market uncertainty being lowered overall [32].

Market risks can be either strategic or operational and although different, there can be overlap between the two [76]. Operational risks can be managed by project managers while strategic risks more often than not, require the involvement of higher executives (such as a board of directors). [76]. Successful commercialization of a technology is dependent on the presence of a market need and the ability to strategize accordingly [80]. Proper marketing strategies will explore positioning opportunities within the market and devise action plans to gain a competitive advantage and to maximize the value of a particular technology [80].

This calls for someone with marketing expertise that would be able to conduct this all within the organizational (internal) and external constraints [80]. Formulation of marketing strategies for early stage technology projects is an important milestone [80]. The concepts behind marketing which strategies to select and when are outside the scope of this thesis. However, they are recognized as an important aspect of development that should be studied and considered.

Finance or financial risks[13] can refer to the risks associated with the limited financing available for development in a project [69][76] and the challenges associated with obtaining funding for a project [70]. This is an important category of risk, as the availability of funding is critical in capital intensive projects [65]. Scale-up costs of technology, time to develop, and human resource additions to an R&D team can all be examples of developmental risks that can cause financial risks to increase [17]. Technology viability, pricing sensitivities, inadequate investments, low-profit margins are examples of financial risks [65].

Organizational risks can be firm-specific risks, related to internal organization factors or those related to R&D teams' relationships with third parties [65]. Regardless of the technological, market or financial opportunities, if a firm is unable to actually put out a product into the market (from a resource point of view), then, they possess high organizational risks. Unavailability of resources and missed milestones are important risks [68]. These can generally be attributed to weaknesses in management, structure of the organization, stakeholders [81], and failure of internal parties to cooperate [69]. R&D managers must also find a balance between short–term and long-term project goals so that allocation of resources can be managed accordingly, as they are often an important source of uncertainty [17].

[13]Financial risks are not widely discussed for R&D and technology projects. I believe that because most of the literature is about the importance of obtaining capital investments (and valuing these projects), thus, its importance is inferred from literature that exposes the role of financing in research and development.

Organizations should establish metrics for projects that allow for clear guidelines that outline when abandoning or terminating a project becomes necessary[14] [17] as sometimes the personal feelings or pride towards a belief about the potential applicability of a technology increase the overall project risk and may become a major factor why delaying or ignoring termination of a project[15] (this then becomes an issue of technology-push)[17].

Environmental risks can be related to several facets such as political or social factors, public interest and acceptance, and public acceptability of the product [71]. Regulatory risks such as legal, industrial policies, and sourcing requirements can all be classified as environmental [76].

The need for competent managers is crucial in order to avoid costs, delays or overall failure of a project [17], as it challenging for organizations to identify underlying latent causes of the uncertainties [20]. R&D managers must define and address critical risks as soon as they are identified [17]. Cooper and Kleinschmidt [21] argued that only having a "formal development process" had no correlation with performance results. They state that many companies found important tasks such as market analysis and customer research were not done or done too late in the development process. They advise on focusing on the quality and nature of these processes in order to build best practices, as this is what will really drive performance and prevent companies from falsely thinking they are progressing[16] [21]. Janney and Dess [82] acknowledge the complexity of risks and uncertainties in R&D projects. They believe the best approach for managers is to identify a primary uncertainty, try to control it and examine whether it affects other uncertainties. They argue that if different aspects of uncertainties are considered, the greater the chance is of observing potential benefits [82].

---

[14] Upon termination reallocation of resources is not only required, but also efficient for the overall performance of the organization. No need to tie up resources where they can be used elsewhere.

[15] Other factors could also be reactions to competitors or customers or technology advancements [17].

[16] As opposed to employees thinking they improving project performance solely based on "going through the motions" of these assessments and processes.

2.3.2 Risk Management in R&D

The literature review conducted on risk assessment methodologies is a summary of the most commonly used tools. There are qualitative and quantitative methods that are used in industry. The purpose of this research is not to focus on risk management methods and tools. However, it is important to discuss the possible options managers may choose to incorporate in their projects. These discussed methods do not represent an exhaustive list.

"Risk" is a term that can reflect opportunities (i.e. positive risk) or threats (i.e. negative risk). The most common usage of this term, however, usually refers to the downside [83]. Anytime the term "risk" will be used throughout this thesis, it will reflect negative risk. Risk management refers to the processes that firms utilize to understand, evaluate, and take appropriate actions to deal with risks, where project failure is reduced and the probability of success increased [74]. Therefore, risk management is a critical factor for business success and is a vital part of the overall management of a project [68]. The subsections will outline the important constructs that make up risk management that can be applied.

The general risk management application can be summarized in a few steps. These are identifying the risks, assessing them, and finally, applying risk management strategies that could mitigate and monitor the risks [74].

Risk identification is particularly important as it allows managers to recognize the critical risks that may prevent reaching project goals [67]. These critical risks can be identified in many ways that may include, but not limited to, using the Delphi technique, scenario analysis, cause-and-effect diagrams, fault-tree analysis, interviews, surveys, questionnaires, as well as historical and empirical data [72][67][84]. Identifying critical risks can be divided into three steps: 1) risk identification, 2) risk analysis and 3) risk prioritization [67].

2.3.3 Risk Management Tools & Techniques

Risks assessments are important as they rank and prioritize identified risks by estimating the likelihood of occurrence, and severity of the consequence, either qualitatively, quantitatively or semi-quantitatively [72]. There are many risk assessment methods that can be used. Failure mode and effects analysis (FMEA) is an analysis tool that assesses for possible ways failures could occur and their effects [84].

The common weakness in these methodologies (and many others) is that they fail to identify the correlation or relationships of different risk factors and compute their conditional probabilities [72]. Sharma and Chanda [72] use the Bayesian Belief Network model (BBN) to establish relationships between risk factors in an R&D project. The BBN approach begins by identifying the risks using any of the previously mentioned methods, then identifies the risk triggers (causes)[17] and the consequences of the risk factors. Finally, the BBN can be constructed [72]. The approaches to constructing the BBN are outside the scope of this thesis, however, see [85] for a full explanation on risk assessments and the use of BBNs. The BBN's interface allows decision-makers to calculate the conditional probabilities and their corresponding effects on dependent risk factors in the project [72].

A probability risk matrix can be used to qualitatively assess risks [86]. It is a popular and widely used tool as it simple to understand and can be customized for risk categories and levels that reflect management's threshold and tolerance for risk [87]. The matrix is simple to understand as the risks are assessed where the likelihood of occurrence and the impact of or consequence are determined based on predetermined metrics or scores [86]. Figure 8 is an example of a general probability matrix. A major drawback with the use of probability risk matrices is the potential of inconsistent assessments as they are highly subjective to a manager (or organization's) aversion to risk [87].

---

[17] The authors identify risk triggers such as new technology, insufficient quality personnel, and inexperienced project leaders. These are causes of the actual risk factors.

		Impact		
		Low	Medium	High
Likelihood	Low			
	Medium			
	High			

Figure 8. 3x3 Probability Impact Matrix

An arguably more comprehensive framework for evaluating business, organizational, and technology risks for innovative technology projects is the Risk Diagnosing Methodology (RDM) that was started by Phillips Electronics [5]. A study by Keizer et. al discusses Unilever's adoption of this methodology, where employees unanimously agreed that the RDM processes allowed them to grasp what the critical risks were and how to handle them better than their previous ad-hoc techniques [65]. RDM is an 8-step process that is completed with the expertise of risk facilitators that have no stakes in the project and can provide guidance in an objective manner [65].

In 1992, Kaplan and Norton developed the balanced scorecard method [88] that drives management to connect their objectives to strategies, by prioritizing processes that are most important [89]. A framework developed by Wang et al. [65] discusses that balanced scorecard (BSC) is a strategic tool that can be applied to R&D projects for risk management purposes. They propose that BSC and quality function deployment (QFD) be used to create a streamlined method where managers can manage risks from a top-down approach. Risks are identified, assessed, planned (mitigation plans) and controlled. For more information on Hauser's QFD and how it was used to reduce cycle time of new product development, see [90].

2.4 Financial Valuation Methods

2.4.1 Traditional Valuation Methods

There is a large amount of literature available that discusses valuation models and methods used throughout the years. The two main approaches to value that have been used widely used to forecast are the discounted cash flow (DCF) and the net present value (NPV) [91].

The biggest assumption associated with these methods is that the initial decisions made at the beginning of the project are static and will not change [92][93]. These are now-or-never approaches to investments [10] and they do not take into consideration management's capability to strategize during project execution, and ability to actively manage a project throughout its entire duration [92]. The cash flows and discount rates carry a high amount of potential uncertainty, and the decision-making risk is high [94]. Despite the limitations of these approaches, the traditional methods should not be scrapped as they are still necessary inputs to an options-based approach to a valuation [6].

The benefits of these traditional valuation approaches are that they are fairly simple, widely accepted, and are able to reflect the magnitude of the economic benefits from an investment plan [3][94]. DCF methods are derived from financial theory, however, Meyers argues that finance theory and strategic planning have a large gap, which contributes to reasons behind their shortcomings [95]. Table 4 outlines the DCF assumptions vs. the realities as summarized by Mun [7].

Table 4. DCF Assumptions vs DCF realities [89]

Discounted Cash Flow Assumptions	**Discounted Cash Flow Realities**
Decisions decided up-front and all cash flows are static for the future	Uncertainty and variability in future outcomes. Not all decisions are made today as some may be deferred to the future, when uncertainty becomes resolved.
Projects are “mini firms”, and interchangeable with whole firms	With the inclusion of network effects, diversification, interdependencies, and synergy, firms are portfolios of projects and their resulting cash flows. Sometimes projects cannot be evaluated as stand-alone cash flows.
All projects are passively managed once they launch	Projects are usually actively managed through project lifecycle, including checkpoints, decision options, budget constraints, etc.
Future free cash flow streams are deterministic and highly predictable	It may be difficult to estimate future cash flows as they are usually stochastic and risky in nature.
Project discount rate used is the opportunity cost of capital which is the proportional to non-diversifiable risk[18]	There are multiple sources of business risks with different characteristics, and some are diversifiable across projects or time.
All risks are completely accounted for by the discount rate.	Firm and project risk can change during the course of a project.
All factors that could affect the outcome of the project and value to the investors are reflected in the DCF model through the NPV or IRR.	Because of project complexity and so-called externalities, it may be difficult or impossible to quantify all factors in terms of incremental cash flows. Distributed, unplanned outcomes (*e.g.,* strategic vision and entrepreneurial activity) can be significant and strategically important.
Unknown, intangible, or immeasurable factors are valued at zero.	Many of the important benefits are intangible assets or qualitative strategic positions.

DCF model can be presented by the following [95]:

$$PV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$ Where [95]:

PV is the present value

C_t is the incremental cash flow

T is the project life

r is the expected rate of return

And,

NPV = PV – cash outlay at time=0

[18] Non-diversifiable risk can refer to risks such as market or systemic risks.

Traditional NPV was initially established for stocks and bonds valuation, and assumes an organization holds real assets passively [96]. This method discounts expected cash flows and the terminal value of the project at a specific discount rate [97][8][10]. The chosen discount rate used is a reflection of the project risks [97]. This puts managers and decision-makers in passive roles as this assumes that the project will play out as planned and ignores the possibility of future changes in the project [10][6][97]. Because of the lack of managerial flexibility (which is seen to add value to projects), it is seen that the traditional approach may actually undervalue a project [98][7], especially for projects that are longer, highly uncertain, and possess higher interest rates, such as technology and R&D projects [97][93]. The weighted average cost of capital (WACC) is often used as the discount rate as it is thought of as the opportunity cost of capital [99]. This, however, is challenging for early R&D projects [99]. Managers involved in these types of projects require methodologies that allow them to justify strategies for development [93] since R&D projects have different phases and should be viewed as a series of decisions, with varying risks and uncertainties [14]. The static NPV approach makes it seem like these qualities damage the investment opportunity's value[19] [97]. Traditional DCF and NPV also assume that projects are independent, which is not the case. There are inherent interdependencies between projects and these should be seen as links in a chain of projects [97]. These methods are suitable for short-term projects with low uncertainties, making these methods limited for R&D environments that are naturally dynamic and fluctuate [14][94]**.** The traditional valuation methods may be a double-edged sword. Managers may give up projects with negative NPVs [8] that have opportunities to grow, while the other side of this is that managers may end up missing opportunities that may come up because of the initial positive NPV that was calculated [9].

Another technique that is sometimes used is the payback period, and similar to DCF and NPV, it lacks the ability to account for risks which may cause managers to reject many long-term R&D projects, as this method favors quick payback [100]. DCF, NPV, payback, and IRR are quantitative valuation methods. A qualitative method that has been used is score cards that guide managers to shape their judgments and structure reasoning [1]**.** This method scores projects qualitatively, such as how applicable a technology is and ranks them based on their respective scores [101][3].

[19] This is not always the case as the option to defer parts of the investment can be considered [97].

A weakness of this approach is that it is difficult to justify why a score was given, and challenging for managers to understand how to improve the value of a project [3].

2.4.2 Financial Options Theory Overview

This section discusses general concepts that apply to the option theory models. Block [102] identified that the most popular valuation approaches included the binomial model, Black-Scholes model, and Monte-Carlo simulations [102]. The most popular models to solve options are the binomial approach and the Black-Scholes [103]. The binomial method was the most frequently used as users found it to be simpler when compared to other methods, such as Monte-Carlo [102].

The variables in financial options are the underlying asset, volatility, exercise price, expiration date, interest rate and the dividends [104]. These variables are typically deterministic, except in real options where these values are based on real assets and require more effort to define [104]. Volatility is an important variable in option pricing models as it is the parameter that represents uncertainty [104]. Many of these variables are not available for real options, as parameters such as time to maturity or the expiration, are difficult to establish when management has the flexibility to make decisions that alter these values during the project [102]. These option theories have a basis on how discount rates are assigned depending on the levels of risk and uncertainty. This could cause problems where the reliability of the valuation is questioned if there is no proper documentation and justification [17]. Instead of varying the discount rate, factors that drive the risks of the NPV should be identified and discussed, and NPV (and risk) ranges assessed [17].

These methods rely heavily on volatility values. The relative volatility of the option is not constant and depends on variables such as the stock price and maturity [105]. Commonly used methods to compute volatility are not applicable for real assets, and there is an argument that this value may be manipulated in order to attain specific decisions [104]. Management must ensure any assumptions made are on conservative grounds for the analysis to be persuasive [104]. There are many methods to determine volatility, however, these methods will not be discussed as they are outside the scope of this thesis. For further reference on different methods to calculate volatility see [7] and [106].

2.4.3 Black-Scholes Model

The Black-Scholes equation is as follows [103][7][107]:

$$C = N(d_1)S_o - N(d_2)Xe^{(-rT)}$$

Where [103]

C is the call option value

S_o is the current value of underlying asset

r is the risk-free rate of return

T is the time to expiry

$$d_1 = \frac{\left[\ln\left(\frac{S_o}{X}\right) + (r + 0.5\sigma^2)T\right]}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \sigma\sqrt{T}$$

σ is the annual volatility

$N(d_1)$ and $N(d_2)$ represent the values of the standard normal distribution at d_1 and d_2

The Black-Scholes model operates with the following assumptions [7][105]:

- The value of a call option increases as the stock price increases (and vice-versa).
- If the call option exercise price increases, the value of the option decreases.
- The longer the time to mature, the more valuable is the option.
- If r increases, the value of the option also increases. Short-term interest rate is assumed constant through time.
- The higher the σ of a stock price, the higher the possibility of the stock price increasing beyond the call option's exercise price and, therefore, the higher the value of the option.
- There are no transaction costs to buy or sell options or stock.

Other limitations include [103]:

- It assumes the underlying assets allows follows a lognormal distribution[20], this is not always the case with real assets
- It does not take into account any ups and downs in the asset value and assumes that increases in value are continuous as directed by the volatility
- The derivation of the equation is very complex mathematically and this causes a loss in intuition for managers trying to apply it, which makes it difficult for them to get on board
- The model was developed for European options that can only be exercised on a certain date. This does not reflect the true nature of real options that can be exercised at any time.
- Adjustments can be made to the model to help improve it, however, they tend to make the model even more complex.

The Black-Scholes option theory has been used in industry to value real assets and investments such as R&D and technology [105]. However, this model has limitations when applied to such projects that are often exposed to varying types and levels of uncertainty. These projects that usually incorporate a series of options that may interact with one another (i.e. compound options) cannot be properly estimated by the Black-Scholes model, thus producing a value that may be higher or lower than the actual [69].

2.4.4 Binomial Model

Cox et al. [108] introduced the binomial model. This model is a discrete-time model that uses binomial trees to show the changes in stock price with time. It assumes there are market opportunities that create payoff patterns for options [14]. There are two approaches to applying these models, risk-neutral probabilities and market-replicating portfolios [109]. However, market-replicating is a more complicated approach [7]. The risk-neutral approach assumes the option is independent of the risk preference of an investor [108][110]. More on these approaches in 2.5.2.

[20] Variance rate is proportional to the square of the stock price and the variance rate of the return on the stock is constant [105].

The idea behind the binomial method is that it follows a multiplicative process over discrete periods. The interest rate is assumed constant, and *r*, the riskless interest rate, follows the following: $u > r > d$ where *u,* is the upswing value and *d,* is the downswing[21] [7]. More detail on binomial lattice application and option valuation is shown in Chapter 3.

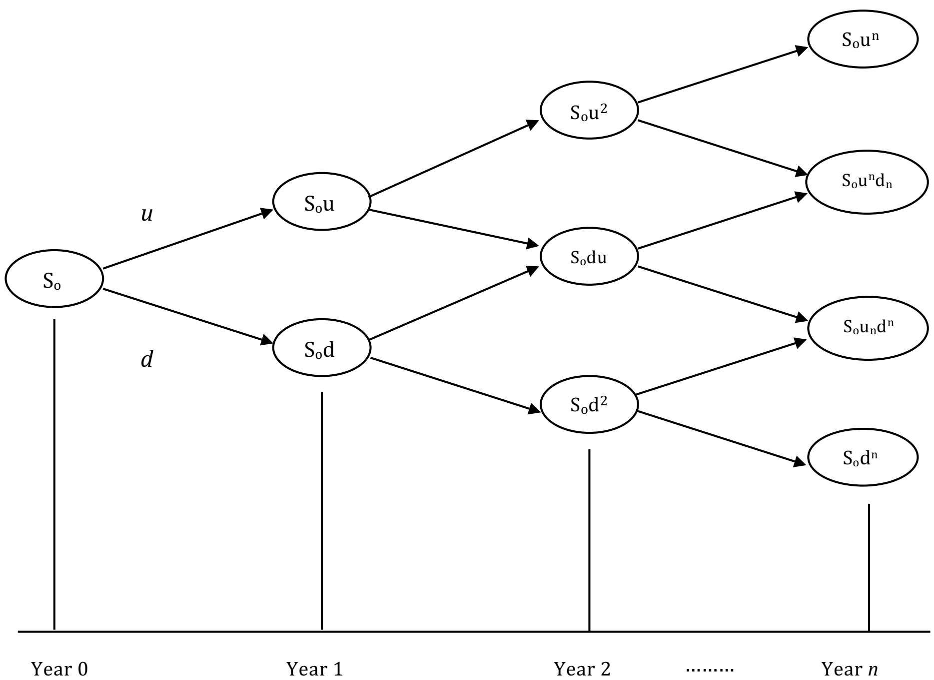


Figure 9. Generic Binomial Lattice [Adapted from [7]]

There are two types of binomial lattices, recombining, and non-recombining where recombining are more commonly used than the latter [7]. Both lattices yield the same values at the end and the main difference between the two is that is the center nodes of the lattices are different, where non-recombining assumes that the volatility of an underlying asset changes with time [7][111]. To use this model, the binomial lattice must be developed and the values for *u*, *d* and *p* must be calculated. *p* and 1−p are the probabilities that are risk-neutral [112].

---

[21] Otherwise there will be riskless arbitrage opportunities and riskless borrowing and lending. No arbitrage opportunity refers to the current value of an investment opportunity cannot be less than the portfolio nor greater than the portfolio [14].

The initial value of the project is required to build the lattice and can be estimated by an initial NPV without the use of options [112] [112][113].

To calculate the upswing (which is a function of the volatility) [14][94][7] :

$$u = \exp\,(\sigma\sqrt{\delta t})$$

and d is calculated by [14][94][7]: $d = \frac{1}{u}$

The volatility is represented by the standard deviation of the logarithmic function of the underlying free cash flow return, and t is the time associated with each step of the tree [7].

The risk neutral probability p is calculated using [14][94][7]:

$$p = \frac{\exp(r\delta t) - d}{u - d}$$

With all these variables, the values for all the nodes can then be calculated using simple multiplication across the lattice [110]. To value an option, the backward induction method is applied [112]. The decision to continue a project can be determined by valuing the option, which is completed using the backward induction process that calculates the value of a real option [113]. Each terminal node has a value that is the maximum of zero and the difference between the value S and the exercise cost X (or investment cost), where MAX (S – X, 0). If this difference between S and X is negative, then this value is zero and considered as an abandonment option [114]. This is done to each pair of vertically adjacent nodes reveals the option value at the very left end of the lattice [115].

One limitation of this of approach is the risk adjusted discount rate that is used to value the option across the entire tree. As this value may not accurately reflect the varying levels of risk across the tree [112].

2.5 Real Options Valuation

This section introduces fundamental concepts of real options (RO) and their value to R&D and technology projects that have been widely discussed in the literature.

2.5.1 Introduction to Real Options: Value as a Decision-Making Tool

RO research has been an important source contributing to financial economics and strategic management through an approach that encompasses investment methodologies and flexibility for decision-makers under uncertain environments [9]. Strategy research has been focused on how RO adoption can create, sustain and improve an organization's competitive advantage [9]. In 1977, Stewart Myers coined the term "real options" [116]. The RO framework gives decision-makers the ability to invest, grow or abandon a project as more information is realized [117][112]. This framework is an extension of financial theory, however, it refers to real assets [112]. Real options valuation (ROV) was developed to evaluate capital investments that required managerial flexibility [112]. Option pricing methodology has been used to value real assets in the natural resources industry but has now been applied in R&D, new technology developments and other areas [97]. There are several real options analysis approaches that can be used to technology investments and R&D decision-making [118][20].

RO theory is built on the belief that if decision-makers are allowed the flexibility to alter the course of a highly uncertain project by incorporating strategic options, then, an organizations' overall value can increase [9]. These real options are thought of as a guide that can lead to strategic paths [9] and allow managers to favorably utilize uncertainties as they evolve through the project [10]. RO is a valuable tool for risky R&D projects [10] because it recognizes that these projects often have longer horizons and are not expected to generate revenues immediately, but still accounts for the future potential [14]. This is accomplished by allowing managers to make decisions at different stages of the project, such as, whether a project should be continued [9][113]. This is unlike the norm, where many financial decisions and resource commitments are made up-front, despite the uncertain outcomes [9]. A better approach would be to stage the investments, as RO allows for this [9]. The sequence of decision-making allows managers to make justified decisions of when to undertake opportunities [14].

Many of the traditional valuation approaches also incorporate standard investment decisions that depend on creating profit, though this may not be useful for R&D firms that may have different goals, that may not be to commercialize and create profit[22] [10].

The framework for RO emphasizes that flexibility of management in highly uncertain environments holds a great value [97]. This method gives managers the ability to make strategic decisions such as staging capital investments when necessary, wait till market uncertainties are managed or future prospects to become promising, expand, or liquidate their assets [9]. Each phase of an R&D project can be thought of as an option that depends on the success of previous stages (and options). If successful, options can be exercised to make larger investments to continue the project and grow (and launch a new technology), however, if there is a failure, then managers can decide to not commit any longer (and abandon the research) [3][20]. This limits the overall risk to only the initial investments of the project [3][20]. The RO managerial tool views strategic management as a process that allows decision-makers to actively work to reduce the downsides of risk and capture the opportunities [119]. The application of RO affects managers' views on risk where it changes from an attitude of avoiding it, to one that chooses to minimize or resolve it, leading to the development of new opportunities and other positive outcomes [82].

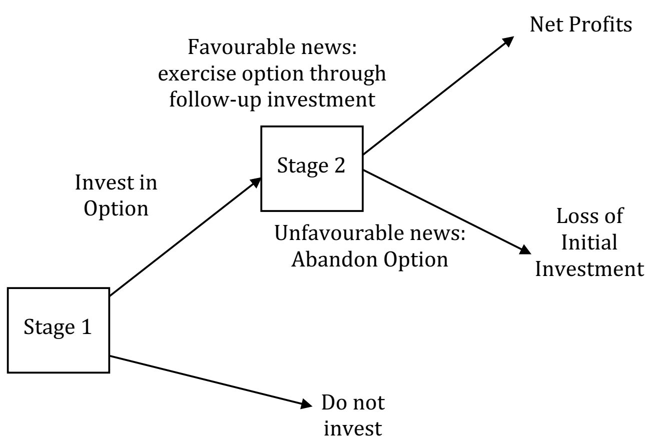


Figure 10. The structure of Real Options [Adapted from [120]]

[22] For example, they could be developing a technology for the "greater good" such as a product that is beneficial to improving the environment.

2.5.2 Real Options Valuation: Financial Options vs. Real Options

It is important to clarify the relationship between real options and financial options and explain the differences. RO apply financial options theory to assess real or physical assets. In financial options, the underlying asset is the stock price [7]. In RO, this can be prices of real assets [7]. Financial options provide investors with alternative choices, where risk averse investors can make a profit, and conservative investors can protect themselves from volatile markets [116].

Table 5. Financial Options vs. Real Options [Adapted from [74]]

Option Terminology	Financial Options	Real Options
Writing the option	Formal contract including legal transaction terms	Initial decision that creates the opportunity. No requirement for formal option contract
Exercising the option	Formally activate the terms of the legal contract	Subsequent beneficial decision in light of the information
Strike price	Transaction price for the option	The decision rule that informs the manager to make the decision
Exercise price	The underlying asset's price when the decision to exercise is made	The cost of making the decision
Liquidity & tradability	Liquid, as markets exist for financial options	Rarely liquid, difficult to trade
Timing	Pre-determined, precise, finite	Can be pre-determined, not-finite and can last indefinitely
Portfolio	A collection of options	A collection of decisions
Underlying asset	Publicly held stock	Tangible and/or intangible assets

Scholes [105] described an option as the security of having the right to buy or sell an asset under specified conditions for a certain period of time. A call option is the right, but not the obligation to purchase, something of value (i.e. stock) at a price that has been agreed on between a buyer and seller [121][79][2][119][122]. The details behind call options vary from market to market. American options can be exercised any time before the date of expiration. European options are exercised at a defined future date [105][97][116][7][106]. There are other option types that exist, such as Bermudan and exotic [7].

A put option is the right to sell something of value at a price that has been agreed on between a buyer and a seller, with the expiration date and option rules specified [116]. An exercise price or strike price refers to the price that was paid for an asset (or fixed share price) when an option is exercised. The final day which an option may be exercised is referred to as the maturity date or expiration date [105][7][94]. A RO is defined as the right, without the obligation to make decisions (such as defer, abandon, alter, etc.) regarding real assets [123][124].

The nature of uncertainties also differs between RO and financial options, where the uncertainty lies in stock prices and the variability of the price of underlying financial assets [119]. Factors that affect the volatility, thus also affect the value of a financial option [79].

In financial option theory, the higher the stock price, the higher the option value. Therefore, when the price of a stock is higher than the exercise price, investors are very likely to exercise the option [105]. If the stock price is less than the exercise price, investors are not likely to exercise, as the value will be close to zero [105]. The value of an option typically decreases as the expiration date nears and if the stock price does not change [105].

In RO theory[23], the value lies in the underlying asset, and if the asset value increases, then so does the value of the RO. Likewise, if the exercise price increases, then the RO value decreases. If the time to maturity is increased, then the RO values are consequently increased [121]. A longer time to expire allows more time to learn about the uncertainties, which increases option value [94]. If uncertainty increases, then so does the RO value, as management can take action and capture this opportunity (and avoid the downside). If the risk-free rate value increases, so does the RO value. Finally, if dividends paid out (by an underlying asset) increase, so does the RO value [121].

---

[23] Defining these variables allows a real option to be valued.

There are two main approaches to real options analysis (ROA), the first one is a market-replicating portfolio method that imitates the payoffs of a project, where the value of a project is valued using the no-arbitrage approach [96][7]. The second approach is the risk-free discount rate method that calculates adjusted probabilities using a risk-free discount rate in order to value the project [96][7]. Both these approaches model the project's uncertainty using geometric Brownian processes or binomial trees [7][96][107].

2.5.3 Types of Real Options

There is a large amount of literature that describes types of options and their details[24]. R&D projects are generally associated with many real options [98], and there is no specific number of real option types that researchers and academics fully agree on [10]. The basic real options are defer or stage, grow, alter the scale (expand, contract), switch, and abandon [125][126]. The specifics behind management's motivation why each option is considered and ultimately exercised is up to them and the opportunity value of the option. The most common ROs are summarized in this section.

Option to delay/defer: if the current technology is not up to par in terms of performance, maturity, etc., then managers can choose to strategically delay a project by a specific amount of time to try and achieve their targets [127]. Management can wait a specified amount of time before they need to exercise [94]. This option is also exercised when uncertainty needs to be resolved, therefore, the value of this option is affected by the uncertainty [67].

Option to abandon (termination): the decision to stop a project is almost always an option [7]. If a technology or project may not meet specific organizational requirements[25] such as market requirements, changes in regulation, under-estimation of required resources or over-estimating potential, then a project can be terminated to avoid additional loss [20][104][127].

---

[24] "Detail" refers to actual specifics of the option. For example, growth option may refer to commercialization, however, commercialization paths are many and this is up to an organization to decide.

[25] Or for example, not meeting TRL target to progress to the next level.

Option to expand or contract: this allows management to make changes such as expand production scale or speed up resource allocation when market conditions are favorable. In the case where conditions are not favorable, then managers can choose to reduce the scales (i.e. contract) [121].

Option to switch: if conditions such as demand or price change (or others), then management can choose to switch resources or shift industries [69]. It gives managers the ability to switch between technologies, markets or products [97][20]. If there is a change in demand, then the type of product produced may be changed (i.e. product flexibility) or the inputs to produce the product may be changed (i.e. process flexibility) [94][121].

Option to grow: Growing typically refers to an increase of commitment or investment to improve a technology's performance [20][69]. This option aims to further develop a technology or build experience [69] and can sometimes be treated as a compound option where future options are chosen and exercised based depend on this option [92].

Other options that could add value to technology projects include:

Stage or compound options: this option refers to staging the investments so that the option to abandon is created midstream if poor information is realized[92]. This is important in R&D intensive firms, capital intensive and start-up ventures [69][6]. This option is a developed form of a growth option, as it has successive stages with increased volume of activity that depends on the previous ones [92]. This option commonly used in R&D as an option to develop a technology may be exercised, then a subsequent option to commercialize[26] [128].

Outsourcing options: reasons for considering this option include cost-cutting, lack of employees or expertise, and enhancing competitive advantage through the expertise of a vendor [20].

License-in option: this option can give early-stage technology projects access to necessary analytical validation methods and saves R&D organizations time and cost [20]. This option allows organizations to identify early stage opportunities [67]. Many factors can delay—or conceal—the need to terminate projects, including personal pride, competitor actions, customer processes, and technology advances. It is thus important to establish the criteria for termination, may increase uncertainty as the technology is a third-party product which may cause problems with technology transfer [20].

---

[26] The nature of the staged option in R&D makes it clear that using the Black-Scholes formula, or any of its variance that allow dividend pay-outs will not be an appropriate method[128].

Collaborate/strategic alliance: this is a strategic option to increase efficiency and reduce risk where organizations may work together to capture competitive opportunities and decrease the downside of risks [67].

It is important to build a bridge between the types of risks and their effects on option consideration (and ultimately selection). The higher the uncertainty, the greater the number of possible future outcomes that must be considered and assessed [3]. If a technology does not look promising for a certain application, then other applications may be possible. Decision-makers are bound by rationality where it is not possible for them to take into account all possible occurrences as a technology develops [3]**.** The following table is a summary of the literature on some of the common risks in R&D and technology, and their effects on the type of options that may be chosen. This is not an exhaustive list and does not replace the need for experts or technology strategists to develop appropriate options.

Table 6. Risks and Options Types [adapted from [69][20]]

Risk Category	**Uncertainty (+/-)**	**Options**
Technology	Technical design (-)	Switch, delay, abandon
Market	Demand (+)	Expand, switch, delay, license, abandon
Financial	Capital & financing requirements (-)	Contract, delay, abandon,
Commercialization	Supply chain & sourcing (-) Regulatory changes (-)	Switching, abandon, strategic alliance Switching, delay, abandon
Organizational	Resource requirements (-)	Outsource, delay, switch, abandon Strategic alliance, defer, abandon

2.6 Real Options Analysis

2.6.1 Applying Real Options: The Steps

Although the specifics behind frameworks developed for each application may vary, the basic method is standard. This section will outline the steps to applying real options analysis. Note that these steps listed are only the computational steps and do not include the steps that would be required for a complete framework for technology and R&D projects (the decision-making aspect too). The steps are as follows [7][129][104][130][121]:

1. Compute the base-case traditional NPV analysis
2. Model the uncertainty (using Monte-Carlo simulations or other) on the base-case
3. Using the information from steps 1 and 2, frame the RO problem:
    a. Identify the options
    b. Select the valuation tool or model (For example: Black-Scholes, using a replicating portfolio [107])
    c. Identify all inputs for valuation
4. Conduct ROA
    a. Apply the model
    b. Obtain the option value
    c. Conduct a sensitivity analysis
5. Report and update analysis

For example, if the binomial model was applied, a general application can be summarized in the following steps [112][131]. A full application will be discussed in Chapter 3 and conducted in Chapter 4. The steps to apply ROA using the binomial model are:

1. Identify all decision sequences, managerial flexibilities
2. Model uncertainties by specifying variables' distributions and random variables
3. Run Monte-Carlo simulations for the models (without the options)
4. Obtain cash flow for each period
5. Estimate volatility of the project
6. Calculate binomial model parameters (*u, d, p*)
7. Build the binomial lattice
8. Add options and solve the tree using the risk free rate (apply backward induction to value option)

The RO valuation models previously introduced incorporate probabilities which are required to be sufficiently reliable [66]. Analysts usually estimate the probability of successful development of a project or a technology from statistics on similar projects when this is available [93]. This is difficult to achieve with early-stage R&D projects, however, it is better to model uncertainty and obtain best estimates of probabilities, as this type of modeling enables management to better choose options for different outcomes [66]. The process of valuing real options has several aspects, it estimates financial gain, but also strategic positioning and knowledge is gained [107].

Any ROA should include a sensitivity analysis as these R&D projects have many assumptions [93]. Examples of common sensitivity analysis variables include [93]:

- Probability of success (of R&D or technology development effort or commercialization)
- Cost to implement
- Market uncertainty
- Volatility
- Expiration of the option

Commonly used approaches to understand how uncertainty behaves include [117]:

- Conducting a sensitivity analysis
- Conducting a scenario analysis (best and worst-case scenarios to understand overall project uncertainty)
- A Monte-Carlo simulation (probabilistic method that assesses the likelihood of each outcome and obtains a probability distribution)
- A Bayesian analysis (to assess the random variables)

As discussed previously, volatility strongly influences the option value of the asset [117], and many of the R&D and technology projects do not have any historical or empirical data to accurately estimate the volatility (and therefore, the probability of success) [117]. However, the literature discusses estimating the volatility with the use of a Monte-Carlo simulation on the base-case cash flow, where a distribution for the project value is produced and the standard deviation represents the volatility [130].

In general, technology projects carry a high amount of technology and market risk, which is challenging to estimate values for the parameters in the model during the initial stages [20]. During these early phases, RO can be naively applied by managers as the uncertainty in assumptions made for variables such as probabilities of success are expected to be high [1].

The use of RO as a decision-making tool has faced many organizational and implementation challenges in practice, as scholars have not been able to encompass the knowledge in an organized and cohesive manner [9]. Another point is that there is no way to actually enforce managers to follow the decision-making options identified [102]. Even though there is the option to abandon, managers may already be deeply invested in the technology and may not want to be recognized as having poor judgement and risk backlash from higher executives [102].

2.6.2 Monte-Carlo Simulations

It is important to discuss the main points and ideas behind Monte-Carlo simulations. More details and steps to applying are discussed in Chapter 3. To counter the uncertainty in the estimations of values in the RO models, a sensitivity analysis is conducted to observe how values change, which can be modeled using Monte-Carlo methods [3]. The name "Monte-Carlo" simulation originated during World War II as a method applied to the development of the atomic bomb [132]. This method is used to solve many problems with stochastic variables in statistics that are not solved analytically [132]. Monte-Carlo simulations are valuable tools in the financial world and in real options [117], and the process is programming- intensive, with outcomes that are hard to verify, as they require rigorous assumptions about probability distributions of the input parameters [104].

Usually, a sensitivity analysis is first performed on the discounted cash-flow model; that is, setting the net present value or ROI as the resulting variable; we can change each of its precedent variables and note the change in the resulting variable [133]. Precedent variables include revenues, costs, tax rates, discount rates, capital expenditures, depreciation, and so forth, which ultimately flow through the model to affect the net present value or ROI. By tracing back all these precedent variables, we can change each one by a pre-set amount and see the effect on the resulting net present value [133]. Input variables to the model are assigned probability distributions. For more information about how to select probability distributions, see [132][7].

The simulation allows continuous distributions to be modeled, resulting in a full range of variability of parameters [132]. The outputs of the simulation provide important insight into the behaviour of variables and may be used as inputs for the RO valuation. A tornado chart is then produced where the most sensitive input variable is shown first. Using this information, managers can then determine which variables are deterministic and which are uncertain. Some of these factors may be correlated, which could require multidimensional simulations. Correlations are often determined from historical data [133].

2.6.3 Real Options in Industry

There are many companies that have adopted real options frameworks as part of their investment methods such as Airbus, GE, Hewlett Packard, Intel, and Toshiba [119]. Hewlett-Packard has employed RO to match supply and demands and the trade-offs between the costs of components and the flexibility [104]. Intel and Toshiba have been using RO to evaluate licensing opportunities, while many companies in Silicon Valley have adopted RO as it has led to increased collaboration between companies [104]. Pharmaceutical company,[27] Merck, has famously analyzed their R&D investments using RO frameworks, allowing them to evaluate their decisions under high risks [104]. They have also used Black-Scholes to value the benefits of joint ventures [109]. Even though the Black-Scholes model is not appropriate for R&D compound options, Merck believed they have enough historical data from their R&D projects to be able to make appropriate assumptions [128]. Shell Oil uses ROA to assess capital projects and their investment strategies and to model for the perfect extraction times for target oil-fields [104].

---

[27] For another application of RO binomial approach in the pharmaceutical industry see [98].

Other industries that have heavily used RO include IT and the energy sector (renewable and non-renewable) [121][134][2][104][94]. Although there are many different applications of RO[28] used in different industries, most have been utilized to value capital investments and project selections. Although useful, this is not the main point of this thesis. For this reason, only the most relevant frameworks related to R&D[29] and technology development (and their risks) will be discussed.

Perhaps the framework that most closely resembles the work proposed in this thesis is Shishko's and Ebbler's framework application [135][136] to NASA's technologies. Their work explores real options and decision-making in a technology context that uses TRLs [135][136]. The model developed targets long, high-risk technology investments up to and including TRL 6 [135][136]. The model is a common framework applicable to the three classes of technologies at NASA: cost-reducing, mission-enhancing and mission-enabling [136]. They discuss the most obvious risks in the initial stages of their development and the expected shift to market risks beyond TRL 6 [136]. They identified that the underlying assumptions of Black-Scholes was not applicable for the early stage projects and complemented their methodology with the use of Monte-Carlo simulations and decision trees to model the variability of their stochastic variables [135] [136]. Their main challenge was estimating the risk-neutral probabilities for these long-term projects, the need for assumptions to be made, and whether NASA as a whole should be risk-neutral [135][136].

Wang et al. [20] developed a RO framework for R&D planning that specifically targets technology-based organizations, and allows managers to identify risks and capture opportunities in three stages. The first stage is opportunity identification, using market-product-technology linkages where market drivers are identified and performance targets are set. The second stage develops the opportunities, where the effects of uncertainties on the technology or performance are assessed and identified in terms of possible options [20].

---

[28] There have been many RO models that have been adapted depending on the application, for example see [93] for a hybrid model developed for risky products. This model splits analysis into financial and technological aspects of the risk.

[29] Looking at R&D as a step-by-developmental process and considering all aspects of risk.

For example, specific uncertainties were analyzed on whether they would positively or negatively influence the project, and a set of options for each potential risk was considered. The third stage is the opportunity evaluation, where the decisions are evaluated and product diffusion speed and its effect on payoffs are studied [20]. The framework accounts for the evaluation of optimal decisions to maximize market opportunities under various demand structures using the diffusion model [20].

This work was applied to an R&D biochip project and results showed that by assessing uncertainties and exploring options to manage them, the expected market payoff increased [20]. Wang et al. emphasize the importance of growing a firm's market research capability in order to fully capture market requirements, and avoid the technology-push approach. They suggest considering the use of Monte-Carlo methods in future research, to fully understand the impact of uncertainties on decisions [20].

The next chapter builds on concepts discussed in the literature review to develop a framework that can be applied by managers, engineers, and decision-makers in technology and R&D projects.

Chapter 3 Development of the ROA Decision Framework

The purpose of this chapter is to develop a real options framework that can be applied across R&D and technology projects. The framework is expected to guide decision-makers into exercising flexibility during projects so that the upside of opportunities is maximized during risky technology development processes. The proposed methods establish the ground work for managers to start thinking ahead, and to consider the challenges and potential opportunities of future stages such as commercialization, in order to create innovative products with a market need. It creates a basic understanding of the prominent risks during development and aims to draw on some of the basic trends and behaviours of these risks during different stages of a project. The trends in these risks are linked to commonly overlooked factors such as resource requirements.

3.1 Framework Methodology

The proposed framework for risk evaluation of a technology development project combines a stage-gate process for decision-making based on technology readiness level with the risk projection method of real options valuation.

The framework describes a process for recommending a small number of options to be placed along the TRL scale and identifies important risks associated with technology projects. The framework also discusses an approach to applying RO valuation methods to guide managers to evidence-based decisions in an individual technology-development project and across a portfolio of projects that may each entail a different level of risk.

The rationale behind using TRLs as opposed to any other maturity assessment approach was primarily due to the popularity of this tool with large organizations (as discussed in Chapter 2), such as NASA and National Research Council of Canada [54] that frequently use it. The application of RO captures the expected value of decisions at different stages of development, using the binomial lattice approach. The remainder of this chapter explains how to select points for determining investment options, how to develop the valuation, and important considerations when using this framework.

This framework can be divided into three phases. The first two phases being largely qualitative, with management screening for appropriate strategies and projects to consider. Defining organizational goals, project milestone planning using TRLs, identifying risks, and conducting analysis are all completed during these phases. The third phase is the application of RO valuation to decision options.

Phase one focuses on defining the problem, collecting data and related information for preliminary planning and analysis. Phase two consists of understanding requirements needed to advance to higher TRLs in the context of the technology and organization. This calls for formal & complete TRL assessments, where technology development phases are described in six general types of activities:

- Scientific research
- Engineering development
- Marketing
- Business development
- Financing
- Commercialization

Critical risk factors are identified and assessed using relevant risk assessment tools. Decision milestone schedules and a plan to collect information to improve estimates as project proceeds (marketing, technology readiness, etc.) are developed. Managers must identify these key risk factors that drive the decisions behind optionalities and affect their overall value. Phase three quantifies the value of different options through the use of the binomial lattice approach. The decisions are valued and the variabilities of parameters are analyzed and discussed.

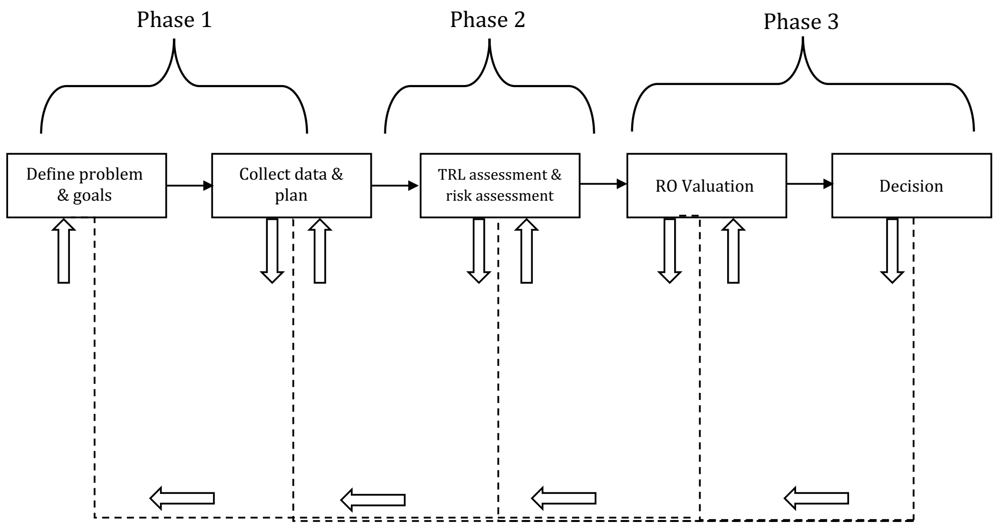


Figure 11. Framework Setup

3.2 Phase 1: Collection of Data & Initial Planning

Phase one gives an overall description of the entire project. Data related to the project description can be a combination of qualitative and quantitative. Managers begin by defining the problem and motivation behind why the particular project will be pursued, and possible project options. Data and information may be collected from various sources, which may include managers, engineers, stakeholders, and investors. In the cases where a relevant or similar project is available, this may be used as a source of data for comparative assessments.

Interviews and surveys can also be used as a method of information gathering. Questionnaires and interviews with managers and stakeholders may be the main approach for information gathering during the early stages. Preliminary project schedules are developed and major milestones can be identified during this phase. Technological area(s) of application and target industries should be considered. Potential R&D team(s) and other key project personnel can be selected, or plans can be made to acquire the appropriate talent. Capital cost requirements and potential financing options may be discussed (if not already secured) and preliminary plans made.

The more information gathered during this phase, the more detailed the TRL and risk assessment can be. R&D data are often limited for high technology projects, and so managers can expect to exercise their judgement and make educated assumptions during these stages.

3.3 Phase 2: Tech Development Stages-gates & TRL Assessment

It is important to use a consistent definition of project development, especially when applying a method of assessment for a range of projects in a portfolio. Phase two begins by establishing the stages of technology development against the TRL scale as part of the framework. Mapping the development helps with the understanding of the type and nature of work in which an organization (and potentially its key partners) will engage in during different TRLs. Figure 12 is a simple illustration that summarizes the major phases captured in the TRL framework. The proposed model maps the stages of development as inspired by the DoD's model [35] and Lee and Gartner's [25]. -

Proposing a very specific framework with too many milestones this early in the research may actually have negative effects on development and take away from the managerial flexibility that has been stressed as an important component to better decision-making.

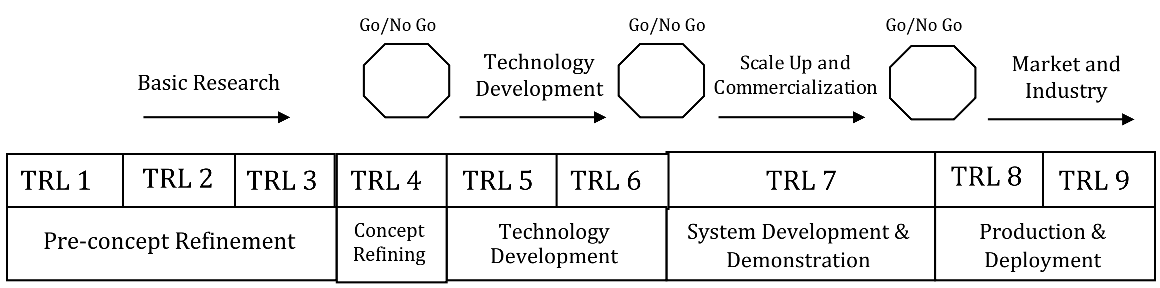


Figure 12. Stages of Technology Development Against TRLs [adapted from[36][25]]

The pre-concept refinement refers to the fundamental research conducted to support understanding scientific phenomenon. The cost associated with resources during these levels are typically low (compared to commercial implementation activities at later TRLs). More resource requirements, costs and the relative risks will be discussed in 3.4. During TRLs 1 to 3, researchers should be in the business of linking scientific and technological advancements with a potential market, to avoid the pitfalls associated with technology-push products. Therefore, early market and feasibility studies are important during this stage, as well as direct contact with first potential users. Concept refinement in TRL 4 refers to applied research where researchers have linked the technology to a potential application and operating environment. TRL 4 is also where the creation of IP assets begins, and patent strategy decisions are made. Industry and competition studies should also be completed during the early TRLs.

The technology development stage (TRLs 5 to 6), is prototyping and pilot-testing intensive. At the end of this stage, the technology should prove to add economic value for its intended application or industry. During these levels, organizations may begin strategic alliances with other organizations of interest[30]. TRL 4 to 6 is a critical period during development as there is a dramatic shift in financial and resource requirements and observed risks. The functional capability of the technology moves from a laboratory environment, to an operational environment, and activities that rely heavily on scale-up. This period is often referred to as the technology "valley of death" and many organizations face great difficulties progressing beyond TRL 6 [56] due to the predominant risk factors in this stage, which is discussed further in the next section.

Nearing the end of TRL 6, a technology prototype should have been successfully demonstrated in a relevant operating environment. Early-stage IP should shift to validated IP, as this has a strong influence on commercialization options and financing and investment activities. A filed or pending patent may be a favorable feature to some investors as it protects aspects of the technology from competitors and may be a "security blanket" as selling the rights to the patent may yield a return [137] if things do not go according to plans.

---

[30] For example, if there is a competitor in the same market, then a strategic option may be to This join forces and collaborate instead of abandoning a project completely or losing to competition.

TRLs past TRL 6 are heavily involved in scale-up work, and aggressively seeking marketing opportunities and other commercialization options. Business development managers and other marketing experts required to fill knowledge gaps should have been hired by this stage. However, building a multi-disciplinary team should begin at early TRLs. By TRL 7, commercialization options should have been considered (and possibly selected). Strategic marketing and distribution plans for technology positioning within an industry should also be completed. This includes market entry strategies as well market penetration plans, and competitive differentiation (if any). Organizations should begin building relationships with key market players and early customers and the community. At the end of TRL 7, the product should have been proven to have commercialization ability. The financing expectations to reach target maturity levels should be explicit and consistent. This is to ensure that the technology can pass through the relevant stage-gate assessments and reviews.

The final stage of production and deployment takes place in TRLs 7 through 9. The technology has been proven suitable for full commercial use (as the technology is now fully implemented and tested). Human and organizational requirements are still high, as new challenges to meet demands arise. Maintaining and controlling IP is important during this stage. Relationships with key market players and users are maintained and strengthened. The social impact of technology should also be considered. Fixing of system bugs and technical glitches is also expected with the launch of a new technology and innovation is continuously driven by feedback from end users.

The framework suggests a minimum of three main stage-gates one at TRL 4, TRL 6, and TRL 7. The framework is also developed with the assumption that organizations utilizing this framework have TRL targets beyond TRL 6. However, this framework can be applied for those that do not wish to commercialize and launch and wish to remain at lower TRLs.

The stage-gates discussed are natural positions where activities, resource requirements (whether financial or organizational) change and management is required to strategize to avoid fatal risks. Stage-gates are logical, reasonable points during to place real options during the project. These gates or logical stopping points are where management should expect to apply real options where their decisions can be evaluated using ROA. Management may choose to add more options as projects progress or risks are recognized, but the recommendation of three options is considered as the bare minimum.

Stage-gates drive decision-making in R&D and empower researchers to make an evidence-based business case for project continuation. In the case where components within a system are assessed to be at different TRLs, then an option may be placed to re-allocate resources and focus on a critical path of a component to advance to higher TRLs, or decide to reach an early decision to abandon the project.

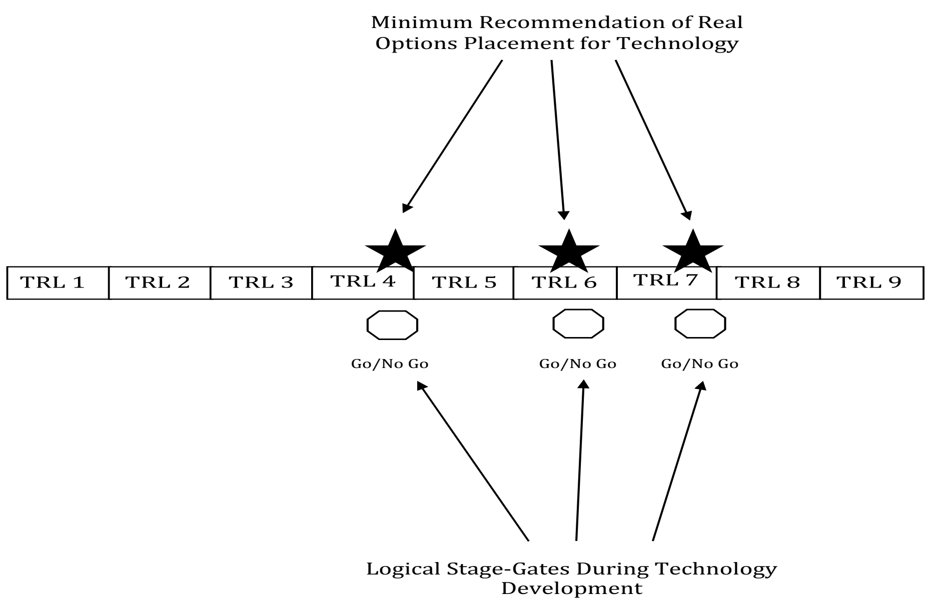


Figure 13. Framework Setup of Stage-gates & Real Options

Completing and documenting a formal TRL assessment is important, however, will not be shown in this framework as any of the assessment methodologies discussed in Chapter 2. Ultimately, the assessment methodology used will be up to management's discretion and must be applied in the context of the technology and the organization.

A sample TRA using the NASA workbook [138] requires organizations to identify alternative routes in the case the technology does not mature according to plans. NASA recommends developing schedules that include milestones, how these milestones will be assessed, and requirements for funding during the first stages to help achieve target TRLs. Potential (known) costs and risks associated with transitioning from early research, to production and beyond, should be identified. This ties in well with the proposed framework as the project plan guides decision-making processes. It also allows managers to consider a variety of applicable options that support technology development.

For completeness, the use of the structured and analysis design technique (SADT) is recommended to be used to help further the breakdown and development of the application of a TRLs. Using these block diagrams can help visualize each TRL as a process with a specific set of inputs, outputs, resource requirements and constraints. These parameters may be specific to a particular technology or firm. For more details on SADT processes, see [139].

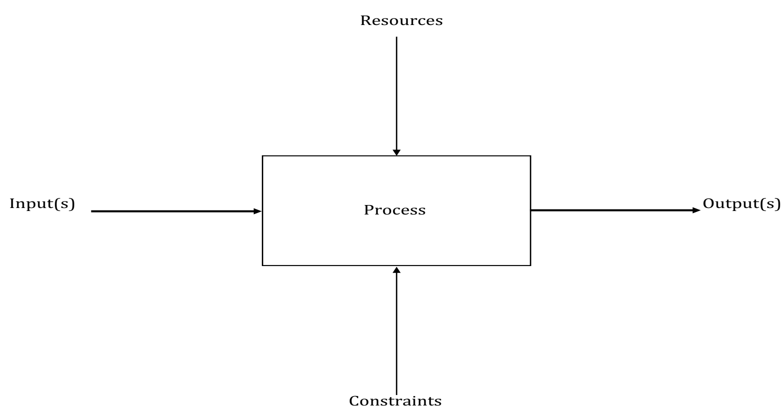


Figure 14. Generic SADT Model

Understanding the activities completed at each TRL and what properly documenting and tracking project progress is important as it can enable better risk identification and assessment during this phase. The next section links the discussion of activities with associated risks and their behaviours and effects on the project.

3.4 Risks in Technology Development

The prevalent risks associated with technology development are discussed in this section. These risks are in no way an exhaustive list but can provide a general frame of reference for managers to be able to understand the behaviours of the major risks at each stage. Decision-makers can use this information when they develop risk mitigation plans and decide on where options need to be placed along the TRL scale. It is from analyzing the literature and understanding the requirements expected at different stages of technology development that these risks were outlined in this section. Figure 15 illustrates the critical risk factors identified for this framework. These risk categories and can be further broken down into specific risks that apply to certain stages of development. Examples will be discussed later in the section. A clear understanding of the stages of development and having clear expectations can lead to a better understanding of risk and the importance of managing them accordingly. During early TRLs, only major risks and challenges are known or identifiable. As the technology progresses to higher TRLs, the assessment becomes more refined and these risks become better understood in the context of the technology of interest.

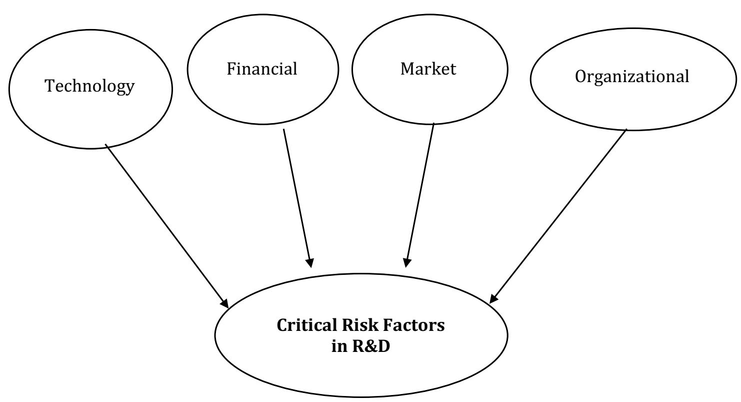


Figure 15. Critical Risk Factors for R&D

Science & Technology Risks: These risks are due to engineering processes, technical design and development. There are many risks associated with this category. They can vary from technical risks such as integration and connectivity of components within a system, contradictory specifications or goals, flawed designs, and technology life cycles.

Financial Risks: This is a major risk category as it can be thought of as the "fuel" for an organization's activities. Capital and financing are important as they are the drivers that will allow technology development to continue, demand to be met, and resources to be obtained and maintained. The need for investors and funding increases as higher TRLs are reached since investment costs go up, as well as the cost of materials and need for human resources begin increasing. Therefore, it can be expected that financial risk will also increase. Financial risks do not disappear as the technology matures, in fact, the goal or an organization should be to control and mitigate this risk to a minimum acceptable level. Financial risks may also increase in the case where patents are infringed, as new costs may arise.

Market Risks[31]: These risks play a large role what technologies actually get pushed through to later stages of development, and which ones have potential market acceptance. The identification of an active market from early research stages prevents technology-push products and reduces the chance of project failure. Examples of market risks include risks associated with commercialization, competitive risk, market demand and structure, production and distribution. Market risks are often overlooked by engineers and managers as prioritization is given to technology risks in the early stages. This behaviour may lead to missing on market opportunities and incorrect assessments due to competitor products and parallel technologies. Market conditions will also determine whether an option can be exercised in time to meet a market window [23]. Customer acceptance and the presence of a receptor market is important. Supply chain management weaknesses, demand fluctuations (which may be caused by other underlying factors such as regulatory or policy changes)[32] can also be described as market risks.

---

[31] Specific risks such as regulatory policies increasing (due to socio-political reasons for example), may add risk in different categories such as market, financial and technological. In this example, market and financial risks may increase and tactics must be employed to reduce risks in different areas.

[32] Regulatory Risks: Could also be called socio-political risks and include safety risks, health risks, environmental risks, industry regulation and policy changes.

Organizational Risks: These risks are characterized by the organizational structure, leadership available, stakeholders, and the organization's culture [72]. These risks result from failed internal processes, including human resources and organizational dynamics. Poor selection of R&D teams, talent acquisition and retention and the domain knowledge of teams during key stages of concept development. Weak protection and management of intellectual property rights can also be a source of organizational uncertainty and weakness.

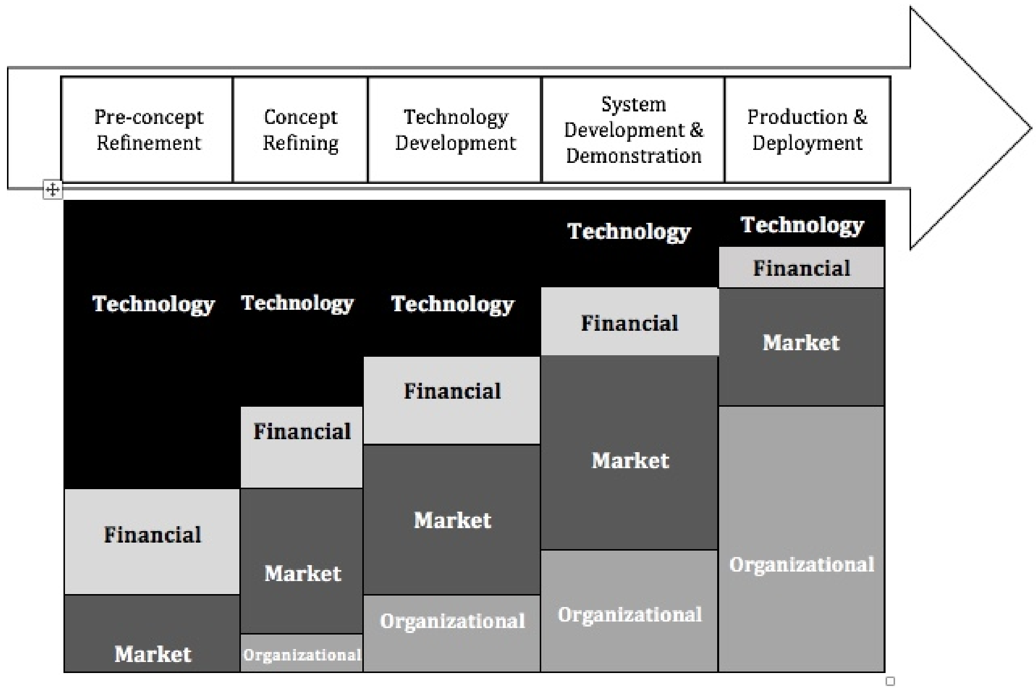


Figure 16. Critical Risk Factors During Stages of Development [Adapted from[140]]

It is important to understand that these risk categories may be correlated. For example, during TRLs 4 to 6, technology development risks should begin to decrease as active learning continues, knowledge is gained, and technical risks are defined and controlled. However, intensive physical modeling and prototyping require large financing requirements, this is turn increases financial risks, since the lack of financing threatens the quality of work and ability to complete tasks required. This, in turn, may increase technology risk since progress may be stopped until financing is obtained. It is critical to note that the consequences of any one of these risks could be catastrophic to the entire likelihood of success of the project, as risks are interrelated. Figure 16 illustrates how classes of risk may change across the stages. The relative magnitude of the classes of risks is not accurately depicted in Figure 16. This is discussed later in this section.

Understanding relative risk creates a frame of reference for determining the effort that may be required to mitigate major risks that change as the project evolves. Technology and market risks are more closely related than one would think, as technical risks are sometimes dependent on the knowledge available about markets since technology specifications are often constrained by market opportunities. Therefore, the more management understands the market, the lower the technical risk may be [78]. Financial risks could also be correlated with market risks, as well as organizational risk. For example, market demand could increase, but because of financial constraints (reduced margins) or organizational inabilities to meet demands, overall profit decreases which in turn increases financial risks. These relationships should be considered when organizations begin to build their profit models during their financial analysis. It is necessary for management to consider suitable strategies during the analysis. The motivation behind the selection of these strategies is out of the scope of this thesis.

Figure 17 illustrates the risk profiles of major risks and their relative magnitudes during stages of development. By the end of the TRL 9, the goal of management should be to reduce the risks where they taper off to an acceptable controlled level. It is valuable to understand how risks behave and the relative degree of prominence as it can allow organizations to better manage these risks and establish resource requirements. Planning is critical in R&D and start-ups because these firms face challenges due to sporadic cash flows, which can cause limitations on their ability to progress to higher TRLs.

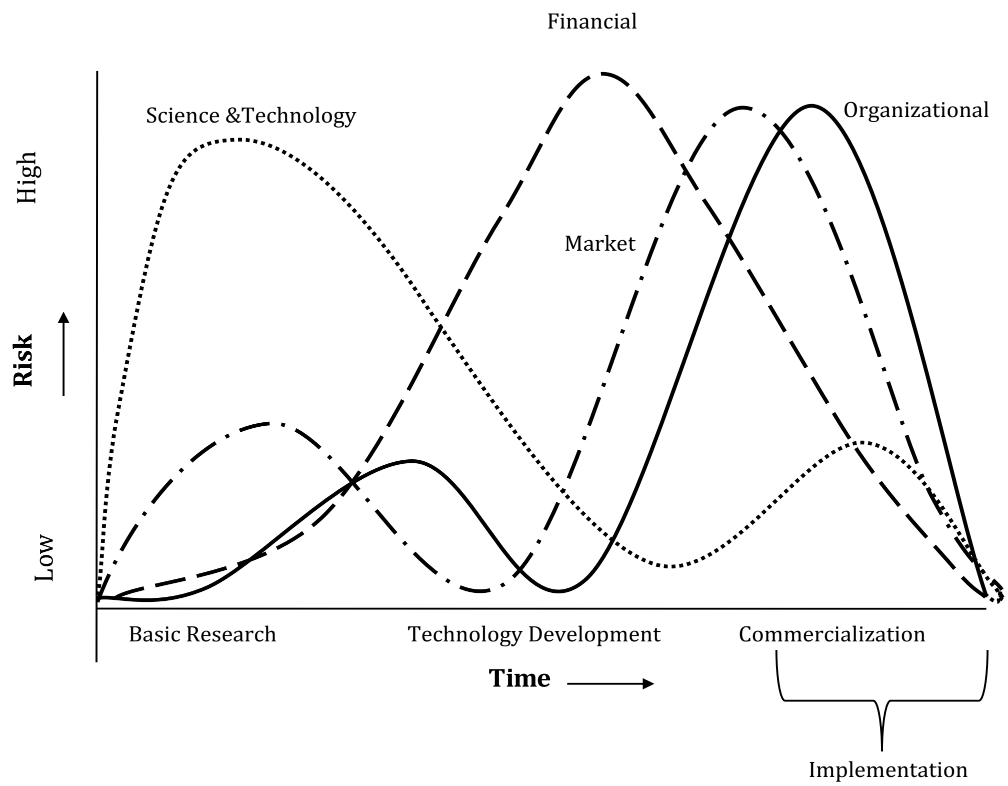


Figure 17. Risk profile of major risks during technology development

Technology risk is expected to be high in the early stages of fundamental research and applied research. The risk of missing a market need, incorrect scale-up, and conflicting requirements exist during this period. Technology risks begin to decrease as technological capabilities grow around TRL 4 and 5. This risk decreases with time and maturity, however at the time of launch (implementation), it can be expected to increase slightly. This is due new system bugs, glitches commonly seen with new technologies [26]. The scale up/commercialization and market entry/production stages reached cause a shift in the nature of risks. Financial risks and organizational risks are expected to increase due to the following: as the start-up tries to grow, this becomes a risky point during the life of the project as having enough capital and access to human resources (organizational) becomes vital. This implicates start-ups to streamline these business processes quickly (lean operations as well) as they have limited available resources. The focus is no longer on technology innovation and knowledge creation, instead, it shifts to product creation and the knowledge domain required and nature of managerial competencies changes. There becomes a need for market expertise where customers are acquired and retained.

The more comprehensive management's understanding of the market and the position of the product, the better the chances to a receptor market, and the higher the value of the product. Therefore, the higher chance to raise capital as investors may have a higher confidence in the success of the technology [141].The gap shown in Figure 18 is described as the "valley of death" and is primarily used to discuss the gap between a scientific breakthrough stage and the commercial-ready prototype stage [78]. The gap is comprised of a variety of factors. The financial gap occurs funding requirements increase, and these are not met or available. Capital is limited and cash flow is irregular and financial risk begins to increase, as discussed. With the shift from science to market driven activities, human resource requirements begin to shift in a similar manner, increasing organizational and market/commercialization risk accordingly.

The risks factors and trends across TRLs discussed in this section are examined on a basic level for general cases. It can be expected that any R&D technology project could face these risks. The specifics around the uncertainties will be determined based on the technology, R&D and marketing team, as well as other factors such as the industry and geographic location (to name a few). It is up to management to construct a detailed risk management plan early on.

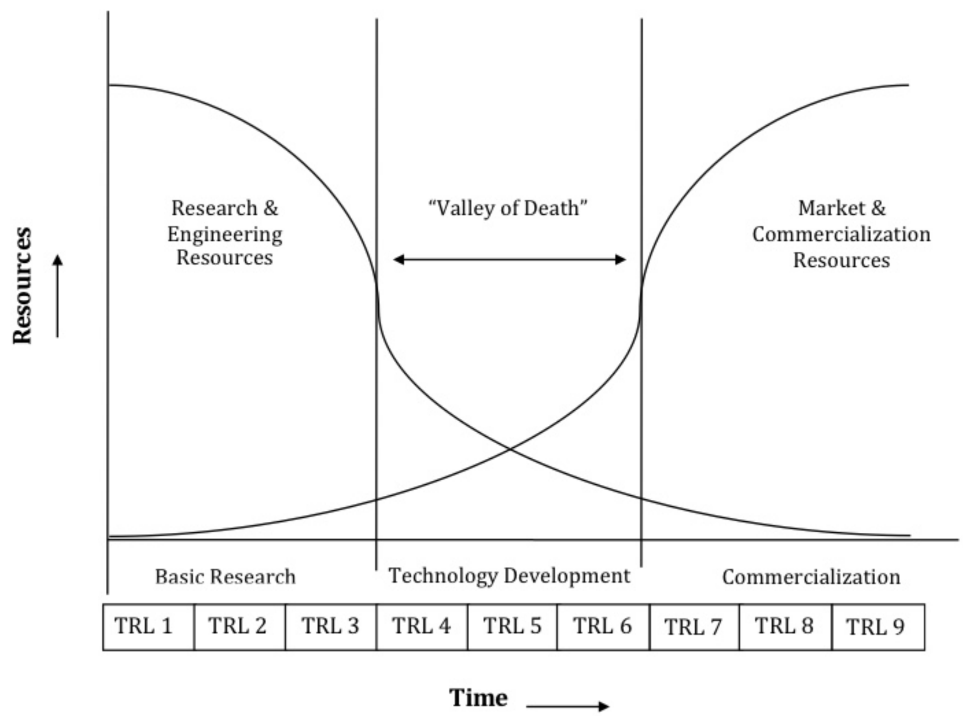


Figure 18. Resource requirements during technology development

Similar to the TRL assessment, it is up to management to construct a plan in the relevant technological context. Risk assessment methodologies such as ones summarized in Chapter 2 could be used in the R&D context. Identifying risks alone is not enough, as they need to be assessed (whether qualitatively or quantitatively) as the impact of these risks will drive managers to place options accordingly.

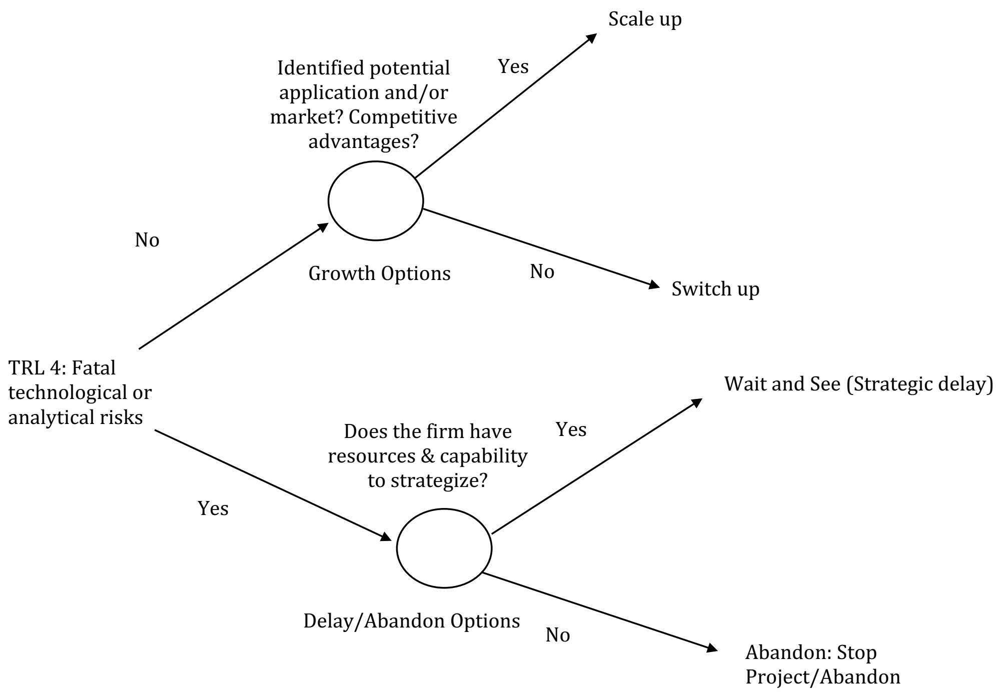


Figure 19. Possible Real Options Considered at TRL 4

In a standard scenario, an organization would reach TRL 4 and an option would be placed and a decision tree would be mapped out. Figure 19 is only an example of the optionalities an organization may choose to exercise. A certain amount of risk is always accepted in order to progress to later stages of development, and depending on an organization's appetite for risk, options can be exercised accordingly.

3.5 Phase 3: Real Options Analysis

The previous sections outlined the qualitative portion of the framework. At this point of the analysis, there should be a basic understanding of the important stages of development the technology will have to go through and the important logical stops that signify the change in the nature of the development and risks associated. With any long and risky high-technology and R&D project, management should establish well-defined connections between the investment opportunity and a real option by properly framing the problem. Then, the option can then be valued [142].

General considerations for RO valuation can be summarized as follows:

- The more volatile a project, the riskier it is and the risk of success and risk of failure are both increased.
- When probability distribution functions are not available from analogous prior projects, expert opinion is used to develop estimates of probabilities.
- Plans to improve estimates as project proceeds should be made and the analysis should be revisited as decisions are incorporated. This approach is iterative.
- All assumptions need to be stated so that discussions with stakeholders are on a common basis of understanding.

3.5.1 Base-Case Discounted Cash Flow & Sensitivity Analysis

As discussed in Chapter 2, the forecast revenues produced through the use of DCF are highly uncertain and unreliable for new technology development projects. DCF calculations are still used as a base-case where assumptions can be developed and applied for the RO analysis. With limited data and financial history for new start-ups and technology projects, accurate estimations and rational assumptions are critical in driving the decisions in the later stages of technology projects.

The valuation begins by conducting DCF and NPV calculations for projects that have passed the qualitative screening [7] and initial planning stages of the technology. Equations used to calculate the NPV are in 2.4.1. The number of years used to forecast, as well as the discount rates used, are up to the discretion of the managers. A particular challenge when calculating DCF is estimating the weighted average cost of capital (WACC) which is often used as the discount rate.

General practice assumes that the entire firm and the project share the same risks, and this approach is not appropriate for innovative technology programs. This means that management must use their judgement in selecting the project's discount rate [110]. Estimating the minimum acceptable rate of return (MARR) for a new start-up is also a challenge in the early stages of a technology when an organization does not yet know parameters such as administrative and overhead costs and do not have any positive cash flow or revenue.

A sensitivity analysis should be completed for the DCF to give a snapshot of the variability of profit and other parameters. The analysis should be completed for key variables, with special consideration to the driving risk factors identified along the TRLs. The sensitivity analysis scenarios chosen by management should be based on the "what-ifs" of perceived risks and their influence the variables. The effects on these variables are then noted and the changes in NPV values are tracked. Sensitivity analysis results may drive the strategic options placed during the course of the project.

3.5.2 Monte-Carlo Simulation

The Monte-Carlo simulation is an extension of the sensitivity analysis where continuous distributions can be modeled giving managers a full range of variability of parameters. The outputs of the simulation provide important insight into the behaviour of variables and may be used as inputs for the RO valuation. The application of a Monte-Carlo simulation can be challenging for early-stage technologies as there is limited information that can be used to produce reliable results. This is discussed in more detail in Chapter 4 of the case study. This is an overview of the application as it assumed the reader is well-versed with basic probabilistic methods. The process is the system model, where the model could be a profit model in the case of many organizations that want to reach higher TRLs. The uncertainty in the parameters is estimated. The assumptions for the "worst-case" and "best-case" scenarios from the sensitivity analysis can be carried and used for the simulation. This can be reflected in the assigned upper and lower bounds of the variables, and other parameters associated with selected distributions. Probability distributions for input variables are often using empirical data, actuarial data or other system models [143]. This can be challenging for R&D when there is no data available.

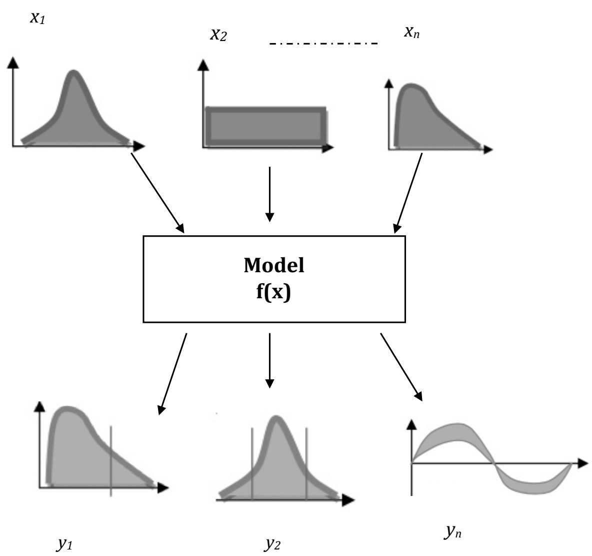


Figure 20. Monte-Carlo Stochastic Uncertainty Modeling [Adapted from [144]]

A simplified method to determine distributions can be done by examining a variable's conditions based on the analysis conducted in the previous stages of the analysis. Distributions are either continuous or discrete. For parameters that can possess negative values such as NPV, a normal distribution can be assigned. For parameters that cannot possess negative values but increase with no limit or become positively skewed, a lognormal distribution may be assigned [129]. For values where minimum and maximum may occur with equal likelihood, a uniform distribution may be assigned. For variables or scenarios where a minimum, maximum and most-likely values may occur (the most-likely falls somewhere between the two fixed bounds), a triangular distribution may be assigned [7]. These distributions do not represent a complete list and are mere examples of the commonly used distributions. However, other distributions may be used. A home-grown simulation tool can be used in Microsoft Excel, MATLAB or any other commercial simulation tool where the number of trials can be selected. The simulation output yields an estimate of the probability of the NPV, a stochastic DCF distribution [143]. As discussed in previous sections, variables may be correlated. These correlations are not accounted for in this framework.

3.5.3 Real Options Problem Framing & Option Valuation

At this stage of the analysis, management should have a good understanding of the elements of risk, their variability and the effect on profit. Action needs to be taken to not only mitigate the downside of the risks but also take advantage of the upswings.

By framing the problem during the qualitative stages of assessment, strategic optionalities at TRLs become more apparent, as more knowledge is gained [133]. A technology development project can be considered as a series of options where each stage is an option on the value of future stages [145] and most developments will have more than one option applicable to them at one stage and all need to be considered during valuation [6][96]. The nature of the options considered at each TRL depends on these risk elements' effect on the model. Managers should be proactive in their approach to R&D planning. The options considered, and ultimately selected, are ones that are deemed to maximize the value of a technology. This could be observed during a short time frame or over a longer period (for example, for the delay option). Ultimately, their goal should be to competitively capture market opportunities, which requires careful consideration of the potential end users and market landscape and warrants market expertise.

This framework utilizes the binomial lattice approach (discussed in Chapter 2), as they are easy to implement, flexible, and simple to explain to management [7]. In addition, most managers without technical training in real options would find the binomial tree representation straightforward and the modeling of problems to have a more intuitive appeal, as well as the ability to include underlying uncertainties and aligning the options more easily than other approaches [110]. Figure 21 is a representation of a simple binomial lattice that is used to value an option.

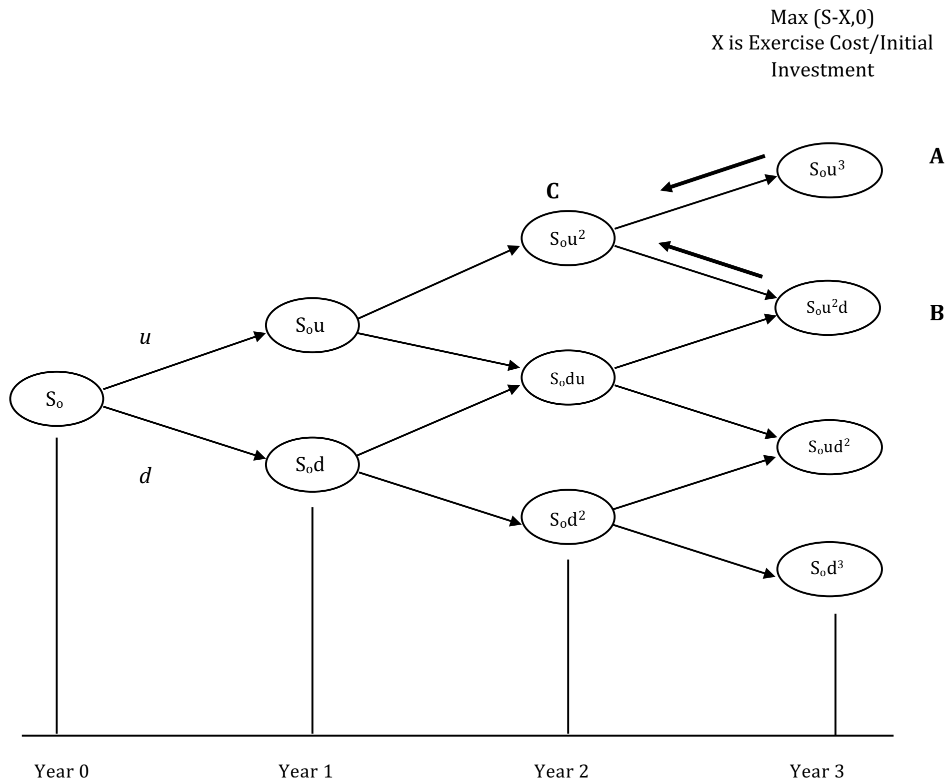


Figure 21. Binomial Lattice Example

There are two important calculations that will be completed during the analysis. The first step is to determine the value of the underlying asset. This is done from the left to the right to illustrate how values can change with time. The first node, S_o, represents the NPV calculated from the DCF. The DCF used at this point is the updated one that reflects the changes made as new information was obtained from the previous steps of the analysis. The nodes to the right represent the possible distribution of future values, and the last nodes represent the range of values at the end of the option life [103]. These values are calculated by simple math using *u* and *d* as multiplication factors. The upswing value, *u*, is always a value above 1, while the downswing, *d*, is always less than 1. Section 2.4.4 presents the equations for *u, d*.

Using the binomial model to calculate values such as u, d and p(s) is challenging for early stage R&D projects. These values are a function of volatility, which cannot be calculated for most innovative technology projects. From volatility, the probability of success, p(s), can be estimated. Because of the limited data available for these projects, management should expect to estimate the probability of success during the early stages. At low TRLs, estimating p(s) = 0.5 may be accepted by some managers and investors. The entire premise of strategic RO application is to drive the value of the project with time. This should overall improve the conditional probability of success in the later stages. This is very important as market risks become more dominant during the later stages and if improvements in p(s) are not observed, abandonment becomes an option.

The next step is the lattice valuation – also referred to as backward induction [112] (arrows going right to left from the top right node shown on Figure 21). This process determines what the optimal decision (or option value) is at each period [112]. Each terminal node has values of the maximum of zero and the difference between value S and exercise cost X (or investment cost), where MAX (S – X, 0). If this difference between S and X is negative, then this is zero and considered as an abandon option. This is done to each pair of vertically adjacent nodes reveals the option value at the very left end of the lattice.

When estimating values such as the probability of success, it can be expected that this will be low at lower TRLs. The value of exercising an option and accepting the risk, is a strategy to lower risk as the technology progresses along the TRL scale. Thus, intuitively increasing value for the probability of success. Closer to implementation, the probability of success becomes more understood than that in the exploratory phase. Estimates of the likelihood of successful development of a technology can be estimated from statistics, and data from comparable projects within a portfolio, which is more likely in a large R&D-intensive organization. In the case where this is not possible, seeking expert advice is a common practice to obtain these estimates [93].This is an iterative process and as more information becomes known, calculations and assumptions should be revisited.

Other considerations are to develop metrics for non-economic factors that influence an organization's reputation. This is of particular importance for government research organizations and smaller start-ups that need to build relationships with clients and their respective communities.

Unlike financial options, ROs do not have expiration dates. Generally speaking, managers should be able to estimate a time-frame for when the decision needs to be made and because of changes in business conditions, competition and technology, check points throughout the project are needed, and should be placed accordingly [104][103]. This strengthens the framework's need for options to be placed (at least) at stage-gates identified in the previous section.

Similar to the sensitivity analysis conducted on the DCF, managers should analyze the variability of the option. The value in this analysis it will help estimate the range of the benefits, the probability of success of the research effort, the cost to implement, and the market uncertainty.

The outcome of the entire RO analysis should give justification to managerial decisions to invest in a technology, despite a negative NPV. This can also allow for better resource allocation across a project or portfolio.

Chapter 4 Application to Case Study: Copperstone Technologies

This chapter is a case study on Copperstone Technologies (CST), where the proposed framework will be applied. The chapter will begin by introducing background information related to the case study. The analysis will be divided into three phases. Phase 1 will discuss how relevant information was collected and summarize the data. Phase 2 will discuss the results from phase 1, outline major risks, and discuss current technological maturity. Phase 3 will apply RO thinking in order to assess decisions at key stages of the project.

Not all aspects of the proposed framework were formally completed. This includes a formal documented risk assessment and a TRA. This was due to the limited access to data from CST and what information they were willing to share for this thesis. Despite the limitations, critical risks were identified and discussed in 4.2.2. The analysis will conclude by discussing some of the limitations of the calculations and assessments and how they could be improved for future applications that are specific to CST.

A short section of this chapter will briefly discuss how the framework could be applied to a project within a large portfolio at National Research Council of Canada. Unfortunately, a full analysis could not be completed as there was no information available about the technology, projects or portfolio. Important points about how the framework can be used as a comparative assessment tool within a portfolio will be discussed for future applications.

4.1 Phase 1: Data Collection & Background

The main challenge of the analysis for this case study was collecting enough data. Available information was very limited and CST was going through many changes within their company, where new talent was being acquired and investors were aggressively being sought after. This made it difficult to obtain information efficiently.

The main method used for information gathering was through informal discussions with CST's Chief Technology Officer (CTO)[33]. These discussions helped shape the optionalities considered and the estimated values. The remaining portion of data collected was through a meeting with CST's business development manager, and a thesis published by one of CST's founders. The thesis discussed details around the technology developed and some of the team challenges. Any other miscellaneous information was obtained through online sources from CST's company website.

4.1.1 Company Background: Copperstone Technologies

Copperstone Technologies (CST) is an engineering start-up founded in 2014 by three University of Alberta students. CST currently develops amphibious robots (AR), they also offer electrical, mechanical, and consulting services related to the field of robotics. CST currently has office locations in Edmonton and Calgary, Alberta, Canada. The current team is comprised of four founders, and a business development manager – who is responsible for all marketing, sales & business strategy related work. A full description of CST's current team bios and the positions they are looking to fill in the near future are in Appendix 2. CST is currently developing strategies for future growth opportunities in marketing and sales, customer service, and product development. A summary of their timeline of activities is in Appendix 2.

CST's main product offering is the AR technology. This technology allows access to soft and wet fresh tailings ponds that are inaccessible using current sampling and measuring equipment. The rover is unmanned and therefore poses a lower risk to personnel safety when compared to traditionally used equipment [146]. The AR technology also requires less personnel support overall and provides autonomous operation for sampling and measurements. The AR can be used for seed broadcasting and planting for reclamation, and tailings mapping and monitoring. CST's main potential customers are oil sands producers, and they are looking at applications that target customers in the mining, gold and potash industry [147].

[33] CST's current CTO is Dr. Lipsett.

CST has been awarded one patent for their "Soft Soil Sampling Device and System" on June 16, 2016. The scope of this patent protects a device collecting surface samples needed for calibrations for other instruments and to measure tailings' properties. The patent also protects the method of deployment. They also have another pending patent filed in 2016, "All-terrain Vehicle", which protects the frame, instrument deployment and drive configuration, and any modifications to the drive system. CST plans to acquire more patents as the technology develops further. The aim is to protect all new drive and control mechanisms for operations in soft terrains, autonomous operations of robots and their instrumentation for monitoring and data processing algorithms [146].

4.1.2 Interview with Business Development Manager

A meeting with CST's current business development manager was conducted. This meeting was valuable as it revealed information about CST's future growth plans, marketing, and sales targets. Some of the key takeaways from the meeting were:

- The largest risk is poor revenue generation.
- Latent causes of potential failures were discussed. Competition, market scale-up, and legal regulatory requirements were concerns.
- The initial market analysis conducted was almost non-existent. Now requiring a rigorous approach to size the market and acquire (and maintain) customers.
- CST is currently looking for investors.
- Conflicting team goals is a large risk. The risk of founders leaving may be unfavorable to investors and can be seen as unstable.
- Market scaling of AR has been a concern for CST.
- CST is currently considering the following commercialization and market positioning options: sales of AR units, licensing of IP, or environmental monitoring.
- An informal market risk assessment for CST's current positioning was done. There was no formal documentation.
- CST is currently field testing with almost all components fully integrated within the system.
- CST has one competitor in the environmental monitoring market in the oil sands.

The ultimate goal is to the penetrate the Alberta tailing ponds market and grow the company while continuing to innovate. There was no information obtained about CST's sales and revenue targets. Maximization of profit potential was an important factor for CST. Therefore, a consistent revenue stream is preferable. Selling AR units may not be the most viable opportunity for CST due to potential inconsistent revenue associated with sales. The organization does not have any current plans, or the resource capability to expand to other markets at this time. This, however, will be considered in the future. Current AR units are built in-house, but CST may source manufacturers depending on the demand and chosen commercialization path. The business development manager was only recently hired, this indicated that there were no real market considerations or studies done. CST plans on expanding their human talent base and plans on growing the team. There is also a need for funding in order to grow and CST has been working to try and secure future funding. CST also has plans for new versions of the AR, with an expanded range of applications. This could bring CST a new competitive advantage and can allow them to remain innovative. These future applications will not be considered in the analysis. Managerial visions and goals were discussed, as there was a difference in opinion between the founders on the best commercialization path for AR. Major risk factors that affect successful commercialization were discussed. More on these risks in 4.2.2. A sample of the interview questions is in Appendix 2. These questions are by no means an exhaustive list, but they do summarize some of the questions that were asked.

4.1.3 Information from Relevant Sources

Other sources of information used included a thesis published by one of the founders of CST, which involved a case study on the AR project [148]. Detailed notes from the thesis are presented in Appendix 2.

Some of the key points from the case-study included:

- CST's business model was not developed at the beginning of the project. Although commercialization models considered included: sales of AR units, rental of AR units, leasing to operators, or monitoring services.
- There was high uncertainty in requirements and technical risks because CST failed to properly plan, collect data, and assess the operating environment. This led to a decrease in the technical success of field trials conducted and resulted in field-testing being delayed. This caused delays in the schedule and budget overruns.

- No formal market analysis or verification of market conditions was conducted. CST's initial market analysis was completed using qualitative data from a small data set. There were many uncertainties related to the market as there was limited understanding of the required technical specifications wanted by customers. CST collaborated with potential customers through informal discussions to try and estimate these specifications. The potential primary market for ARs is in environmental monitoring, with only a small number of potential clients, but a large amount of potential application (land).
- There was no formal risk management completed during design. However, safe work practices and risk mitigation were conducted during fabrication and testing.
- The project funding came internally from within the organization. Therefore, available funds were limited.

Conversations with CST's current CTO also revealed that CST's AR project began at around TRL 4 and is currently about to enter TRL 7[34]. This was achieved through an informal TRL assessment. Basic financial projections were obtained from CST for the ROA. The values shown in the work done in this section may not reflect the true values for the AR project as CST did not share all their financials for this thesis. CST's financials are discussed in 4.3.

4.2 Phase 2: Current TRL and Critical Risks

This section assesses the information and data collected from phase 1. As previously mentioned, no formal risk assessment or TRA was conducted. However, it was recommended to CST that formal assessments be completed and documented. The assessment process should identify alternative routes in the case the technology does not mature according to initial plans. TRA and risk assessments should be conducted throughout the project and not just at stage-gates, although those provide a general recommendation of when project progress needs to be assessed.

[34] As of July 2017.

4.2.1 AR Current Technological Maturity

Figure 22 illustrates CST's initial maturity in 2014 and their most current TRL position as of July 2017.

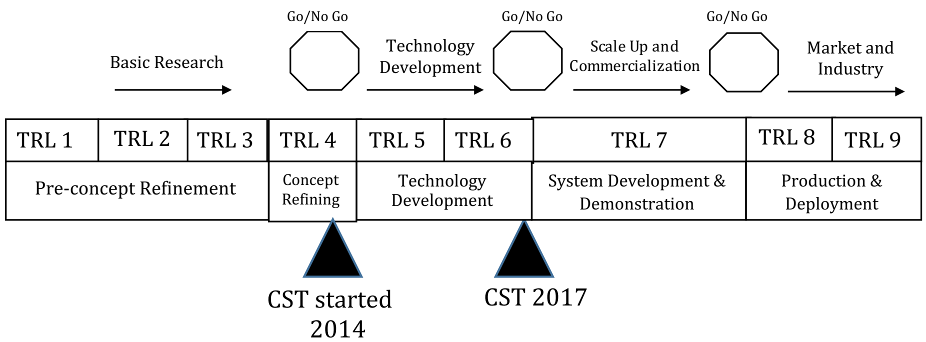


Figure 22. CST Current TRL Positioning

CST's AR project began at around TRL 4. This was determined and confirmed through meetings with their CTO. ROA will be applied at that stage-gate. This will be done for demonstrative purposes and to provide a discussion of the common factors that may be considered during those stages of development, and how they could influence the overall success of the project. This can provide insight to important information that may have been overlooked in the past.

CST's AR is designed around a multiple screw drive propulsion system, and the initial proof-of-concept system is battery powered with an electric drive that allows control of the motor. It also allows for design of assumptions during the process of proving the system [146]. Some of the activities conducted during the technology development stage between TRL 5 and TRL 6 included developing seed broadcaster and seedling planting mechanisms and development of the industrial controller for teleoperation. Screw-drive cleaning mechanisms and a new drive system to improve mobility on frozen sand and other conditions were also activities completed during this phase. Some of the most recent activities related to mudline monitoring included: system integration and mapping, testing of long-term deployment for remote monitoring, as well as autonomous data analytics and reporting.

As of July 2017, the AR project is in the system development and demonstration phase, about to enter TRL 7, where some of the field-testing has been completed. According to the proposed framework, CST is at the second stage-gate where they would consider (commercialization) options that would support progress to higher TRLs.

Future R&D activities for commercial prototyping will include optimization of the screw-drive propulsion system, innovations for long-term reliability for longer operational durations and sampling and deployment capabilities. In addition, CST plans to use higher density power sources. There was no formal timeline provided by CST, however, the aim is to have an initial launch for AR with monitoring system analytics capabilities between 2018 and 2019 and another launch of AR for deep deposits and longer durations around 2019. As for development requirements for the next 2-4 years, CST predicts fabrication resource requirements will need to be expanded, and a larger shop may be needed. A laser cutter, mill, and welder will be required for any future prototyping and assembly work. CST predicts that only one shop employee will be needed. Any other fabrication or manpower requirement that is not supported by CST's capabilities will be outsourced. For short-term requirements, CST requires a part-time electrician, as well as a technologist that will be needed for manufacturing and production needs.

In addition to the increase in resource requirements, additional funding will be required. CST is currently seeking new investors. The need for marketing expertise has also been recognized at this stage. CST's business manager is formulating growth strategies and strategies to keep CST's competitive advantage within the niche market of oil sands. Commercialization options have been identified but not yet selected. More on each option will be discussed in 4.3.5.

4.2.2 Critical Risk Factors

The general risk categories are financial, science & technology, marketing and organizational as discussed in Chapter 3. In order to better frame the problem to identify the critical risk factors, it was important to assess the information from the interview, conversations and other materials. CST's ultimate goal was to launch the AR technology into the market and generate a profit. Although there had been discussions about possible commercialization paths (i.e. whether they wanted to sell their units, license, etc.), the choice was still unclear. This is where the value of ROA is captured. These commercialization options can be valued so that an evidence-based decision can be made. The main risks that are considered to have a direct impact on profit are discussed in this section. These risks are not an exhaustive list. They are, however, the most important as viewed by CST's team at this point in time (i.e. at the TRL 6 stage). Table 7[35] gives a brief representation of two of the risks identified and their effects on profit.

A factor that has a substantial effect on the market risk for the AR project are regulatory laws. Provincial and federal laws should strongly be considered. If regulatory policies regarding tailings are increased, CST could potentially see an increase in the customer demand, as the technology currently falls under the category of compliance industry. Conversely, if the policies are no longer strict and are reduced, the market for ARs can expect to dramatically decrease. It is important for management to be proactive for future development and applications of this technology. CST must strategically plan to position their AR technology for operational use, where the technology is critical for improving efficiency and performance, as opposed to being in the regulatory monitoring and compliance space.

[35] This table does not accurately reflect full the extent of how multi-dimensional risk elements are and how they may affect one another. This addressed in this section. A sensitivity analysis can help better understand the behaviours of these risks.

An area of concern for CST at this point is related to scaling-up, as there are three aspects to consider. There is a need for the design process to encompass a physical scaling of technology i.e. from lab to operating environment. There is the market aspect of scaling up, where suppliers, manufacturers and distribution channels need to be considered. Finally, there is a performance related scale-up where design complexity is accounted for.

Competition in the market is also an important factor that was identified. Because financial risks are also dominant throughout the project (since R&D is capital intensive), there is the concern that if CST does not commercialize within an appropriate time-frame and capture current market opportunities, AR technology replicas may arise and damage CST's future plans to launch. Financial constraints are an important risk identified that may delay technology growth and delay commercialization. Financial risks are currently being mitigated as CST tries to acquire funding and plan accordingly. It is also important to be aware that each commercialization option will come with its own risks and challenges. Distribution and supply channel constraints are also another risk that may delay or prevent successful commercialization of technology to end users. In order to mitigate this risk, CST is collaborating with service companies for their prototyping and field-trials, in hopes of having better access to customers.

Demand is also another important factor. It can also be linked to regulatory policies and competition. For example, demand may become lower if competition is high. Demand may also decrease or increase depending on how government regulatory policies change. If they increase, the demand can expect to go up, if they loosen the policies then demand may decrease. This is a very one-dimensional way to look at how variables may change as it ignores the effects of other possible variables. To elaborate, demand may be high, however, profit may still decrease due to CST's reduced margin or inability to meet demand. A sensitivity analysis or a multi-dimensional Monte-Carlo simulation can be used to better understand how these variables might affect one another.

Table 7. Example of Possible Effects Risk on Profit

Critical Factors	Change	Effect on Variable(s)	Potential Strategy
Regulatory Policies	Increase	Demand increases, expenses increased, profit increases	Selling price increased
	Decrease	Demand decreases, profit decreases	Pivot to operational positioning instead of regulatory
Competition	Increase	Demand may decrease, profit decreases	Market strategy for new start-up is to offer discounts
	Decrease	Demand may increase	Higher prices, monopolize the area/industry

Technology development risks are still important during this stage of development, however, less prominent as CST begins to shift from knowledge creation to product creation. CST has passed the "valley of death" at this point. However, there is always a risk when new improvements are added to the technology. CST hopes to add updates to their design in order keep their competitive advantage in the industry. In order for them to accomplish this without having large costs, they developed a design that allows for easy modification without the need to make significant changes to system design.

Other factors such as customer relationships and reputation within the community may also be a factor. However, for CST, this is not a critical issue as they have built strong relationships (some further along than others) with operators in the Alberta oil sands and do not consider this a risk at this time.

4.3 Phase 3: ROA Application

The application of ROA to the AR project assesses decisions at two stages-gates. Although TRL 4 was reached in the past, ROA will still be applied at that stage-gate. This will provide a discussion on key factors associated with this stage of development. At the TRL 6 stage-gate, options should be valued by CST where the decision on whether commercialization costs will be paid out right away or whether timing of the investment (waiting) may be an option. The trade-offs between proceeding right away or a choosing to wait can be a considered and evaluated.

4.3.1 ROA Problem Set-up

The following were assumptions and considerations applied during the entire analysis. These will remain consistent and be carried to the next steps of the analysis. Any changes to these assumptions will be noted in the relevant sections. The general assumptions and considerations are:

- All the financials are based on information provided by CST. The base financial evaluations will not be changed (i.e. CST's estimation for expenses, gross revenue, etc.). This is because there was not enough information provided for this thesis. Therefore, it is assumed that CST's current plans, which may include field-testing with customers, new R&D investments will continue as originally planned. The ROA will add on to the base financials for CST (i.e. costs associated with options will be added to the original estimated expenses).
- All revenue and expenses from consulting activities were omitted from the analysis. This is not a core element of the AR project, and the revenue is considered minuscule compared to potential revenue from AR.
- Equity and financing were also ignored during the analysis. This is mainly due to unavailability of information about CST's current and previous financing activities.
- Year 0 at 2014 is the founding year of CST where they began at TRL 4. A WACC of 15% was used and a MARR of 20%. The WACC and MARR values were selected based on CST's business manager's recommendation. A nine-year cash flow was completed. There is no underlying reason why nine years were selected, this was CST's preference.

- The expenses at early TRLs (starting at 2014) include mostly R&D expenses, incurred expenses for materials and equipment. At medium TRLs, at years 2017 and beyond, the nature of expenses would begin to shift from R&D to activities that involve engagement of other companies and a projected revenue and estimated expenses. These activities included field testing. Expenses related to patenting were also incurred, as well as other professional fees. These expenses are all reflected in CST's financials.
- The technology life cycle of ARs was ignored during the analysis. This was mainly due to the limited information provided about the technology.
- Taxes and inflation were ignored in the calculation. This was done in order to simplify the calculations presented in this thesis.

4.3.2 Base-case DCF

DCF is used as a base-case where estimated values and assumptions can be determined and applied to the RO application. With limited information and no historical data for CST, estimations and assumptions can have serious effects on the decisions in the later stages of technology projects. These assumptions can influence the value of an option, which may ultimately drive the decision. Based on the general assumptions and considerations in 4.3.1, a DCF was completed. A summary of the cash flow is outlined in Table 8.

Table 8. Base-case DCF Results

	Year	**FV**	**PV**
0	2014	($121K)	($121K)
1	2015	($37K)	($33K)
2	2016	($39K)	($30K)
3	2017	($30K)	($18K)
4	2018	$336K	$162K
5	2019	$1.40M	$564K
6	2020	$2.31M	$773K
7	2021	$2.96M	$827K
8	2022	$4.03M	$938K
WACC	15%		
MARR	20%		
Income	$3.26M		
NPV	$3.06M		

At first glance, the positive NPV looks promising. However, this is not a reliable source of information for a young start-up such as CST, and an innovative technology in its early stages, such as the AR. This calculation assumes there will be no changes throughout the developmental process as the company grows and the technology matures along the TRL scale, which is reflected by the constant discount rate. This analysis does not take into consideration possible challenges that may arise during the course of the project, and the effects of decisions made related to development and commercialization. For example, CST does not currently know which commercialization path they will pursue. Each option considered will require different conditions. Selling of AR units will require different resource requirements than the IP licensing option. Therefore, it is naïve to assume that decisions made during the project will yield the static results in Table 8 and have no effect on operating costs and income.

Another issue with the DCF and NPV estimates is the value used for the MARR. The choice in value for the MARR was subjective. When discussing this with CST's business development manager, the argument was CST is at a very early stage and there is no MARR at this time. This is attributed to CST not knowing any of their parameters (such as overhead costs), and are estimated to the best of their abilities. This strengthens the argument that these values cannot be considered accurate estimates.

Despite the unreliability of the DCF and NPV values, the results from the DCF should not be overlooked, as they are used as a base-case calculation for the RO analysis. From the DCF results, a well thought-out sensitivity analysis can be produced, which will provide CST with insight on the variability of parameters.

4.3.3 Sensitivity Analysis & Monte-Carlo Simulation

A sensitivity analysis is valuable as it provides managers with a tool to better understand how factors may influence profit and decisions made during the project. For CST's analysis, a scenario analysis was chosen over the Monte-Carlo simulation. This is mainly due to unavailability of information on parameters and their value. Instead, a three scenario analysis was an appropriate and acceptable analysis for CST. They were more interested in the bounds or limits of the cash flow values based on the main variables. A Monte-Carlo simulation could have been easily applied, which is why it was fully set-up in this section and will be explained. Although a Monte-Carlo simulation was not completed, there was insight from setting it up. It gave perspective on how some of the parameters could behave and how they might be related to one another. The thought-process of how the sensitivity analysis was completed as outlined in this section.

The sensitivity analysis calculations began by first considering the risk factors that were identified in 4.2.2. CST's goal is to maximize profit. This meant that all major parameters needed to be carefully examined. Demand was an important factor as it ultimately could be affected by competition, regulatory changes, and other socio-political factors such as community trust and reputation. Therefore, these factors also have a direct effect on any of the gross revenue obtained from AR operated activities. If any of these factors change, they may cause CST to increase or decrease their costs of services accordingly. Operating expenses were also a significant factor that may affect profit, as any increase in expenses may reduce profit margins. A simple profit model that described these parameters was assumed to have fixed indirect costs as follows:

$$Profit = (Selling\ Price - Expenses) \times Demand - Fixed\ Indirect\ Costs$$

Where the units are as follows:

$$Profit\ is\ in\ \$$$

$$Revenue\ is\ \$/AR\ Unit$$

$$Expense(s)\ is\ \$/AR\ Unit$$

$$Demand\ is\ AR\ Units$$

$$Fixed\ Admin\ Costs\ are\ in\ \$$$

The revenue specifically refers to that from operations involving AR. The source of AR revenue could be due to several options. Depending on the option CST chooses to exercise will influence the profit model accordingly. Examples of potential sources of revenue could include selling or renting AR units to operators in the oil sands. All of these options could also include a source of income from technical support provided to customers.

The next step was to examine the variables and assign each a probability distribution. Administrative or fixed indirect costs were assumed to be constant. Demand is a discrete variable and was assumed to follow a triangular distribution. There would be a maximum number for demand on AR units or services, a minimum value and an estimated most-likely value that would lie in between those two numbers. The minimum value would logically be a demand of zero. Expenses per AR unit and gross revenue were both said to follow normal distributions. These insights helped with the understanding of some of the parameters and shape the sensitivity analysis. Three scenarios were analyzed. Each scenario calculated a "best-case" and "worst-case". The results are summarized in Table 9 and a tornado diagram is shown in Figure 23 The NPV was calculated for the following scenarios:

1. Capital costs and costs related to AR were increased and decreased by 20%.
2. Gross revenue was increased and decreased by 20% (i.e. demand or sales increase).
3. A MARR of 17% and at 23%.

Table 9. DCF Sensitivity Analysis Results

Expected NPV				Input		
Variable	Downside	Upside	Range	Downside	Upside	Base Case
AR Expenses	$2.80M	$3.22M	$340K	$2.63M	$1.75M	$2.19
MARR	$2.57M	$3.65M	$1.08M	23%	17%	20%
Gross Revenue	$2.25M	$3.87M	$1.61M	$10.60M	$15.89M	$13.24M
CF Year 0	($135K)	($106K)	$29K	($135K)	($106K)	($121K)
CF Year 1	($40K)	($25K)	$15K	($46K)	($29)	($37K)
CF Year 2	($32K)	($29K)	$4K	($42K)	($37)	($39K)
CF Year 3	($41K)	$1K	$42K	($62K)	$2K	($30K)
CF Year 4	$104K	$220K	$116K	$216K	$456K	$336K
CF Year 5	$423K	$704K	$281K	$1.05M	$1.75M	$1.40M
CF Year 6	$589K	$957K	$368K	$1.76M	$2.85M	$2.30M
CF Year 7	$631K	$1.02M	$391K	$2.26M	$3.66 M	$2.96M
CF Year 8	$729K	$1.15M	$419K	$3.13M	$4.93M	$4.03M

A major limitation of these results is that they are based on estimated values that may not be accurate. However, there is still value in this tool as it allows CST to better understand how some of the variables might behave under certain conditions. This sensitivity analysis also fails to properly define relationships between the variables. As mentioned in Chapter 3, multidimensional relationships between variables will be ignored for this thesis, however, is recommended for future applications.

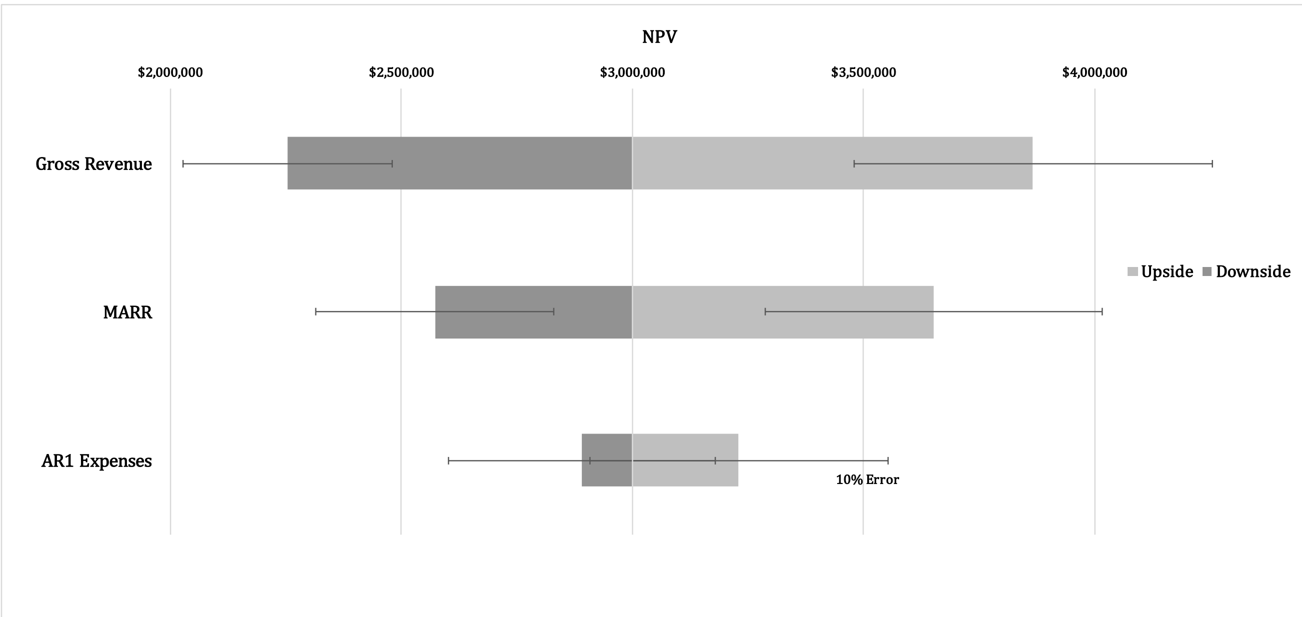


Figure 23. Tornado Diagram Range of NPV Results

A Monte-Carlo simulation Microsoft Excel template can be used to conduct this analysis. Using the random number generator in Excel, the function RAND(), would easily simulate the range of profit values. Values then can be easily categorized according to those below zero or greater than zero. The resulting profit's probability distribution will yield valuable information about the mean and standard deviation.

4.3.4 RO Valuation at TRL 4

As previously discussed, CST is about to enter TRL 7 and has continued with the AR project. There is value in applying ROA at TRL 4. This will help develop a complete analysis and allow gaps or important aspects that may have been overlooked to be identified. This may also help guide some of the decision making that is done at TRL 6 and 7. At TRL 4, CST had completed the necessary analytical studies and has assessed the context in which the technology will operate. Analytical studies and assessments were completed through preliminary modeling and simulation [23]. At TRL 4, CST began testing the analytical assumptions within the context of the relevant tailing ponds environment. Between 2014 and 2015, CST had just started and had very limited funds and limited human resources. The technology was also limited, where initial feasibility studies and determining applications and potential markets for the technology were in the process of being conducted. Abandonment or termination of a project is an option in the flexible RO approach and because of these limitations mentioned, abandonment was set as the first possible option. It should be noted that delaying a project is an important option that could be used by R&D and technology firms to reassess their work and try to address some of the factors or risks discussed. A small firm like CST did not have the capital or resources to be able to delay the project and re-invest. This is why delaying was not considered.

The other two options considered were growth type options. If CST's technology was found to not have any fatal design risks, but managers had failed to identify a market application for their technology, a market pivot could have been considered. There are several factors that may contribute to the choosing of this option. For example, high competition or low demand, or no identified market receptors. This option would have added value to CST as it would have allowed them to modify the business model and make necessary changes, without losing on the previous investment and domain knowledge the team had acquired so far. This would have enabled CST an opportunity to exploit a prior investment with a sequential one [1]. Exercising the market pivot option may actually have warranted the need for another option (a few months to a year) after it had been exercised, depending on the CST's requirements and their threshold for risk. This is because there would be a "sanity check" that may be needed after choosing to pivot, where CST may need to go back after some time and reassess again to make sure their short-term and long-term goals are being considered.

The final option considered is the option that is the path that CST pursued which has led them to their position today. This option was to continue to grow and build capabilities according to their initial project plans. There were no fatal risks identified and CST was able to continue to the technology development stage. Figure 24 illustrates a simple decision tree for CST at TRL 4. It is important to understand that CST is in the growth stage and cannot expect income to be significant (if any). In fact, because of how the proposed framework is structured, it is a logical approach to estimate cash flows short term since CST can expect to exercise another option at TRL 6, therefore needing another option and resulting in new estimated values.

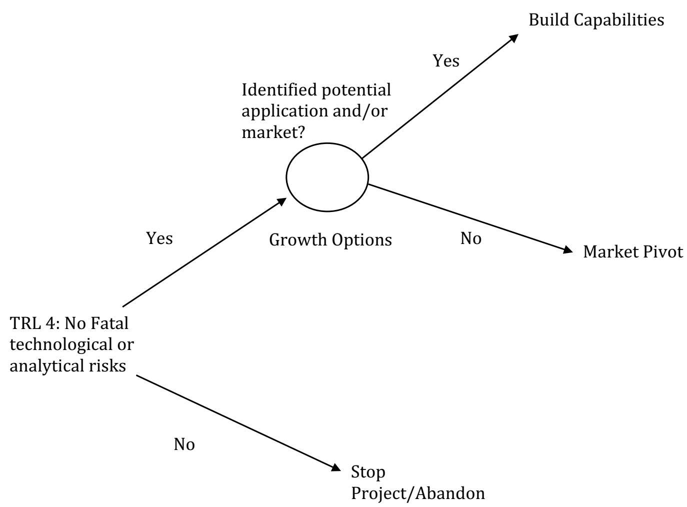


Figure 24. Decision Tree at TRL 4

The next step is to build the binomial lattice and value the options. Only the market pivot and build capabilities options will be shown. The abandonment option would result in the loss of the initial investments made into the project. The probability of success, *p(s)*, is assumed to be 0.5 for both options. This was satisfactory for CST as they are in the early stages of the project and willing to accept higher risk. The expectation is that technology development will lower the risk and improve p(s) as the project matures. Otherwise, the technology project should be reconsidered, unless the investors have a higher appetite for risk and are willing to gamble. It is important to note that CST's initial estimations for expenses and gross revenues were not changed. This is because information was not shared in terms of where the revenue was coming from and why expenses increased one year to the next.

These base-case values were left as is and results of the ROA were added onto the base-case estimations. All other assumptions and results are summarized below. Financial projections are all provided by CST are shown in Appendix 2. All spreadsheet calculations are in Appendix 3.

Market pivot

The pivot option was valued with the following assumptions:

- Assuming the year is 2014.
- No identified market applicability for the technology according to CST's initial business plans for the technology. No fatal technology or analytical risk identified.
- The option is to be exercised in 2015.
- Taxes and inflation are ignored in the calculations.
- CST will outsource market experts to identify market opportunities. This is estimated to increase expenses by 20% for one year.
- The probability of success, p(s)=0.5. The u=1.5 and d=0.67. The reasoning behind p(s) was previously discussed.
- All equity or financing implications associated with this option are ignored for simplicity.
- Acceptable domain expertise and technical knowledge is present within the existing team.
- No technological or design flaws.
- AR will remain in the same TRL for a maximum of one year. Assuming that the operating environment, market or industry will be identified by then. No major technological maturity or project changes are assumed during this time.
- The time to exercise is allowed flexibility, as the specific CST activities that were conducted in 2014 -2015 and the details about the pace at which the project was developed are unknown. This is all estimated.
- Finally, a revised cash flow will be conducted up till the year 2019, as according to CST's project plans (and information known), another option will be exercised at the next stage-gate at that time. All other cash flow values and assumptions are consistent with the DCF calculations.

Option Valuation:

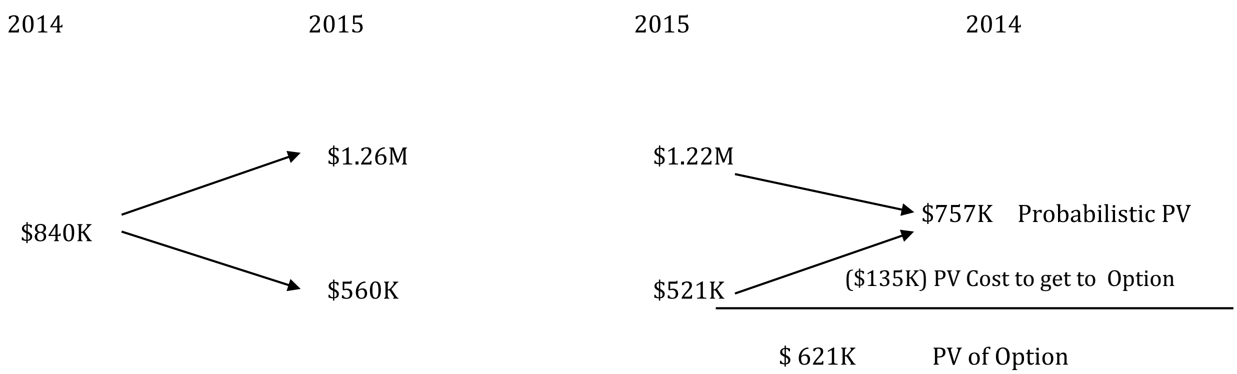


Figure 25. Market Pivot Lattice Valuation

Build capabilities

The build capabilities option was valued with the following assumptions:

- Financials of actual expenses incurred in 2014 by CST were used for this option.
- The option is to be exercised in 2015.
- Taxes and inflation are ignored in the calculations.
- CST has enough resources to be able to exercise this option.
- No known competition with the same potential technological capabilities.
- The probability of success p(s)=0.5. The u=1.5 and d=0.67. The reasoning behind p(s) was previously discussed.
- The time to exercise is allowed flexibility, as the specific CST activities that were conducted in 2014 -2015 and the details about the pace at which the project was developed are unknown. This is all estimated.
- Finally, a revised cash flow will be conducted up till the year 2019, as according to CST's project plans (and information known), another option will be exercised at the next stage-gate at that time. All other cash flow values and assumptions are consistent with the DCF calculations.

Option Valuation:

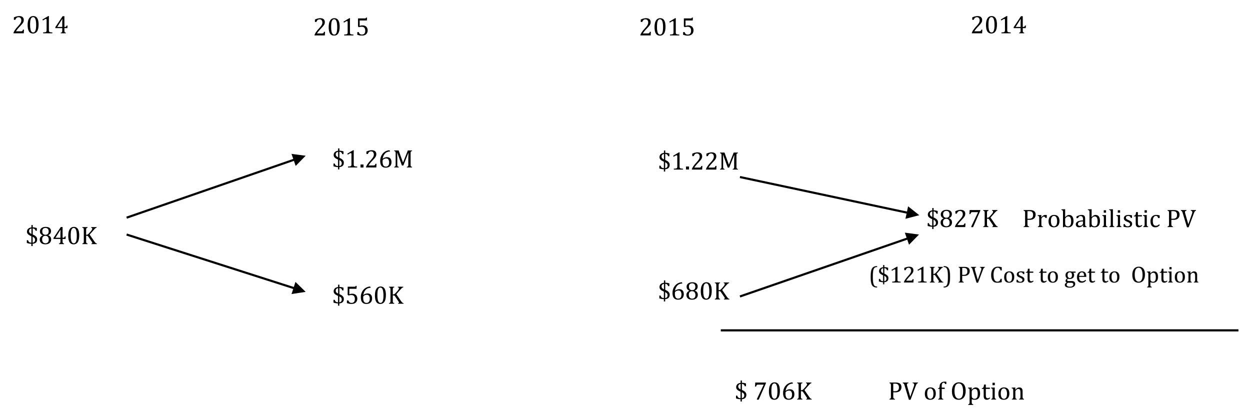


Figure 26. Build Capabilities Lattice Valuation

The cost to implement the market pivot option is $135K with an overall present option value of $621K. The building capabilities option is valued at $706K with an implementation cost of $121K. The difference in costs between the two options can be attributed to the increase in expenses due to the need to hire market experts in the market pivot option. From those values, building capabilities yield a higher PV and costs less overall, making it the most desirable option by the numbers. However, the difference between the values is $85K. In a project that may potentially yield large revenues, this is not a significant difference. This calculation can be used to reinforce and support the decision made in 2015 to continue and grow.

If CST had exercised the market pivot option, then the need for another option may have been warranted (staged-option). This can be argued to be necessary in order for managers to make educated and justified decisions before moving forward with their new redefined goals. The value of the options in the early stages is not so much about the income generation. It is important that managers do not become obsessed with the numbers during early development. A well-rounded decision considers all aspects of an option, the benefits, and challenges, and refers to the numbers to reinforce general estimates. The process of conducting ROA can open up important conversations about what the short-term goals, long-term goals and expectations moving forward are. The cost to implement an option can provide some insight on the magnitude of effort required and resources and financing.

4.3.5 RO Valuation at TRL 6

CST is currently at the commercialization stage-gate. At this point, major AR system integration issues have been addressed and a huge portion of testing has been completed. CST's activities and concerns have begun to shift from technology development, to the preparation for scale-up and commercialization. The resource requirements change at this stage where the need for market and scale-up expertise becomes an important key for success. CST has been looking for new investors and clients, and according to their business manager, they have potential clients and investors that are interested in the technology. There have been plans made for field trials with potential customers. At this point in time, it is appropriate for CST to consider options that support their goal to launch the technology into the market. Growth for a small start-up such as CST is very risky because of the need for human resources and financial capital, as the business shifts from knowledge creation to product creation. It is important that business processes mature quickly in order to bring the technology to the market.

The three options that were of particular interest to CST were to operate as a data monitoring service for tailing ponds, to license their IP, or to sell AR units. Figure 27 illustrates a decision tree at TRL 6. CST's current equity and financing position was ignored during the analysis, mainly due to limited information and ongoing investor related activities. Once the conditions are better understood, the analysis should be included to reflect these changes.

The probability of success at this stage is expected to be greater than the estimated value of 0.5 at TRL 4, as technological capability has been proven and no fatal risks (technology or market) have been identified. However, for the purpose of this thesis, a probability of 0.5 was not changed for TRL 6's ROA. It is important to understand that at this stage of development, realistically, investors would expect a higher p(s). A low p(s) at later stages signifies a lot of unresolved uncertainty and could be too risky and unfavorable for investors.

Table 10. Summary of Commercialization Options Pros and Cons

	Monitoring Services	**Licensing & Royalties**	**Sales**
Pros	Competitive advantage, high margins	Low overhead, consistent revenue & predictable costs, product/market expansion, innovation focus	Capital influx, high margins
Cons	Complex & high overhead, sales channel access	Lower margin, maintenance responsibilities	High capital requirements, distribution challenges, inconsistent revenue

The current technological capability of the AR allows operations in soft tailing ponds, as well as high strength tailings. This gives CST a competitive advantage, high-profit margins, and allows them to strategically dominate in soft tailing ponds monitoring as there are currently no competitors. It is also a legal regulatory requirement for producers to monitor and meet specific data collection rates. The cons associated with the implementation of the monitoring option include high and complicated overhead costs, as well as challenges accessing sales channels. CST will be fully responsible for all manufacturing, maintenance, and operation of the rover, which increases the load on their resources. Other risks CST faces include the potential of new strategic competitors entering the market as well as policy and regulatory changes, which in turn may negatively affect the demand for services and the technology.

CST may choose to license out over a term or offer out one-time perpetual licenses, and they may or may not choose to implement royalties. The choice behind the licensing structures and fees are ultimately up to CST's preference. However, CST is keen on a one-time license fee as it meant less overall resource commitments to this project and a greater ability to continue developing new technologies and staying innovative. A reasonable outcome with the implementation of this option would be that CST continues to build strong relationships with the clients they are licensing to and will later develop more products to sell or license to these customers, depending on the circumstances.

Selling of AR units is the final option considered by CST. The major benefit is the high-profit margins and capital influx associated with pursuing this route. However, for a small start-up such as CST, this option may face some challenges. For example, inconsistent revenue that may arise due to factors such as distribution channel challenges and high capital requirements to manufacture the rovers. There is also the question of resource constraints and whether CST could handle customer demands with the current team size and capability. A major factor that must be considered when choosing the sales route is the life of the technology as this can impact the revenue and demand for AR. Special consideration should be taken with the sales option as it possesses capital intensive requirements that may have negative effects on CST's focus on innovation and their competitive advantage. Some the requirements for this option include shop facilities, procurement channels, staff for fabrication and provisions to offer warranty and after-sales services. Therefore, this option may not be a sustainable path to choose as new technology development projects may need to be put on hold if the sales option is exercised. In addition, assuming there is a fixed number of potential clients for the next few years in Alberta, CST may sell one unit to a customer, and depending on the choice of maintenance services, that customer may no longer be a source of revenue for CST (i.e. they are a one-time client). Therefore, important factors such as market size and well as technology life are important.

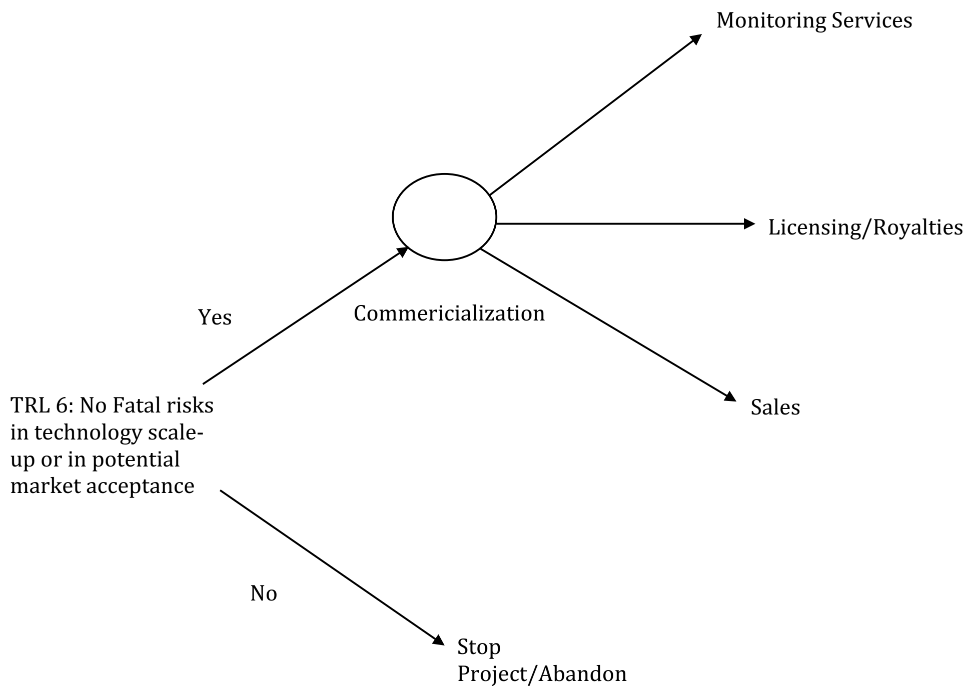


Figure 27. Decision Tree at TRL 6

Similar to options at TRL 4, CST's initial estimations for expenses and gross revenues were not changed. These base-case values were left as is and new ROA estimations were added onto the base. For all three commercialization options, it will be assumed that if chosen, CST will implement the option for a maximum of two years. They will then reassess whether they are on track with their project goals. Two years is only a recommendation, however, CST can choose to place an option whenever they see fit. Based on this assumption, a cash flow will only be conducted till the year 2021. All quotes and services charges stated for all three options are as reported by Copperstone Technologies.

Monitoring Services

The monitoring services option was valued with the following assumptions:

- This option is to be exercised in 2019.
- Operations and rental of AR is quoted at $5,000/day for 8 hours of operation (for the calculations, the price will remain constant for the next two years but it may be a strategic move to raise prices in a year if there are still no competitors).
- Minimum monitoring requirements of 100 days per year at 8 hours per day resulting in an estimated gross revenue of $500,000 per year per customer.
- Maintenance and technical support fees are covered within the quoted monitoring fees.
- Regular maintenance requirements are estimated at three weeks per year. This is based on technical expertise and knowledge of engineers at CST and expected minor glitches or bug fixes that may be needed after the technology is launched.
- The maintenance expenses for CST are quoted at $25K per client.
- CST will require at least a month commitment signed contract by customers.
- The breaking of contract or cancellation is not refundable, and any refunds are up to the full discretion of CST's management.
- There are no competitors in the monitoring of soft tailing ponds and assumed that no new competitors will arise within the next two years.
- Overhead costs and expenses associated with manufacturing and production are assumed constant for the next two years.
- No regulatory or policy changes for two years after the option is exercised.
- CST current's resources are able to support the potential customer demands within the area of operation. In the case where a new AR unit needs to be built to meet demands, CST will build in-house, financed from private investors.
- Potential of 3 customers for the first two years after implementation. For ROA base calculations, the next two years will have a constant number of customers.
- CST will only operate in Alberta for 2 years after implementation.
- Taxes and inflation are ignored in the calculations.
- Additional service charges imposed by CST may be added at their discretion in cases where damage to equipment occurs on site and is deemed the customer's fault.

- The probability of success p(s)=0.5 in order to remain conservative. However, the probability is expected to be higher than it was at TRL 4[36]. The u=1.5 and d=0.67 as previously discussed.

Option Valuation:

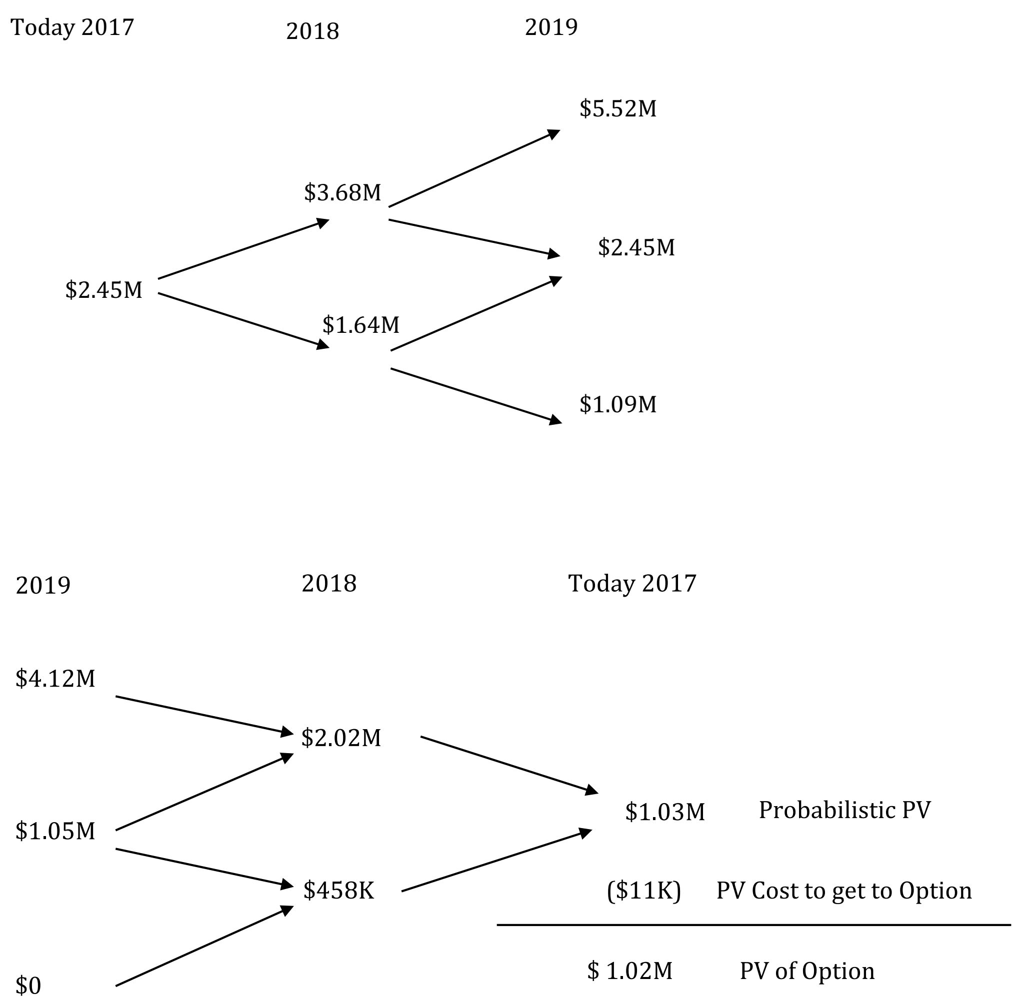


Figure 28. Monitoring Lattice Valuation

[36] This has a direct relationship with the perceived risks at this point in time. Market risk control is an important factor in all decision-making from this point on and CST is strategically planning

Licensing and Royalties

The licensing option was valued with the following assumptions:

- CST will license the IP as a one-time perpetual license at a fee of $400K.
- Targeting only the small market in the Alberta oil sands and IP usage restricted to Alberta (i.e. not worldwide use). Limitations of use will be presented during the license contract offering.
- A conservative assumption of two customers in two years.
- Implementation of licensing option will increase expenses by 10% as lawyers may be advised and other process or legal fees may be associated. This increase in expenses is expected to occur in 2018.
- Any requests for improvements from the licensee will result in an additional charge. This will be negotiated upon request.
- Maintenance or consulting services are charged to customers at $150/hour.
- The costs associated with maintaining the patent are constant and factored into the expenses (since the IP has already been approved and fees have been paid out).
- Any income directly from the use of IP will result in a 20% royalty structure for the first 5 years. ROA will not include this in the calculations, however, once information is known, they should be updated to reflect a better estimate.
- Taxes and inflation are ignored in the calculations.
- The probability of success p(s)=0.5 in order to remain conservative. However, the probability is expected to be high than it was at TRL 4[37]. The p(u)=1.5 and p(d)=0.67 as previously discussed.

---

[37] This has a direct relationship with the perceived risks at this point in time. Market risk control is an important factor in all decision-making from this point on and CST is strategically planning

Option Valuation:

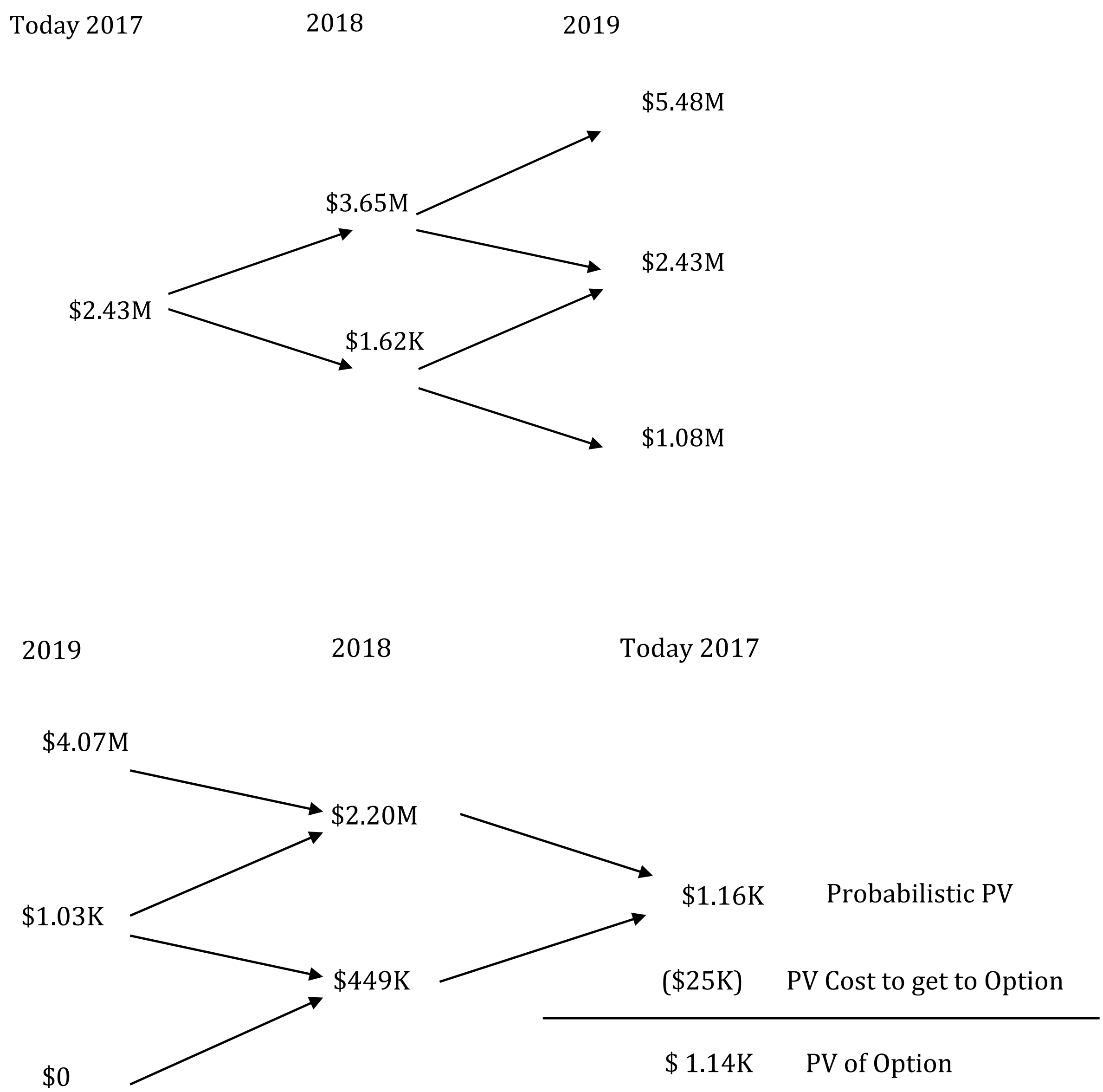


Figure 29. Licensing Lattice Valuation

Sales

The sales option was valued with the following assumptions:

- CST estimates to sell 2 units in 2 years.
- The option is to be exercised in 2019.
- There will be no major technology improvements on the hardware or software and system integration will be assumed to be ready for market launch.
- The selling price per unit is $200K.
- The cost for CST to build an AR unit is approximately $120K including the cost of labor and parts.
- If this option is chosen, CST plans to build one AR unit in 2017 and one unit in 2018 in order to meet expected future demand.
- Any unit sold will also require customers to purchase maintenance services quoted at $150/hour. Regular maintenance is estimated to be scheduled for a maximum of three weeks per year and is based on technical expertise and knowledge of engineers at CST and expected minor glitches and bugs that may arise after launch.
- CST is the only company qualified to provided technical support or maintenance services. No competitors can provide this service.
- Manufacturing costs are assumed constant for the next 2 years.
- Refunds on AR purchases are only conducted under full discretion of CST.
- The cost to implement is based on the same values provided in the base-case analysis (i.e. fixed admin costs and other expenses, the growth of CST is not anticipated for the next two years- however, is possible).
- There is no direct competition for the next two years after the option is exercised.
- No regulatory or policy changes for the next two years after the option is exercised.
- Taxes and inflation are ignored in the calculations. Service charges imposed by CST may be added at their discretion.
- CST has the capabilities and resources to build in-house the five units estimated to sell within the first year.
- The rovers will be built in house for the first two years, and if demand is high (i.e. more than 5 units per year) outsourcing options can be considered later on.

- The probability of success p(s)=0.5 in order to remain conservative. However, the probability is expected to be high than it was at TRL 4[38]. The p(u)=1.5 and p(d)=0.67, as previously discussed.

Option Valuation:

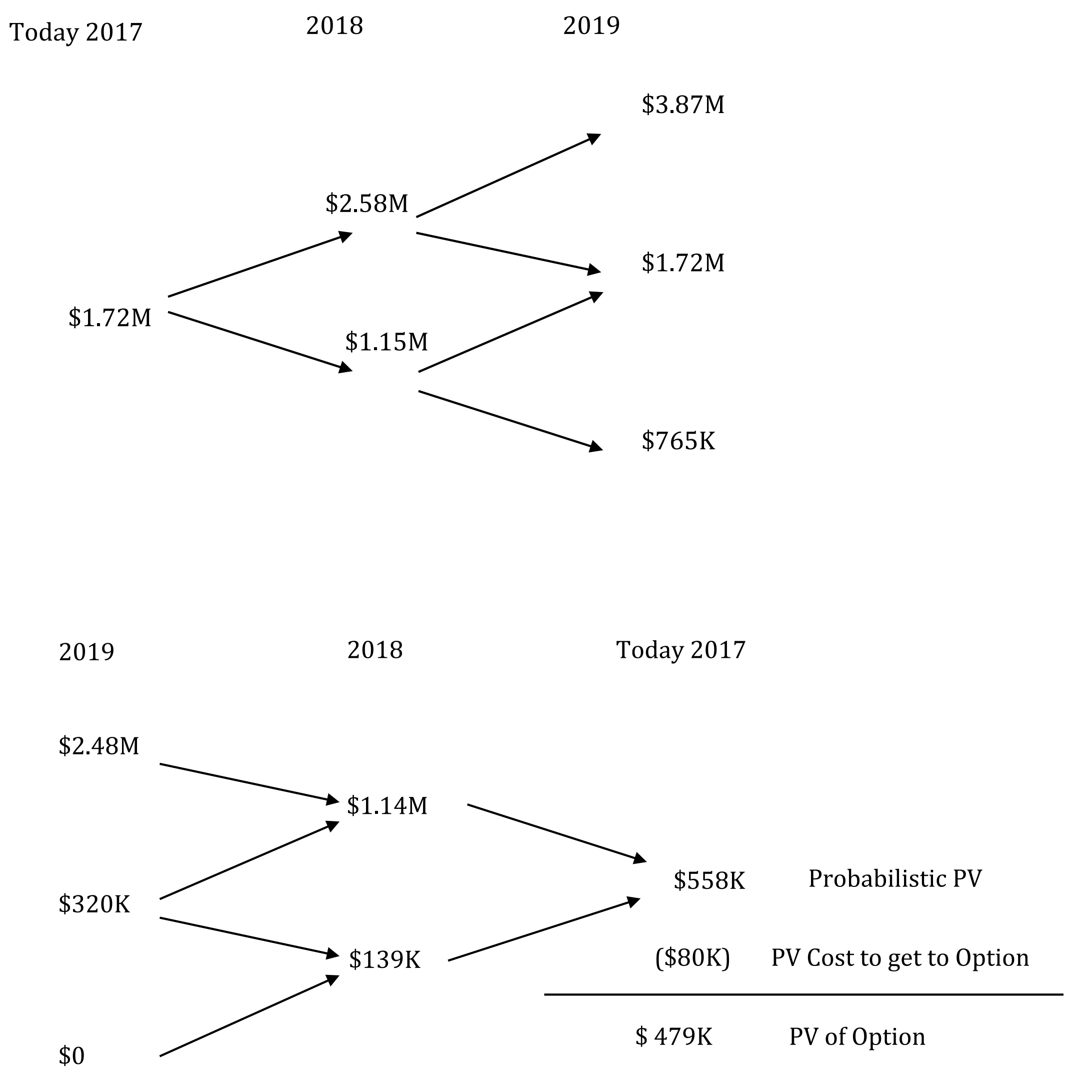


Figure 30. Sales Lattice Valuation

38 This has a direct relationship with the perceived risks at this point in time. Market risk control is an important factor in all decision-making from this point on and CST is strategically planning

The estimated present cost to implement the monitoring option was $11K with a value of $1.02M. The present cost to implement the licensing option was estimated to cost around $25K and was valued at $1.14M and the estimated present cost to implement the sales option was $80K while the option was valued at $479K.

The assumptions made during the calculations have a significant impact on the magnitude of values for cost implementation and value. For example, the cost to implement for sales can be considered "low" because the assumption that CST had two available units for sale was made, and that they would build one unit in 2017 and one in 2018. This of course was based on an assumption for potential demand. Additional overhead costs were assumed to already be included in CST's initial projections for growth. The realistic cost to implement these options are expected to be different once CST updates the values. A more accurate estimation was not possible during the study as details behind some of the values on their financial projections were not shared and it was difficult to gauge estimates on expenses and overheads when CST already had incorporated their own plans for growth in these projections. The monitoring option also deems to have a low implementation cost; this is because it was assumed that CST had basic capabilities to meet minimum demand. Similar to the sales option, a better estimation can be expected once these values are updated. This is especially the case once true maintenance costs are reflected in the calculations.

From these results, licensing and monitoring costs are comparatively lower than the sales option. This aligns well with the initial assumptions made about each option. The licensing option yields the highest value, again, reinforcing some of the expectations related to this option. As it is low maintenance and high margin costs. Of course, to better have an idea of the range of these values, a sensitivity analysis should be conducted.

The value in ROA as explained throughout this thesis comes in the ability to make stream-lined decisions based on important assessments made throughout the application of this framework. The choice behind why these options were implemented after for a period of maximum two years has already been addressed at the start of this section. In the case where an implemented option does not go according to plan, managers can reassess, or in extreme conditions, abandon. The process of estimating how much an option will cost will give insight on the effort that will be required and the resources. This is beneficial for CST because it aids in the process of project planning. Estimates of the option values can also be used to support their project progress discussions and future plans when speaking to investors and trying to secure financing During the course of this thesis, CST did not select an option.

4.3.6 Sensitivity Analysis for Exercised Option

A sensitivity analysis should be conducted on the options considered, and more specifically on the option chosen. When considering more than one option, values of different options may be close in numbers. It is important to conduct a well thought-out sensitivity analysis in order to obtain a full range of values (or at least understand the boundaries), that show the variability in parameters. This is also similar for the option chosen.

A full sensitivity analysis was not completed in this case study as the calculations are trivial. The value is in the thought process, and the variables should be varied with risk elements in mind. CST did not select an option during the course of this study. However, it is recommended that CST conduct a sensitivity analysis when they decide whether they will proceed with any of the recommended options in this study, or any other options in the future. The list of the possible scenarios listed below for the analysis is not an exhaustive list. Some applicable sensitivity analysis scenarios relevant to CST include:

1. Varying the probability of success (this could be from 0.4 to 0.6 or what CST chooses).
2. Year the option is exercised. This will allow CST to study how early or late implementation of an option can affect its value and the overall PV of income.
3. Varying the upswing and downswing values used in the lattice valuation.
4. Varying the expenses related to implementation (increase/decrease by 20% for example).
5. Varying customer demand and competition.
6. Modeling the effects of regulatory changes (which will also affect demand).

4.3.7 Other Case Study Considerations

The commercialization options considered were relatively well understood in terms of advantages and disadvantages. However, in the case where CST may be considering between options that are not as clear, a SWOT analysis[39] could be used to qualitatively assess these options. Ultimately, market conditions will determine whether the option exercised can do so in time to meet a market window.

Data analytics and collection are an integral part of successful and efficient AR operations. There is a need for the implementation of IT systems that allow access to real-time data collected by AR. Data exchange programs have been developed for oil and gas industry allowing for seamless automation of data transfer and remote access. An example of such IT platforms include is the Partner Data Exchange [2] that was developed by CGI. Integrating a platform as such into AR technology can allow for oil sands producers, governments to interpret real time data from tailings.

[39] Strengths, weaknesses, opportunities, threat analysis that organizations employ when assessing their capabilities and factors (internal or external) that can impact a project or decision.

4.4. National Research Council of Canada Case Study

The initial project plan for this thesis was to conduct ROA on a National Research Council of Canada (NRC) project. The project would be within the Security and Disruptive Technologies (SDT) portfolio. The goal was that a comparative assessment would be completed using a similar project within that portfolio.

4.4.1 NRC Case Background

One potential application of the proposed framework would be the NRC Boron Nitride Nanotubes (BNNT) technology within the SDT portfolio. The project was challenged by many unforeseen risks, mainly due to misinterpreting the potential market. BNNT's were discovered in 1995. They remained at a lower level of maturity than expected for two decades and have not reached a stage of development where any receptor market has been identified. This has led BNNTs to remain in the R&D sphere. Although there was no identified business or consumer market for BNNT's, NRC opted to use the structurally similar Carbon Nanotubes (CNT) as a proxy market for BNNT [149]. BNNTs share similar mechanical properties and conductivity of CNTs. However, are more superior as they possess greater thermal and chemical stability, electrical insulation and the ability to produce current when subjected to mechanical stress [150].

BNNTs are light-weight, extremely strong and tiny. They are described to be 100 times the strength of steel and can withstand up to 2,000 degrees Celsius. Despite these positive qualities, NRC argues that these qualities are also the reason that has led to difficulties to commercially produce BNNTs [151]. The capabilities and potential future applications of BNNTs have been considered for applications as transparent military armor, strong enough to hold against explosions, or as BNNT coatings for buildings to shield against ultraviolet light and fire. For more information about BNNTs, see [152].

4.4.2 Recommendations for Future NRC Portfolios

There was not enough information provided by NRC to conduct a comparative study on the BNNT case. However, with enough data, the proposed methodology in this project could be considered as a valuation tool across their entire SDT portfolio. It is important to identify the potential approaches to commercialize the BNNT technology. There is an implication that R&D organizations can no longer fully rely on their internal R&D capacity and do not have the ability to cover all disciplines that contribute to the firm [153]. Therefore, it is crucial that NRC employ external market expertise (if possible) in order to objectively study the potential markets. Based on several informal conversations with managers at NRC, there is a tendency for the same group of employees to stay within the same portfolio for several years (15+) [54]. Further research on the skills and competencies acquired and developed over time, and their influence on the decisions and strategies during the cross-functional processes of developing and commercializing technologies should be considered by NRC's portfolio managers. One possible way is to analyze historical data from past projects and identify trends or patterns in developmental and managerial activities that may have contributed to the success, or increased the risk of failure for a particular project.

NRC is heavy on early theoretical research and can expect to begin any project at TRL 1-2. They can expect to exercise at least four options at TRL 2, 4, 6 and 7. This would be expected for the BNNT project. Projects for which there is high NRC capability but low potential impact for Canada, may not be pursued. Projects for which there is low NRC capability, but very high potential and sustainable impact for Canada, may be pursued as part of an evolving NRC strategy for programs, hiring, and facilities [23]. Contrary to RO application for CST, options exercised for NRC may be years from present time. This can be expected with very long, projects with extensive theoretical research. It is important that Portfolio managers at NRC are able to plan and budget accordingly with important milestones clearly defined so that project progress can occur. This can avoid the pitfall of endless years of theoretical research with no future application and no short-term or long term goals, tying up resources that can be allocated elsewhere.

A general recommendation for the BNNT case is to begin by reassessing information available and assessing technological maturity as of today, using a formal TRA. Any components that are not yet at the target TRL need to be addressed accordingly. The use of the CNTs' success as a proxy for BNNTs should be approached with caution to avoid oversimplifying assumptions and avoid personal biases that may cause managers to view outcomes more optimistically. The effects of these biases can encourage investments in technology-push projects that could have a higher risk of failure. Distinctions between the CNT application and BNNT application must be made and any market overlap should be identified. The impact of market overlap on the success of the CNTs and potential BNNTs need to be considered.

Short-term and long-term project and portfolio goals need to be redefined, and clear and specific milestones must be set. A formal market analysis needs to be conducted to reflect the market landscape today. An option to wait-and-see for one year may be possible for NRC depending on their current financial and resource constraints. NRC must identify all critical risks moving forward and devise alternative options and back-up plans to avoid project overruns and slow or stagnant project progress. Using staged options is valuable for the BNNT project as it will break down a very long project into smaller and manageable tasks. This way managers can keep updating progress and value their decisions for short-term and long-term progress as they continue to grow. This approach can overall help the SDT portfolio managers to better budget and allocate resources accordingly while keeping the portfolio balanced and running efficiently.

Chapter 5 Conclusion

5.1 Conclusion

The aim of the research conducted was to develop a decision-making framework that can be applied to single R&D and technology projects, or across entire portfolios. The proposed framework is a strategic tool for managers, researchers, and decision-makers used to value decisions made in highly risky projects. It combines a stage-gate approach for risk-based decision-making by using the technology readiness level scale alongside a real options approach. This approach is argued to drive organizations to make evidence-based decisions for technology development and project continuation.

The framework recommends a minimum number of three real options to be placed along the technology readiness levels at different points during the project. These are key decision points during technology development as there is a significant change in activities, risks, resource requirements and financial requirements. The first option is at the TRL 4 stage-gate where the technology is about to enter the technology development phase. The second option is to be assessed at TRL 6 where the project shifts to product creation. Beyond this stage, scale-up, marketing, and commercialization activities are dominant. The final option is recommended at TRL 7, before a technology is about to enter the production and deployment phase. The major risk categories associated with technology projects are identified as science and technology, financial, market and organizational. The research discusses the general behavioural trends of these risk categories and how they change during a project, and their effects on different aspects of a technology development. This is a flexible framework that allows management to add options as needed, as more information is obtained during a project. This approach was developed as a streamlined methodology that supports risky technology and R&D projects in ways that traditional valuation methods such as discounted cash-flow (DCF) and net present value (NPV) could not.

The framework was then applied to an autonomous rover (AR) project currently being developed by Copperstone Technologies (CST). CST's main goals for the AR project and the overall company was to make a profit while allowing the founders to work on new technologies and bring more innovations to the market. Factors such as competition, demand, and regulatory policies were determined as critical risks through interviews with CST's business development manager and their chief technology officer.

The effects of these risks on the overall project success and potential profit were discussed. Scale-up activities at the second stage-gate were also determined to be important. Technology and design risks were also discussed. The importance of CST ensuring they have a system design that allows future modifications that reflect improvements without having to make large design changes was critical to their success and their future competitive advantage.

Options were retroactively valued at TRL 4. CST's decision to continue development and build capabilities back in 2014 was determined to have been the appropriate option for them at the time. It was in-line with CST's goal to remain innovative and the valuation supported their initial plan to commercialize the technology as a tool that will be utilized in the niche market of the Alberta oil sands. Decisions were also valued at the second stage-gate, which is where CST's currently positioned today. Based on the results from the interview, three commercialization options were considered and assessed. Launching the AR technology in the market and operating as a monitoring service was the first option considered. The second option was to license the IP to oil sands operators through a one-time perpetual license fee. The final option was to sell AR units. Advantages and disadvantages of each option were discussed. During the course of this thesis, CST did not select a commercialization option. Therefore, no additional information was collected after the valuation at TRL 6.

Monitoring and sales options were found to take away from CST's ability to continue to develop new technologies and remain innovative. This was due to the high resource requirements needed from these two options. The sales option also posed issues as it did not meet CST's preference for an option that will produce consistent revenue. Licensing of IP was determined to allow CST the most flexibility to continue to innovate and create new technologies. These observations were proven through the cost to implement the option, as well as the potential income that could be generated upon implementation.

The reliability of the valuation was also addressed. Due to the limited available information for this case study, many estimations and assumptions were made and stated accordingly. An important assumption that had an effect on the valuation of option was the probability of success (p(s)). During early stages of a technology it was argued that CST was willing to accept higher risk as they entered the technology development phase. Realistically speaking, the p(s) should have increased at the second stage-gate where the technology's capabilities had grown, and risks from the previous stages had been mitigated accordingly. However, because of the limited availability of data for this study, the p(s) of 0.5 was used for both stage-gate valuations. It was explained that investors would expect a higher p(s) at higher TRLs and low or unchanged p(s) at later stages signified unresolved uncertainty and a higher volatility which would and could be unfavourable for many investors and a sign that the project may need to be reassessed or abandoned.

Finally, a potential application to a Boron Nitride Nanotubes (BNNT) project by National Research Council Canada (NRC) was introduced, and the value of the proposed framework to their portfolio was briefly discussed. Unfortunately, there was no data or information obtained by NRC in order to conduct a comparative assessment.

In conclusion, the framework developed is a useful tool that can allow managers to better understand risks and how they change as a technology progresses relative to the TRL scale. It enables a more consistent discussion about the comparative value of different options and can be used to justify spending on long and risky technology development projects. Framework limitations, challenges and directions for future research are discussed in the following sections.

5.2 Framework Limitations

The framework has limitations in its current applicability. It does not outline an alternative approach to estimate upswing, downswing, and the probability of success for early-stage technology projects, which may weaken the quantitative aspect of the assessment and raise questions about reliability from managers and others using it. Difficulties in obtaining exact or relatively accurate inputs for ROA may result in some managers undermining the validity of results during decision-making. Although this was stressed throughout Chapter 4, some decision-makers may become obsessed with the numbers produced from the ROA and disregard the real value of the framework. The proposed methodology does not replace the need for technology development strategists. The outlined framework could be further refined to provide clear ties between strategy and option selection. Value drivers such as building up of scale to gain competitive advantage in a market, or innovative product differentiation should be clearly linked to strategies and a portfolio of real options that are applicable. This can help inexperienced users capture opportunities if they are able to understand RO application better. This can also reduce some of the vagueness that inexperienced managers may feel towards the concept of real options valuation. An improved method to present these concepts in an organized manner that is simple for everyone involved in a project to understand is necessary. This can be done using step-by-step approaches to option valuation or perhaps an in-house tool built specifically to a portfolio that can be used by decision-makers.

The framework discusses the possibility of correlated variables and risk elements but does not outline a defined approach to assess these relationships and properly quantify them beyond using a sensitivity analysis. More detailed mapping of risks along the TRL scale should be considered as well as their potential effects on other categories. The research also stresses the importance of having available and appropriate resources, but does not really define a method that organizations can use to assess their capabilities and need for additional capabilities as a whole. A possible approach to overcome this limitation is to perform an organizational capabilities audit. For more information see [154].

The developed framework does not directly take into consideration technology-life cycles and their effect on the option value and cost to implement. During the development of the framework (Chapter 3) and the analysis (Chapter 4), there was mention of the technology-life cycle and the possible effects on option value. There was nothing beyond stating that this factor can influence the value of option. The framework can be strengthened by incorporating technology-life cycles into the analysis. This can aid managers to better estimate when and whether (and the degree of which) the potential profits will offset R&D costs. This can support decisions as the technology-life cycle can help organizations to predict adoption and decline of the technology and can provide more insight on how risks might affect the lifespan of a technology. The effect of intellectual property (IP) may also have an influence on the technology-life cycle. This should be considered for future applications.

5.3 Recommendations for Future Research

In addition to improvements that can be made to the limitations discussed in 5.2, there are other areas for future research that can be considered.

The methodology should be refined further as more data becomes available and we develop a better understanding of internal capabilities and resource restraints. As start-ups begin to grow their portfolios, this warrants the need to consider market cannibalization. This refers to the effect that new products being developed within an organization have on the performance of other existing products. The performance is often measured through sales of these products [1]. One aspect that could be further examined are the decisions behind which products to release first and the strategy behind how technology risks could be blended across several products[40]. Projects should not always be assumed to be independent, as they may be linked in several ways. These linkages can have effects on other projects that may be kept at lower TRLs in order to support higher TRL projects.

[40] Based on conversations with Dr. Michael Lipsett and Dr. Sahil Raina at the University of Alberta

Future research should take into consideration the differences between public and private sectors when implementing such a framework. Metrics for success need to be defined as some R&D organizations may be driven by scientific competence that achieve a non-economic impact in Canada[41]. Aspects such as types of financing whether government funded or private investors, should be studied and their effect on strategic decision making during development. Potential risks and critical factors of success should be studied in more depth and organized by industry and magnitude of impact in order to further streamline the methodology. This may require extensive data from various industries in order to produce a somewhat complete list.

Future research could also incorporate a formal process within the framework when dealing with residual risk from lower TRLs that may be carried forward into the later stages of development and how these can be accounted for quantitatively. Keeping in mind that the lowest TRL for a component, means that the entire system is at that lowest TRL, regardless of what TRLs the other components are at.

Future improvements should incorporate portfolio management and resource allocation guidelines for organizations that are more seasoned and have been operating for several years and are more “set in their ways”. Ensuring resources are properly managed and utilized across projects is a success factor in new product development [21]. The research should explore a process for resource allocation and management so that resources can be optimized across a portfolio with projects that have varying levels of risk. Research should also consider concepts related to technology transfer[42] between functional groups within an organization and processes to ensure smooth transitions between the two groups.

[41] From e-mail communication between NRC and Dr. Lipsett

[42] This refers to the transfer that occurs from technology to new product development. Sometimes it may be an entirely new team that takes over the new product development.

References

[1] M. C. Dissel, R. Phaal, C. J. Farrukh, and D. R. Probert, "Value Roadmapping," *Res. -Technology Manag.*, vol. 52, no. 6, pp. 45–53, 2009.

[2] G. Martin-Barrera, C. Zamora-Ramirez, and J. M. Gonzalez-Gonzalez, "Application of real options valuation for analysing the impact of public R&D financing on renewable energy projects: A company's perspective," *Renew. Sustain. Energy Rev.*, vol. 63, pp. 292–301, 2016.

[3] F. Hunt, R. Mitchell, R. Phaal, and D. Probert, "Early valuation of technology: real options, hybrid models and beyond.," *J. Soc. Instrum. Control Eng.*, vol. 43, no. 10, pp. 730–735, 2004.

[4] G. Ajamian and P. Koen, "Technology Stage-Gate: a structured process for managing high-risk new technology projects," *PDMA Toolb. new Prod. Dev.*, vol. 1, pp. 267–295, 2002.

[5] J. Wang, W. Lin, and Y. H. Huang, "A performance-oriented risk management framework for innovative R&D projects," *Technovation*, vol. 30, no. 11–12, pp. 601–611, 2010.

[6] L. Trigeorgis, "Topics in Real Options and Applications Real Options and Interactions With Financial Flexibility," *Financ. Manag.*, vol. 22, no. 3, pp. 202–225, 1993.

[7] J. Mun, *Real Options Analysis Tools and Techniques for Valuing Strategic Investments and Decisions*, Second Edi. Wiley Finance, 2006.

[8] L. Trigeorgis, "The Nature of Option Interactions and the Valuation of Investments with Multiple Real Options," *J. Financ. Quant. Anal.*, vol. 28, no. 1, pp. 1–20, 1993.

[9] R. Ragozzino, J. J. Reuer, and L. Trigeorgis, "Real Options in Strategy and Finance: Current Gaps and Future Linkages," *Acad. Manag. Perspect.*, vol. 30, no. 4, pp. 428–440, 2016.

[10] A. Menichini and M. Celiktas, *Case: Real Options in Defense R&D*. 2016.

[11] "Real Option," *Investopedia*. [Online]. Available: http://www.investopedia.com/terms/r/realoption.asp. [Accessed: 01-Jul-2017].

[12] A. M. Batkovskiy, A. V. Leonov, A. Y. Pronin, E. G. Semenova, and A. V. Fomina, "Models of Economic Evaluation of High-Tech Products," *Indian J. Sci. Technol.*, vol. 9, no. 28, 2016.

[13] D. F. Rico, "ROI of Technology Readiness Assessments Using Real Options: An Analysis of GAO Data from 62 U.S. DoD Programs," *Unpubl. White Pap.*, 2007.

[14] H. S. . Herath and C. S. Park, "Economic Analysis of R&D Projects: An Optons Approach," *Eng. Econ.*, vol. 44, no. 1, pp. 1–35, 1999.

[15] R. G. Cooper, "Managing Technology Development Projects," *IEEE Eng. Manag. Rev.*, vol. 35, no. 1, pp. 67–76, 2007.

[16] J. C. Mankins, "Technology readiness and risk assessments: A new approach," *Acta Astronaut.*, vol. 65, no. 9–10, pp. 1208–1215, 2009.

[17] G. L. Tritle, E. F. V Scriven, and A. R. Fusfeld, "Resolving Uncertainty in R&D Portfolios," *Res. - Technology Manag.*, vol. 43, no. 6, pp. 47–55, 2000.

[18] L. M. Meade and a. Presley, "R&D project selection using the analytic network process," *Eng. Manag. IEEE Trans.*, vol. 49, no. 1, pp. 59–66, 2002.

[19] W. D. Bodensteiner, E. A. Gerloff, and J. C. Quick, "Uncertainty and stress in an R&D project environment," *R&D Manag.*, vol. 19, no. 4, pp. 309–322, 1989.

[20] J. Wang, C. Y. Wang, and C. Y. Wu, "A real options framework for R&D planning in technology-based firms," *J. Eng. Technol. Manag.*, vol. 35, pp. 93–114, 2015.

[21] R. G. Cooper and E. J. Kleinschmidt, "Winning businesses in product development: The critical success factors," *Res. Manag.*, vol. 50, no. 3, pp. 52–66, 2007.

[22] C. Carlsson, R. Fullér, M. Heikkilä, and P. Majlender, "A fuzzy approach to R&D project portfolio selection," *Int. J. Approx. Reason.*, vol. 44, no. 2, pp. 93–105, 2007.

[23] M. G. Lipsett, "Personal Communication." 2017.

[24] K. M. Kelm, V. K. Narayanan, and G. E. Pinches, "Shareholder Value Creation during R&D Innovation and Commercialization Stages," *Acad. Manag.*, vol. 38, no. 3, pp. 770–786, 1995.

[25] Y. Lee and R. Gaertner, "Technology Transfer from University to Industry: A Larg–Scale Experiment with Technology Development and Commercialization," *Policy Stud. J.*, vol. 22, no. 2, pp. 384–399, 1994.

[26] D. Klar, J. Frishammar, V. Roman, and D. Hallberg, "A Technology Readiness Level scale for iron and steel industries A Technology Readiness Level scale for iron and steel industries," *Ironmak. Steelmak.*, vol. 43, no. 7, pp. 494–499, 2016.

[27] E. W. Eldred and M. E. Mcgrath, "Commercializing New Technology — II," *Res. Manag.*, vol. 40, no. 2, pp. 29–33, 1997.

[28] J. Birkinshaw and M. T. Hansen, "The Innovation Value Chain," no. July, 2007.

[29] L. Y. Cohen, P. W. Kamienski, and R. L. Espino, "Gate system focuses industrial basic research," *Res. Manag.*, vol. 41, no. 4, pp. 34–37, 1998.

[30] M. Hoegl, K. Weinkauf, and H. G. Gemuenden, "Interteam Coordination, Project Commitment, and Teamwork in Multiteam R&D Projects: A Longitudinal Study," *Organ. Sci.*, vol. 15, no. 1, pp. 38–55, 2004.

[31] U.S Government Accountability Office, "Technology Readiness Assessment Guide Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects," 2016.

[32] Y. Z. Mehrjerdi and M. Dehghanbaghi, "A Dynamic Risk Analysis on New Product

Development Process," *Int. J. Ind. Eng. Prod. Res.*, vol. 24, no. 1, pp. 17–35, 2013.

[33] J. M. Eckhause, D. R. Hughes, and S. A. Gabriel, "Evaluating real options for mitigating technical risk in public sector R&D acquisitions," *Int. J. Proj. Manag.*, vol. 27, no. 4, pp. 365–377, 2009.

[34] N. Azizian, S. Sarkani, and T. Mazzuchi, "A comprehensive review and analysis of maturity assessment approaches for improved decision support to achieve efficient defense acquisition," in *Proceedings of the World Congress on …*, 2009, vol. 2.

[35] C. Dion-schwarz, "How the Department of Defense Uses Technology Readiness Levels," 2008.

[36] A. Olechowski, S. D. Eppinger, and N. Joglekar, "Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities," in *Portland International Conference on Management of Engineering and Technology (PICMET)*, 2015, pp. 2084–2094.

[37] I. Ameka and W. Dhewanto, "Technology Push vs. Market Pull in Technology University Innovation Commercialization," *Inf. Manag. Bus. Rev.*, vol. 5, no. 7, pp. 337–341, 2013.

[38] H. Munro and H. Noori, "Measuring Commitment to New Manufacturing Technology: Integrating Technological Push and Marketing Pull Concepts," *IEEE Trans. Eng. Manag.*, vol. 35, no. 2, pp. 63–70, 1988.

[39] L. S. Wheatcraft, "Developing Requirements for Technology-Driven Products," *INCOSE Int. Symp.*, vol. 15, no. 1, pp. 681–693, 2005.

[40] G. Di Stefano, A. Gambardella, and G. Verona, "Technology push and demand pull perspectives in innovation studies: Current findings and future research directions," *Res. Policy*, vol. 41, no. 8, pp. 1283–1295, 2012.

[41] G. F. Nemet, "Demand-pull, technology-push, and government-led incentives for non-incremental technical change," *Res. Policy*, vol. 38, no. 5, pp. 700–709, 2009.

[42] M. Faizal, A. Zaidi, and S. N. Othman, "Understanding the Concept of Dynamic Capabilities by Dismantling Teece, Pisano, and Shuen (1997)'s Definition," *Int. J. Acad. Res. Bus. Soc. Sci.*, vol. 2, no. 8, pp. 367–378, 2012.

[43] D. J. Teece, G. Pisano, and A. M. Y. Shuen, "Dynamic Capabilities and Strategic Management," *Strateg. Manag. J.*, vol. 18, no. 7, pp. 509–533, 1997.

[44] J. C. Mankins, "Technology Readiness Levels. A White Paper," 1995.

[45] K. Tomaschek, A. L. Olechowski, S. D. Eppinger, and N. R. Joglekar, "A Survey of Technology Readiness Level Users.," in *INCOSE International Symposium*, 2016, vol. 26, no. 1, pp. 2101–2117.

[46] C. Piaszczyk, "Model Based Systems Engineering with Department of Defense Architectural

Framework," *Syst. Eng.*, vol. 14, no. 3, pp. 305–326, 2011.

[47] B. Sauser, J. E. Ramirez-marquez, and W. Tan, "A Systems Approach to Expanding the Technology Readiness Level within Defense Acquisition," 2009.

[48] Department of Defense, "Technology Readiness Assessment Deskbook," 2005.

[49] Dan Newman, "Technology Readiness Level and they Valley of Death," 2017. [Online]. Available: http://www.boeing.com/features/innovation-quarterly/may2017/feature-thought-leadership-newman.page. [Accessed: 04-Jul-2017].

[50] NASA, "NASA Engineering Handbook," 2007.

[51] NASA, "NASA TRL Definitions." [Online]. Available: https://www.nasa.gov/sites/default/files/trl.png. [Accessed: 01-Jan-2017].

[52] R. Valerdi and R. J. Kohl, "An Approach to Technology Risk Management," in *Engineering Systems Division Symposium*, 2004, vol. 3, pp. 1–8.

[53] J. C. Mankins, "Technology readiness assessments: A retrospective," *Acta Astronaut.*, vol. 65, no. 9–10, pp. 1216–1223, 2009.

[54] National Research Council of Canada, "Personal Communication." 2017.

[55] J. C. Mankins, "Approaches to Strategic Research and Technology (R&T) Analysis and Road Mapping," *Acta Astronaut.*, vol. 51, no. 1–9, pp. 3–21, 2002.

[56] R. A. Bauer, P. S. Millar, and C. D. Norton, "Bridging the Technology Readiness 'Valley of Death' Utilizing Nanosats," 2015.

[57] J. C. Mankins, "RESEARCH & DEVELOPMENT DEGREE OF DIFFICULTY. A White Paper.," 1998.

[58] W. L. Nolte, B. M. Kennedy, and J. Dziegiel Roger J., "Technology Readiness Level Calculator," *White Pap. Air Force Res. Lab. 2004.*, pp. 1–16, 2003.

[59] J. E. Kasser, "Applying Holistic Thinking to the Problem of Determining the Future Availability of Technology," *IEEE Trans. Syst. Man, Cybern. Syst.*, vol. 46, no. 3, pp. 440–444, 2016.

[60] J. W. Bilbro, "Using the Advancement Degree of Difficulty (AD2) as an input to Risk Management," *Multi-dimensional Assess. Technol. Matur. Technol. Matur. Conf.*, 2008.

[61] S. Gavankar, S. Suh, and A. A. Keller, "The Role of Scale and Technology Maturity in Life Cycle Assessment of Emerging Technologies A Case Study on Carbon Nanotubes," *J. Ind. Ecol.*, vol. 19, no. 1, pp. 51–60, 2014.

[62] B. Basu and S. Ghosh, "Chapter 11 Assessment of Technology and Manufacturing Readiness Levels," in *Biomaterials for Musculoskeletal Regeneration: Applications*, Springer, 2016, pp.

235–246.

[63] B. Sauser, D. Verma, J. Ramirez-Marquez, and R. Gove, “From TRL to SRL: The concept of systems readiness levels,” in *Conference on Systems Engineering Research, Los Angeles, CA*, 2006.

[64] J. Fernandez, “Contextual Role of TRLs and MRLs in Technology Management,” *Sandia Natl. Lab. SAND2010-7595*, no. November, 2010.

[65] J. A. Keizer, J. I. M. Halman, and M. Song, “From experience: Applying the risk diagnosing methodology,” *J. Prod. Innov. Manag.*, vol. 19, no. 3, pp. 213–232, 2002.

[66] V. Thorn, F. Hunt, R. Mitchell, D. Probert, and R. Phaal, “Internal technology valuation : real world issues,” *Int. J. Technol. Manag.*, vol. 53, no. 2–4, pp. 149–160, 2011.

[67] J. Wang and C. Y. Yang, “Flexibility planning for managing R&D projects under risk,” *Int. J. Prod. Econ.*, vol. 135, no. 2, pp. 823–831, 2012.

[68] H. Mikkelsen, “Risk management in product development projects,” *Int. J. Proj. Manag.*, vol. 8, no. 4, pp. 217–221, 1990.

[69] M. Benaroch, “Option-Based Management of Technology Investment Risk,” vol. 48, no. 4, pp. 428–444, 2001.

[70] K. Rudnik and A. M. Deptuła, “System with probabilistic fuzzy knowledge base and parametric inference operators in risk assessment of innovative projects,” *Expert Syst. Appl.*, vol. 42, no. 17–18, pp. 6365–6379, 2015.

[71] R. Balachandra and J. H. Friar, “Factors for Success in R&D Projects and New Product Innovation : A Contextual Framework,” *IEEE Trans. Eng. Manag.*, vol. 44, no. 3, pp. 276–287, 1997.

[72] S. K. Sharma and U. Chanda, “Developing a Bayesian belief network model for prediction of R&D project success,” *J. Manag. Anal.*, pp. 1–24, 2017.

[73] J. a Keizer, J. Vos, and J. I. M. Halman, “Risks in New Product Development Risks in New Product Development,” no. February 2003, pp. 1–26, 2005.

[74] T. Daim, *Managing Technological Innovation: Tools and Methods*, Volume 1. World Scientific Publishing, 2017.

[75] Y. H. Park, “A Study of R&D Investment Framework and Success Factors,” *Asian J. Qual.*, vol. 9, no. 1, pp. 103–112, 2008.

[76] J. Wu and Z. Wu, “Integrated risk management and product innovation in China: The moderating role of board of directors,” *Technovation*, vol. 34, no. 8, pp. 466–476, 2014.

[77] R. G. McGrath and I. C. MacMillan, “Assessing technology projects using real options

reasoning," *Res. …*, vol. 43, no. 4, pp. 35–49, 2000.

[78] L. M. Brandscomb and P. E. Auerswald, *Taking Technical Risks: How Innovators, Managers, and Investors Manage Risk*. MIT Press, 2003.

[79] R. G. McGrath, "A Real Options Logic for Initiating Technology Positioning Investments," *Acad. Manag. Rev.*, vol. 22, no. 4, pp. 974–996, 1997.

[80] L. Vincent, "Marketing Strategies for Commercialization of New Technologies," *Technol. Innov. Gener. Econ. Results*, pp. 257–287, 2016.

[81] B. Kayis *et al.*, "IRMAS - development of a risk management tool for collaborative multi-site, multi-partner new product development projects," *J. Manuf. Technol. Manag.*, vol. 18, no. 4, pp. 387–414, 2007.

[82] Jay J. Janney and Gregory G. Dess, "Can Real-Options Analysis Improve Decision-Making? Promises and Pitfalls," *Acad. Manag.*, vol. 18, no. 4, pp. 60–75, 2004.

[83] D. Hillson, "Extending the risk process to manage opportunities," *Int. J. Proj. Manag.*, vol. 20, no. 3, pp. 235–240, 2002.

[84] S. L. Murray, K. Grantham, and S. B. Damle, "Development of a Generic Risk Matrix to Manage Project Risks," *J. Ind. Syst. Eng.*, vol. Vol. 5, no. 1, pp. 35–51, 2011.

[85] N. Fenton and M. Neil, *Risk Assessment and Decision Analysis with Bayesian Networks*. CRC Press, 2012.

[86] V. Dumbrava, "Using Probability – Impact Matrix in Analysis and Risk Assessment Projects," *J. Knowl. Manag. Econ. Inf. Technol.*, no. Special Issue, pp. 76–96, 2013.

[87] L. Anthony Cox, "What's wrong with risk matrices?," *Risk Anal.*, vol. 28, no. 2, pp. 497–512, 2008.

[88] R. S. Kaplan and D. P. Norton, "The balanced scorecard. Measures that drive performance," *Harvard business review*, pp. 71–79, 2005.

[89] S. A. Mastroianni, "Risk Management among Research and Development Projects," 2011.

[90] J. R. Hauser, "How Puritan-Bennett used the house of quality," *Sloan Manage. Rev.*, vol. 34, no. 3, pp. 61–70, 1993.

[91] E. Schwartz, "The real options approach to valuation: Challenges and opportunities," *Lat. Am. J. Econ.*, vol. 50, no. 2, pp. 63–177, 2013.

[92] U. Dzyuma, "Real options compared to traditional company valuation methods: Possibilities and constraints in their use," *e-Finanse*, vol. 8, no. 2, p. 51, 2012.

[93] J. E. N. Iii and R. De Neufville, "Hybrid real options valuation of risky product development projects," *Int. J. Technol. Policy Manag.*, vol. 1, no. 1, p. 29, 2001.

[94] S.-C. Lee, "Using real option analysis for highly uncertain technology investments: The case of wind energy technology," *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 4443–4450, 2011.

[95] S. C. Myers, "Finance theory and financial strategy," *Midl. Corp. Financ. J.*, vol. 5, no. 1, pp. 6–13, 1987.

[96] B. De Reyck, Z. Degraeve, and R. Vandenborre, "Project options valuation with net present value and decision tree analysis," *Eur. J. Oper. Res.*, vol. 184, no. 1, pp. 341–355, 2008.

[97] E. S. Schwartz and L. Trigeorgis, *Real Options and Investment under uncertainty: Classical Readings and Recent Contributions*. MIT Press, 2004.

[98] N. T. Nang, N. Takezawa, and N. Takezawa, "Real options and the evaluation of research and developement projects in the pharmaceutical industry: A case study," *J. Oper. Res. Soc. Japan*, vol. 45, no. 4, pp. 385–403, 2002.

[99] J. Yliopisto, "Real Options Analysis as a tool for Start-Up Company Investment Valuation," University of Jyväskylä, 2015.

[100] K. Milis and R. Mercken, "The use of the balanced scorecard for the evaluation of Information and Communication Technology projects," *Int. J. Proj. Manag.*, vol. 22, no. 2, pp. 87–97, 2004.

[101] R. G. Cooper, S. J. Edgett, and E. J. Kleinschmidt, "Best practices for managing R&D portfolios," *Res. Manag.*, vol. 41, no. 4, pp. 20–33, 1998.

[102] S. Block, "Are 'Real Options' Actually Used in the Real World?," *Eng. Econ.*, vol. 52, no. 3, pp. 255–267, 2007.

[103] P. Kodukula and C. Papudesu, *Project Valuation Using Real Options: A Practitioner's Guide*. J. Ross Publishing, 2006.

[104] C. W.-N. . Chan, C.-H. . Cheng, A. . Gunasekaran, and K.-F. . Wong, "A framework for applying real options analysis to information technology investments," *Int. J. Ind. Syst. Eng.*, vol. 10, no. 2, pp. 217–237, 2012.

[105] F. Black and M. Scholes, "The Pricing of Options and Corporate Liabilities," *J. Polit. Econ.*, vol. 81, no. 3, pp. 637–654, 2016.

[106] T. A. Luehrman, "Investment Opportunities as Real Options: Getting Started on the Numbers," *Harv. Bus. Rev.*, vol. 76, no. 4, pp. 97–105, 1998.

[107] C. M. Sipp and E. G. Carayannis, "Real Options and Strategic Technology Venturing," *Real Options Strateg. Technol. Ventur. A New Paradig. Decis. Mak.*, vol. 31, pp. 15–39, 2013.

[108] J. C. Cox, S. A. Ross, and M. Rubinstein, "Option Pricing: A Simplified Approach," *J. financ. econ.*, vol. 7, pp. 229–263, 1979.

[109] G. Sick, "Chapter 21 Real options," in *Handbooks in Operations Research and Management*

Science, vol. 9, no. C, 1995, pp. 631–691.

[110] L. E. Brandão, J. S. Dyer, and W. J. Hahn, “Using Binomial Decision Trees to Solve Real-Option Valuation Problems,” *Decis. Anal.*, vol. 2, no. 2, pp. 69–88, 2005.

[111] P. Kodukula and C. Papudesu, *Project valuation using real options: a practioner’s guide*. J. Ross Publishing, 2006.

[112] B. Tan, E. Anderson, J. Dyer, and G. Parker, “Using Binomial Decision Trees and Real Options Theory to Evaluate System Dynamics Models of Risky Projects,” *Syst. Dyn. Rev.*, pp. 1–15, 2009.

[113] S. Benninga and E. Tolkowsky, “Real Options - An Introduction and an Application to R&D Valuation,” *Eng. Econ.*, vol. 47, no. 2, pp. 151–168, 2002.

[114] W. Bailey, B. Couët, and A. Bhandari, “Unlocking the value of real options,” *Oilf. Rev.*, pp. 4–19, 2003.

[115] C. Wernz, I. Gehrke, and D. R. Ball, “Managerial decision-making in hospitals with real options analysis,” *Inf. Syst. E-bus. Manag.*, vol. 13, no. 4, pp. 673–691, 2015.

[116] O. Yu, “Application of real options analysis to technology portfolio planning: a case study,” *Int. J. Qual. Reliab. Manag.*, vol. 25, pp. 52–59, 2008.

[117] L. T. Miller and C. S. Park, “Decision Making Under Uncertainty—Real Options to the Rescue?,” *Eng. Econ.*, vol. 47, no. 2, pp. 105–150, 2002.

[118] A. K. Dixit and R. S. Pindyck, *Investment under uncertainty*. Princeton University Press, 1994.

[119] M. Boyer, P. Christoffersen, P. Lasserre, and A. Pavlov, “Value creation , Risk Management and Real Options,” 2003.

[120] R. Adner and D. A. Levinthal, “What Is Not a Real Option: Considering Boundaries for the Application of Real Options to Business Strategy,” *Acad. Manag. Rev.*, vol. 29, no. 1, pp. 74–85, 2004.

[121] B. Fernandes, J. Cunha, and P. Ferreira, “The use of real options approach in energy sector investments,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 4491–4497, 2011.

[122] S. M. Ross, “An Elementary Introduction to Mathematical Finance: Options and Other Topics,” *J. Am. Stat. Assoc.*, vol. 99, no. 466, pp. 563–563, 2004.

[123] T. Driouchi and D. Bennett, “Real options in multinational decision-making: Managerial awareness and risk implications,” *J. World Bus.*, vol. 46, no. 2, pp. 205–219, 2011.

[124] E. A. Martínez-Ceseña and J. Mutale, “Application of an advanced real options approach for renewable energy generation projects planning,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 4, pp. 2087–2094, 2011.

[125] L. Trigeorgis and J. J. Reuer, "Real Options Theory in Strategic Management," *Strateg. Manag. J.*, vol. 38, no. 1, pp. 42–63, 2017.

[126] D. M. Lander and G. E. Pinches, "Challenges to the practical implementation of modeling and valuing real options," *Q. Rev. Econ. Financ.*, vol. 38, no. 3, pp. 537–567, 1998.

[127] T. Eschenbach, N. Lewis, M. Henrie, E. Baker, and J. C. Hartman, "Real Options and Real Engineering Projects," *Eng. Manag. J.*, vol. 19, no. 4, pp. 11–19, 2007.

[128] A. Kumaraswamy, "A real options perspective of firms' R&D investments," New York University, 1996.

[129] T. E. Copeland and V. Antikarov, *Real Options: A Practitioner's Guide*. New York, 2001.

[130] M. Amram and N. Kulatilaka, *Real options: Managing strategic investment in an uncertain world*. Oxford University Press, 1998.

[131] B. Tan, E. G. Anderson, J. S. Dyer, and G. G. Parker, "Evaluating system dynamics models of risky projects using decision trees: alternative energy projects as an illustrative example," *Syst. Dyn. Rev.*, vol. 26, no. 1, pp. 1–17, 2010.

[132] A. M. Law, *Simulation Modeling & Analysis*, 4th Editio. 2007.

[133] J. Mun and T. Housel, "A Primer on Applying Monte Carlo Simulation, Real Options Analysis, Knowledge Value Added, Forecasting, and Portfolio Optimization," 2010.

[134] M. Benaroch, "Real Options Models for Proactive Uncertainty-Reducing Mitigations and Applications in Cybersecurity Investment Decision-Making," 2017.

[135] R. Shishko, D. H. Ebbeler, and G. Fox, "NASA technology assessment using real options valuation," *Syst. Eng.*, vol. 7, no. 1, pp. 1–12, 2004.

[136] R. Shishko and D. H. Ebbeler, "A Real-Options Approach for NASA Strategic Technology Selection," 1999.

[137] H. ELKUS, "Why Investors Like to See a Patent Before Backing an Entrepreneur," *The Wall Street Journal*, 2013. [Online]. Available: https://blogs.wsj.com/experts/2013/12/03/why-investors-like-to-see-a-patent-before-backing-an-entrepreneur/. [Accessed: 01-Jun-2017].

[138] NASA, "NASA ESMP TRL Assessment Workbook." 2015.

[139] D. A. Marca, "Augmenting SADTTM To Develop Computer Support for Cooperative Work David A. Marca 1," *Architecture*, 1991.

[140] SDTC, "Risk Profile vs. Stages of Technology Development & Commercialization." [Online]. Available: https://roelfwoldring.files.wordpress.com/2009/07/enterpriserisk.jpg. [Accessed: 01-May-2017].

[141] O. Fuerst and U. Geiger, *From Concept to Wall Street: A Complete Guide to Entrepreneurship*

and Venture Capital, 1st Editio. Financial Times Prentice Hall, 2003.

[142] A. Triantis, “Applying a Real Options Analysis,” *Accenture Academy*, 2013. [Online]. Available: https://www.accentureacademy.com/d/blog/257/?GoBackTo=74F5C9A9#/u/blog/257.

[143] M. Lipsett, “ENG M 620: Real Options Valuations.” 2017.

[144] P. Balogh, P. Golea, and V. Inceu, “Profit Forecast Model Using Monte Carlo Simulation in Excel,” *Rom. Stat. Rev.*, vol. 61, no. 12, pp. 33–40, 2013.

[145] J. Flatto, “The application of real options to IT valuation process a benchmark study,” University of New Haven, 1996.

[146] Copperstone Technologies, “Copperstone Technologies Engineering Consulting and Robotic Systems for Remote Environmental Monitoring,” 2017.

[147] Copperstone Technologies, “Copperstone Technologies Robotic Systems for Environmental Monitoring,” 2017.

[148] S. Dwyer, “Agile Design Project Methodology for Small Teams Developing Mechatronic Systems,” University of Alberta, 2017.

[149] W. Baird, “Boron Nitride Nanotubes,” 2014.

[150] National Research Council of Canada, “NRC Makes World-First Demonstration of Pilot-Scale Boron Nitride Nanotube Production,” 2014. [Online]. Available: http://www.marketwired.com/press-release/nrc-makes-world-first-demonstration-of-pilot-scale-boron-nitride-nanotube-production-1941973.htm.

[151] National Research Council of Canada, “Pure Strength Super Tubes: the strong-and-petite type.” [Online]. Available: http://www.nrc-cnrc.gc.ca/eng/about/centennial/100_years/2010_beyond.html/#s86. [Accessed: 11-Aug-2017].

[152] National Research Council of Canada, “A big opportunity for microscopic fibres,” 2016. [Online]. Available: http://www.nrc-cnrc.gc.ca/eng/achievements/highlights/2016/microscopic_fibers.html. [Accessed: 11-Aug-2017].

[153] J. Busby and C. Pitts, “Real options and capital investment decisions,” *Manag. Account.*, vol. 75, no. 10, pp. 38–39, 1997.

[154] N. Smallwood and D. Ulrich, “Capitalizing Capabilities,” *Harvard Business Review*, 2004.

Appendix 1 Supporting Information for Literature Review

1.1 Definitions of TRLs

Table 11. TRL Software Definitions[Adapted from [31]]

TRL Definition	Description
1 Basic principles observed and reported.	Lowest level of software technology readiness. A new domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms.
2 Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies using synthetic data.
3 Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
4 Module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment).	Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy element as appropriate. Prototypes developed to demonstrate different aspects of eventual system.
5 Module and/or subsystem validation in a relevant environment.	Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment
6 Module and/or subsystem validation in a relevant end-to-end environment	Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.
7 System prototype demonstration in an operational, high-fidelity environment.	Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations, where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.
8 Actual system completed and mission qualified through test and demonstration in an operational environment.	Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenario
9 Actual system proven through successful mission-proven operational capabilities.	Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system.

Table 12. TRL Hardware Definitions [Adapted from [31]]

TRL Definition	Description
1 Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.
2 Technology concept and/or application formulated	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.
3 Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.
4 Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.
5 Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.
6 System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.
7 System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).
8 Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).
9 Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission

1.2 GOA Risk Assessment

Table 13. GOA TRA Steps [Adapted from [31]]

Steps	Best Practices	Associated Tasks
1	Design the overall technology maturity assessment strategy for the program or project. Identifies all the technology maturity assessments for the overall program strategy throughout the acquisition, including guidance on reaching agreement with stakeholders on the scope and schedule	• The technology needs of a program are well-understood and the assessment strategy reflects those needs. • The schedule and events needed to conduct assessments was discussed, developed, and documented in one or more strategy documents • The technology maturity assessment strategy is aligned with the systems engineering plan, acquisition strategy, or similar plans.
2	Define the individual TRA's purpose, develop, a TRA plan, and assemble the assessment team. Includes developing a plan for a specific assessment of critical technologies and criteria for selecting the team that will conduct the TRA, including agreements such as statements of independence	• A charter, charge memorandum or similar instrument was developed to identify the TRA's purpose, required level of detail, overall scope, TRL definition, and who will receive the TRA report was determined. • The expertise needed to conduct the TRA and specific team members who are independent of the program were determined • The assessment approach was outlined, including appropriate TRL calculators (if used) • An approach for how the data is to be documented and information reported was defined • A plan for handling how dissenting views was identified • Pertinent information needed to conduct the TRA was obtained
3	Select critical technologies Includes the criteria and steps to identify and select critical technologies for evaluation; responsible parties facilitating the selection of critical technologies may include the specific organizations, people, and subject matter experts with key knowledge, skills, and experience	• The program's purpose, system, and performance characteristics and system configurations were identified in a technology baseline description document • A work breakdown structure, process flow sheet, or other documents that characterize the overall system, subsystems, and elements were used to select critical technologies • Programmatic and technical questions and the technology's operational environment were used to determine if a technology was critical • Relevant environment for each critical technology was derived from the operational environment
4	Evaluate critical technologies Includes the criteria, analytical methods, steps, people, and guidance used to facilitate the evaluation of critical technologies; the sources and data, analyses, test demonstrations, test environments compared to derived relevant environments, pilots, simulations, and other evidence used to evaluate the maturity and readiness of critical technologies; the agreement of the program manager, technology developer, and TRA lead on what constitutes a specified TRL level, goal, or objective	• TRLs, or another measure were used as a common measure of maturity • Consistent TRL definitions and evidence needed to achieve the designated category or TRL were determined before the assessment • The assessment clearly defined inclusions and exclusions; the assessment team determined whether the test articles and environments were acceptable • The assessment team interviewed testing officials to determine whether the test results were sufficient and acceptable • The assessment team documented all pertinent information related to their analysis
5	Prepare, coordinate and submit TRA report Includes the elements to be included in the TRA report and how the report is developed, submitted for initial and final review, and communicated; also includes how dissenting views are addressed, documented, and reported and who is involved	• An official TRA report was prepared that documented actions taken in steps 1-4 above • Official comments on the TRA report were obtained and dissenting views were explained • If the TRA was conducted by the technology developer or program manager for their own internal use where an official report is not required, it should be documented for future reference and use. This may include a TRA self-assessment conducted during early development and later used as a reference source to ascertain initial risks.
6	Using TRA results and developing a Technology Maturation Plan Describes how technology developers, program managers, and governance bodies use the TRA results to make informed decisions and how potential risks and concerns are identified and the use of such information in other	• TRA results were used to make decisions about the program's development priorities • Program management identified risks and concerns related to the TRA were provided as inputs to risk, cost,and planning efforts • A technology maturation plan was developed to track progress toward higher technology maturity levels for troubled or selected technologies

1.3 Potential Risks in R&D

I Product Family & Brand Positioning risks
1. New product helps to achieve business strategy
2. Project is important for project portfolio
3. New product contributes to brand name position
4. Project includes global roll out potential and schedule
5. New product fits within existing brand
6. New product fits with brand image
7. New product enhances potential of product family development
8. New product provides opportunities for platform deployment
9. New product supports company reputation
10. New product has brand recovery potential
11. New product has brand development potential
12. New product's platform will be accepted by consumers

II. Product technology risks
1. New product's intended functions are known and specified
2. New product fulfils intended functions
3. In-use conditions are known and specified
4. Interactions of product in-use with sustaining materials, tools etc. are understood
5. Components' properties, function and behavior are known
6. Correct balance between product components is established
7. Assembled product meets safety and technical requirements
8. Alternatives to realize intended product functions available
9. New product shows parity in performance compared to other products
10. New product shows stability while in storage (factory, shop/warehouse, transportation, at home)
11. New Product format meets functional requirements

III. Manufacturing Technology Risks
1. Raw materials available that meet technical requirements
2. Process steps to realize the new product are known and specified
3. Conditions (temperature, energy, safety, etc.) to guarantee processing of good product quality known and specified
4. Production means (equipment and tools) necessary to guarantee good product quality are available
5. Scale up potential is possible according to production yield standards
6. Production system requirements (quality & safety standards, training of human resources, facilities etc.) will be met
7. Product packaging implications are known and specified
8. Manufacturing efficiency standards will be met
9. Alternative approaches to process the intended product will be available
10. Adequate production capacity available
11. Adequate Production Start Up assured
12. Reusability of rejects in production foreseen

IV. Intellectual property Risks
1. Original know-how will be protected
2. Required external licenses or know how known and available
3. Relation to legal and patent rights of competitors known and arranged
4. Relevant patent issues are understood
5. Patent crossing potential known and arranged
6. Trade mark registration potential known and arranged

V. Supply chain & Sourcing risks
1. Suppliers will meet required quality
2. Capacity available to meet peak demands
3. Appropriate after sales services available
4. Contingency options available for each of the selected suppliers
5. Financial position of each supplier is sound
6. Past experiences with each of the suppliers are positive
7. Suppliers are ready to accept modifications if required
8. Supply contracts can be canceled
9. Each supplier will be reliable in delivering according to requirements
10. Required quantities will be produced against acceptable prices
11. Appropriate contract arrangements with suppliers will be settled

VI. Consumer Acceptance Risks
1. Product specifications meeting consumer standards and demands
2. New product fits consumer habits and/or user conditions
3. New product offers unique features or attributes to the consumer
4. Consumers will be convinced that they get value for money, compared to competitive products
5. New product appeals to generally accepted values (e.g. health, safety, nature, environment)
6. New product offers additional enjoyment, compared to competitive products
7. New product will reduce consumer's costs, compared to competitive products
8. Non-intended product use by consumers is adequately anticipated
9. Target consumer's attitudes will remain stable during the development period
10. New product will be communicated successfully with target consumers
11. New product will provide easy-in-use advantages, compared to competitive products
12. Primary consumer requirements are known
13. Target consumers will accept the new product's key product ingredients
14. Niche marketing capabilities available if required
15. Communication about new product is based on realistic product claim
16. Advertising will be effective
17. Product claims will stimulate target consumers to buy
18. New product has repeat sales potential

Figure 31. Potential Risks [Adapted from [65]]

VII. Trade Customer Risks
1. Product specifications will meet trade customer standards and demands
2. Trade customers will welcome the new product from the perspective of potential sales
3. Trade customers will welcome the new product from the perspective of profit margin
4. Trade customers will welcome the new product given required surface and volume on shelf and storage facilities
5. Trade customer's attitude will remain stable during the development period
6. New product will be communicated successfully to trade customers
7. Right distribution channels will be used
8. Trade will give new product proper care
9. Trade supporting persons will endorse the new product
10. Stock demands will be met

VIII. Competitor Risks
1. Product will provide clear competitive advantages
2. Introduction of new product will change existing market share positions
3. Introduction of the new product will have impact on market prices
4. New product will be launched before competitors launch comparable product
5. Response actions towards public and media expected from competitors will be anticipated
6. New product enables the creation of potential barriers for competitors
7. Implications of being technology leader or follower for this project have been identified
8. Competitor's actions will be monitored and followed with adequate response
9. Competitor's challenges will be monitored adequately

IX. Commercial Viability Risks
1. The market target is clearly defined and agreed
2. Market targets are selected based on convincing research data
3. Capital cost projection for new product is feasible
4. Delays in product launch will leave the commercial viability of the new product untouched
5. Sales projections for new product are realistic
6. Estimated profit margin are based on convincing research data
7. Profit margin will meet the company's standards
8. The estimated return on investment will meet the company's standards
9. Volume estimates are based on clear and reliable estimates
10. Product viability will be supported by repeat sales
11. Supplier will get attractive purchasing agreements
12. Knowledge of pricing sensitivity is available
13. Adequate investments to secure safety in production will be made
14. Long term market potential is to be expected
15. Financing of capital investment is secured
16. Fall back to prior product concept is feasible
17. New product is commercially viable in case of market restrictions

X. Organizational & Project Management Risks
1. Internal political climate is in favor of this project
2. Top management actively supports project
3. Project goals and objectives are feasible
4. Project team is sufficiently authorized and qualified for the project
5. Project team will effectively utilize the knowledge and experience of (internal) experts
6. Roles, tasks and responsibilities of all team members are defined and appropriate
7. Decision making process in project is effective
8. Communication between members in the project team is effective
9. Required money, time and (human) resources estimations are reliable and feasible
10. Required money, time and (human) resources will be available when required
11. Project team will be informed in time about project progress
12. External development partners will deliver in time, conform budget and technical specifications
13. Sound alternatives are available to external development partners
14. Collaboration within the project team is effective
15. Sponsor's interest for the project is secured
16. Project will effectively be organized and managed
17. Collaboration with external parties is effective
18. Collaboration between project team and the parent organization is effective
19. Project team is highly motivated and committed
20. Project team is paying attention to the right issues
21. Project has an effective planning and contingency planning
22. Project team is learning from past experiences

XI. Public Acceptance Risks
1. It is clearly understood who is responsible for PR of the project
2. The key opinion formers for the new product are known
3. Support of key opinion formers will be assured
4. Legal and political restrictions will be adequately anticipated
5. Environmental issues will be adequately anticipated
6. Safety issues will be adequately anticipated
7. Possible negative external reactions will be effectively anticipated
8. In case of new technology prior (external) experience will be consulted

XII. Screening & Appraisal
1. New product performance targets will be tested and measured adequately
2. Trade customer appreciation will be tested and measured adequately
3. Consumer appreciation will be tested and measured adequately
4. Adverse properties as a consequence of the technological change will be tested and measured adequately
5. Credibility of the (internal) measures to external agencies is warranted
6. Tests will provide reliable evidence

Appendix 2 Case Study Supporting Information

The information in A2.1 to A2.5 is courtesy of Copperstone Technologies [146][147].

2.1 Copperstone Team Bios

Co-founder and President

Jamie Yuen, M.Sc., EIT, Mechanical Engineering

Jamie's focus is on mechanical, electronics hardware, software design and testing. His role is to manage the day-to-day production operations, contracts and procurement.

Co-founder and Director

Nicolas Olmedo, B.Sc., EIT, Mechanical Engineering

Nicolas works on the design and development of robotic system including mechanical, electrical, and software components. He is also involved in business development activities.

Co-founder and Director

Stephen Dwyer, B.Sc., EIT, Mechanical Engineering

Stephen is the primary firmware developer, implements hardware and firmware embedded systems design and development, as well as mechanical and robotic design and development.

CTO and Advisor

Michael Lipsett, Ph.D., P.Eng, Mechanical Engineering

Michael is a Professor in the Engineering Management Group at the University of Alberta with a Ph.D. from Queen's University on Robot Looseness Fault Detection. He has been a Research Engineer for Atomic Energy of Canada Limited, developed remote and robotic tooling, performed lab and field prototype evaluation, and has experience in project management. Michael has been a Research Associate at Syncrude and supervised the development of BMI remote monitoring technology and all Copperstone initiatives.

Business Development, Marketing, Sales & Strategy

Sarah Prendergast, MBA (Finance)

Sarah is the most recent addition to CST. She joined in April 2017 after completing an MBA in Finance from the University of Alberta. She has a BSc in Biological Sciences from the University of Alberta and brings a wide-range of expertise to the team. She is currently working on business strategy and positioning for CST, as well as operating organization and the marketing, sales and business strategy.

Pre-VMS Program

Currently have two business mentors with a combination of industry background and successful entrepreneurial experience. Their names have not been shared.

Positions that have not been filled:

________– Advisory Board
PhD in Finance – Corporate finance, venture capital and innovation

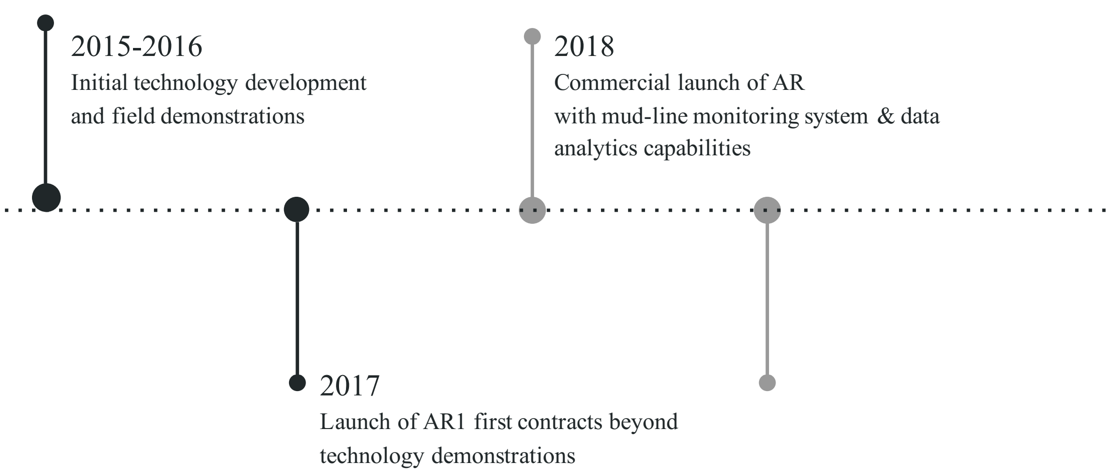
_______– Advisory Board
MBA Finance, JD
Legal Council (______, _______ & ________)

________– Advisory Board
Computer Engineering Technology and Professional Management
Software Developer (_____, _____& _______)
Successful Entrepreneur (_________)

2.2 Activities Timeline

The strategy that Copperstone is deploying focuses on commercialization of the AR1 and development of the AR2. In order to provide the services required by the pilot projects through BGC and ArcelorMittal for the summer of 2017, Copperstone is focused on production of seed broadcasting and seedling planting technology to be included in the AR, as well as improved mobility through centrifuged tailings and frozen sand. The field project for ArcelorMittal for the spring of 2018 will include development of an autonomous system for the rover and mudline mapping technologies. These product development improvements allow Copperstone to deliver the services that oil sands and mining companies have requested and have indicated are highly in demand. The development of these technologies are the key milestones for Copperstone's in 2017 and will provide an excellent entry into the primary market of end users by catering to their product needs.

In addition to production technology milestones, Copperstone has expected purchase order expectations after the completion of the pilot and field projects for BGC and ArcelorMittal. After the successful utilization of the AR technology in the field, Copperstone expects to sign at least two larger tailings monitoring or reclamation contracts by the end of 2017. Coinciding with this increase of market share, Copperstone expects to begin hiring outside of the core founding team in order to bring in expertise in sales and marketing, business development, and overall business strategy.



2.3 Copperstone Technologies Financials

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022
GROSS REVENUE	0	0	$0	$144,000	$600,000	$1,750,000	$2,750,000	$3,500,000	$4,500,000
EXPENSES	$72,073	$43,838	$13,079	$160,034	$242,511	$321,505	$411,339	$506,526	$422,737
NET REVENUE	($72,073)	($43,838)	($13,079)	($16,034)	$357,489	$1,428,495	$2,338,661	$2,993,474	$4,077,263
ADMIN EXPENSES	$48,830	($6,449)	$26,368	$14,300	$21,300	$26,300	$31,300	$31,750	$42,513
NET INCOME	($120,903)	($37,389)	($39,447)	($30,334)	$336,189	$1,402,195	$2,307,361	$2,961,724	$4,034,750

2.4 Sample of Interview Questions with Business Development Manager

Sample of Interview Questions

- Challenges CST is facing right now?
- Updates on the market study
- Where would you begin ensuring you have a complete competent team?
- What is current detail or plan around IP? Need more information to regarding the updates
- When did Copperstone apply/get the patent and what does it cover?
- Current distribution channel plan for Copperstone? What were some of the challenges faced?
- Do you use TRLs? If not, would you use them?
- At what TRL did CST start at in 2014?
- How was the price for the AR1 reached? i.e. then 150/hour, 5000/day
- How many AR1's does CST currently have? (for rental purposes)
- Current R&D activities: Copperstone's current plan/target for the next two years?
- Stakeholder analysis: who are the current stakeholders? Was there a formal analysis done?
- Are there any established relationships with suppliers?
- What is CST's current position in the market? Are they planning on re-positioning within the next two years?
- Any formal risk assessment conducted? If so, what stages was this done?
- Are you hiring new talent?
- What does the financing currently look like? Are you looking for new investors?
- What is the biggest perceived at this point during the project?
- What are the plans for the consulting side of the business?
- Are there plans to operate outside Northern Alberta?

- What commercialization options will you be considering and which one are you learning towards?
- What is your relationship with your competitor ConeTec?
- Where are the ARs currently being built? How long does it take to build one? How much does it cost?
- What were the biggest difficulties during technology development (besides need for capital)?
- Do you have any contracts signed with customers?
- How did you conduct a market study analysis?

2.5 Summary from Relevant Thesis Document

The following is a summary from [148].

In general:

- CST did not communicate with the client as frequently as they should have, which meant the feedback was limited- this resulted in wasted efforts developing and configuring design. parameters on the user end, that were later deemed unnecessary by the client.
- There was a lack of scheduled progress reports and updates.
- Work-breakdown was a challenge for the team. This affected team collaboration and understanding of requirements which lead to improper prioritization.
- Lack of technical and managerial planning lead to over runs on budget and schedules.
- Lack of structured scope or vision.
- Lack of proper documentation throughout the project. Initial scope documents were not updated to reflect changes. This was similar to design documentation as well, which lead to an increase in difficulty in reviewing changes which led to a more time demanding processes.
- Technical success feedback was limited.
- Discipline of progress tracking was an issue.
- Due to limited time and improper time management prototypes were not properly tested.
- Issues with insufficient infrastructure and capabilities to test and address technical problems.

<u>Specific to the AR Technology Project:</u>

- High uncertainty in requirements and technical risks because team did not properly collect information regarding operating environment and conditions, which affected the team's overall understanding and affect field testing. There was a lack in taking appropriate action when dealing with areas of high uncertainty (this overall reduced the technical success of field trials conducted) – resulting in field testing being pushed to a later time i.e. schedule over runs and additional costs.
- Limited to non-existent effort into conducting a formal market analysis. There was no verification of market conditions that were projected at the start of the project. entire market analysis consisted of qualitative data that represent a very small data set from limited sources.
- The team was successful in completing the prototype within a short time frame. CST's team did better than previous work they had done in the past, so prototyping this round was improved in design, assembly and maintenance areas.
- CST was able to act quickly to make changes suggested based on client feedback. This was also due to the fact that the design was more robust and planned better for changes.
- This prototype was developed with MORE stakeholder feedback and was tested in the operating environment.
- Logics and transportation of rover to operational environment was challenging.
- High ambiguity about the operating conditions, and the team should have identified the need to address these areas of high uncertainty and should have taken appropriate action. Failure to do so resulted in reduction in technical success during field testing.
- There was no formal risk management completed during design. However, safe work practices and risk mitigation were used during fabrication and testing.
- High uncertainties due to limited understanding of the market and required technical specifications (most of the specifications were obtained through discussion with a potential customer).
- The project funding came internally from within the organization. Funds were limited.
- The business model of the technology was not decided on at the start of the project however, the models considered for commercialization included sales of AR units, rental, leasing to operators, or providing measurement data services.
- The potential primary market for ARs is in environmental monitoring, with only a small number of potential clients, but large amount of potential application (land).
- CST collaborated with a potential client during testing and demonstration activities.

- CST spent time reviewing and completing design and development o of the mechanical subsystem components. These were expensive activities and diligence was important as costs to make changes later would be high.

Appendix 3 Real Options Analysis Supporting Calculations

3.1 Base-Case DCF

	Year	FV	PV
0	2014	($120,903)	-$120,903.00
1	2015	($37,389)	-$32,512.17
2	2016	($39,447)	-$29,827.60
3	2017	($30,334)	-$19,945.10
4	2018	$336,189	$162,128.18
5	2019	$1,402,195	$563,510.72
6	2020	$2,307,361	$772,730.53
7	2021	$2,961,724	$826,562.81
8	2022	$4,034,750	$938,353.90
		WACC	15%
		MARR	20%
		Income	$3,263,286.14
		NPV	$3,060,098.27

3.2 Sensitivity Analysis

CASE 1:Increase costs by 20%			
	Year	**FV**	**PV**
0	*2014*	($135,318)	($135,318)
1	*2015*	-46156.6	($40,136)
2	*2016*	($42,063)	($31,806)
3	*2017*	-62340.8	($40,990)
4	*2018*	287686.8	138737.8472
5	2019	1337894	537669.5923
6	2020	2225093.2	745179.2106
7	2021	2860418.8	798290.3905
8	2022	3950202.6	918690.8738
downside		**WACC**	0.15
		MARR	0.2
		Income	3138567.914
		NPV	$2,890,319
CASE 1: decrerase costs by 20%			
	Year	**FV**	**PV**
0	*2014*	($106,488.40)	-106488.4
1	*2015*	($28,621.40)	-24888.17391
2	*2016*	($36,831.20)	-27849.67864
3	*2017*	$1,672.80	1099.893154
4	*2018*	$384,691.20	185518.5185
5	2019	$1,466,496.00	589351.8519
6	2020	$2,389,628.80	800281.8501
7	2021	$3,063,029.20	854835.2347
8	2022	$4,119,297.40	958016.9199
Upside		**WACC**	0.15
		MARR	0.2
		Income	3388004.375
		NPV	$3,229,878

CASE 2:Increase MARR to 23%			
	Year	**FV**	**PV**
0	*2014*	($120,903)	($120,903)
1	*2015*	-37389	($32,512)
2	*2016*	($39,447)	($29,828)
3	*2017*	-30334	($19,945)
4	*2018*	336189	146880.1318
5	2019	1402195	498061.3678
6	2020	2307361	666323.1146
7	2021	2961724	695358.5588
8	2022	4034750	770150.743
		WACC	0.15
dowside		**MARR**	0.23
		Income	2776773.916
		NPV	$2,573,586

CASE 2: decrease MARR to 17%			
	Year	**FV**	**PV**
0	*2014*	($120,903.00)	-120903
1	*2015*	($37,389.00)	-32512.17391
2	*2016*	($39,447.00)	-29827.59924
3	*2017*	($30,334.00)	-19945.09739
4	*2018*	$336,189.00	179407.2761
5	2019	$1,402,195.00	639556.7772
6	2020	$2,307,361.00	899498.3629
7	2021	$2,961,724.00	986832.7464
8	2022	$4,034,750.00	1149025.683
Upside		**WACC**	0.15
		MARR	0.17
		Income	3854320.846
		NPV	$3,651,133

CASE 3:Increase revenue by 20%			
	Year	FV	PV
0	*2014*	($120,903)	($120,903)
1	*2015*	-37389	($32,512)
2	*2016*	($39,447)	($29,828)
3	*2017*	-1534	($1,009)
4	*2018*	456189	219998.5532
5	2019	1752195	704167.8723
6	2020	2857361	956924.4175
7	2021	3661724	1021919.966
8	2022	4934750	1147665.132
		WACC	0.15
		MARR	0.2
upside		**Income**	4050675.941
		NPV	$3,866,425

CASE 3:decrease revenue by 20%			
	Year	FV	PV
0	*2014*	($120,903)	($120,903)
1	*2015*	-37389	($32,512)
2	*2016*	($39,447)	($29,828)
3	*2017*	-59134	($38,882)
4	*2018*	216189	104257.8125
5	2019	1052195	422853.5719
6	2020	1757361	588536.6432
7	2021	2261724	631205.6595
8	2022	3134750	729042.6614
		WACC	0.15
downside		**MARR**	0.2
		Income	2475896.348
		NPV	$2,253,772

	Expected NPV		Input			
Variable	**Downside**	**Upside**	**Range**	**Downside**	**Upside**	**Base Case**
AR1 Expenses	$2,890,319	$3,229,878	$339,559	$2,632,370	$1,754,914	$2,193,642
MARR	$2,573,586	$3,651,133	$1,077,547	23%	17%	20%
Gross Revenue	$2,253,772	$3,866,425	$1,612,653	$10,595,200	$15,892,800	$13,244,000
CF Year 0	($135,318)	($106,488)	$28,829	($135,318)	($106,488)	($120,903)
CF Year 1	($40,136)	($24,888)	$15,248	($46,157)	($28,621)	($37,389)
CF Year 2	($31,806)	($27,850)	$3,956	($42,063)	($36,831)	($39,447)
CF Year 3	($40,990)	$1,100	$42,090	($62,341)	$1,673	($30,334)
CF Year 4	$104,258	$219,999	$115,741	$216,189	$456,189	$336,189
CF Year 5	$422,854	$704,168	$281,314	$1,052,195	$1,752,195	$1,402,195
CF Year 6	$588,537	$956,924	$368,388	$1,757,361	$2,857,361	$2,307,361
CF Year 7	$631,206	$1,021,920	$390,714	$2,261,724	$3,661,724	$2,961,724
CF Year 8	$729,043	$1,147,665	$418,622	$3,134,750	$4,934,750	$4,034,750

3.3 Building Capabilities Option Valuation

	Year		**FV**	**PV**	
	2014	0	-120,903.00	-120,903.00	
	2015	1	-37,389.00	-32,512.17	
	2016	2	-39,447.00	-29,827.60	
	2017	3	-30,334.00	-19,945.10	
	2018	4	336,189.00	192,217.15	
	2019	5	1,402,195.00	697,138.73	
	2020	6	[redacted]		
	2021	7			
	2022	8			
	WACC	15%			
	MARR	20%			
	Prelim Investment			-120,903.00	
	PV Income			839,583.19	
			Today 2014		**2015**
					1,259,374.78
upswing	1.5		839,583.19		
downswing	0.67				559,722.13
P(Success)	0.5				
		Prob Weighted			
		Max(V,0) Y1	Eqvt Y0		
	Best	1,221,985.78		827,222.13	
	Worst	680,625.13		839,583.19	probabilistic PV of revenue
				-120,903.00	Present cost of investment to get to option
				706,319.13	Present value of option

3.4 Market Pivot Option Valuation

	Year		**FV**	**PV**			
	2014	0	-135,317.60	-135,317.60			
	2015	1	-37,389.00	-32,512.17			
	2016	2	-39,447.00	-29,827.60			
	2017	3	-33,194.00	-21,825.59	20% increase in expenses in year 2014		
	2018	4	336,189.00	192,217.15			
	2019	5	1,402,195.00	697,138.73			
	2020	6	[redacted]				
	2021	7					
	2022	8					
	WACC	15%					
	MARR	20%					
	Prelim Investment			-135,317.60			
	PV Income			837,702.69			
			Today 2014		**2015**		
					1,256,554.04		
upswing	1.5		837,702.69				
downswing	0.67				558,468.46		
P(Success)	0.5						
		Prob Weighted					
		Max(V,0) Y1	Eqvt Y0				
	Best	1,219,165.04		756,628.04			
	Worst	521,079.46		756,628.04	probabilistic PV of revenue		
				-135,317.60	Present cost of investment to get to option		
				621,310.44	Present value of option		

3.5 Monitoring Services Option Valuation

Year		FV	PV
2014	0	-120,903.00	-120,903.00
2015	1	-37,389.00	-32,512.17
2016	2	-39,447.00	-29,827.60
2017	3	-30,334.00	-19,945.10
2018	4	336,189.00	192,217.15
2019	5	1,402,195.00	697,138.73
2020	6	2,732,361.00	1,181,275.06
2021	7	3,386,724.00	1,273,195.00
2022	8	[redacted]	
WACC	15%		
MARR	20%		
Prelim Investment			-10,970.72
PV Income			2,454,470.06

Expenses increased in year 2020 and 2021 with 25K for each customer.
Gross revenue 500K per customer,one customer in 2020 and one in 2021.

			Today 2017		**2018**		**2019**
upswing	1.5						
downswing	0.67				Net income		
P(Success)	0.5						5,522,557.63
					3,681,705.09		
			2,454,470.06				2,454,470.06
					1,636,313.37		
							1,090,875.58
			Prob Weighted				
			Max(V,0) Y2	Eqvt Y1			
		Best	4,120,362.63				
				2,020,217.46			
		Mid	1,052,275.06		1,032,386.81	probabilistic PV of revenue	
				457,510.89			
		Worst	0.00		-10,970.72	Present cost of investment to get to option	
					1,021,416.10	Present value of option	

3.6 Sales Option Valuation

Year		FV	PV
2014	0	-120,903.00	-120,903.00
2015	1	-37,389.00	-32,512.17
2016	2	-39,447.00	-29,827.60
2017	3	-30,334.00	-19,945.10
2018	4	216,189.00	123,606.76
2019	5	1,402,195.00	697,138.73
2020	6	2,507,361.00	839,710.13
2021	7	3,161,724.00	882,379.14
2022	8	[redacted]	0
WACC	15%		
MARR	20%		
Prelim Investment			-79,581.11
PV Income			1,722,089.27

Expenses are high for year 2021 this is because CST has own plans to develop technology (not shared with me for this thesis) - not really an issue

Assumed they will build one new unit in 2017 and one in 2018

			Today 2017		2018		2019
upswing	1.5						
downswing	0.67				Net income		
P(Success)	0.5						3,874,700.85
					2,583,133.90		
			1,722,089.27				1,722,089.27
					1,148,059.51		
							765,373.01
			Prob Weighted				
			Max(V,0) Y2	Eqvt Y1			
		Best	2,472,505.85				
				1,144,544.73			
		Mid	319,894.27		558,099.67	probabilistic PV of revenue	
				139,084.46			
		Worst	0.00		-79,581.11	Present cost of investment to get to option	
					478,518.56	Present value of option	

3.7 Licensing Option Valuation

Year		FV	PV
2014	0	-120,903.00	-120,903.00
2015	1	-37,389.00	-32,512.17
2016	2	-39,447.00	-29,827.60
2017	3	-30,334.00	-19,945.10
2018	4	311,937.90	178,351.51
2019	5	1,402,195.00	697,138.73
2020	6	2,707,361.00	1,170,466.87
2021	7	3,361,724.00	1,263,796.57
2022	8	[redacted]	
WACC	15%		
MARR	20%		
Prelim Investment			-24,836.36
PV Income			2,434,263.44

Expenses increase by 10% for year 2018

2020 and 2021 both incur additional revenue of $400K each.

			Today 2017		**2018**		**2019**
upswing	1.5						
downswing	0.67				Net income		
P(Success)	0.5						5,477,092.74
					3,651,395.16		
			2,434,263.44				2,434,263.44
					1,622,842.29		
							1,081,894.86
			Prob Weighted				
			Max(V,0) Y2	Eqvt Y1			
		Best	4,074,897.74				
				2,220,420.08			
		Mid	1,032,068.44		1,160,498.04	probabilistic PV of revenue	
				448,725.41			
		Worst	0.00		-24,836.36	Present cost of investment to get to option	
					1,135,661.68	Present value of option	

Appendix 4 Ethics Approval

UNIVERSITY OF ALBERTA

RESEARCH ETHICS OFFICE

308 Campus Tower
Edmonton, AB, Canada T6G 1K8
Tel: 780.492.0459
Fax: 780.492.9429
www.reo.ualberta.ca

Notification of Approval

Date:	July 20, 2017			
Study ID:	Pro00073487			
Principal Investigator:	Sally Mattar			
Study Supervisor:	Michael Lipsett			
Study Title:	Real options analysis application			
Approval Expiry Date:	Thursday, July 19, 2018			
Approved Consent Form:	Approval Date 7/20/2017	Approved Document CONSENT FORM REV DOC 3		
Sponsor/Funding Agency:	National Research Council of Canada	NRC		

RSO-Managed Funding:

Project ID	Project Title	Speed Code	Other Information
RES0034112	Risk-Based Technology Development Valuation Using Real Options		

Thank you for submitting the above study to the Research Ethics Board 1. Your application has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Anne Malena, PhD
Chair, Research Ethics Board 1

Note: This correspondence includes an electronic signature (validation and approval via an online system).