System Dynamics Models
for the Valuation of Real Options in Infrastructure Investments

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ABSTRACT

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As public utilities and government owners face increased budget constraints and greater expectations, alternative project delivery methods will increasingly be used to fast track projects, reduce costs, promote innovation and ensure proper performance for various types of facilities and infrastructure systems. The goals of public utility owners along with economic and financial considerations suggest why some project delivery methods have been selected over other project delivery methods. In response, the first phase of this doctoral research presents a model for selecting the optimum project delivery method that considers economic sustainability as well as other goals of multiple project stakeholders. This first phase of research contributes to the existing body of knowledge and benefits industry practitioners by identifying best practices that improve the project delivery selection process while enhancing risk mitigation efforts. The procurement selection process uses multiple-criteria decision-making and financial risk analysis to select the most economically sustainable delivery method given each project’s unique characteristics. A present value analysis establishes a range of values that considers variables that will potentially impact lifecycle costs. The selection of the procurement process is based on best value where financial risks to the concerned government and other project stakeholders are mitigated through service fee agreements and project finance structures, which are both dynamic and provide for real options.

The second phase of this research presents an innovative approach for the valuation of the types of real options on project finance structures which are specifically procured through a design-build-finance-operate project delivery method (also known as a public-private partnership) (P3).
This second phase of research includes an investigation into systems engineering and System Dynamics (SD) simulation modeling. An SD model is used for the valuation of real options attached to a P3 project’s finance structure. The valuation of these real options is based on the simulation results related to infrastructure performance. The significance of this research is made greater considering that P3s are increasingly being pursued because of their ability to alleviate pressure on government budgets, promote innovation and implement new technologies. These types of contracts, however, tend to be long-term and often need to account for future yet-to-be-seen variables that potentially impact the feasibility of this procurement method. This is especially true when the P3 project exists within a portfolio of competing assets across infrastructure systems. This second phase of research presents An SD model that is used to analyze the complexity of an infrastructure asset procured through a P3 within such a portfolio. An illustrative case demonstrates how discrete and continuous events potentially impact the successful procurement of infrastructure within a portfolio of competing assets comprising a regional transportation system. This second phase of research contributes to the existing body of knowledge by demonstrating how An SD model can simulate the real-world causal relationships that impact the procurement of infrastructure through P3s. The SD model is used for the valuation of real options to promote public initiatives, encourage private participation and enhance economic sustainability of P3 as a viable procurement strategy.

The third and final phase of this doctoral research considers the increasing complexity of infrastructure procurement as individual assets are increasingly viewed as being part of a larger network of interdependent systems. In response, the objective of this final phase is to present a methodology to simulate the behavior of assets that span across different types of infrastructure systems. This investigation presents a method for analyzing investments that traverses across
different infrastructure systems with individual assets procured through a variety of project delivery methods. This third investigation also utilizes an SD simulation model. In the final phase of this doctoral research, however, the SD model captures the causal relationships between competing assets where simulation results elucidate the compounding effects of multiple investments that traverse across two or more infrastructure systems. By doing so, this research contributes to the existing body of knowledge and demonstrates how SD models are effectively used to value real options that are termed *exotic*. These exotic types of real options occur within a portfolio of competing infrastructure assets where the valuation of each real option must consider the compounding effects of competing alternatives as well as the value of the underlying asset. This research presents a methodology for the valuation of multiple types of exotic options in real investments that traverse across various types of infrastructure systems. This method can also be applied to the valuation of other types of exotic options in various industries including research and development pursuits.
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CHAPTER 1. INTRODUCTION

1.1 Problem Statement and Overview

There is not sufficient public money to pay for new infrastructure as existing assets and facilities reach the end of their useful lives. The current scarcity of available funds needed to meet current infrastructure requirements is a significant factor in the renewed use of the design-build-finance-operate project delivery method and other alternative procurement methods (Algarni et al. 2007). On a concurrent basis, new investment opportunities in the form of real options are being created as markets continue to respond to the increased use of these alternative project delivery methods. However, Borison (2003) identifies several fundamental issues which continue to preclude the utilization of classic and other more familiar analytic approaches for the valuation of these real options. In addition, much of the existing body of knowledge focuses only on discrete options within a single infrastructure asset (Chiara, 2006). Both the issues raised by Borison (2003) and the gap in literature cited by Chiara (2006) creates a quandary. This dilemma is further exacerbated when considering that individual assets are increasingly viewed as being part of a larger network of interdependent systems.

In response, this current research presents a method for analyzing and valuing multiple investments that span across different types of infrastructure systems. The culmination of this research presents a method that utilizes SD models to simulate the real-world events and the causal relationships that impact asset performance across different types of infrastructure systems. The results from the SD model’s simulation runs elucidate the compounding effects on multiple investments that traverse across two or more infrastructure systems. At the same time the current research circumvents several of the fundamental issues that are related to the application of finance option
theory in the domain real investments cited by Borison (2003). This research also fills the gap in literature cited by Chiara (2006) by valuing multiple real options on projects that traverse infrastructure sectors on a concurrent basis.

In order to achieve this primary research objective, this report first presents an industry-accepted model for selecting the optimum project delivery method that takes into account economic considerations and the other goals of multiple project stakeholders. This research next shows how alternative procurement strategies can be structured to include various types of options attached to both the project finance structure as well as being embedded in the actual technical design. This research shows how these types of options, which are embedded in the actual design of infrastructure facilities, improve project performance. The current research presents a process for valuing the compounding effects of different types of real options within a single project using an SD model and net present value (NPV) analysis. By doing so, the SD model is used for the valuation of real options on a project using straightforward NPV analysis as a concept already readily discernable to practicing engineers and other decision-makers. The use of SD models in the current research also enables several of the fundamental issues pointed out by Borison (2003) related to the direct application of option pricing from finance theory into the domain of real investments to be resolved. This research expounds upon the existing body of knowledge and uses an SD model and its relatively straightforward simulation process to capture the complexity and compounding effects of an option upon another option. In this manner this doctoral research expands existing theory and builds upon the existing body of knowledge to include the valuation of real options that are termed exotic. These exotic types of real options occur within a portfolio of competing infrastructure assets where the valuation of each real option must consider the compounding effects of competing alternatives as well as the value of the underlying asset(s). The
SD model captures the causal relationships between competing assets where simulation results elucidate the compounding effects of multiple investments that traverse across two or more types of infrastructure systems. The use of SD simulation modeling facilitates this research to build upon previous work completed by Chiara (2006) by creating a methodology to simultaneously value several options on multiple infrastructure assets on a concurrent basis.

It is worth noting that this doctoral research was completed in three phases. Each phase has its own research objective but they each contribute to the overarching goal to create more economically sustainable methods for procuring and managing assets delivered under various delivery methods and across infrastructure sectors. In response, this doctoral research takes into consideration the increasing number of public utility owners who are facing increased budget constraints and greater expectations but who also seek to use alternative project delivery methods in order to fast track projects, reduce costs, promote innovation and ensure proper infrastructure performance. To begin to satisfy this overarching research goal, the first initial phase of this investigation identifies and presents a model for selecting the most economically sustainable project delivery method given a project’s unique characteristics. The first phase of research concludes that under specific conditions, design-build-operate (DBO) is considered (at least in the United States) as a more economically sustainable delivery method compared with other various procurement strategies for water and wastewater treatment facilities. While the first phase of this research is focused on water facilities in the U.S., the methodology for selecting the optimum procurement method can be applied to other infrastructure systems regardless of their locations. More importantly, this first phase of research shows how opportunities are created to include options in the project agreement and on the asset’s financial structure as well as within the actual technical design of the facility.
The second phase of this doctoral research investigates the design-build-finance-operate (DBFO) project delivery method. Also known as public-private partnerships (P3), this procurement method was common prior to the 1940s, with most public projects in the United States after World War II being directly financed by and built under government supervision. Over the past three decades, however, a renewed use of P3 and greater use of private financing sources are due in part to the scarcity of available funds (Algarni et al. 2007). At the core of P3 agreements are project companies, which operate and manage infrastructure assets over prescribed concession periods made with governments (Chiara 2006). At the center of the P3 finance structures are project sponsors who provide equity. This equity is leveraged to raise long-term commercial debt that is used to finance the design and construction as well as the long-term operations and maintenance costs of the facility. The anticipated return on the project sponsor’s investment is actualized on a partially concurrent basis with the repayment of long-term debt from a cash flow generated from the project’s revenue (Yescombe, 2014). Figure 1.1 shows a typical cash flow diagram with design and construction costs, which are represented with downward arrows, preceding a fifteen-year concession period. Figure 1.1 also includes downward arrows that represent the costs for operation and maintenance (O&M), which initiate the concession period upon beneficial use of the facility following the completion of construction. The O&M cash flow is represented by a uniform series of increasingly greater costs as infrastructure and facilities require greater amounts of resources during its useful life until it is either replaced or until significant upgrades are made or major rehabilitation effort has occurred. Finally, Figure 1.1 shows upward facing arrows that represent the anticipated revenue. The revenue stream (i.e. user rates, tolls etc.) is represented by a geometric series that account for exponential increases due to inflation. This revenue is dedicated to the
repayment of principal and interest from commercial debt as well as the return on equity made by the project sponsors.

Figure 1.1 Typical Cash flow Diagram for a P3 Project

P3 projects are typically long-term contracts between governments trying to satisfy public infrastructure needs and a consortium of private partners including equity sponsors and financial lenders who require minimum attractive rates of returns (MARR). MARRs for P3 projects vary widely and are based on the perceived risk level for each individual project. In response to these competing interests, an objective of the second phase of this doctoral research is to enhance the goals of government owners while mitigating risks to project equity sponsors through the inclusion of real options that are attached to the financial structure of the P3 project agreement. Historically, these types of relevant real options include decision points to exercise minimum revenue
guarantees (MRG) or the right-to-abandon (AO) a P3 project prior to the start of construction. This second phase of research contributes to the existing body of knowledge by demonstrating how an SD model can simulate the real-world causal relationships that impact the P3 project delivery method. The SD model is used for the valuation of real options in order to promote public initiatives, encourage private participation and enhance the economic sustainability of P3. The second phase of this doctoral research presents an illustrative case study of a proposed transportation project procured through P3. The illustrative case study is based on a proposed P3 pilot program that is being developed by the Massachusetts Department of Transportation and a proposed third crossing of the Cape Cod Canal in the U.S. Commonwealth of Massachusetts. The basic timeline of risk-sharing for the P3 project in the illustrative case is presented in the Figure 1.2. Figure 1.2 is consistent with the work of Chiara (2006) in which project sponsors must not decide a priori about the number and times to exercise minimum revenue guarantees throughout the concession period and during the operational phase of a P3 project. In contrast with Chiara (2006), the current research includes, in addition to MRGs, an AO that can only be exercised during the pre-concession period and prior to the start of construction. With the use of the SD model, this research demonstrates how to value multiple types of real options on a single infrastructure asset procured through P3. The SD model also sheds light on how the existence of both of these real options within a single asset can impact each other’s perceived and actual values.
It is significant that this research is also consistent with Wang and Neufville (2005) to the degree that real options are categorized into two categories in terms of being either “in” or “on” projects. In these terms, a real option “on” a project is a financial option attached to a “thing” whereas a real option “in” a project is an option created by changing the actual technical design. The current research also recognizes the merit in the arguments first presented in Borison (2003). Borison (2003) presents several fundamental issues which continue to preclude the utilization of classic and other more familiar analytic approaches for real-option valuation. Finally, the current research also considers that previous literature in the domain of real options has focused on discrete options within a single infrastructure asset (Chiara, 2006).

In response, the third and final phase of the current research presents a method that circumvents several of the issues first presented by Borison (2003) by utilizing the SD simulation modeling method. In the third phase of research, the SD model and its simulation results bypass the issues of closed-form analytic approaches that have been commonly used for the valuation of real options.
The third phase of research further builds upon this objective by extending the investigation to include an analysis of the compounding and the more complex effects of multiple real options between competing assets that span across different types of infrastructure. The complexity of the causal relationships between infrastructure assets is captured in the SD model where simulation results are used to value the compounding effects of these more exotic types of real options both “in” the technical design of infrastructure systems as well as “on” their finance structures. The third phase of research presents as an illustrative case an SD model used for the valuation of real options “in” the shale gas industry and “on” the finance structures for technology used for treating the wastewater that is produced as a by-product. The SD model can be continuously calibrated as new field data becomes available. The SD model can also be expanded as other technologies are identified and/or truncated due to obsolescence. Hence, the SD model can assist decision-makers tasked with making real investments in water resource management within the shale gas industry. While this culminating third phase of doctoral research presents an SD model used for the valuation of real options in the shale gas industry, other SD models can be applied to investments “in” the technical design of other infrastructure assets and industries as well as “on” their project finance structures. Future research shall include the development of SD models to value similarly exotic types of real options that traverse other types of infrastructure as well as during research and development pursuits.
1.2 Research Objective

The primary goal of this research is to develop a simulation modeling method that analyzes the causal relationships between infrastructure systems while enhancing the economic sustainability and resiliency of assets through dynamic procurement processes that include real options. To achieve this primary goal, this doctoral research was completed in three phases and investigates on a partially concurrent basis the following.

- Phase I - The role of project delivery methods in infrastructure procurement;
- Phase II - SD simulation modeling and valuation of real options “on” infrastructure; and
- Phase III – SD simulation modeling and valuation of exotic options from finance theory into the domain of real investments.

The main research objectives during each phase are listed below.

1.2.1 Phase I - Project Delivery Methods Research Objectives

The research objectives included in Phase I are:

**Objective 1a:** To present a model for selecting the most economically sustainable procurement process given a project’s unique characteristics. For purposes of this doctoral research, economically sustainable is equivalent to the delivery method with the greatest value defined as the highest ratio of benefit to cost between all procurement processes under consideration.

**Research Questions:** Does a model or method exist for selecting the optimum procurement strategy based on a project’s unique characteristics? What is the basis for determining the most favorable procurement strategy in terms of economic sustainability?

**Hypothesis:** If a risk-adjusted present value (PV) analysis can establish a range of cost estimates for all delivery methods under consideration and for all phases of project, then each procurement process can be evaluated in terms of its economic sustainability
**Objective 1b:** To investigate how the sponsoring government can allocate financial risks to the project participant best able to manage that risk.

Research Questions: Can a project’s finance structure be developed where economic risks are mitigated through dynamic service fee agreements between project participants? Do existing federal revenue procedures or other regulatory guidelines influence the allocation of risk between project participants?

**Hypothesis:** If the procurement process includes options on the project’s finance structure and embedded in dynamic service fee agreements then its economic sustainability and the resiliency of a project shall be enhanced.

**Objective 1c:** To investigate how options within the actual technical design of a facility or an asset enhances the economic sustainability of a project.

Research Questions: Can the sustainability and resiliency of project by mitigating risks through adaptive technical designs? Can the actual technical design of an asset include options that result in risk-sharing and cost-saving mechanisms to the sponsoring government as well as other project stakeholders?

**Hypothesis:** If a project’s actual technical design includes options to expand as demand for it ramps up or other design criteria that result in cost-savings and/or risk-sharing mechanisms then the economic sustainability of a project shall be enhanced.

### 1.2.2 Phase II - SD Models and Valuation of Real Options “On” Infrastructure

The research objectives included in Phase II are:

**Objective 2a:** To advance the economic sustainability of infrastructure procurement through risk-sharing and risk-mitigation contracts. The risk-sharing and risk-mitigation contracts under consideration during Phase II include real options such as the right to abandon a project (AO) prior
to the start of construction as well as minimum revenue guarantees (MRG) that are provided by the government owner to a private equity sponsors during a project’s commercial operation.

**Research Questions:** How can the parameters of an AO and a series of MRGs be structured while considering the compounding effects of multiple types of real options within a single project? How can a straightforward method that is readily discernable to practicing engineers and other industry practitioners be developed for the valuation of these types of real options on project finance structures?

**Hypothesis:** If NPV analysis can take into consideration the compounding effects of multiple types of real options (i.e. AOs and MRGs) then the parameters of multiple risk mitigation contracts can be structured within a single project.

**Objective 2b:** To investigate simulation modeling as a method to analyze infrastructure overtime and in response to a variety of exogenous and endogenous factors.

**Research Questions:** Can a SD simulation model be constructed to analyze the competing feedback effects from market forces, information limitations, costs of entry and exit, and inflexibility of resources across a portfolio of infrastructure assets?

**Hypothesis:** If simulation results accurately reflect how an infrastructure asset performs overtime and in response to a variety of exogenous and endogenous factors then a more straightforward method already discernable to industry practitioners for the valuation of real options (i.e. NPV analysis) can be included as part of the SD model.

**Objective 2c:** To expand the SD model so that it includes the valuation of real options related to infrastructure performance and so that it presents a holistic method for decision-making related to private participation (i.e. equity sponsorship and commercial lending) during the procurement of infrastructure using a P3 procurement process.
**Research Questions:** Can an SD model include the mathematical representation of multiple types of real options (i.e. AOs and MRGs)? Can the SD model simulate the compounding effects of multiple types of real options within a single project? Can the SD model’s simulation results assist in structuring and valuing multiple types of real options within a single project?

**Hypothesis:** If the SD model can simulate the compounding effects of multiple types of real options within a single project then the model can be used to value the discrete and compounding effects of an AO and a strip of MRGs using NPV analysis.

### 1.2.3 Phase III - SD Models and Valuation of Exotic Options

The research objectives included in Phase III are:

**Objective 3a:** To investigate the use of SD models to simulate and analyze multiple real options while recognizing several fundamental issues which continue to preclude the utilization of classic and other more familiar analytic approaches for real-option valuation.

**Research Questions:** Can SD simulation modeling circumvent the issues of applying the direct use of option pricing from finance theory into the domain of real investments? Are the assumptions made during the application of closed-form analytic approaches appropriate for real option valuation? Are the mechanics and incremental processes of closed-form analytics used in the domain of finance applicable to option pricing in real investments?

**Hypothesis:** If the SD model and its simulation results are used to overcome the issues of closed-form analytic approaches, then greater flexibility is afforded to the process of valuing even more complicated options in the domain of real investments. In this sense the SD model is effectively being used to value real options that are termed *exotic* in the domain of finance option pricing.
**Objective 3b:** To investigate and extend the SD model to include an analysis of the compounding effects of multiple real options that exist between competing assets that span across different types of infrastructure systems.

**Research Questions:** How can the SD model capture and simulate the complexity of the causal relationships between infrastructure assets where simulation results can be used to analyze and value the compounding effects of these more exotic types of real options?

**Hypothesis:** If simulation results from an SD model are used to value exotic types of real options that span across different types of infrastructure systems then a more robust procurement strategy will satisfy a greater number of objectives (i.e. economic and environmental sustainability, end-user satisfaction, serviceability, resiliency etc.).

**1.3 Research Significance**

This research is significant because it enhances sustainability of infrastructure procurement by presenting an innovative method to select and administer the optimum project delivery method given a project’s unique characteristics. This research also advances issues that hinder the application of option pricing in real investments and advances option pricing theory to include an analysis of exotic types of options on multiple assets. Of equal importance, this doctoral research is significant because it demonstrates how SD models can simulate the real-world causal relationships between assets and facilities that traverse across infrastructure systems. This doctoral research contributes to the existing body of knowledge by advancing one of the next frontiers of infrastructure management tools, namely SD simulation modeling. For practicing civil engineers and other decision-makers, system dynamics and other simulation methods will allow infrastructure to be better modeled. These simulation models can be constructed and used to
forecast the impacts of the real-world causal relationships between entire systems of infrastructure acting as interdependent networks.

As previously stated, the amount of available public funds is insufficient to deliver new infrastructure and maintain existing assets. In response, alternative project delivery methods and private sources of finance will increasingly be used to meet infrastructure procurement (Algarni et al. 2007). On a concurrent basis, Wang and Neufville (2005) show how real options can be structured to enhance the economic sustainability of infrastructure using straightforward NPV analysis. Other research, including Chiara (2006), points outs that much of previous research in option pricing has focused on one type of risk-mitigation contract within a single infrastructure asset. Finally, other research, including Borison (2003), recognize several fundamental issues that continue to preclude the utilization of more familiar analytic approaches for real-option valuation from finance theory into the domain of non-financial real investments.

The significance of this research is that it benefits industry practitioners by identifying the best practices that improve the project delivery selection process while enhancing economic sustainability of infrastructure procurement. The procurement selection process uses multiple-criteria decision-making and financial-risk analyses to select the most economically sustainable delivery method given each project’s unique characteristics. A present value analysis establishes a range of values that considers variables that will potentially impact lifecycle costs. The selection of the procurement process is based on best value where financial risks to project stakeholders are mitigated through project finance structures that provide for the inclusion of real options. This doctoral research is consistent with Wang and Neufville (2005) in recognizing the economic sustainability of individual assets and entire infrastructure systems can be enhanced by attaching real options on a project’s finance structure as well as embedding other types of options within the
technical design. The current research is also consistent with Wang and Neufville (2005) in its use of a straightforward valuation technique for real options using net present analysis, a method which is readily discernable by practicing engineers and other decision-makers. Finally, this current research introduces the SD simulation modeling method to value complex optionality in real investments across different types of infrastructure systems. This doctoral research expands upon previously published investigations in real option theory that has been limited in its breadth to focus on discrete options within a single asset as pointed out by Chiara (2006) while also circumventing several of the issues shown by Borison (2003) that continue to preclude the utilization of more familiar analytic approaches in finance theory for the valuation of options in real investments.

1.4 Research Methodology

The research for this doctoral report was completed during three phases that span a duration of approximately five years. Each of Chapters 3, 6 and 7 included in this report are related to a discrete group of research objectives and tasks. However, the investigations and literature reviews required to support these semi-autonomous research objectives were performed on a partially concurrent basis. As such, the investigations performed during subsequent phases of research were shaped, influenced and directed by the analyses performed and conclusions drawn during preceding phases of research. Furthermore, while these three Chapters are based on specific research objectives, other sections of this report are based on the literature reviews and/or conference papers that support this overarching doctoral research. Figure 1.3 is a graphical representation of the schedule for completing the three phases of this research along with milestones. It should be noted that red diamonds indicate the start and finish of this doctoral research while green diamonds represent significant milestones including publications in peer review scholarly articles that directly support
Chapters 3, 6 and 7 of this report. A blue diamond represents an interim milestone when a conference paper was presented in support of various sub-tasks required to achieve each research objective presented in Chapters 3, 6 and 7.

Figure 1.3 Framework & Timeline of Research

The following is a narrative of the research methodology, objectives and specific tasks along with the relevant work products developed during each phase of this research.
1.4.1 Phase 1 – Role of Project Delivery Systems in Infrastructure Procurement

This doctoral research is a culmination of previous investigations that began with Fitch et al. 2015 in which an illustrative case study focuses on the selection of the most economically sustainable project delivery method for water and wastewater treatment facilities in the United States. This first phase of doctoral research presents a model for selecting and administering an economically sustainable procurement process given a project’s unique characteristics. The model includes: (1) Performing a risk-adjusted present value (PV) analysis to establish a range of values that take into account variables that will impact costs for each delivery method under consideration; and (2) Developing a project finance structure where risks are mitigated through dynamic service fee agreements that include real options. For purposes of this research, the term economically sustainable is equivalent to the delivery method with the greatest value defined as the highest ratio of benefit to cost between all procurement processes under consideration. To varying degrees, the economic value of a project will be impacted by financial risk and how well those risks are allocated by the sponsoring government to the project participant best able to manage that risk. The current research identifies existing revenue procedures that influence the allocation of risk between public and private project participants. More importantly, this first phase of research shows how opportunities are created to include options on both the project’s financial structure and embedded in the actual technical design of the asset.

1.4.2 Phase 2 – Investigation into Systems Dynamics and Valuation of Real Options

As a successor to the first phase of research, Fitch et al. (2017) presents an SD model used in tandem with NPV analysis for the valuation of multiple real options for a transportation project procured through P3. In this second phase of research, the SD model simulates the real-world causal relationships that impact the valuation of an AO on the P3 project prior to the start of
construction and a string of MRGs after the P3 project is in operation and during its concession period. The investigation in Fitch et al. (2017) concludes that system dynamics can be used for structuring the parameters of an AO and a series of MRGs while considering the compounding effects of multiple types of real options within a single P3 project. In that research the definitions for AOs and MRGs are consistent with Wang and Neufville (2005) that categorize real options in terms of being either “in” or “on” projects. In these terms a real option “in” a project is an option created by changing the actual technical design whereas a real option “on” a project is a financial option attached to a “thing.” In the work of Fitch et al. (2017) only real options “on” the P3 transportation concession project agreement are considered and this research treats any technology as if it were in a “black box.”

1.4.3 Phase 3 – System Dynamics Models for the Valuation of Exotic Options

This doctoral report integrates the previous research efforts completed during the first two phases and also presents an SD model to investigate (1) water resource management in the shale gas industry and (2) the valuation of real options “on” project finance structures and “in” technical designs of interdependent systems. The development of the second SD model began with Fitch et al. 2016 in which a system lexicon is presented and a problem statement is defined to select the appropriate level of abstraction to model water resource management in the shale gas industry. In successor follow-on work (F. Kautz, Limits to Growth at the Water-Energy Nexus: Water Resource Dynamics in Shale Gas Production, working paper W.P.I., 2016) and in Fitch et al. (2017) an SD model is presented and used to forecast the amount of wastewater (e.g. flowback and produced water) that will be created at a single shale gas well site. The SD model is also used to forecast how the quantities of treated and/or disposed water is anticipated to shift among several alternatives in response to a variety of exogenous and endogenous factors.
The current investigation builds upon these previous bodies of research and expands the SD model that was constructed to simulate water usage and treatment in shale gas production. The SD model presented in this doctoral report has been expanded to include the valuation of real options between various sources of wastewater treatment alternatives. To expound upon the theory of real options and achieve the current research objective, however, certain elements within the original SD model have been truncated while new sectors have been added in this investigation. For example, in the previous versions of the model, the quantities of fresh water used during shale gas operations are calculated based on the model’s simulation results. In the current research the quantity of fresh water continues to be included in the model but is not necessarily required for the valuation of real investments for alternative technologies used in the treatment of wastewater produced during shale gas extraction. At the same time, the SD model has been expanded to capture the valuation of investments and the real options related to wastewater treatment alternatives. More specifically, the SD model is utilized for the valuation of various real investments for the infrastructure required to recycle and reuse wastewater produced at the shale gas well site. While the current investigation is focused on the reuse of flowback and produced water, the methodology can be used to model other infrastructure platforms regardless of type and asset classification.

Finally, it is noteworthy that the overarching purpose of this research is to demonstrate how an SD model can be utilized for analyzing and valuing more complicated and more exotic types of real options. To achieve this goal, reasonable efforts have been made to effectively capture the key constituents and causal relationships within the illustrative case study and construct a robust simulation model for water treatment alternatives within the shale gas industry. The current research recognizes, however, that for purposes of brevity the model does not capture all possible scenarios. In general, the illustrative case study does not present all likely technological
advancements with regards to water treatment or its reuse in this doctoral report. Nor could the SD model reasonably capture every possible exogenous and endogenous factor within the water-energy nexus. Nevertheless, the illustrative case study captures the essence of water treatment alternatives in the shale gas industry and achieves the broader research objective. Specifically, the SD model effectively demonstrates how system dynamics and simulation modeling can be used for the valuation of multiple investments and real options in capital project delivery and the procurement of assets that traverse across different types of infrastructure systems.

1.5 Report Organization

Figure 1.4 transposes the activities and milestones shown in Figure 1.3 into a graphical representation of how this report is organized. Figure 1.4 shows that Chapters 1, 2, 4, 5 and 8 are narratives that present tasks and methodologies which support the overarching doctoral research and are part of the necessary structure for this report as a whole. Figure 1.4 also shows that Chapters 3, 6 and 7 are purposely dedicated to presenting the discrete investigation that was completed during each one of the three semi-autonomous phases of this doctoral research.

This report is structured in order to show the linear development of this doctoral research and to introduce theories in preceding sections necessary to fully grasp the concepts that are presented in follow-on successor Chapters. This doctoral report includes along with this introductory Chapter a literature review presented in Chapter 2 and a conclusion with proposed future research is included in the narrative found in Chapter 8. In this regard, this report follows the standard construct of other doctoral research reports and theses. Figure 1.4 shows these Chapters in black text and with black flowlines. Figure 1.4 purposely shows the sub-tasks completed during Phase 1 with red text and red flowlines in order to signify the semi-autonomous research objective of
understanding the role of project delivery systems in infrastructure procurement. The research completed during Phase 1, required follow-up investigations into pricing theory and simulation modeling in order to present a new method for valuing options in real investments. The literature reviews and investigations related to real options and SD simulation modeling are presented in Chapters 4 and 5, respectively. The combined application of these concepts is presented in illustrative case studies in Chapters 6 and 7. Figure 1.4 also shows the research tasks related to Chapters 4 and 5 are in black text, because similar to this introductory Chapter, these narratives are predecessors and are required to fully comprehend the research methodology in the illustrative case studies presented in subsequent Chapters 6 and 7. Finally, Figure 1.4 shows the research methodologies and objectives presented in Chapters 6 and 7 with blue and green text and flowlines, respectively, because they are considered semi-autonomous and are specifically related to the last two phase of this doctoral research.
Figure 1.4 Research Objectives and Report Organization
CHAPTER 2. LITERATURE REVIEW

The literature review for this doctoral research was completed in three phases with successor follow-on phases expounding on the work completed during preceding phases and containing their own research objectives:

1. Phase 1 includes an investigation into the process of selecting and structuring the optimum project delivery method, particularly on water and wastewater projects, taking into account the project stakeholders’ multiple objectives, including economic considerations.

2. Phase 2 includes a review of literature and the existing body of knowledge related to the research objective of developing a simulation model to value real options on project finance structures with particular emphasis on minimum revenue guarantees and the right to abandon a project prior to the start of construction.

3. Phase 3 includes a literature review and a comprehensive investigation into more complex or exotic types of real options and how SD models can be used for the valuation of multiple real options that traverse various types of infrastructure systems.

The following narrative of the literature review and existing bodies of knowledge highlights previous works that significantly impacted the course of direction during each phase of this current research. This narrative is followed by Table 3.1, which includes a comprehensive list of the existing literature and previous research either referenced and/or expounded upon during this doctoral research. Several gaps in literature are presented, with such gaps underscoring the significance of the current research objectives. Finally, the review of literature concludes with various existing records and documents that are either referenced and/or have contributed to the illustrative case studies presented during each phase of this current research. Tables 3.2 through 3.4 include the relevant documents and work products developed by public procurement agencies,
government owners, professional organizations, scholarly conferences and papers as well as industry leaders and other project participants that contribute to the illustrative case studies presented in Chapters 3, 6 and 7. Tables 3.1 through 3.4 reflect an abridged form of the complete list of reference included in the bibliography of this report.

2.1 Role of Project Delivery Systems in Infrastructure Procurement

The literature review began during the first phase of this doctoral research with the objective of identifying a process for selecting an optimum project delivery method that takes into account economic considerations and the other goals of multiple project stakeholders. During the 1990s the increased use of combined delivery methods coupled with inexperience in the public sector necessitated research into the processes of alternative project delivery. Concurrent with the increased use of design-build (DB), there has been in more recent years a re-emergence of the design-build-finance-operate (DBFO) also known as the build-operate-transfer (BOT) procurement process in various infrastructure sectors. This first literature review shows that while DBFO was common prior to the 1940s, most public projects after World War II were directly financed and built under government supervision. The literature review also reveals, however, that the renewed use of DBFO and other alternative financing sources within the U.S. is due partly to a scarcity of available funds needed to meet infrastructure development requirements (Algarni et al. 2007). Consequently, there has been over the past two decades a significant amount of research directed at modeling the allocation of risk within the framework of privately financed projects based on NPV analysis.

During this first phase of research, greater emphasis is placed on investigating alternative delivery methods on water and wastewater projects. The results of this investigation underscore the necessity of including flexibility within project agreements and on finance structures as well as
providing the opportunity of options by changing the actual technical design of the facility. In this respect the current investigation into alternative delivery systems for water and wastewater projects is consistent with Wang and Neufville (2005). Wang and Neufville (2005) categorize real options in terms of being either “in” or “on” projects. In these terms a real option “in” a water or wastewater project is an option created by changing the actual technical design of the facility whereas a real option “on” the same water or wastewater project is a financial option attached to a “thing” and does not necessarily take into account the technical design of the asset. As a result this first phase of doctoral research provides a springboard into the second phase of research and an investigation that expounds into the domain of real options.

2.2 Real Options “on” Infrastructure Systems

In the second phase of this doctoral research, a successor follow-on literature search aims at developing a simulation model to value real options “on” project finance structures regardless of the type of infrastructure. More specifically, this second investigation focuses on previous research involved with constructing SD models for procuring and managing infrastructure. A separate literature review conducted on a concurrent basis identifies previous investigations where various methods are presented for the valuation of real options “on” transportation concession projects procured through P3.

As a result of these concurrent investigations, the work of Rashedi and Hegazy (2015) is significant in that an SD model is constructed as part of an infrastructure management plan. In Rashedi and Hegazy (2015) the SD model simulates the “aging chain” of deterioration rates and rehabilitation processes of a theoretical infrastructure system. A realistic but variable rate of deterioration captures the nonlinear progression as infrastructure assets move toward increasingly worsening states of condition before receiving major rehabilitation. Budget shortfalls are precluded during
the preservation of existing infrastructure and on a concurrent basis with the procurement of new infrastructure by introducing a range of financial expenditures used for maintenance and rehabilitation purposes. The budgeted costs for maintenance and rehabilitation offset the stochastic rates of deterioration based on the current conditions of the various individual assets and the probability of these same assets moving during the next timestep to a state of further deterioration. Consistent with Rashedi and Hegazy (2015), the SD model in this current research includes the relevant constituent agents and parameters required to provide a holistic perspective of the infrastructure system and its operational behaviors and requirements. In Rashedi and Hegazy (2015), the illustrative case study demonstrates causal relationships between assets within a particular infrastructure sector. Likewise, the illustrative case in the second phase of research in Chapter 5 focuses on an infrastructure system explored through an SD model to demonstrate the causal relationships within a portfolio of similar assets. In the current research, however, the simulation results are used for the valuation of real options within the framework of the P3 procurement process. The results of this second phase of research concludes that system dynamics can be used for structuring the right to abandon a project prior to the start of construction and minimum revenue guarantees while taking into account the compounding effects of multiple types of real options within a single project. As a result the second phase of research necessitated a literature review of the use of SD models for the valuation of multiple real options that traverse infrastructure sectors.

2.3 Valuation of Exotic Options in Real Investments

The third and final phase of this doctoral research builds upon the first and second literature reviews with the primary objective to construct an SD model that can be used for the valuation of multiple real options within project finance structures. Hence, as part of the third phase of this
research, the literature review focuses on more complex types of options found in the domain of financial theory. An investigation is performed on a concurrent basis to better understand how SD simulation models can be constructed and used to value these exotic types of options in the domain of non-financial or real investments. The third phase of research is also consistent with Borison (2003) in recognizing several fundamental issues continue to preclude the utilization of classic and other more familiar analytic approaches for real-option valuation. In the work of Borison (2003), the term “classic” is used to refer to the direct application of option pricing from finance theory into the domain of non-financial or real investments. In addition, much of previously published investigations in the domain of real investments have been focused on discrete options within a single infrastructure asset (Chiara, 2006). The current research aims to resolve both of the issues that are related to the application of financial option theory in the domain of real investments on multiple projects that traverse infrastructure sectors.

2.4 List of Existing Literature and Previous Research

Table 2.1 shows a comprehensive list of the existing literature and previous research either referenced and/or expounded upon during this doctoral research. The table includes the list of authors in the left-most column with checkmarks placed in one or more columns which correspond to the research subject matter(s). It should be noted that some literature shows a single check-mark in a specific column, while other literature includes two checkmarks indicating that the existing literature spans across more than one area of research and contributed to multiple sections of this doctoral report. In addition, the research which corresponds to the column titled “Infrastructure Procurement and Asset Management” was primarily expounded upon during the first phase of this current research and the illustrative case presented in Chapter 3. Other previous research and bodies of knowledge that correspond either to real options and/or SD models were primarily used
during the investigations in the second and third phases of this doctoral research and the illustrative cases presented in Chapters 6 and 7. Nevertheless, it should be noted that all phases of this doctoral research were completed on a partially concurrent basis with many cross-references between the investigations throughout all three phases.

Table 2.1 Literature Review and Previous Research

<table>
<thead>
<tr>
<th>Researcher / Author</th>
<th>Infrastructure Procurement &amp; Asset Management</th>
<th>Real Investments &amp; Valuation of Real Options</th>
<th>Systems Engineering &amp; SD Simulation Models</th>
</tr>
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<tbody>
<tr>
<td>Albin, S., (1997)</td>
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<td>Barlas (1996)</td>
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<td>Feldstein &amp; Fabozzi (2008)</td>
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<td>Culp (2011)</td>
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<td>Dahl et al. (2005)</td>
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<tr>
<td>Researcher / Author</td>
<td>Infrastructure Procurement &amp; Asset Management</td>
<td>Real Investments &amp; Valuation of Real Options</td>
<td>Systems Engineering &amp; SD Simulation Models</td>
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<tr>
<td>Forrester (1958 &amp; 1961)</td>
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<td>Garvin (2003)</td>
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<td>Huang, Yu-Lin and Chou, Shih-Pei (2006)</td>
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<td>Ibbs et al. (2003)</td>
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<td>Park et al. (2013)</td>
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<td>Rakic &amp; Radenovic (2014)</td>
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<td>Rashedi and Hegazy (2015)</td>
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<td>Fichman et al. (2011)</td>
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</table>
2.5 Gaps in Literature

Several gaps in literature were identified during each phase of this doctoral research. The gaps in literature directed the course of subsequent phases of research and underscore the significance of the current research objectives. To begin, during the first phase of research, a review of literature related to alternative project delivery methods shows that of paramount importance to success in both DBFO and Design-Build-Operate (DBO) contracts are the inherent incentives and the need to include various options for contractors to design and construct facilities that guarantee performance while minimizing O&M costs.

This suggests that the DBO project delivery method has been recognized as both efficient and sustainable in economic terms (Dahl et al. 2005). A review of prior research, however, reveals that risk allocation within the framework of DBO, particularly for water and wastewater infrastructure, has not yet been widely explored. To fill this gap, the first phase of research examines how different types of risks impact project performance as determined through PV analysis. This first phase of research reveals that a significant amount of existing literature on project performance and risk allocation has been completed on DB and DBFO. A lesser amount of research, however, has focused specifically on DBO with the majority of that literature focusing on highway and/or building construction, with significantly lesser amounts of research focused on procurement of water and wastewater facilities. The first phase of research aims to fill the gap in literature related to DBO projects specifically related to water and wastewater infrastructure in the U.S. By doing so, this first phase of research concluded that a critical requirement of alternative project delivery methods is to include flexibility within project finance agreements as well as providing options to change the actual technical design of the facility.
The second phase of research includes a review of literature in support of developing an SD model for the valuation of options in real investments identified during the first phase of this doctoral research. In Rashedi and Hegazy (2015), an SD model is used in an illustrative case study to demonstrate causal relationships between assets as part of an aging chain of assets within a particular infrastructure sector. The second phase of research expounds upon the first phase of this doctoral research as well as the previous research completed by Rashedi and Hegazy (2015). This second phase of research fills the gap in literature and presents an illustrative case in Chapter 6 that focuses on an infrastructure system explored through an SD model. Similar to Rashedi and Hegazy (2015), the SD model presented in Chapter 6 demonstrates the causal relationships within a portfolio of similar assets. Unlike Rashedi and Hegazy (2015), however, the current research introduces simulation modeling and SD models as a new method where simulation results are used for the valuation of multiple real options within the P3 procurement process. The illustrative case presented in Chapter 6 of this doctoral report values multiple real options “on” a single transportation project. The results of this second phase of research make possible a greater understanding of using SD models for the valuation of real options and provide a foundation for the third and final phase of this doctoral research.

During the third and culminating phase of this doctoral research, a review of existing literature identifies two significant gaps:

1. Several fundamental issues continue to preclude the utilization of classic and other more familiar analytic approaches for real option valuation that were first identified in Borison (2003).
2. The existing body of knowledge and previously published investigations in the domain of real investments have focused on discrete options within a single infrastructure asset. (Chiara, 2006)

The third phase of this research expounds upon Borison (2003) and aims to resolve the application of option theory taken from the domain of finance and applied to options on real investments. The culminating phase of this doctoral research also fills the gap first identified by Chiara (2006). Chapter 7 presents an SD model used to value multiple types of real options on several projects that traverse across different types of infrastructure systems. This third phase and the culmination of this doctoral research utilizes an SD model to investigate the real-world causal effects of multiple infrastructure systems. Simulation results from the SD model are used to understand the compounding effects of multiple real options on several projects. The same simulation results are also used for the valuation of multiple real options that span across different types of infrastructure systems. In this sense the current research fills the gap in literature first pointed out in Chiara (2006). The SD model also allows for complex options in real investments to be valued based on the existing body of knowledge related to exotic options within the domain of the financial services industry. The SD model allows for these types of exotic options in real investment to be valued in a more straightforward manner using NPV analysis. By doing so, this current research also resolves the issues first pointed out by Borison (2003) that preclude the utilization of classic and other more familiar analytic approaches for real-option valuation.

2.6 Literature and Previous Research Related to Illustrative Case Studies

Various bodies of literature contributed to the illustrative case studies presented during each phase of this doctoral research including municipal records, engineering reports and other public documents. A common thread across all three illustrative case studies is attributed to the research
presented in Taylor et al. (2011). Specifically, in response to the proliferation of case study publications in the field of Construction and Engineering Management (CEM), Taylor et al. (2011) presents a protocol for meeting the “burden of proof” when presenting CEM theory in case study research. The current research is consistent with Taylor et al. (2011) and presents the illustrative case studies within this framework and aims to satisfy the “burden of going forward” during each phase of this doctoral report.

2.6.1 Sustainability of Design-Build-Operate Water / Wastewater Facilities

For the illustrative cases studies presented in Chapter 3 - Role of Project Delivery Systems in Infrastructure Procurement several relevant documents and work products developed by local and state procurement agencies, government owners, professional organizations and industry leaders contribute to the illustrative case study. Table 2.2 includes these existing bodies of knowledge.
Table 2.2 Contributing Research and Literature Illustrative Case Study on DBO Water / Wastewater Projects

<table>
<thead>
<tr>
<th>Resource</th>
<th>Contribution to Illustrative Case Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Diego County Water Authority (2013)</td>
<td>Administrative and Finance Committee</td>
</tr>
<tr>
<td>Spokane County (2007)</td>
<td>Spokane County Regional Water Reclamation Facility Request for Proposals</td>
</tr>
<tr>
<td>Spokane County (2008)</td>
<td>Price Proposal Evaluation Memorandum for the Spokane County Regional Water Reclamation Facility</td>
</tr>
<tr>
<td>U.S. Environmental Protection Agency (April 2013)</td>
<td>“Drinking Water Infrastructure Needs Survey and Assessment: Fifth Report to Congress”</td>
</tr>
</tbody>
</table>

2.6.2 P3 Transportation Project for the Third Crossing of the Cape Cod Canal

For the illustrative case study presented in Chapter 6 – Real Options “on” Infrastructure several relevant documents and work products developed by procurement agencies and government owners contribute to the illustrative case study. Table 2.3 includes these existing bodies of knowledge.
Table 2.3 Contributing Research and Literature Illustrative Case Study “on” P3 Transportation Concession Projects

<table>
<thead>
<tr>
<th>Resource</th>
<th>Contribution to Illustrative Case Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massachusetts Department of Transportation (2014)</td>
<td><em>Project SPAN – Third Crossing of Cape Cod Canal: Industry Day Overview</em></td>
</tr>
<tr>
<td>North Carolina Department of Transportation (2014)</td>
<td><em>Comprehensive Agreement Public Private Partnership For I-77 Hot Lanes As Specified in CA Documents</em> <a href="https://www.ncdot.gov/projects/i-77expresslanes/.../ExecutedComprehensiveAgreement">https://www.ncdot.gov/projects/i-77expresslanes/.../ExecutedComprehensiveAgreement</a></td>
</tr>
</tbody>
</table>

**2.6.3 Water Usage in the Shale Gas Industry at the Marcellus and Utica Formations**

For the illustrative cases study presented in Chapter 8 - Valuation of Exotic Options “In” Real Investments several relevant documents and work products developed by procurement agencies, government owners, professional organizations, scholarly articles and industry leaders contribute are referenced in the illustrative case study. Table 2.4 includes these existing bodies of knowledge.
### Table 2.4 Contributing Research and Literature Illustrative Case Study on Water Usage in Shale Gas Industry

<table>
<thead>
<tr>
<th>Resource</th>
<th>Contribution to Illustrative Case Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chase, E.H. 2014</td>
<td>Regulation of EDS and Chloride from oil and Gas Wastewater</td>
</tr>
<tr>
<td>Yin (1994)</td>
<td><em>Case Study research: Design and Methods</em></td>
</tr>
</tbody>
</table>

#### 2.6.4 Interviews with Government Owners and Industry Leaders

In addition, several public utility owners and industry leaders were interviewed and contributed their knowledge to the current research. Specifically, this research was made possible by Jackson Jenkins of the Pima County Regional Wastewater Reclamation Department; David Moss of Spokane County Regional Water Reclamation Facility; Tim Suydam of the San Diego County Water Authority; and Ethan Britland of the Massachusetts Department of Transportation. The industry leaders who were consulted with during this research include Dick Dyne of CH2M Hill; Joseph Sullivan of Hawkins Delafield and Wood LLP; Alan Cohen of HDR Inc.; Gordon Culp of
Smith Culp Consulting; Scott Berry of the Associated General Contractors of America; Harold Smith of Raftelis Associates; Jerry Bish of Greeley and Hansen; Carolyn Briones and Mark Manley, CFA of Black and Veatch’s Management Consulting Division.
CHAPTER 3. PHASE I – ROLE OF PROJECT DELIVERY SYSTEMS IN INFRASTRUCTURE PROCUREMENT

3.1 Changing Role of Project Delivery Methods in the United States

In the years following World War II, the delivery method used most often in the U.S. was Design-Bid-Build (DBB). In more recent decades alternative project delivery methods have been increasingly required because infrastructure developed during the post-World War II economic expansion is now in need of upgrades or complete replacement. Today U.S. infrastructure needs large and immediate investment, although funds from public agencies are not sufficient to meet demand Algarni et al. (2007). The current research presents a model used to select the optimum project delivery method based on the effective allocation of risks between project participants. Consequently, the costs associated with each risk and the total cost for the project as a whole are lessened. For each project delivery method under consideration the model includes performing: (1) Optimizing Risk Allocation and (2) Performing a risk-adjusted PV Analysis. The central goal of Optimizing Risk Allocation (ORA) is to allocate risk to the project participant best suited to manage that particular risk. The model includes risk management strategies where benchmark costs associated with each risk are incorporated into the financial PV analysis. The following case study demonstrates how risk allocation impacts the risk-adjusted PVs for the same project under various delivery methods. It also suggests why DBO projects have been selected over other methods given the goals of public utility owners and U.S. federal tax regulations.

A discussion on the process of selecting the optimum procurement strategy necessitates an overview of alternative project delivery methods, which for purposes of this report include Design-Build, Design-Build-Operate (a.k.a. Design-Build-Operate-Maintain) and Design-Build-Finance-
Operate (a.k.a. Build-Operate-Transfer or Public-Private Partnership). For purposes of this report, Design-Build (DB) is defined as a project delivery method in which the owner uses a competitive proposal process to contract with a private entity to design and build a project. Design-Build-Operate (DBO) is defined as a project delivery method in which the owner uses a competitive proposal process to contract with a private entity to design and build a project but also adds operation to the DB foundation. Specifications related to the operations of the facility are typically included under contract service provisions and require the contractor to operate and maintain the facility for a term in accordance with carefully defined performance guarantees. Lastly, Design-Build-Finance-Operate (DBFO or P3) is defined as a project delivery method in which the owner uses a competitive proposal process to contract with a private partner to design, finance, construct, maintain and operate the facility. Similar to DBO, the contractor is required to operate and maintain the facility for a specified concession period and ownership of the assets remains with the local government. Typically, the member who provides financing leads the DBFO team, with the designer, builder and operator as subcontractors (Culp 2011). Although an in-depth discussion is beyond the scope of this report, the following discussion highlights key aspects of each delivery method that potentially impact the allocation of risk within a project’s framework.

3.2 Design-Bid-Build

Sometime referred to as the “traditional method,” DBB is the most commonly used project delivery method in the world. Furthermore, as a result of the growth in federal grant funding, the use of DBB in the United States steadily expanded between 1916 and 1980 for interstate highways and for local wastewater treatment facilities. In the United States public procurement continues to utilize DBB with separate competitions and separate contract awards for professional design services and for construction by the government owners. The owner typically contracts separately
with the architect or the engineer for design when using DBB. After the design is nearly entirely completed, the owner obtains competitive bids in the market for the lowest price and executes a contract with a general contractor to build the project. In turn, the general contractor may self-perform some work but typically contracts with numerous subcontractors, suppliers and vendors. Under the DBB project delivery method, the general contractor is responsible for managing the subcontracts and suppliers and for producing the project within the prescribed schedule and within the bid or tendered contract price. Neither the designer nor the contractor in DBB has contractual responsibility for operations and maintain or financing the project. During the DBB project delivery method the owner shall be responsible for these advanced finance elements of the project as well as the follow-on successive phase of the project’s lifecycles (Miller 2012).

### 3.3 Design-Build

While DB has been perceived as beneficial for compressing project duration for building and highway projects, its ability to lower overall costs and implement performance guarantees has been uncertain. In a study comparing DB to DBB, Ibbs et al. (2003) concluded that although DB contracting compressed project schedules, the benefits in capital cost savings were debatable. A study completed by Shrestha et al. (2012) comparing highway projects delivered using DB versus DBB concluded that there was little statistical difference in cost between the delivery methods, but the delivery time for DB projects was significantly less than DBB projects. For public water infrastructure, however, Molenaar et al. (2004) concluded that there were not enough completed projects to statistically investigate Design-Build performance.
3.3.1 DB Water and Wastewater Treatment Facilities

Water and wastewater infrastructure often involves high levels of technical innovation and complex mechanical systems to meet improved regulatory standards or to meet greater demand within the same footprint of existing facilities. In DB, owners struggle with the level of control over final design to ensure performance of plant processes after the facility is in operation. Within DB projects, owners are limited to developing the basic description of the project or risk negating the transfer of design liability to the DB contractor. While the contractor may guarantee the project will work as intended during acceptance testing, the owner will retain risks—risks which may not become apparent until well into operations of the facility (Culp 2011). The balance between ensuring project performance and maintaining an equitable amount of contractor liability over design has spurred interest in procurement processes that include operations.

3.4 Design-Build-Operate

Like DB, the DBO contract includes provisions and technical specifications using performance-based requirements. Thus, design liability for constructability is again largely transferred to the DBO contractor. DBO provides greater flexibility than DB in assigning risk to the party best able to manage that risk by integrating operations into the contract. While many of the incentives embedded in the foundation of DBFO are present in the DBO procurement process, DBO offers an opportunity for lower O&M costs in the U.S. due to the tax-exempt status afforded by IRS Revenue Procedure 97-13 (Rev. Proc. 97-13).

As the current research demonstrates, it is likely that DBO will be increasingly used for procuring water and wastewater facilities due to intrinsic incentives of a combined delivery method and the opportunity for lower O&M costs afforded by Rev. Proc. 97-13. The current research shows how PV analysis is used to establish a range of values that account for variable O&M costs. The current
research also demonstrates how financial risks to the concerned government and the contractor are mitigated through dynamic service-fee agreements that take into account variable O&M costs. This report shows how these dynamic service-fee agreements are akin to real options attached to the project finance structures.

Specifically, DBO contractors guarantee that the project will work during the operating period after the design and construction are complete. Performance-based payment structures include inherent incentives for the contractor to produce facilities that minimize O&M costs. Operating service agreements also provide owners with relatively stable payment structures that reduce uncertainties related to funding and expenses during operation. The service agreements also provide owners with recourse in the event of non-performance during the operations period. Under the DBO contract, fluctuating O&M expenses are replaced with relatively predictable payments that consequently assist owners in their planning efforts and stabilize user and tax rates. Further, the service payment agreement will theoretically remove the possibility of discretionary reductions to expenditures required for maintenance activities (Garvin 2003).

DBO also provides an opportunity for operational expenses to be passed through to the owner who may be better able to manage risks associated with particular aspects of operations. For example, owners may be better suited to benefit from economy of scale when negotiating costs for energy, chemicals and other products for the concerned government. The DBO contract also may include provisions that account for matters of public policy, such as regulatory requirements and existing labor agreements. Such provisions preserve public policy while stabilizing O&M costs.

3.5 Design-Build-Finance-Operate & Public-Private Partnerships

A DBFO consortium, also commonly referred to as a public-private partnership or P3, is typically led by an equity sponsor whose investment and loan repayment will become jeopardized if service
is not properly provided. Hence, DBFO has the flexibility to assign financial risk to the equity sponsor who is most capable of its management. As a result, the equity sponsor investment instills an owner-like responsibility for managing operations of the facility without actually transferring ownership (Culp 2011). The central goal for using DBFO is to alleviate spending of government budgets through funding provided by external financiers (Algarni et al. 2007). Although government budgets may be relieved of capital costs, DBFO does not typically provide tax-exempt financing for public agencies in the U.S. (Culp 2011). Under IRS Code Section 146, Congress provides states with an annual volume cap for federal tax-exempt private activity bonds (PAB) used to fund public-private partnerships. Each state is allowed to issue only a limited amount of PABs in each calendar year, and qualified PABs are only tax-exempt if an allocation of the state’s volume cap is drawn down when the bonds are issued. The volume cap is equal to the greater of $75 in 2011 dollars (adjusted for inflation) times the population of the state or $225 million (adjusted for inflation), Feldstein (2008). The 2013 ASCE Report Card for America’s Infrastructure concluded that eliminating this annual cap on PABs is one way to resolve the funding deficit in water and wastewater infrastructure investment. The annual cap limits the use of PABs for water and wastewater infrastructure, which are generally multi-year projects. Most of the tax-exempt bonds historically have been issued to politically attractive, short-term projects such as housing and education loans AGC of America (2011).

As a result of the annual cap on PABs, DBFO includes risks associated with higher end-user rates resulting from higher capital costs. The annual volume cap on federal tax-exempt PABs used to fund public-private partnerships means non-tax-exempt financing is often required for financing design and construction of facilities. The non-tax-exempt status of private financing results in higher cost of capital; as a result, financiers may require higher end-user rates in order to match
the real rate of return on otherwise tax-exempt investments. Thus, added contractual complexities may be required in order to prevent financiers from seeking a rate of return equal to tax-exempt investments through increased user fees (Culp 2011).

3.6 Real Options and the Selection of the Project Delivery Method

Much of the existing literature related to the theory of option valuation in real investments has largely focused on a single infrastructure asset procured through the P3 procurement process (Chiara, 2006). In addition, real options are categorized as either being “in” or “on” projects in the work of Wang and Neufville (2005). In these terms, a real option “in” a project is an option created by changing the actual technical design whereas a real option “on” a project is a financial option attached to a “thing.” The following model demonstrates how real options “on” project agreements and finance structures impact the risk-adjusted PV as a function of the delivery method under consideration. In this sense, the ORA and the risk-adjusted PV analysis only considers real options “on” the project delivery method under consideration and treats any technology as if it were in a “black box.” Subsequent illustrative case studies for structuring DBO water and wastewater treatment projects show how real options both “on” and “in” a project can provide greater opportunities to employ risk-mitigation and cost-savings contracts within project agreements.

3.7 Net Present Value Analysis for the Selection of Procurement Methods

The raison d'être for this research is to present a model for selecting and administering an economically sustainable procurement process given a water or wastewater project’s unique characteristics. The model includes: (1) Performing a risk-adjusted PV analysis to establish a range of values that accounts for variables that will impact costs for each delivery method under consideration; and (2) Developing a volumetric and pollutant loading-based payment structure
where financial risks are mitigated through dynamic service-fee agreements. For purposes of this report, economically sustainable is equivalent to the delivery method with the greatest value defined as the highest ratio of benefit to cost between all procurement processes under consideration. To varying degrees, the economic value of a project will be impacted by financial risks and how well those risks are allocated by the sponsoring government to the project participant best able to manage that risk. The current research identifies existing U.S. tax regulations and revenue procedures that influence the allocation of risk between public and private project participants.

3.8 Case Study – Pima County Regional Wastewater Reclamation Project Background

The Pima County Regional Wastewater Reclamation Department (PCRWRD) owns and operates wastewater treatment facilities and conveyance systems in Eastern Pima County, Arizona. The PCRWRD system is made up of two major wastewater treatment facilities, conveyance pipes, lift stations and several small wastewater reclamation facilities. New effluent limitations mandated by the Arizona Department of Environmental Quality set lower limits of nitrogen and ammonia concentrations in the effluent discharged from the Roger Road Wastewater Treatment Facility into the Santa Cruz River. To comply with the improved standards, the new Agua Nueva Water Reclamation Facility was procured using DBO.

The process for selecting the delivery method for the new Water Reclamation Campus (WRC) is an industry model. The delivery method impacted various aspects of the project including financing, procurement, ownership and the associated levels of risks carried by the involved parties. The Regional Optimization Master Plan (ROMP) considered the DBB for the conceptual timeframe and estimated costs for design and construction but recommended consideration of alternative project delivery methods including DB, DBO, DBFO, Design-Build-Maintain (DBM)
and Design-Build-Finance-Own-Operate (DBFOO). Early in the selection process, DBM and DBFOO were eliminated as non-practical because of complexities related to (1) the creation and administration of scope documents; and (2) the transfer of county property, respectively. Although the selection process considered DBB, this research focuses only on the findings related to DB, DBFO and particularly DBO.

3.8.1 Optimizing Risk Allocation

A Multiple Criteria Analysis (MCA) is used as part of the process to select the delivery method for the new WRC. Each project delivery method is evaluated and ranked against several criteria ranging from the ability to manage cost and schedule to the goals and requirements of the county and regulatory compliance. While the MCA evaluated and ties together multiple qualitative and quantitative criteria, the current research focuses primarily on the ORA and its impact on the risk-adjusted PV for the delivery methods under consideration. The ORA defines how each delivery method effectively allocates risk to the project participant best able to manage that risk and the owner’s ability to enforce that allocation of risk.

3.8.2 Risk-adjusted PV

Probability distributions and a range of probable impacts on costs are factored into the risk-adjusted PVs for each procurement process under consideration. The allocation of these risks varies depending on the procurement process. The risk management strategy includes developing unique probability distributions and cost impacts associated with each risk under each procurement method. The objective of the risk-adjusted PV analysis is to identify the project delivery method with the lowest statistical mean, or highest expected value, and the smallest standard deviation, or
greatest predictability. Prior to developing the risk-adjusted PVs, the baseline PVs of project lifecycle costs are calculated for each delivery method under consideration using the following:

\[ PV(iN) = CC_0 + \sum_{t=1}^{T} \frac{NCF_t}{(1+i)^t} \]  

(3.1)

Where \( CC_0 \) denotes the capital costs for design and engineering in year 0; \( NCF_t \) denotes the net cash flow in year \( t \); and \( i \) = discount rate accounting for the effects of both interest and inflation.

For the current case study, annual capital costs are inflated to the year in which the costs are expected to be incurred at an inflation rate of 5.0% based on Engineering News Record and other historical data. Annual O&M costs are escalated at 2.5% annually based in part on Bureau of Labor Statistics CPI Data. Energy costs are anticipated to inflate at 3.0% annually. Lastly, the discount rate is set equal to the weighted average cost of capital based on the owner’s cost of debt and historical interest and investment earnings. Table 3.1 includes the lifecycle costs factored into the PV analysis for each procurement process under consideration.

**Table 3.1 New WRC Capital and O&M Costs**

<table>
<thead>
<tr>
<th>New WRC Project</th>
<th>DB</th>
<th>DBO</th>
<th>DBFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs (Design, Construction)</td>
<td>$212,011,000</td>
<td>$206,250,000</td>
<td>$206,250,000</td>
</tr>
<tr>
<td>Yearly Operation &amp; Maintenance Costs</td>
<td>$7,220,000</td>
<td>$5,095,000</td>
<td>$5,095,000</td>
</tr>
</tbody>
</table>

For the current case study, baseline capital cost estimates for construction and design are developed for the ROMP based on traditional DBB and Construction-Manager-At-Risk (CMAR) project delivery. The original capital cost estimates for design and construction are adjusted to reflect
inherent differences between procurement processes and are anticipated to be 5% less for DB and 7.5% less for DBO and DBFO. The greater level of collaboration under DB results in design and construction costs that are anticipated to be 5% lower than costs under CMAR. For delivery methods that include contract operations of the facility, the input from operators during design and construction is anticipated to reduce costs even further. For the Pima County analysis, the reduction is assumed to be 7.5% lower than more traditional delivery methods (PCRWRD 2008).

Similarly, original O&M cost estimates developed for the ROMP are adjusted as necessary for DB, DBO and DBFO. Historical data demonstrates that privately operated DBO and DBFO facilities utilize less staff than DB facilities operated by public agencies (PCRWRD 2008).

The current research is primarily concerned with the method for evaluating the impact that various risks have upon the PV under each procurement process. Several economic variables are factored into the risk-adjusted PVs. These variables include annual capital costs that are inflated from the present to the year in which the capital costs are expected to be incurred. For the current case study, the annual capital inflation is 5.0% based on historical ENR and Handy-Whitman Data (PCRWRD 2008). In addition, the tax-exempt interest rate and term that represent the owner’s cost to borrow money to fund the design and construction utilizing DB and DBO. It is anticipated that funding under DB and DBO will use traditional revenue bonds. Under DBFO, a private cost of equity is factored into the risk-adjusted PV. Table 3.2 includes the economic variables used during this case study research to simulate the risk-adjusted PV analysis.
Table 3.2 Economic Variables for calculating the risk adjusted PV

<table>
<thead>
<tr>
<th>Interest Rates</th>
<th>Rate &amp; Term (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tax Exempt</td>
<td>5.0%</td>
</tr>
<tr>
<td>Muni Bond Term</td>
<td>20</td>
</tr>
<tr>
<td>Private Rates</td>
<td>6.0%</td>
</tr>
<tr>
<td>Private Bond Term</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inflation Rates</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Inflation Rates</td>
<td>5.0%</td>
</tr>
<tr>
<td>O&amp;M Inflation Rates</td>
<td>2.5%</td>
</tr>
<tr>
<td>Energy Inflation Rate</td>
<td>3.0%</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

The current case study risk-adjusted PVs consider the potential cost impacts that were originally identified during risk quantification workshops in Pima County. The results of these risk quantification workshops are included in Appendix II of the PCRWRD Alternative Delivery Report. The risk-adjusted PV is based on the probability distributions that represent the likelihood and cost impacts associated with various risk. The analysis includes (a.) Determining whether it was feasible to quantify the potential cost impact that a risk could have on the project; and (b.) For each of these quantifiable risks, defining the range of probable impacts on cost under each project delivery method being considered.

The risk-adjusted PV Analysis includes calculating a range of PVs for lifecycle costs for each procurement process under consideration. The risk-adjusted PV analysis is performed using the software Crystal Ball® and analyzes the economic impact of quantifiable risks on the PV of lifecycle costs for each procurement process under consideration. In order to replicate the risk-adjusted PV analysis, Appendix II from the PCRWRD Alternative Delivery Report is referenced for probability distributions of quantifiable risks and the potential cost impacts on various aspects and phases of the project under DB, DBO and DBFO.
The risk-adjusted PV analysis performed during the current research endeavors to replicate as closely as reasonably possible the actual analysis presented in the PCRWRD Alternative Delivery Report. Nevertheless, this research includes its own straightforward assumptions related to the causes and effects of dependent and independent joint probability distributions. In particular, the following PV analysis utilizes a geometric series for annual O&M and energy inflationary costs and uses a discount period of 20 years of operation. As this report shows in the following sections, by setting the discount period for operations for the facility to a period of no more than 20 years, the current research is consistent with the prescribed provisions of Rev. Proc. 97-13. The risk-adjusted PV analysis included 5,000 trials making it reasonable for estimating the expected PV for the new WRC utilizing each project delivery method. Comparison between the range of PVs for the new WRC using DB, DBO and DBFO are presented in Figures 3.1 and 3.2.
Figure 3.1 Risk Adjusted Present Value Comparison between DB and DBO

Figure 3.2 Risk Adjusted Present Value Comparison between DBFO and DBO
Consistent with the actual findings for PCRWRD, the simulation in this case study research results in a lower range and a lesser standard deviation of risk-adjusted PVs for DBO than for DB and DBFO. Furthermore, given the risk assumptions used in the analysis, DBO offers the greatest potential savings and the lowest risk-adjusted mean PV and 90% certainty level. Table 3.3 includes the estimated baseline PV as well as the risk-adjusted mean and 90% certainty PVs for the new PCRWRD WRC using DB, DBO and DBFO.

<table>
<thead>
<tr>
<th>Procurement Process</th>
<th>Baseline PV</th>
<th>Risk Adjusted Mean PV</th>
<th>90% Certainty PV</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBO</td>
<td>$312,255,063</td>
<td>$350,392,286</td>
<td>$369,622,757</td>
<td>$11,875,300</td>
</tr>
<tr>
<td>DB</td>
<td>$330,493,242</td>
<td>$368,825,467</td>
<td>$391,417,544</td>
<td>$13,359,314</td>
</tr>
<tr>
<td>DBFO</td>
<td>$331,512,091</td>
<td>$373,244,656</td>
<td>$393,520,229</td>
<td>$12,451,354</td>
</tr>
</tbody>
</table>

The risk-adjusted PV estimates account for impacts to costs associated with the variability of risks. The variability of each risk was defined by the probability distributions that were developed for each quantifiable risk. For the PCRWRD project, these probability distributions were developed during risk quantification workshops with participation from project stakeholders. While reasonable efforts were employed to ensure accuracy, any change to a probability distribution and variability will impact the result of the model in different ways and to varying degrees. Sensitivity analyses are performed to gain a better understanding of the potential impact to the PVs due to the relationships between input and output variables. A Tornado Diagram (Figure 3.3) graphically...
identifies which risks are the greatest potential contributors to variability for PVs for the DBO project delivery method. Table 3.4 includes the input and outputs graphically depicted in the tornado diagram for DBO.

Figure 3.3 Tornado Diagrams – Risk Sensitivity and Variability
Table 3.4 Input and Outputs of the Variability for DBO

<table>
<thead>
<tr>
<th>Input Variable</th>
<th>DBO Risk Adjusted Present Value</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downside</td>
<td>Upside</td>
</tr>
<tr>
<td>Construction Impacts</td>
<td>$335,334,139</td>
<td>$370,329,609</td>
</tr>
<tr>
<td>O&amp;M Inflation</td>
<td>$343,359,999</td>
<td>$373,622,177</td>
</tr>
<tr>
<td>Capital Inflation</td>
<td>$341,641,958</td>
<td>$364,717,837</td>
</tr>
<tr>
<td>Construction Labor Shortage</td>
<td>$345,905,220</td>
<td>$362,262,876</td>
</tr>
<tr>
<td>Energy Inflation</td>
<td>$347,675,996</td>
<td>$360,009,274</td>
</tr>
<tr>
<td>Cost of Construction Materials</td>
<td>$353,294,367</td>
<td>$364,670,373</td>
</tr>
<tr>
<td>Debt Interest Rate</td>
<td>$355,862,140</td>
<td>$360,330,634</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>$355,849,935</td>
<td>$357,214,351</td>
</tr>
<tr>
<td>Design Impacts</td>
<td>$356,767,623</td>
<td>$357,802,795</td>
</tr>
</tbody>
</table>

3.9 Contract Structure for DBO Water and Wastewater Projects

The current illustrative case study replicates the findings of the PCRWRD. Furthermore, this case study shows how the ORA between project participants effects the results of the risk-adjusted PV analysis. The case study also indicates that exogenous factors, such as Rev. Proc. 97-13, can have a potentially significant impact on selecting the optimum project delivery method in terms of economic sustainability. In this sense, the current research shows that these kinds of exogenous factors have a direct impact on the selection of real options related to the selection of the optimum project delivery method as well as on the valuation of real options attached to the project’s finance structure.
To place it in historical context, Rev. Proc. 97-13 was published on January 10, 1997, with the purpose of setting forth “safe harbor” conditions under which management contracts do not result in private business use as defined by the Internal Revenue Code. Thus, Rev. Proc. 97-13 precludes the need for private activity bond volume cap allocations to secure tax-exempt status. Among the conditions set forth in Rev. Proc. 97-13 is a requirement for certain management contracts to be no more than 20 years for public utilities including water and wastewater facilities. Rev. Proc. 97-13 defines a capitation fee as the stated dollar amount for a specific period that a service provider shall receive while the services that are actually provided vary depending upon other exogenous as well as endogenous factors. Under DBO agreements, a capitation fee is structured with at least 80% of the compensation for services in each annual period based on a periodic fixed fee and up to 20% of the total annual compensation based on variable fees. The risk management strategy that is closely adhered to and effectively implemented during the procurement of the contractor will result in actual costs more closely aligning to estimated costs used when selecting the DBO project delivery method. The prescribed conditions in Rev. Proc. 97-13 create a framework for developing a risk management strategy. This type of risk management strategy essentially establishes the framework for structuring real options particularly as they relate to O&M expenses within a DBO contract. Rev. Proc. 97-13 and the structure for the embedded real options allows for flexible allocation of risks through dynamic service agreements.

The primary challenge in structuring a risk-neutral service-fee agreement is that treatment requirements and production levels fluctuate from year to year. Selecting a fixed fee based on one annual production level under these uncertain terms negates the interests of the contractor and the concerned government. To be as risk-neutral as possible, O&M service agreements are structured to include programmed resets (i.e. real options) that correspond to different production rates for
water and wastewater levels. The service agreement includes a separate fixed fee payable for each reset level with fees competitively established through the procurement process. The service agreement obligates the owner to select a reset level and related fixed fee on an annual basis. A competitively established unit price for additional production applies if actual production exceeds the selected reset level. The reset structure is intended to conform to the general principal of a fixed fee for a fixed scope of work on a pre-negotiated basis compliant with Rev. Proc. 97-13. Rev. Proc. 97-13 provides that a variable component of up to 20% may be included in the total capitation fee. The 20% variable component is designed to protect the service provider against unforeseen risks. For the 20% variable component, the service agreement specifies payments to the contractor in addition to those for the annual resets for supplemental treatments (Peterson and Torkelson 2003). As will be shown in Chapter 7 of this report, the 20% variable component on top of the 80% annual fixed service-fee is essentially what is referred to as compound option (i.e. an option upon another option). The following two case studies demonstrate how Rev. Proc. 97-13 is used to structure real options within the O&M service agreements with at least 80% of the compensation for services based on a fixed fee and variable fees constituting up to 20% of the total annual compensation.

3.9.1 Spokane County Regional Water Reclamation Facility (SCRWRF)

The County of Spokane, Washington (County) provides collection and wastewater treatment services to residential, commercial and industrial customers in the North Spokane and Spokane Valley service areas through an agreement with the City of Spokane. The county began a program in 1980 to eliminate septic tanks and connect customers to the county’s sewer system. The original program included the expectation that approximately 30,000 existing septic tank customers would connect to the county’s sewer system by 2015. Historically all of Spokane County wastewater was
treated at the existing Riverside Park Water Reclamation Facility which is owned and operated by the City of Spokane. As a result of the septic tank elimination program and a projected population increase, the existing Riverside Park Water Reclamation Facility would not have been capable of supporting both the county’s and city’s wastewater treatment needs.

In planning for the new SCRWRF, the county emphasized aquifer and river protection as primary objectives. In addition, the county’s objectives for the new facility are to accommodate the projected growth and to provide reliable wastewater service to county customers. The county selected a membrane bioreactor facility with an initial capacity of 8 million gallons per day (mgd), expandable to 12 mgd in the near term and up to 24 mgd in the longer-term future. The procurement process was conducted pursuant to the State of Washington’s Water Quality Joint Development Act (Act). By utilizing a DBO project delivery method, the county planned to secure benefits including timely, efficient and cost-effective scheduling, optimal risk allocation, competitive design selection, clear assignment of performance responsibilities to a single contracting entity, long-term facility O&M efficiencies and cost savings.

3.9.2 Twin Oaks Valley Water Treatment Plant

In the early 2000s, San Diego County faced an immediate challenge in meeting its treated water needs. Up to 90% of the water used in the county comes from the Colorado River and Northern California and is imported by the San Diego County Water Authority (Water Authority). This imported water must be purified at a water treatment plant before it can be used for drinking and other potable water uses. Nearly half the treated water serving the San Diego region had been purified at the Skinner Water Treatment Plant in Riverside County, owned by the Metropolitan Water District of Southern California. Growth in both southern Riverside County and San Diego’s
needs have increased warm weather demand for treated water from the Skinner facility beyond its rated production capacity.

Through its Regional Water Facilities Master Plan, the water authority determined that additional treated water capacity was needed immediately to serve the future demands of its member agencies and to ensure reliability of the treated water supply in San Diego County. Due to this immediate need, the water authority decided to implement a regional water treatment plant using a DBO procurement process. The new Twin Oaks Valley Water Treatment Plant is located in San Diego County and has a treated water production capacity of 100 mgd.

Pursuant to Rev. Proc. 97-13 the service-fee agreements for SCRWRF and Twin Oaks Valley Water Treatment Plant include real options in the form of resets that correspond to annual production rates for wastewater and water levels, respectively. It is worth noting that annual production rates for the Twin Oaks Valley Water Treatment Plant decreased with the construction of the seawater desalinization plant in Carlsbad, California, which was commissioned in 2016. Figures 3.4 and 3.5 below graphically shows the reset amounts for the SCRWRF and Twin Oaks Valley Water Treatment Plant DBO Projects.
Figure 3.4 Reset Wastewater Flow Rates (MGD) for SCRWRF Wastewater Treatment Plant

Figure 3.5 Reset Wastewater Flow Rates (MGD) for Twin Oaks Water Treatment Plant
3.10 Real Options and Water / Wastewater Treatment Facilities

Economically sustainable project delivery is a paramount goal as public utility owners are faced with greater expectations under growing budget constraints. To meet these demands, DB, DBO and DBFO will likely continue to be increasingly used to procure water and wastewater facilities. While DB offers accelerated project delivery over DBB, historically, it has not provided equivalent cost savings for design and construction services. Nor does DB offer the level of performance guarantees and equal predictability of reduced expenses for O&M as do DBO and DBFO projects. Existing U.S. tax regulations, however, place a cap on tax exempt PABs, which in turn constrains the utilization of DBFO. Although not a foregone conclusion, these and other factors create an environment where DBO is more favorable for procuring water and wastewater facilities.

The current research contributes to the body of knowledge and benefits industry practitioners by identifying tax regulations and best practices that when jointly considered improve the project delivery selection process while enhancing risk mitigation efforts on DBO water and wastewater projects. In accordance with the prescribed conditions set forth in Rev. Proc. 97-13, the DBO delivery method provides opportunities to include real options both on the financial structure as well as within the technical designs of water and wastewater facilities. In some cases, these real options mitigate risk by selecting operational expenses to be passed-through to the owner who may be better able to manage risks associated with particular aspects of operations. The prescribed conditions set forth in Rev. Proc. 97-13 can assist public utility owners in structuring the parameters of real options. Furthermore, Rev. Proc. 97-13 establishes risk management strategies early in a program, which can later effectively allocate risk and maximize the value of the DBO program. Although the prescribed conditions of Rev. Proc. 97-13 allow for 20% of the annual
compensation to be a variable component, this case study research suggests that the actual amount of the variable component is likely to be less.

3.10.1 Real Options “on” Water / Wastewater Treatment Project Delivery Process

Consistent with the actual findings for PCRWRD, the simulation performed for this research demonstrates that the variability of long-term O&M costs ranks among the top factors impacting the range of present values. Specifically, the simulation results in 66% cumulative variation with equivalent range of costs of $32,262,178. Similar sensitivity analysis for DBFO indicate that the top-ranking variable above O&M inflation was the interest rate required by private investors (PCRWRD 2008). Taking into consideration that O&M inflation is a long-term factor that represents a significant risk to DBO success, management is compelled to reduce its variability. The simulation and resultant range of risk-adjusted PVs represent the value of the real option “on” the selection of the project delivery method. The real option valuation within the project selection process suggests why DBO is selected over other procurement strategies for delivering water and wastewater facilities within the U.S. In addition, the results of the variances of impacts due to risks (Figure 3.3) help structure real options “on” the project agreement and its financial structure, while treating any technology within the technical design as a “black box.”

3.10.2 Real Options “in” DBO Water / Wastewater Treatment Project Delivery Process

Real options “in” DBO water and wastewater project delivery include modifications to the technical design of the facility as well as the project agreement and its financial structure. These risk management and cost savings strategies afforded by DBO include operational expenses, including energy consumption, to be passed through to the owner who may be better able to manage its associated risks. As in the PCRWRD case study, energy inflation ranked above energy
consumption because performance specifications can set forth prescribed limits for lowering its variability. As the SCRWRF and Twin Oaks Valley Water Treatment Plant DBO Project case studies further demonstrate, real options related to energy consumption and other variable O&M costs are represented through dynamic service-fee agreements in accordance with Rev. Proc. 97-13.

The Twin Oaks Valley Water Treatment Plant DBO Contract includes a fixed cost component of the service agreement based on charges for operating the plant at water production levels of 50, 70 and 95 mgd. Electricity utilization charges were provided by the owner in the request for proposal, and pre-qualified contractors were required to provide guaranteed maximum electricity utilization in kilowatt hours used for each million gallons of water production (kWh/MG). The amounts of guaranteed maximum electricity utilization were provided for water production at 10 mgd increments ranging between 50 and 100 mgd. The goal of structuring the electricity utilization charges as pass-through costs to the owner is to reduce risk-contingency costs related to fluctuating electricity rates while promoting energy-saving innovation. The DBO contract includes a real option requiring any cost savings which are the result of a lower actual amount of electricity used below the specified guaranteed maximum will be equally shared between the contractor and owner. Hence, the DBO procurement process for the Twin Oaks Valley Water Treatment Project incentivizes the designers and engineers to include real options “in” the technical design of the facility. Unlike the reset values, which are attached to finance structure, these real options are cost-savings mechanisms aimed at enhancing the technical performance of the facility during its operational phase.

Table 3.5 includes the guaranteed maximum electricity utilizations for the Twin Oaks Valley Water Treatment DBO Project. [San Diego County Water Authority (2005)] While in operation
the Melded Municipal and Industrial Treatment Rate is set to recover the costs of treating water for the San Diego County Water Authority. The San Diego County Water Authority sets the Twin Oaks Valley reimbursement to ensure that the customer service rate category is reimbursed from Melded Treatment Rate revenues for the initial development costs for the Twin Oaks Valley Water Treatment Plant that were funded by customer service revenues. These costs are amortized and recovered over time so that treatment customers fully pay these costs [San Diego County Water Authority - Administrative and Finance Committee (2013)].

Table 3.5 Twin Oaks Water Treatment Plant Guaranteed Maximum Electricity Utilizations.

<table>
<thead>
<tr>
<th>Annual Average Treated Water Delivered to Water System (In Millions of Gallons Per Day)</th>
<th>Guaranteed Maximum Electricity Utilization (In Kilowatt Hours Per Million Gallons of Treated Water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>389</td>
</tr>
<tr>
<td>60</td>
<td>361</td>
</tr>
<tr>
<td>70</td>
<td>341</td>
</tr>
<tr>
<td>80</td>
<td>326</td>
</tr>
<tr>
<td>90</td>
<td>314</td>
</tr>
<tr>
<td>100</td>
<td>305</td>
</tr>
</tbody>
</table>

The Twin Oaks Valley Water Treatment Plant DBO contract also includes provisions for the contractor to pay for major replacement and maintenance of equipment at specified intervals during the operation of the facility. In contrast, for the SCRWRF the costs for major repairs and replacement of equipment are financed through a fund maintained by the owner with annual preset contributions during the operation phase. The goals under both strategies are to maintain the useful lifespan of the facilities beyond the duration of the DBO contracts while eliminating unanticipated and disputed expenditures. In these cases the real options related to major replacement of equipment can be viewed as real options attached both to the project finance structures as well as embedded within the actual technical design of the facilities.
For the SCRWRF, separate annual reset groups were established and are selected by the owner prior to the start of a contract year. Separate annual reset groups were specified in order to establish a baseline facility flow and loading. The selected annual reset group is in turn the basis for the fixed component of the annual service-fee, which is based on the following formula:

\[
SF = BOC + RC + EI
\]

(3.2)

Where SF denotes the annual service-fee; BOC = Base Operating Charges; RC = Reimbursable Charge; and EI = Extraordinary Items Charge or Credit. Pursuant to Rev. Proc. 97-13, the BOC is equal to the sum of the Fixed Component (FC) and the Variable Component (VC). The FC is the sum of Facility and Electricity Elements (FE and EE). The FE and EE are determined from the annual reset group selected by the owner prior to the start of a contract year. In addition, the SCRWRF operating charges also include a VC which is the sum of the Non-electricity Flow and Loading Adjustment Element (NLAE) and the Electricity Flow and Loading Adjustment Element (ELAE). The VC compensates the DBO contractor for variations in influent loadings in excess of the flows and loadings applicable in any contract year based on the annual reset group selected by the owner [Spokane County (2007)]. Proposed annual service-fees (based on 2012 dollars) are provided in Table 3.6. Table 3.6 also shows the financial relationships between the fixed and variable components and payment distributions for the service provider for each annual reset group for a given year.
Table 3.6 Service-fees for Various Assumed Flow and Loadings

<table>
<thead>
<tr>
<th>Annual Reset Group</th>
<th>First Year (2012) Service-fee (In Millions of Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reset Group 1</td>
</tr>
<tr>
<td></td>
<td>Percent Fixed Cost</td>
</tr>
<tr>
<td>Reset Group 1</td>
<td>$6.70</td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Reset Group 2</td>
<td>$6.75</td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Reset Group 3</td>
<td>$6.85</td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Reset Group 4</td>
<td>$6.95</td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

Flow and Loadings

<table>
<thead>
<tr>
<th>Flow (MGD)</th>
<th>BOD$_5$ (lbs./day)</th>
<th>TSS (lbs./day)</th>
<th>Total Nitrogen (lbs./day)</th>
<th>Phosphorus (lbs./day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10,842</td>
<td>10,842</td>
<td>1,735</td>
<td>325.3</td>
</tr>
<tr>
<td></td>
<td>11,676</td>
<td>11,676</td>
<td>1,868</td>
<td>350.3</td>
</tr>
<tr>
<td></td>
<td>13,344</td>
<td>13,344</td>
<td>2,135</td>
<td>400.3</td>
</tr>
<tr>
<td></td>
<td>16,000</td>
<td>16,000</td>
<td>2,700</td>
<td>480.0</td>
</tr>
<tr>
<td></td>
<td>6.50</td>
<td>7.00</td>
<td>8.00</td>
<td>8.00</td>
</tr>
</tbody>
</table>

During its first two full years of operation, 2012/13, the wastewater treated at SCRWRF remained within the range of Reset Group 1 with actual annual cost averages for BOC and VC equal to $5,949,536 and $45,221, respectively. Pursuant to Rev. Proc. 97-13, the agreement will typically contain a carry forward provision in order to protect the contractor in the event that annual variable amounts exceed the 20% limitation in a particular year. Under the “carry forward” provision, a portion of the variable payment not paid in a prior year can be carried forward and paid in a future year without violating the 80-20 fixed/variable compensation rule for that year. The provision protects the contractor from non-payment for work performed that would result from a year-by-year application of the 80/20 rule (Peterson and Torkelson 2003). During its first two full years of operation, 2012/13, the actual variable component paid for the SCRWRF services amounted to approximately 1% of the total compensation.
3.11 Phase I – Conclusion Role of Project Delivery Systems

This initial investigation aims at developing a model for selecting the most economically sustainable project delivery method for water and wastewater treatment facilities in the United States. This first phase of doctoral research presents a model for selecting and administering an economically sustainable procurement process given a project’s unique characteristics. The model includes: (1) Performing a risk-adjusted PV analysis to establish a range of values that take into account variables that will impact lifecycle costs for each delivery method under consideration; and (2) Developing a project finance structure where risks are mitigated through dynamic service-fee agreements that include real options. The illustrative case studies included in this first phase of research show that the economic value of a project will be impacted by financial risks and how well those risks are allocated by the sponsoring government to the project participant best able to manage that risk. The current research also shows how Rev. Proc. 97-13 is used to construct the framework of DBO project agreements and how it is used to allocate risk between public and private project participants. The valuation of the project selection process suggests why DBO is selected over other procurement strategies for delivering water treatment facilities within the U.S. More importantly, this first phase of research shows how opportunities are created to include options on both the project’s financial structure and embedded in the actual technical design of the facility. Unlike the reset values, which are attached to the project’s finance structure, other real options include cost-savings mechanisms through the enhancement of the technical performance of the facility during its operational phase. As a result, this first phase of research necessitates a follow-up investigation into real options both “on” project finance structures as well as real options “in” the actual technical design.
CHAPTER 4. REAL OPTIONS

4.1 Real Options and the Role of Infrastructure Procurement

The primary objective of the current research is to investigate and promote the use of SD models for the valuation of real options on project finance structures and real options embedded within the technical design of infrastructure systems. Beginning with Phase II of this research, the value of a real option is determined consistent with the pricing formulation used by Black-Scholes (1973) expressed for a simple call option on share of stock as:

\[ c = SN(d_1) - Xe^{-r(T-t)}N(d_2) \]  \hspace{1cm} (6.1)

Where the parameters \( d_1 \) and \( d_2 \) equal:

\[ d_1 = \frac{\ln(S/X) + (r + \sigma^2/2)(T-t)}{\sigma \sqrt{T-t}} \]  \hspace{1cm} (6.2)

And

\[ d_2 = d_1 - \sigma \sqrt{T-t} \]  \hspace{1cm} (6.3)

Luehrman (1998) points out that in order to effectively value a real option based on the Black-Scholes method, the pricing model needs to be correlated to the infrastructure’s characteristic. The process of correlating the five variables that determine the value of a simple call option on a share of stock using the Black-Scholes pricing model must be matched to the corresponding variables in the real options. To begin, most real options involve spending money to construct asset or actualize a course of action. This value corresponds to the amount of money expended to a financial option’s exercise price denoted as \( X \) in Table 4.1. In a similar manner, the present value of the real option, which can be determined by the expected financial return, corresponds to the stock price \( S \). The length of time the company can defer the decision to exercise the call option in the domain of finance corresponds to the real option’s time to expiration \( t \). Continuing, the risk-free rate of
return, $r_f$ in the Black-Scholes pricing model corresponds to the time value of money during the valuation of a real option. Finally, the riskiness of the project corresponds to the standard deviation of the stock ($\sigma^2$) corresponds to the riskiness of the project.

### Table 4.1 Mapping a Call Option to a Real Option

<table>
<thead>
<tr>
<th>Variable</th>
<th>Call Option</th>
<th>Real Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>Stock Price</td>
<td>Present Value of Asset to be Required</td>
</tr>
<tr>
<td>$X$</td>
<td>Exercise Price</td>
<td>Expenditure Required to Acquire the Project Assets</td>
</tr>
<tr>
<td>$t$</td>
<td>Time to Expiration</td>
<td>Length of Time the Decision may be Deferred</td>
</tr>
<tr>
<td>$r_f$</td>
<td>Risk-free Rate of Return</td>
<td>Time Value of Money or WACC</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>Variance of returns on Stock</td>
<td>Riskiness of The Project</td>
</tr>
</tbody>
</table>

In the following successor Phase III, however, the current research is consistent with Borison (2003) that recognizes several fundamental issues which continue to preclude the utilization of classic and other more familiar analytic approaches for real-option valuation including Black-Scholes. In the work of Borison (2003), the term “classic” is used to refer to a direct application of option pricing from finance theory into the domain of non-financial or real investments. The current research aims to resolve several of these issues by utilizing the SD modeling method. Specifically, Borison (2003) points out three fundamental issues that exist when using classic and other closed-form analytic approaches for the valuation of real options:
1. Applicability of the direct use of option pricing from finance theory into the domain of real investments;

2. Assumptions made during the application of closed-form analytic approaches for real option valuation; and

3. The mechanics and incremental processes involved with the valuation of real options during these applications.

In the current investigation, SD models and simulation results are used to overcome the issues of closed-form analytic approaches commonly used for the valuation of real options. The current research further builds upon this primary objective by extending the investigation to include an analysis of the compounding and complex effects of multiple real options between competing assets that span across infrastructure sectors. The complexity of the causal relationships between infrastructure assets is captured in the SD model where simulation results are used to analyze and value the compounding effects of these more exotic types of real options. By doing so, decision-makers can best identify and implement infrastructure procurement alternatives that are more robust in satisfying multiple combinations of various objectives (i.e. economic, sustainability, serviceability, resiliency, etc.).

In its most theoretical form, the central tenet of the classic approach for the valuation of real options is the premise that the calculation’s product represents the internal valuation of strategic business opportunities, which are by necessity aligned with financial markets (Amram and Kulatilaka, 1999). In this sense the calculated value represents an estimate of the shareholder’s incremental wealth created by an investment. From a for-profit business perspective, the value of an investment is applicable when the option is based on a strategy that can be viewed as a decision threshold. Taking into consideration that firms are required to act in the interest of shareholders and that
financial opportunities are intrinsically aligned with markets, an investment shall be made if it is available for less than its estimated value and sold if marketable for more than its estimated value. As such, these actions aim to increase the wealth of the firm’s shareholders and are applicable to decisions about the firm’s investments. For the current research, the increase in wealth represents the return on equity invested in either (a) A P3 transportation concession project as presented in Chapter 6; or (b) A water treatment alternative within the shale gas industry as presented in Chapter 7.

In Chapter 6 the current research recognizes that the central goal of P3 projects, especially on large-scale projects, is to alleviate government budgets by seeking capital from external financiers (Algarni et al. 2007). The core principle of the P3 project agreement and project-finance structure is that the project company owns, operates and manages an infrastructure asset over a concession period with the government (Chiara 2006); and the method of project-finance under a P3 agreement is based on raising long-term debt against the cash flow generated from the project’s revenue (Yescombe, 2014). As such, P3 projects are typically long-term contracts between government owners intended to satisfy public infrastructure needs and a consortium of private partners (including equity sponsors and financial lenders) who require a minimum attractive rate of return (MARR) that varies based on perceived risk levels. Hence, the goal of the current research is to investigate how to enhance the goals of government owners and private partners using an SD model for the valuation of real options. An illustrative case study demonstrates how an SD model can be used for the valuation of real options during the conceptual and preliminary stages of a P3 transportation project.

Historically, relevant real options included decision points to exercise a MRG, an AO (prior to the start of construction), or expand the asset’s capacity as demand increases. In order to distinguish
between these types of real options, the current research is consistent with Wang and Neufville (2005) and categorizes real options into two categories in terms of being either “in” or “on” projects. In these terms, a real option “in” a project is an option created by changing the actual technical design, whereas a real option “on” a project is a financial option attached to a “thing.” Consistent with these definitions, real options “in” a P3 project would be concerned with actual design of the infrastructure and would require an in-depth understanding of the physical characteristics of the asset(s) related to the design criteria and performance. In this regard real options “in” transportation projects would include future options to upgrade or expand capacity of the infrastructure as demand for its use ramps up. In contrast, the current research only considers real options “on” the P3 project agreement and treats any technology itself as a “black box.” In Chapter 6, the current research strictly aims to hedge the risks of unanticipated financial losses through MRGs and the AO prior to construction.

In both Chapters 6 and 7, the current research purposefully moves away from mathematically complex or somewhat more theoretical methods for the valuation of real options. For example, in the work of Chiara (2006) a model supports the introduction of a new set of financial products based on the multi-least-squares Monte Carlo method, which is used for pricing multiple-exercise options. In Rakic and Radenovic (2014) a binomial option pricing model is presented and a risk-neutral probability approach is investigated to price whether an AO on a P3 toll road investment increases its value. In contrast in the work by Neufville et al. (2006) a simpler spreadsheet model is presented for the valuation of real options using a NPV analysis. In other research, Lee et al. (2014) uses NPV analysis and explains how to determine a project-specific discount rate for the NPV calculation.
Recognizing that all of these approaches advance real option theory, the current research aims to be more consistent with Neufville et al. (2006) and Lee et al. (2014) and uses NPV analysis for the valuation of real options. In the work of Neufville et al. (2006), real options “in” an infrastructure asset are used for determining the financial value for including in the original technical design the ability to expand a parking garage as future demand may increase. In that work, the NPV of the real option is calculated using a spreadsheet model. In the current research NPV analysis is also utilized, but it is derived using an SD model. The SD model is selected in order to understand how an asset’s value changes under various circumstances and over time. In doing so, the emphasis of the current research is to demonstrate how an SD model is used for the valuation of real options “on” a P3 project using a straightforward NPV analysis through concepts readily discernible by practicing engineers and other decision-makers. The current research is also consistent with Lee et al. (2014) where the discount rate represents the rate of return as well as the risk-adjusted cost of capital for owners. In that work, the weighted average cost of capital (WACC) method and the capital asset pricing model (CAPM) are two common methods presented for determining the risk-adjusted discount rate. Lee et al. (2014) presents these methods applied to the NPV calculation based on the financial criteria of building owners in order to achieve a robust analysis. In the illustrative cases in Chapters 6 and 7 of this report, the WACC is used as the discount factor within the mathematical equations embedded in the stock and flow diagrams.

In Chapter 7 the SD model in the illustrative case study calculates investors’ return on equity represented by net present values that consider the operating costs and well head price of natural gas, making this research particularly timely. In such investments, Borison (2003) concludes that the applicability of the classic approach is consequently applicable to financial investments when a suitable replicating portfolio behaves in standard ways. In the work by Amram and Kulatilaka
(1999), however, it is noted that financial options analysis is not always suitable in the domain of real investments. In contrast, a more suitable approach to real option analysis is necessary when staged investments are made within infrastructure systems, and when considerable uncertainty exists, and/or when there is a possibility of learning. In response, the current research utilizes an SD model to simulate and analyze how an infrastructure system, comprised of a portfolio of similar assets, performs over time and in response to a variety of endogenous and exogenous drivers (e.g. limitation of resources, regulatory constraints, market forces,).

Furthermore, Borison (2003) points out that the underlying assumptions made in classic and other closed-form analytic approaches assume that a portfolio of traded investments can be valued based on a no-arbitrage argument and where it is generally assumed that the asset’s price movements follow a geometric Brownian motion. This overarching principle leads to the assumption that standard financial tools, such as Black-Scholes, can be applied directly to the valuation of real options. In the work of Smith and Nau, 1995, however, a more integrative approach to option valuation takes into consideration that firms have a variety of stakeholders including owners and managers. This integrative approach presumes that a firm’s owners and managers consider an investment under a somewhat unified set of beliefs and preferences. Thus, the goal of investment and financing decisions is to maximize equally the utility of the firm’s owners and managers. Within the context of this integrated approach, Borison (2003) concludes capital markets are only partially complete with respect to uncertainties and that only some risks related to real options have market equivalents. For these kinds of options, uncertainties with market equivalents can be effectively hedged. However, risks which do not have market equivalents cannot be hedged using a valuation approach that is traditionally used in the domain of finance theory. Hence, the current research utilizes a SD model and relies upon the simulation results to capture uncertainties and
risks that do not necessarily have direct market equivalents but nevertheless are sought to be hedged through the valuation of real options using NPV analysis.

Finally, Borison (2003) states that the mechanics of the classic approach are simpler compared against other approaches given the use and power of the Black-Scholes algorithm. In contrast, an integrated approach requires greater effort, because it relies on spreadsheet modeling and because each risk must be evaluated and modeled separately. The current research simplifies the mechanics and processes required for the valuation of real options by utilizing an SD model. The SD model is embedded with the mathematical representation of real-world causal relationships. The SD model’s explicit representation of causal relationships and its relatively straightforward simulation process allows it to capture the complexity and compounding effects of an option upon another option (e.g. call on a call option, put on a put option, call on a put option and vice versa) or the ability to switch between various real investments. In this research the SD model is used specifically to value individual investments and multiple options to switch between and/or expand individual assets as well as the collective value of the complete portfolio of competing alternatives. The current research seeks to provide a straightforward analysis and gain a better understanding of how an SD model can be constructed to value the complex optionality in real investments across infrastructure sectors. By doing so, the current investigation introduces a SD modeling simulation method that assists decision-makers in the procurement of infrastructure assets that incorporates real option theory.

4.2 Valuation of Real Options “on” Project Finance Structures

In the illustrative case study presented in Chapter 6 of this report, two forms of optionality, an AO and a MRG, are considered in the SD model for the illustrative case study. These types of discrete options have multiple exercise dates and can be contractually structured in various terms, as shown
In Table 4.1 (Chiara 2006). In these types of P3 transportation projects, both the concerned government and the concessionaire (i.e. project company) are typically responsible for performing preliminary development tasks and consequently face substantial project development risks. Even if these tasks are completed successfully, the project could become financially unviable or functionally impracticable because of external factors and fail in the pre-construction phase rather than in subsequent phases. In order to reduce these investment risks, the concerned government or contracting authority may grant an AO to the concessionaire during the pre-construction phase. This option increases the concessionaire’s flexibility in investment decisions and thus increases the value of the project. It is an investment option held by the concessionaire (the buyer of the option) with an expiration date set to the forecast date to commence construction. Additionally, the AO could be an American-style option, which allows exercise of the option at any point prior to the start of construction (i.e. the expiration date of the option). In the illustrative case study the AO is a European option with the exercise or maturity date just prior to construction commencement.

Table 4.2 European, Bermudian and Australian Options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>European option</td>
<td>An option that can be exercised one time, only at the end of its life.</td>
</tr>
<tr>
<td>Bermuda option</td>
<td>An option that can exercised one time, on specified dates during its life.</td>
</tr>
<tr>
<td>Australian option (simple multiple exercise option)</td>
<td>An option that can be exercised M times, on specified N (N≥M) dates during its life.</td>
</tr>
</tbody>
</table>

In addition, P3 concession projects face substantial revenue risks during the operations phase. To mitigate these risks, a MRG may also be incorporated into the concession agreement. Under the prescribed terms of the MRG, the concerned government is obligated to cover the shortfalls between a pre-specified level of the MRG and the operating revenues realized by the
concessionaire (through tolls). The availability of the MRG increases the concessionaire’s willingness to invest and can also increase the creditworthiness of a project that may otherwise face significant revenue risks. In the illustrative case the MRG is constructed and valued as a series (or strip) of European-style put options, which may be exercised during the operations phase.

4.3 Real Options “In” Infrastructure Systems

Consistent with Borison (2003) the current research recognizes that several fundamental issues continue to preclude the utilization of real option analysis and their application in various industries. Although there has been a significant amount of literature related to the valuation of real investments, a corresponding level of application of optionality has not been actualized in various domains including research, manufacturing and infrastructure procurement. To illustrate this point, the work of Ford and Lander (2011) recognizes that uncertainties and ineffective risk management strategies are primary causes for cost overruns, delays and substandard product performance. Yet while the value of real options as tools in managing uncertainty and thereby increasing project value are recognized, Ford and Lander (2011) also view existing tools, methods and conflicting objectives related to real options as barriers to their expanded use in management practices. Ford and Lander (2011) conclude that the application and use of simulation models must be further utilized to expand the application of real option theory within management practices across various industries. In the work of Fichman et al. (2005), complex options are investigated as tools for the management of uncertainty in the domain of research and information technology (IT). In that work, empirical data supports the amount of value created by staged-growth and staged-abandonment options as well as switching options and their ability to effectively manage uncertainty in product development in the domain of IT. Fichman et al. (2011) concludes that by structuring flexibility in product development, the goals of selecting the optimum project and its
successful execution can be achieved regardless of whether an organization actually attempts to quantify it using an option pricing model.

Recognizing that these barriers continue to preclude the application of real option theory by industry practitioners, the current investigation builds upon previous research and aims at utilizing SD models to promote the valuation of real investments and optionality during the procurement of infrastructure. Beginning in the work of Fitch et al. (2017), an SD model is used for the valuation of real options found within a P3 transportation project. Both that previous work and the current investigation are consistent with Wang and Neufville (2005) that categorizes real options into two broad categories in terms of being either “on” or “in” projects. In these terms a real option “on” a project is a financial option attached to a “thing” and treats any technology as if it were in a “black box.” Fitch et al. (2017) only considers real options “on” the P3 project agreement and strictly values real options to hedge the risks of unanticipated financial losses through MRGs and AOs on a P3 project. The current research continues to be consistent with Wang and Neufville (2005) but now considers real options “in” a project. This approach requires greater consideration toward the actual design of the infrastructure system and requires a greater understanding of the physical characteristics of the asset(s) related to their performance specifically in terms of volumetric unit costs. In this regard real options “in” water treatment alternatives include future options to employ new systems or upgrade and expand capacity of an existing infrastructure system as demand for its use ramps up. The current research aims to analyze and value the real investments of infrastructure required for the various options for water reuse within a shale gas field comprised of multiple well sites. Once again, while the illustrative case study focuses on real investments found at the nexus of energy production and water resource management, the overarching
objective of this investigation is to present a methodology for constructing and utilizing SD models for the valuation of multiple real options regardless of the type of infrastructure systems.

4.3.1 Exotic Options on Multiple Real Assets

The current research presented in this paper also takes into consideration that much of previously published investigations in the domain of real investments have been focused on discrete options within a single infrastructure asset (Chiara, 2006). The current research is also consistent with Borison (2003) which recognizes that several fundamental issues continue to exist with the applicability, assumptions and mechanics of utilizing classic analytic approaches of financial options analysis in the domain of real investments. The current research acknowledges the merits of these issues while also recognizing that the underlying theory that supports the various types of complex financial options afford greater physical flexibility and increased amounts of opportunity to better analyze and value real investments across multiple infrastructure platforms. Hence, the current research objective necessitates an investigation into complex options in the domain of financial analysis while at the same time recognizes the shortfalls of directly applying the traditional mathematical formulation for their valuation in the domain of real investments. The current research aims to resolve these conflicting perspectives by utilizing an SD model to investigate in a more straightforward manner the compounding effects of multiple real options across different types of infrastructure systems based on theory related to exotic financial options. Consistent with Haug (2006) the types of exotic options that can be contractually structured in various terms that are relevant to this investigation are included in Table 4.2.
Table 4.3 Exotic Types of Options

<table>
<thead>
<tr>
<th><strong>Barrier option</strong></th>
<th>A barrier option is an option whose existence depends upon the underlying asset's price reaching a preset barrier level.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compound option</strong></td>
<td>A compound option is an option on an option. The exercise payoff of a compound option involves the value of another option.</td>
</tr>
<tr>
<td><strong>Switching option</strong></td>
<td>A switching option is structured so that an operation can be dynamically turned on and off. Management may shut down part or all the operation when conditions are unfavorable and may restart operations when conditions improve.</td>
</tr>
<tr>
<td><strong>Expansion Option</strong></td>
<td>An expansion option is an embedded option that allows a firm to purchase an option, which is a right to undertake certain actions, to expand its operations in the future.</td>
</tr>
</tbody>
</table>

Finally, the current research investigates the theory of exotic options within the domain of real investments while it simultaneously and purposefully moves away from more theoretical and somewhat mathematically complex methods for the valuation of optionality. As an example, the work of Rakic and Radenovic (2014) uses a binomial option pricing model along with a risk-neutral probability approach to price whether an AO on a P3 toll road investment increases its value. In another preceding example, Chiara (2006) presents a model to support the introduction of a new set of financial products based on the multi-least-squares Monte Carlo method, which is used for pricing multiple-exercise options. Recognizing that these approaches advance real option theory, the current research is more consistent with Neufville et al. (2006) where a spreadsheet model is presented for a simpler approach in the valuation of real options using NPV analysis. In that work, the analysis of real options “in” an infrastructure asset is used for determining the financial value for including in the original technical design the future option to expand a parking garage. In the current research, NPV analysis is also utilized, but it is calculated through equations.
embedded directly within an SD model. The SD model is selected to understand how the compounding effects and value of multiple assets change over time and under various circumstances. By doing so, the illustrative case study demonstrates how an SD model is used for the valuation of real options “in” and across various infrastructure platforms using a straightforward NPV analysis through concepts readily discernable by practicing engineers and other decision-makers.
CHAPTER 5. SIMULATION MODELS

5.1 Simulation Modeling Methods

In order to achieve the primary research objective, this study investigates on a concurrent basis: a. system dynamic modeling; b. infrastructure procurement processes including project agreements and project-finance structures; and c. real option theory. The first step in building any simulation model is choosing the method that will be used to map real-world systems. Given a set of constraints, the chosen method will dictate the means and methods for constructing the model and must also be selected based on the real-world systems and the purposes of the model. The three most widely adopted methods for simulating complex systems are system dynamics (SD), discrete event simulation (DES), and agent-based modeling (ABM) (Borshchev 2012). The SD modeling method is selected because the goal of the current research is to provide a comprehensive approach for the valuation of real options within the P3 procurement process. The SD model represents a decision-support tool with mathematically embedded behaviors and is used to study how infrastructure performance may change over time within a portfolio of similar assets in response to a variety of endogenous and exogenous drivers (e.g. regulatory constraints, market forces etc.). The SD method was also selected over the alternatives in this particular study because it abstracts away from individual objects. Additionally, the SD method was selected because it describes the underlying physical and non-physical structure of interdependencies, feedback, accumulations, delays and other phenomena associated with infrastructure systems. Finally, the SD modeling method was utilized to resolve the fundamental issues that exist when closed-form analytic approaches for the valuation of real option including the applicability of the direct use of option pricing from finance theory into the domain of real investments (Borison, 2003). In the current investigation, SD models and simulation results are used to overcome the issues of closed-form
analytic approaches commonly used for the valuation of real options. The current research further builds upon this primary objective by extending the investigation to include an analysis of the compounding effects of multiple real options between competing assets that span across infrastructure sectors. By doing so the SD modeling method can be used as a tool both to government owners and by other project stakeholders in analyzing how an asset or an infrastructure system will behave over time and under various scenarios. The following narrative presents an overview of the process of developing an SD model. The SD models presented in Chapters 6 and 7 are discrete and are built independent of each other. Nevertheless, the general process is the same for building any SD model and for brevity specific examples are selected from either one or the other illustrative case studies and presented in the following narrative.

5.2 System Dynamics Modeling Method

The current research constructs two SD models (presented in Chapters 6 & 7) to analyze competing feedback effects on market forces, information limitations and costs of entry and exit. The SD modeling method is the feedback-based and object-oriented simulation process created by Forrester (1958) that can be used to model complex systems, including infrastructure portfolios. It is noted, that systems dynamics and the methods for constructing a SD model may be novice concepts to many of today’s practicing civil engineers. With government owners increasingly soliciting proposals for wider scopes of services and over longer time spans, however, system dynamics is a beneficial tool that will likely be used more frequently in managing portfolios of infrastructure assets. For practicing civil engineers, the level of effort and duration for constructing the SD model can be approximated from its similarities with already existing and better-known project controls tools. In this regard, constructing the SD model is analogous to developing several resource-loaded schedules on a concurrent basis and for multiple projects. Although there are
numerous differences between traditional project controls methods and SD modeling, both nevertheless require input from multiple stakeholders and both must capture relationships between various disciplines and across numerous industries.

In order to accurately analyze an infrastructure system and draw clear concise conclusions, all non-relevant factors must be excluded from the problem to ensure the model is feasible and the results are timely. In keeping with this doctrine, the current investigation recognizes that a problem statement must be defined at the appropriate level of abstraction. The illustrative case study presented in Chapter 6 includes an analysis of the procurement of infrastructure using P3 within a portfolio of competing transportation assets. Furthermore, it yields the problem statement: *In order to support private equity sponsorship and commercial lender participation in the P3 procurement process, risk mitigation contracts in the form of MRGs and AOs shall be valued based on the simulation results of a SD model and using NPV analysis.* Likewise, a problem statement is also used in developing the SD model presented in Chapter 7, which simulates water treatment technologies within the shale gas value chain.

### 5.2.1 Logical Sequence for Constructing the SD Model

After defining the problem statement, the processes and logical sequence for constructing the SD model are consistent with Sterman (2000) and begin with the identification of key variables and reference modes. These first steps help to further define the problem statement and are predecessors to developing the casual loop diagrams (CLD) and the derivation of formulas and equations that constitute the mathematical representation within stock and flow diagrams. CLDs and stock and flow diagrams are developed in the current research in order to show how feedback relationships can (a) impact the P3 procurement process presented in Chapter 6; and (b) create shifts in the amount of water treated between the alternative technologies required for its reuse at
the well site presented in Chapter 7. The SD model captures the dynamics of feedback structures and shifting loop dominance as competing alternatives are reduced or eliminated. The logical sequence for constructing the SD model is consistent with Sterman (2000) and proceeds as follows:

1. Define the problem statement and identify key variables;
2. Develop reference modes for key variables that are central to the problem;
3. Develop a causal map (i.e. CLDs) of the feedback processes responsible for the dynamics of the system; and
4. Create a stock and flow diagram that contains the mathematical representation of the systems.

![Figure 5.1 Logical Sequence for Constructing an SD Model](image)

**Figure 5.1 Logical Sequence for Constructing an SD Model**

### 5.2.2 Systems Engineering and Lexicon

Along with the identification of reference modes, a system lexicon assists in determining the level of abstraction (or detail) an SD model should be developed so that it most effectively solves a particular problem. The SD model in the illustrative case study presented in Chapter 7 simulates
how constituent water treatment agents will perform in order to meet current and forecast demands for shale gas production within the Marcellus and Utica Shale Formations through 2040. A literature review in support of this case study also indicates that shale gas production will result in an indeterminate amount of water that will require treatment as the various processes and technologies continue to evolve in this relatively new industry. A variation of the system lexicon shown in Figure 5.2 is first presented in Fitch et. al (2016). The system lexicon presents some of the critical agents within a hierarchy that is required for achieving sustainable water resource management within the shale gas value chain.

![Figure 5.2 Lexicon for Shale Gas Production and Water Resource Management](image)

The lexicon in Figure 5.2 is used to help determine the appropriate level of abstraction for developing a simulation model for the valuation of infrastructure and technology required to achieve sustainable water resource management within the shale gas value chain. The lexicon is
the starting point for developing the simulation model which is eventually populated with all of
required agents relative to both (a) shale gas production within the Marcellus and Utica Shale
Formations and (b) water resource management. It’s important to note that the current research
does not consider every constituent component at every hierarchy of the shale gas value chain.
Most notably, at the β level, the current research focuses on flowback and produced water that are
resultant byproducts from shale gas production. Consistent with the modeling building practice
outlined in Sterman (2000), the β level purposely excludes from this investigation non-relevant
factors. Specifically, the model excludes factors related to the potential risk of unintentional
contamination of aquifers from hydraulic fracturing fluid. A simulation model of the constituent
agents related to unintended contamination risks would be worthy in its own right. however, these
factors are outside of domain of the current research objective, which is to demonstrate how an SD
model can be built for the valuation of infrastructure and technologies used for treating flowback
and produced water.

5.2.3 Reference Modes

In previous research [Sterman (2000) and Rashedi and Hegazy (2015)] the steps for constructing
an SD model are specified to be performed on a partially concurrent basis (Figure 5.1). However,
for the dynamic systems to be effective in mapping real-world systems, the model requires constant
iteration, testing and refinement. As a result, reference modes are developed as an early activity
but are so-called because they are referred to throughout the modeling process (Sterman 2000).
Among the reference modes included in the current research, Chapter 7 presents (a) the projected
growth of shale gas production for the industry as a whole through 2040 as well as (b) shale gas
production at a single well site. A more complicated reference mode, presented in Chapter 7,
captures how water treatment shifts between various alternatives of its reuse as a function of the
cost and capacity of each technology relative to one another. For purposes of calibrating the SD model during the latter stages of its development, Sterman (2000) places greater emphasis initially on the timeline measured along the horizontal axis. Conversely, less emphasis is placed with stating the exact quantities along the vertical axis (Sterman 2000). Despite this practice, the upper and lower bounds are often included in reference modes and are referred to when calibrating the SD model by fine tuning the parameters and equations that will be eventually embedded in the stock and flow diagram. Lastly, any non-significant historical can be intentionally omitted from reference modes (Sterman 2000).

### 5.2.4 Casual Loop Diagrams

In addition, researchers have used alternative sequencing with different specific grouping patterns for constructing the SD model. Beginning with Forrester (1958), the development and use of CLDs is often approached as an adjunct activity or communication device rather than as a starting point in developing a stock and flow SD model. In contrast, Rashedi and Hegazy (2015) CLDs are developed based on key variables as the first step for constructing a SD model used to analyze infrastructure deterioration. Consistent with Albin (1997), the current research builds upon the reference modes and captures the positive feed-back and balancing loops within the system dynamics. These loops form the CLD presented in Chapter 7 and illustrate the basic mechanisms that drive the system dynamic’s behavior. The positive feedback loops, also known as reinforcing loops, are denoted by a positive (+) symbol and will continuously amplify a trend or any other physical and non-physical flow. Conversely, negative loops, which are sometimes called balancing loops, are denoted by a minus (-) symbol and are goal-seeking flows of the same physical and non-physical subject matter and are bound within a specified limit (Sterman 2000). For the case study
presented in Chapter 7, the CLD is a preceding activity and is used as a visual aid on a concurrent basis during the development of the stock and flow diagram and SD model architecture.

### 5.2.5 Stock and Flow Diagrams

The SD models and the stock and flow diagrams presented within the current research was developed utilizing the computer software iThink 10.1.2®. Chapter 6 presents the SD model and stock and flow diagram that simulates a transportation infrastructure asset through a P3 consortium. Chapter 7 presents the SD model and stock and flow diagram that simulates the processes of water reuse and treatment/disposal within the shale gas value chain. Consequently, the current SD models employ the industry-accepted general structure for stock and flow diagrams including stocks, flows, valves and clouds (Figure 5.3). Stocks represented by rectangles signify both physical and non-physical accumulations and “traces” left by an activity (Rehan et al. 2011). Flows represent activities or actions that transport quantities into or out of a stock instantaneously or over time. Inflows and outflows are represented by pipes or arrows pointing into (adding to) and out of (subtracting from) stocks, respectively. Unless there is a net value of zero, material stock exists at a given point in time and will remain even when the processes of inflows and outflows are complete.
5.2.6 SD Language Overview

The SD models in this report were developed using the software iThink 10.1.2®, which is a visual programming language for system dynamics modeling. The program is distributed by isee systems (formerly High-Performance Systems) and allows users to run models created as graphical representations of a system using four fundamental building blocks (i.e. stocks, flows, valves, and clouds). For the current research STELLA language reflects the mathematical equations and is used to represent the embedded relationships that connect the various stocks and variables throughout the SD models used to (a) analyze the economic impact of quantifiable variables on the NPV of lifecycle costs and revenues for a proposed new third crossing of the Cape Cod Canal using a P3 procurement process presented in Chapter 6; and (b) capture and simulate the processes of shale gas extraction through a single well site along with its demand for water reuse technologies presented in Chapter 7. The SD model presented in Chapter 7 also simulates the range of NPVs for the real investments in water reuse technologies as demand for shale gas production ramps up.
and subsides at the well site. The initial nominal values, parameters and equations used for both the model’s sector frames are included in appendices to this report.

5.3 Limitations to the SD Modeling Method for Valuing Real Options

In general terms, SD models are not designed to provide pinpoint solutions but instead are built to display the dynamic behavior of a system under consideration. The ability to calibrate an SD model based on historical data brings it greater credibility. Sterman (1984) presents appropriate statistical approaches for evaluating the historic fit of a model but brings to light some specific drawbacks of these analyses when evaluating a model’s ability to simulate real-world conditions based entirely on historical data. In some cases, however, the calibration of SD models brings a significant amount of effort for simulation results to accurately replicate real-world behavior. The SD models presented in Chapters 6 and 7 were calibrated based on various sources of information from the existing body of knowledge with much of the data obtained through extensive literature searches. Calibrating the SD model to historical data is only a part of model validation process. Barlas (1996) discusses SD model development and emphasizes other validity tests, while Sterman (2000) presents twelve tests in detail including structure assessment, parameter assessment, extreme condition tests, integration error and sensitivity analysis. For the illustrative case study presented in Chapter 7, the SD model is validated with two different types of validation tests and in a manner consistent with Barlas (1996) and Sterman (2000). Specifically, the SD model is validated by performing two direct structure tests and two structure-oriented behavior tests. The SD model is validated through a direct structure test by comparing the simulation results with the knowledge of real-world processes. These tests are particularly relevant for the valuation of real options in the illustrative case study. The amount of effort required to properly calibrate and validate the SD model to ensure that it is replicating real-world behavior can be extensive. This
level of effort should be considered when selecting the SD modeling method for the valuation of real options.

CHAPTER 6. PHASE II – REAL OPTIONS “ON” INFRASTRUCTURE

6.1 Valuation of Risk Mitigation Contracts in P3 Transportation Projects

To achieve the objective in Phase II of this report, the current research uses an SD model for the valuation of real options during the development of the P3 procurement process. The current research builds upon existing literature related to the application of real options within P3 procurement process. For example, in the work of Park et al., (2013), real option theory is used to advance the framework of infrastructure procurement by enhancing risk sharing among contracting parties. This is considered acutely beneficial within P3s because the equity sponsors and debt lenders are particularly concerned with revenue risk. In order to hedge against financial loss, sponsors and lenders can require the public partner or concerned government to provide real options in the form of risk-sharing mechanisms known as minimum revenue guarantees (Rakic and Radenovic 2014). Broadly defined, minimum revenue guarantees (MRG) are risk-mitigation contracts designed to cover the difference between a minimum guaranteed net revenue and the actual net revenue during a predetermined operating period. Furthermore, the right to abandon (AO) a project prior to the start of construction can be included within the P3 contract and likewise represents a risk-mitigation element. The AO reduces the potential financial loss to the private partner if competing market forces makes the infrastructure project infeasible. Taking both mitigation options into consideration along with the risk variables associated with transportation projects creates an ideal scenario for the current investigation into the application of an SD model used for the valuation and incorporation of MRGs and AOs within the P3 contract. The current research builds upon the existing body of knowledge by demonstrating how an SD model can be
constructed and used for the valuation of these types of real options in order to promote public initiatives, support private equity sponsorships and commercial financial lending within the P3 procurement process. Lastly, the SD model is extended to analyze the compounding effects created by the interaction that occurs between the MRG and AO within the same P3 project agreement.

In order to accurately analyze an infrastructure system and draw concise conclusions, all non-relevant factors must be excluded from the problem to ensure the model is feasible and the results are timely. In keeping with this doctrine, the current investigation recognizes that a problem statement must be defined at the appropriate level of abstraction. The illustrative case includes an analysis of the procurement of infrastructure using P3 within a portfolio of competing transportation assets, and it yields the problem statement: *In order to support private equity sponsorship and commercial lender participation in the P3 procurement process, risk mitigation contracts in the form of MRGs and AOs shall be valued based on the simulation results of an SD model and using NPV analysis.*

Historically, policy-planners and decision-makers, including government entities, have issued requests for proposals from infrastructure procurement agents for specific platform systems. Increasingly, government owners are soliciting proposals for a wider scope of services in order to meet broader sets of capabilities and over significantly longer time spans (DeLaurentis et al. 2004). These types of proposals are increasingly being used for combined delivery methods where a consortium will finance, design and build an infrastructure project as well as provide operations and maintenance (O&M) services. Procurement of these infrastructure systems can include multiple assets and require interfacing with multiple contracting authorities. Hence, an SD approach can be used to identify and analyze problems to validate existing systems and determine the systems that have yet to be procured in order to provide the anticipated capabilities.
6.2 P3 Transportation Projects

Under the overarching term “P3 procurement,” a private sponsor finances the design, construction, maintenance, and operation of a public project for a specified concession period; at the end of which it transfers ownership to the government agency with anticipation of recouping its costs and achieving profits Algarni et al. (2007). The P3 procurement process has been used in successive waves, with project agreements and project-finance structures evolving into various forms to meet the needs and characteristics unique to various types of infrastructure. The dividing lines between these types of project agreements and project-finance structures are inexact to varying degrees, but Yescombe (2014) categorizes project finance structures into three general types of agreements: 1. Process-plant Agreements, 2. Concession Agreements and 3. Private Finance Initiative (PFI) Models. While the use of an SD model for the valuation of real options can be applied to any variation of these types of P3 agreements, the focus of illustrative case is based on a transportation concession project agreement.

6.2.1 P3 Transportation Concession Project Agreements

In order to effectively value the MRG and AO, the SD model must capture the relevant elements of the financial structure under a toll road concession project agreement. These elements and stakeholders include the concerned government or contracting authority, equity sponsors, commercial lenders, the project company and its subcontracts. Figure 6.1 includes the typical basic structure for a concession project agreement in accordance with Yescombe (2014). Under this type of project agreement, charges in the form of tolls are to be paid by users to the project company. The illustrative case study is based on this type of agreement for a toll-road concession project that typically includes as subcontracts: 1. a design-build contract for the engineering and construction
of the infrastructure; 2. an operating contract to operate the tolling system; and 3. a maintenance contract for the duration of the project operating term.

![Diagram of Transportation Concession Project Agreement]

**Figure 6.1 Transportation Concession Project Agreement**

### 6.2.2 P3 Financial Structure

Elements related to the overall financial structuring which are likely to be negotiated between the project company and its lenders include the debt-coverage ratio, debt:equity ratio, debt-service profile, interest rates and fees and other additional costs (Yescombe, 2014). A discussion of each of these topics is beyond the breadth of this report, but two significant factors that are critical for achieving the primary research objective include the debt:equity ratio and the MARR required by
the project’s equity sponsors and commercial lenders. The debt:equity ratio is a function of the risks perceived by the financiers (i.e. equity sponsors and commercial lenders), and projects with greater risk have less financial leverage or lower debt:equity ratios. Table 6.1 shows the typical debt:equity ratios based on the project agreement type and perceived project risk (Yescombe, 2014).

Table 6.1 Public-private Partnerships Debt:equity Ratios

<table>
<thead>
<tr>
<th>Project Agreement / Financial Structure</th>
<th>Debt:equity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation Concession Agreement</td>
<td>80:20</td>
</tr>
<tr>
<td>Process-plant with an Offtake Contract</td>
<td>85:15</td>
</tr>
<tr>
<td>Accommodation-based Contract</td>
<td>90:10</td>
</tr>
<tr>
<td>‘Merchant’ power plant project with no Offtake Contractor</td>
<td>70:30</td>
</tr>
<tr>
<td>Natural Resources Project</td>
<td>50:50</td>
</tr>
</tbody>
</table>

It is noteworthy that Yescombe (2014) shows a debt:equity ratio of 80: 20 for transportation concession projects. In comparison, revenue risk transportation projects completed by the Departments of Transportation (DOT) in the U.S. states of Virginia and North Carolina suggest that lower debt:equity ratios closer to 60: 40 have been used to finance P3 projects (Virginia DOT, 2004 and North Carolina DOT, 2014). The MARRs required by sponsors and lenders and typical debt:equity ratios are factors used for calculating the WACC that is used for financing the P3 project in the illustrative case study. The current investigation in turn uses the WACC as the discount factor during the NPV analysis and valuation of real options. The illustrative case contained within this research is consistent with Yescombe (2014) and is based on a transportation concession project agreement and thus uses a debt:equity ratio of 80:20.

It is also noteworthy that P3 project-finance structures for transportation concession projects completed in the U.S. have included a public investment component (Virginia DOT, 2004 and North Carolina DOT, 2014). Under this project-finance structure the inclusion of an MRG within
the concession agreement is less advantageous. In addition, the level of due diligence and surety bond requirements on P3 projects delivered in the U.S. diminishes the ability and reduces the necessity to include an AO within the contractual terms of the P3 project agreement. The primary goal of the current research, however, is to demonstrate how an SD model can be used for the valuation of real options in P3 projects. The SD model in the illustrative case study does not aim to be an all-encompassing model that captures every aspect of P3 project finance in order to promote a broader and more robust utilization of this procurement method. As such, some components (i.e. public investment, complex debt service profiles, due diligence etc.) are considered unnecessary to include in the model while still achieving this overarching and primary research goal. As a result, these elements are purposefully omitted from the illustrative case study, and the SD model is based on a slightly simplified P3 project-finance structure within an abridged concession contract. Nevertheless, SD models can readily be expanded to include these contracts and other components found in more complex P3 project arrangements.

6.3 Cape Cod Canal Third Crossing

The current research examined several projects that were recently procured or will be procured using P3 as potential case studies for the application of SD modeling and real options. The current research selected the third crossing of the Cape Cod Canal in Massachusetts as the illustrative case study for various reasons. Prominent among the motivating reasons is that the third crossing of the Cape Cod Canal is still in its conceptual stages and has been considered as a pilot project to be delivered using a P3 procurement process. Furthermore, the infrastructure upon completion will be competing for traffic demand against two existing bridges traversing the same waterway. Lastly, management of the Cape Cod Canal crossing will require coordination with several local, state and federal government entities on a concurrent basis. In addition to the various local municipal
governments, a P3 consortium will be required to work with the Massachusetts Department of Transportation (Mass DOT), the Massachusetts Department of Environmental Protection Agency, the U.S. Environmental Protection Agency and Army Corps of Civil Engineers (Mass DOT, 2014). For these reasons, the third crossing of the Cape Cod Canal was selected for the illustrative case study not only to serve as a theoretical example but also in order to provide a useful tool for the stakeholders of this project in its early stages. Nevertheless, the aim of the current research is to advance SD modeling and its use for the valuation of real options in other P3 projects and across other various infrastructure platforms.

6.3.1 Background and General Description

Cape Cod is a geographic cape that is located at the very southeastern part of the Commonwealth of Massachusetts. It is separated from the mainland by approximately 17.5 miles of canal, which is owned, operated and maintained by the U.S. Army Corps of Engineers. Cape Cod’s permanent population per Census 2010 is 215,088 and has an increased summer tourist population. During June, July and August the population increases to approximately 700,000. In addition, there are two nearby islands, Nantucket and Martha’s Vineyard, and access to these areas is mainly through Cape Cod. Currently, there are two existing highway bridges and one movable railroad bridge that cross the canal. The two highway bridges, the Sagamore Bridge and Bourne Bridge, opened in 1935 and are currently considered functionally obsolete. They require significant year-round maintenance that include regular lane closures. This routine maintenance results in significant traffic congestion characterized by slower speeds, longer trip times, and increased vehicular queueing particularly during the peak summer tourist months. Furthermore, O&M costs for the existing bridges are increased due to their age, the corrosive coastal environment and the lack of opportunity to temporarily close either bridge in its entirety for a prolong duration in order to
perform major improvements and/or upgrades. Finally, the existing bridges present a public safety concern, as they would be the only roadways from Cape Cod in the event of an evacuation due to an extraordinary weather event (e.g. hurricanes, resultant flooding) or other emergencies. The third crossing of the Cape Cod Canal Project is currently being managed by the Mass DOT, and the delivery method has not been determined (Mass DOT, 2014). This case study includes the construction of an SD model based on a P3 project agreement and project-finance structure. The SD model is used to analyze the third crossing of the Cape Cod Canal with emphasis placed on the valuation of MRGs and AOs included under a P3 project agreement.

6.4 P3 Project Agreement Assumptions and SD Model Inputs

For purposes of brevity, a complete discussion of the terms and conditions of a theoretical P3 contract between the contracting authority and a project company as well as its finance structure and sub-contracts is precluded from being presented in this research. The following points show how the SD model is constructed within the general framework of a theoretical P3 agreement. Nevertheless, the following are some of the key points required to understand how the SD model is constructed within the general framework of a theoretical P3 agreement. To begin, within the boundaries of the SD model, the project company shall enter into contract with a contracting authority (i.e. Mass DOT), to design, build, operate and maintain a Cape Cod Canal crossing through a P3 procurement delivery method. More specifically, the contracting authority and project company will enter into a concession agreement based on a project-finance structure that consists of a debt:equity ratio of 80:20. The private sponsorship and commercial lending will finance the design, construction and O&M costs of the infrastructure asset in exchange for a stream of revenue over a prescribed project term of 30 years. The anticipated useful life of the infrastructure asset is 75 years extending 45 years past the project term agreement. As a result,
prior to the end of the concession agreement, the project company shall perform significant upgrades of the infrastructure so that the contracting authority receives a fully functional asset following the end of the 30-year concession agreement. This project-finance structure will also be based on a design and construction schedule of 5 years before the bridge and its related access infrastructure becomes operational. Table 6.2 includes the key parameters and general cash flows for the P3 agreement.

Table 6.2 Cape Cod Canal Bridge Design & Performance Criteria

<table>
<thead>
<tr>
<th>Conceptual Design &amp; Performance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
</tr>
<tr>
<td>Number of Traffic Lanes</td>
</tr>
<tr>
<td>Summer Daily Traffic Volume</td>
</tr>
<tr>
<td>Winter Daily Traffic Volume</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conceptual Estimate of Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design / Pre-construction Activities</td>
</tr>
<tr>
<td>Construction</td>
</tr>
<tr>
<td>Annual O&amp;M (Initial Value at Time Step / Month 64)</td>
</tr>
<tr>
<td>Annual Toll Operation (Initial Value at Time Step / Month 52)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Schedule and Terms of Concession Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual Design and Construction Duration</td>
</tr>
<tr>
<td>Duration of Concession Agreement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll Rates (Initial Value)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Finance Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debt:equity Ratio</td>
</tr>
<tr>
<td>WACC</td>
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</tbody>
</table>
6.5 SD Model - Architecture

The SD model was developed using the software iThink 10.1.2® and analyzed the economic impact of quantifiable variables on the NPV of lifecycle costs and revenues for the third crossing of the Cape Cod Canal using a P3 procurement. Figures 6.2 through 6.6 present the SD model for the theoretical Cape Cod Bridge (CCB), which is partitioned into five sectors. While the five sectors are presented separately in this paper, the SD model contains mathematically embedded relationships that connect the various stocks and variables throughout the entire SD model. The five sectors contained within the CCB SD model include 1. Cash Flows and NPV, 2. CCB Financing, 3. CCB Abandonment Option, 4. CCB Project NPV with MRG or AO and 5. CCB Minimum Revenue Guarantee and Compound Option. The following sections provide a description of the SD model architecture. The initial nominal values, parameters and equations used for each of the model’s sector frames are included as Appendix I to this report.
Figure 6.2 CCB Cash flows and NPV
The model sector that represents the cash flows and NPVs for the proposed CCB contains the elements responsible for computing the NPV of the revenue and cost components of the project-finance structure. The present values (PV) of the cash outflows are captured in three stocks: 1. Debt and Equity Payouts, 2. O&M Costs and 3. Toll Operations Cost. Two stocks capture the PV of the cash inflows: toll revenue collected during the peak tourist summer months and toll revenue collected during the off seasons. The sum of all five PV stocks is accumulated in the converter variable “CCB project NPV no RO,” which represents that NPV of the project without consideration to the value of the MRG or AO.

The cash outflow that represents debt and equity payments is calculated in the adjacent sector frame in the SD model “CCB Financing” and is based on the 80:20 debt-to-equity ratio and the total combined costs for both design and construction. The design and construction costs or spend schedules are shown as variables in this frame but flow into adjacent sector “CCB Financing” for the monthly principal and interest payments to be calculated. Those monthly cash outflows then return to their original “CCB Cash Flows and NPV” model sector where they are discounted to a PV for debt and equity payouts. The repayment period is assumed to be 35 years, which is consistent with the 5-year duration of the design and construction and 30-year duration for the operating period under the concession agreement.

This sector of the model also includes the monthly traffic flows for both the peak tourist season and off season. The monthly traffic flows are treated as statistical variables and characterized by a normal distribution with a standard deviation specified in the converter variables: a. mean excursion summer and b. mean excursion off season. The nominal values selected for the base cases shown here are multipliers of 0.10 and 0.08, which are applied to the traffic schedules for summer and off-season months, respectively.
The model sector “CCB Financing” includes a flow for aggregating the schedules of borrowing (or “draws”) for both the design and construction phases. The accumulation of debt in the stock debt balance is the time integral of both borrowing (principal) and interest charges as shown in this sector’s stock and flow diagram. The “outflow” from debt balance is represented by the flow principal and interest payments, which is based on a repayment period of 35 years (5 years for design and construction followed by 30 years of operation). The time period is set in the converter variable repayment period.
This sector of the model also includes cost schedules for the design and construction phases that are treated as statistical variables modeled with a uniform distribution that act as multipliers. The converter variables include the design spend excursion multiplier and construction spend excursion multiplier. These multipliers are used to specify the sampling range for a uniform distribution function. This sector of the model also includes the converter credit shortfall, which is strictly a diagnostic variable and does not affect the borrowing or debt repayment dynamics in this model. This variable is included in the model for slightly more complex diagnostics for understanding funding deficits.

6.5.1 CCB Abandonment Option

The model sector for the AO (Figure 6.4) draws on three stocks representing the PVs of cash outflow including debt and equity repayment, O&M costs and toll operation costs. This sector also draws on the two stocks representing the PVs of revenues including the summer and off-season toll collections. The NPV sum of these stocks is equivalent to the value that grants the concessionaire the option (but not the obligation) to abandon the project no later than the start date for construction. The AO provides an incentive (granted by the concerned government or contracting authority) for the private equity sponsors and commercial lenders to engage in a joint venture for the development of critical infrastructure.
The formulation for this option is based on the work of Huang and Chou (2006) in which an illustrative case was based on the procurement of rail infrastructure. In the current research, the maturity for the AO is 16 months, which is the duration beginning at the inception of the design effort to start of construction. The “strike” of this option is the sum of the fixed and variable costs, which in the illustrative case represents the debt and equity repayments, O&M as well as toll
operation costs. Consistent with Black-Scholes (1973), the price for this European-style put option (i.e. exercisable only at maturity) is expressed as:

\[
f = P^0[N(k_1) - 1] - I^0[N(k_2) - 1] = I^0N(-k_2) - P^0N(-k_1)\tag{6.4}
\]

Where \( P^0 \) equals the present value of operating revenues, \( I^0 \) equals the present value of the total investment costs at \( t=0 \) and \( N(\cdot) \) is a cumulative normal distribution function. The parameters \( k_1 \) and \( k_2 \) are given by:

\[
k_1 = \frac{\ln\left(\frac{P^0}{I^0}\right) + \left(\frac{\sigma^2}{2}\right)t_B}{\sigma \sqrt{t_B}}\tag{6.5}
\]

And

\[
k_2 = \frac{\ln\left(\frac{P^0}{I^0}\right) - \left(\frac{\sigma^2}{2}\right)t_B}{\sigma \sqrt{t_B}} = k_1 - \sigma \sqrt{t_B}\tag{6.6}
\]

Where \( \sigma^2 \) is the variance and \( t_B \) is the time to maturity of the option. The SD model captures volatility (\( \sigma \)) in the discounted monthly toll revenues as functions of fluctuations in traffic volume during both the summer and off-season months. The SD model includes an excursion or input multiplier on the mean value for both of these traffic volumes. The resultant product is the standard deviation of a normal distribution that represents the volatility (\( \sigma \)) of traffic volume.
Figure 6.5 CCB project NPV with MRG or AO
The model draws on a similar Black-Scholes option pricing framework as for the aforementioned AO to develop a series (or “strip”) of put options that gives the concessionaire the ability to exercise an MRG, if and when a monthly revenue falls below the total costs for project delivery and its operations. In effect, the public partner is guaranteeing the difference, or shortfall, in revenues needed to establish a break-even “floor” on net income. The construction of the MRG in this case study is based on monthly rather than annual revenues and expenditures, but the model can be modified to include multiple exercise dates under various contractually structured terms. Similarly, the MRG can be set at a level less than the total amount expenditures.

Again, the formulation of the MRG is based on the work of Huang and Chou (2006). The time to maturity for each MRG in this put option strip is at the end of a one-month period (i.e., a European option), but the total value (and price) of the option is the result of the summation of the values for
the entire option strip over the total concession period. For each MRG option in the strip, the holder
(i.e. the investor/concessionaire in this case) can exercise the option depending on whether the
option is “in the money” (i.e. the monthly toll revenue falls below the monthly expenditure of
operating costs) or “out of the money” (in which case that option in the strip would be worthless
for that month).

The “strike” for each option in the strip is the sum of the fixed and variable costs for that month,
which in this case includes debt and equity repayments, O&M costs and toll operation costs. The
price for a put option in the series follows the Black-Scholes (1973) framework expressed as:

\[
Q_{t_n}(R, M, O) = M_{t_n}^0 N(-d_2) - R_{t_n}^0 N(-d_1)
\]  

(6.7)

Where the parameters \(d_1\) and \(d_2\) equal:

\[
d_1 = \frac{\ln\left( \frac{R_{t_n}^0}{M_{t_n}^0} \right) + \left( \frac{\sigma^2}{2} \right) t_n}{\sigma \sqrt{t_n}}
\]

(6.8)

And

\[
d_2 = \frac{\ln\left( \frac{R_{t_n}^0}{M_{t_n}^0} \right) - \left( \frac{\sigma^2}{2} \right) t_n}{\sigma \sqrt{t_n}} = d_1 - \sigma \sqrt{t_n}
\]

(6.9)

Where \(R_{t_n}^0\) is the present value of revenue flows for the \(n^{th}\) option in the strip, \(M_{t_n}^0\) is the present
value of the specified minimum revenue guarantee in the concession agreement for that \(n^{th}\) option
(which in this implementation is set equal to the total costs at the \(n^{th}\) monthly interval), and \(\sigma^2\) is
the variance (of revenues in this implementation). The total value of the MRG is found by
aggregation,

\[
Q = \sum_{i=1}^{m} Q_{t_i}
\]

(6.10)
where $Q_{t_i}$ is the monthly value of the MRG. Two main variants of the MRG to be considered are the following:

1. The concerned government grants the concessionaire the payment of an amount defined as the difference between a predetermined fixed level of traffic income and the actual traffic income for a contractual time interval (i.e., a put option held by the concessionaire and granted by the contracting authority). The time to maturity for each individually exercisable option in the option strip can be monthly or quarterly, for example. In the sample MRG structure developed here, the maturity for each option is set at one month with exercise possible only at the maturity date (hence a *European* option construct). The duration of this strip of European options runs from the beginning of tolling operations to the time of transfer at 30 years from commencement of operations. This is the basic form adopted for the MRG case results presented in the paper.

2. The concerned government grants the concessionaire the payment of an amount defined as the difference between a predetermined level of traffic income and actual traffic income, and in reverse the concessionaire agrees to pay the concerned government all revenues that exceed some predetermined level. Hence, the concessionaire is holding a put option and contracting authority is holding a call option.

### 6.5.2 Valuation of Compound Option (AO linked to MRG)

Under the same model sector and within a concession agreement where both an AO and MRG are present, they interact with each other to produce a *compound* option (defined as an *option on an option*). The activation of the MRG option is contingent upon the concessionaire’s decision to invest at $t=0$ (prior to the start of construction). Hence the concessionaire is effectively holding a compound option – a call on a put – under which the exercise payoff of the option to invest is related to both the AO and the MRG. For instance, as the level of revenue support under the MRG
is increased, the concessionaire’s risk of financial loss decreases following the start of construction. As a result, *ceteris paribus*, the value of the AO will decrease. At some level, the MRG will effectively make the AO worthless. Notwithstanding the compounding effect of the options, the AO and the MRG increase flexibility for the concessionaire (and for the concerned government in the case of the AO), and hence, increase the value of the project agreement (for the concessionaire).

To account for these conditions, the SD model includes the parallel calculation of the change in value for the AO under the scenario where an MRG is introduced into the P3 contract prior to the inception of the AO at the beginning of the design phase. Under this scenario the AO time to maturity (hence the exercise date for this European option) is fixed at the end of the design phase or just prior the start of construction. The SD model takes into account that the decision to exercise the AO will depend on the value of exercising the MRGs over the duration of the project term. Recall that in the illustrative case, the MRG is comprised of a strip of 360 one-month options exercisable at the end of a month when revenue falls below the prescribed minimum revenue. The MRG put options are exercisable at the end of each month over the 30-year concession agreement, with the option payoff for the $n^{th}$ option in the strip expressed as:

$$\max(0, M_n^0 - R_n^0)$$  \hspace{0.5cm} (6.11)

Where $R_n^0$ equals the present value of revenue for the $n^{th}$ option period in the strip and $M_n^0$ is the prescribed minimum revenue in the concession agreement for the $n^{th}$ option or monthly period during which this option is live.

The SD model architecture provides the link between the value of the MRG, which is measured over the entire duration of the concession agreement, and the value of the AO, which expires at the start of construction. This model sector accounts for the response of the AO value to the
projected exercise of the MRG based on simulated revenues and total project costs over the
duration of the concession agreement. The value of the compound AO-MRG option can be
computed based on the PVs of the AO and the MRG for the duration of the toll operations period
as well as the NPV of the project when no options are present, \( t \) from the following relationship
(Huang and Chou, 2006):

\[
f_M = \sum_{i=1}^{m} F_{t_i} - \left[ (P^0 - I^0) + \sum_{i=1}^{m} Q_{t_i} \right]
\]  
(6.12)

Where \( f_M \) is the value of the AO, \( (P^0 - I^0) \) is the value of the project with no options present, and
the aggregation of \( Q_{t_i} \) is the value of the MRG over the agreement period during which the MRG
is active. The value of the AO-MRG compound option, which takes the form of a call on a put, can also be computed from first principles in the Black-Scholes framework adopted here by
evaluating the bivariate cumulative normal distribution functions that appear in the formulation
for a compound call-on-a-put option (Hull, 2015).

The SD model sectors for the AO and the MRG, as well as the combined structure of the AO-
MRG compound option are provided in Figures 6.4 and 6.6. All of the model elements required to
compute the “simple” form of the AO are retained in Figure 6.6, which accounts for the high
density of connectors in this expanded sector. By doing so, direct comparisons can be made
between the AO-MRG compound option and the original simpler form of the AO. It should be
noted that an alternative and slightly more complicated SD model would include a control variable
that acts as an on/off switch for the compound option. Such a control variable would be used to
determine if the AO is acting in isolation or is operating as a compound option that takes into
account the payoff history of the MRG over the concession agreement. An illustrative result is
included in the simulation shown in Case C of the current study where the revenue generated from
vehicle tolls is low enough and the cost variance for construction is large enough to generate a negative NPV project without any additive effect from the AO, MRG or AO-MRG compound option.

6.6 CCB Case Study Simulation

The following sections describe the outputs from running SD simulations over the 35-year project agreement, which includes 5 years for design and construction and a 30-year duration for toll operations. Illustrative results from these case studies demonstrate how an SD model can be used for analyzing a P3 project’s financial structure performance over time under various scenarios. In particular, the results of the simulation runs show how System Dynamics can be used for structuring the parameters of an AO and a series of MRGs while taking into account various revenue and cost multipliers as well as the dynamics of multiple interacting real options existing within a single P3 project.

6.6.1 Baseline Case A - Nominal settings with $6 toll and moderate variance in design and construction costs

In this simulation the vehicle tolls are set to $6.00 per vehicle and the variance in the design and construction cost multipliers are 1.05 and 1.2, respectively. Figure 6.7 includes the key results for this baseline case, in which the NPV of the CCB project is positive (approximately $165.3 million) and hence represents a viable investment opportunity. Also, under this baseline case the abandonment option payoff is zero given the large positive NPV of the project. Figure 6.8 shows that if a $4 million monthly Minimum Revenue Guarantee is added with the toll kept at $6, the affect is marginal with an NPV for the CCB project of approximately $167 million.
Figure 6.7 Case A – Positive NPV of the CCB

Figure 6.8 Project NPV with MRG
6.6.2 Case B. Revised settings with $3 toll and $4 million per month MRG support

In this simulation the vehicle tolls are lowered to $3.00 per vehicle and the variance in design and construction cost multipliers are retained at 1.05 and 1.2, respectively. The MRG is included in the scenario analyses at a level of $4 million per month (i.e., monthly option strip for the duration of toll operations). Figure 6.9 shows that the project NPV without the contributions from an MRG is a negative at approximately -$70 million. With the addition of the MRG at a support level of $4 million per month results in a positive project NPV of approximately $50 million. Figure 6.10 shows that aggregate value of the MRG put option is approximately $120 million. By comparison, the sole addition of the AO produces a project NPV of $8.3 million in this case. Figure 6.11 shows a comparison of the value of the AO, MRG, and compound AO-MRG options in this case (approximately $78 million, $120 million, and $168 million, respectively) and confirms that the additional flexibility conferred with the AO-MRG compound option is reflected in its greater value.
Figure 6.9 Case B - CCB Project NPV with MRG

Figure 6.10 Case B – MRG & AO Price & NPV for Project
6.6.3 Case C. Revised settings with $3 toll and high variance in design and construction costs with MRG support

In this simulation vehicle tolls are left at $3.00 per vehicle but a relatively high variance in the design and construction cost multipliers is assumed at 1.2 and 3.0, respectively. Construction cost multipliers on this order are not that rare for large infrastructure projects, as discussed by Flyvbjerg (2014). The MRG support level for this case study is set at $5.5 million per month. Figure 6.12 shows that the project NPV without the addition of any options is roughly -$240 million, whereas an MRG support level of $5.5 million per month produces a project NPV of approximately $9.3 million. This suggests that at these high variances in the construction costs in particular, an MRG support level of even $5 million per month would be insufficient to generate a positive NPV for the project at this reduced toll level.
6.7 Case Studies Summary

These aforementioned cases illustrate the dynamic complexity of abandonment options and minimum revenue guarantees operating separately or in tandem as a contractual element in notional P3 agreements such as this one for the design-build-operate-transfer financing of the new Cape Cod Canal Bridge. As noted above, MRGs can be structured in a variety of ways related to the number and times that the option can be exercised, the guaranteed revenue amount, etc. By changing the parameters of the MRG, its NPV may not be large enough to offset the large variances in development costs and produce a positive NPV for the project investment as a whole. This simulation indicates that the perceived value of an abandonment option will depend to varying degrees on the presence (or absence) of an MRG and its specific terms.
6.8 Case Study Conclusion

The P3 procurement process is recognized for its ability to deliver infrastructure while alleviating government budgets, promoting innovation and implementing new technologies. At the same time P3 projects tend to be long-term contractual agreements that need to account for near-term development costs and long-term yet-to-be seen variables that potentially impact their financial feasibility and operational functionality. Previous research has shown that real options employed during the P3 procurement process can mitigate these risks.

The current research contributes to the existing body of knowledge and benefits industry practitioners by demonstrating how an SD model can simulate the real-world causal relationships that potentially impact the financial feasibility and operational functionality of the P3 procurement process. The current investigation shows how an SD model can be constructed and used to analyze how a P3 project’s financial structure performs over the duration of the project agreement and under various scenarios. In particular, the SD model is used in the case studies presented in this paper for the valuation of real options employed during the P3 procurement process to mitigate financial risks. The results of this investigation indicate that system dynamics can be used for structuring the parameters of an AO and a series of MRGs while accounting for the compounding effects of multiple types of real options within a single project. Finally, the results of this investigation suggest that system dynamics can be used for identifying and managing risks that potentially impact the P3 project’s financial feasibility.
CHAPTER 7. PHASE III – SD MODELS FOR THE VALUATION OF OPTIONS “IN” REAL INVESTMENTS

7.1 SD Simulation Models for the Value Multiple Real Options

Infrastructure procurement is becoming more complex as individual assets are increasingly understood as parts of larger networks of interdependent systems. In response, this report presents a method for analyzing investments that span across different infrastructure systems. This second illustrative case also utilizes an SD model to simulate the causal relationships between competing assets. In this second case study the simulation results elucidate the compounding effects of multiple investments that traverse across two or more infrastructure systems. This report presents a SD model that simulates the real-world causal relationships between water treatment alternatives within the shale gas industry. In doing so, this research contributes to the existing body of knowledge by demonstrating how SD models can be used to value multiple and more complex real options within a portfolio of competing infrastructure assets. The valuation of each real option must consider the compounding effects of competing alternatives as well as the value of the underlying asset, which in the illustrative case is a function of the well head revenue and operating costs of shale gas production. The SD model is calibrated based on in-situ observations and/or industry data identified during the literature review. These same sources are used to structurally assess and validate the SD model ensuring that it captures the relevant constituent agents. The SD model is further validated through direct structure tests as well as structured-oriented behavior tests before accepting and presenting conclusions about the model’s simulation results.
7.2 System Dynamics Modeling Water Management in the Shale Gas Value Chain

This research investigates multiple types of competing options in real investments that span across different types of infrastructure systems. Nevertheless, similar to the illustrative research methodology presented in Chapter 6 – Phase II of this report, the current investigation continues to be consistent with Sterman (2000). To accurately analyze and value real investments that span across different infrastructure systems, greater effort is required in the current investigation to determine which non-relevant factors are excluded from the model to ensure its feasibility while making sure that the results remain timely and accurate. Other research, including the work of Ford and Sobek (2003), investigate the use of SD models for valuing complex investments among various alternatives or switching options. That work presents a method for constructing an SD model which integrates product development processes, uncertainty in management strategies and the valuation for alternatives related to manufacturing and product development. Ford and Sobek (2003) conclude that the calibration of an SD model with regards to multiple uncertainties can improve the valuation of investments among various investments in the development of mutually exclusive products.

For the illustrative case, the U.S. Energy Information Administration Annual Energy Outlook 2018 (AEO2018) is referenced and with specific forecasts indicating that U.S. natural gas consumption will increase through 2050. AEO2018 further states that U.S. natural gas production will continue to grow because of the continued development of shale gas, which will account for nearly two-thirds of natural gas production by 2040. AEO2018 also estimates that continued development of natural gas extraction from the Marcellus and Utica shale formations will be the main driver of growth in total U.S. shale gas production and the main source of total U.S. dry natural gas
production. Figure 7.1 represents a reference mode for the AEO2018 estimated growth for shale gas production through 2040.

**Figure 7.1 Projected Shale Gas Production in the U.S. Through 2040**

In this case study the reference mode for shale gas production can be viewed as a representation of the historical and projected growth in shale gas production through 2040. For the purpose of calibrating the SD model during the latter stages of its development, Sterman (2000) places greater emphasis initially on the timeline measured along the horizontal axis. Conversely, less emphasis is placed with stating the exact quantities along the vertical axis (Sterman 2000). Despite this practice, the upper and lower bounds are often included in reference modes and are used when calibrating the SD model by finetuning the parameters and equations that will be embedded in the stock and flow diagram. Lastly, any nonsignificant historical data can be intentionally omitted from reference modes (Sterman 2000). In this case the reference mode for shale gas production (Figure 7.2) does not reflect the period prior to 2005 before its production began to ramp up. The AEO2018 projected growth for shale gas production through 2040 also suggests that the
illustrative case is particularly timely. Notwithstanding the current forecast of total U.S. shale gas production and the derivation of its reference mode, the level of abstraction for the SD model included in this paper captures water reuse at a single well site rather than an entire shale gas play. Nonetheless the SD model and its simulation results support the dynamics hypothesis and achieve the primary research objective, which is the valuation of a multiple real options that traverse industries.

Figure 7.2 Reference Mode for Projected Shale Gas Production in the U.S. Through 2040

The reference mode for the production of shale gas at a single well head is represented in Figure 7.3 and shows the lifecycle is on average between twelve and sixteen months. (Jiang et al. 2014).
According to Keister (2014) the quantity of produced water from a single shale gas well site ranges between 1,514 to 15,142 liters per day (lpd) and lasts for the life of the gas well. As a result, the reference mode for the water produced has a timeline equal to the production of natural gas. Consistent with the work of Chace (2014) and Gao and You (2015), three general categories of water treatment and/or disposal are included in the SD model: (1) centralized wastewater treatment (CWT), (2) deep injection disposal wells (for untreated flowback or produced water), and (3) onsite treatment for reuse in hydraulic fracturing. Wastewater from shale gas production can be transported (typically by tanker trucks) to CWT facilities for treatment and then discharged to surface water or stored for reuse. Wastewater can also be transported (again typically via truck) to disposal wells and pumped underground without any treatment. Onsite treatment for reuse in...
drilling or hydraulic fracturing can employ various treatment technologies, including multi-effect distillation (MED), multistage flash (MSF) and reverse osmosis (RO).

In response to the high demand of water treatment and monitoring, Gao and You (2015) investigate the lifecycle economic and environmental optimization of the shale gas supply chain network. In that work a proposed model covers the well-to-wire lifecycle of electricity generated from shale gas including freshwater acquisition, shale well drilling, hydraulic fracturing, shale gas production, wastewater management, shale gas processing and electricity generation as well as transportation and storage. As part of the investigation into the lifecycle optimization problem, Gao and You, (2015) provides the unit cost rates for various water reuse methods as well as other treatment and disposal practices. Table 7.1 includes the unit costs rates for various reuse methods and water treatment and disposal practices. The unit costs presented in the work by Gao and You (2015) provide the basis for calculating the NPV of each real option in the SD model included in the illustrative case study.

Table 7.1 Economic Comparison between Water Management Options

<table>
<thead>
<tr>
<th>Onsite Treatment Method</th>
<th>Unit Cost ($ / barrel water)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reuse Technologies</strong></td>
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</tr>
<tr>
<td>Reverse Osmosis (RO)</td>
<td>4.7</td>
</tr>
<tr>
<td>Multi-effect Distillation (MED)</td>
<td>5.4</td>
</tr>
<tr>
<td>Multistage Flash (MSF)</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Other Water Treatment &amp; Disposals</strong></td>
<td></td>
</tr>
<tr>
<td>Central Waste Treatment Facilities (CWT)</td>
<td>1.2 – 3.8</td>
</tr>
<tr>
<td>Underground Disposal / Deep Well Injection</td>
<td>1.0 – 1.4</td>
</tr>
</tbody>
</table>

The strategy of choosing between the various methods for disposing, treating and/or the reuse of flowback and produced water from shale gas operations is included in the decision tree shown in Figure 7.4. Figure 7.4 shows that if the operating margin supports the well going live within a
shale gas play, then management currently has the option for employing any of the various forms of water reuse (i.e. RO, MED, MSF) or alternatively has the options to dispose of the produced water through deep well injection or its treatment at CWT facilities. If management chooses to utilize water reuse technology, the decision on which option to employ is a function of both its cost and the capacity of available water reuse options. The decision thresholds for choosing water reuse options are reflected in the decision tree (Figure 7.4) and are also represented in the reference modes for each water reuse alternative included as part of Figure 7.5.

**Figure 7.4 Decision Tree Analysis of Shale Gas Well Site & Water Resource Management Options**

The relationships between water reuse options is captured in Figure 7.5 and form the basis for the system dynamics hypothesis. The SD model is used in turn to explain why and how the behavior of reference modes for sub-constituents (i.e. water reuse options) change in response to a variety of endogenous and exogenous drivers during the lifecycle of single shale gas well. More specifically, Figure 7.5 shows that beginning with RO, the unit costs are successively greater for MED and MSF. As a result the reference mode shows that at time, $t_0$ when the shale gas well goes
live, RO will be the first and only water reuse technology employed until the amount of produced water reaches maximum capacity. At maximum capacity, $t_1$ the next most economical water reuse option (i.e. MED) will be employed in combination with RO. At some point, $t_2$ the amount of produced water being treated by both RO and MED reaches maximum capacity and the water reuse technology with the greatest unit cost (i.e. MSF) will be employed and utilized in combination with and on a concurrent basis with the two already employed options (i.e. RO and MED). Finally, the reference modes in Figure 7.5 show that as the life of the gas well nears completion and the amount of produced water begins to dissipate, the sequence is reversed. The water reuse technology, MSF with the greatest unit cost, is the last-in and first-out (LIFO) of operation. Finally, at some point between $t_5$ and $t_6$, RO with lowest unit cost becomes the first-in and last-out (FILO) of operation until the end of the well’s production at time, $t_7$. 
Figure 7.5 Reference Mode for Water Reuse by Cost & Capacity

For purposes of both brevity and clarity, neither the reference modes shown in Figure 7.5 nor the SD model presented in this report provides for the valuation of other options including treatment at CWT facilities or deep well injection. Nor does this research or the SD model presented in this report consider various other options including expanding individual systems, transmitting produced water through pipes and/or trucking water to alternate sites with similar treatment technologies. In this sense, the model is intentionally kept simple to demonstrate in the most concise way the ability of the SD model to be used for the valuation of switching between the real options that constitute water reuse technologies and their compounding effects upon one another. The current research is presented on the presumption that while a more complicated and all-encompassing model would be more realistic, no additional value would be achieved with regards
to this primary research objective, which is to present an SD model for the valuation of multiple and compounding real options that traverse industries.

Consistent with Albin (1997), the current model builds upon the reference mode in Figure 7.5 and captures the positive feedback and balancing loops within the system dynamics. These loops form the causal loop diagram (CLD) and illustrate the basic mechanisms that drive the system dynamic’s behavior (Figure 7.6). The CLD for the water reuse options include four positive feed-back loops and three (3) balancing loops. The positive feedback loops, also known as reinforcing loops, are denoted by a positive (+) symbol and will continuously amplify a trend or any other physical and non-physical flow. Conversely, negative loops, which are sometimes called balancing loops, are denoted by a minus (-) symbol and are goal-seeking flows of the same physical and non-physical subject matter and are bound within a specified limit (Sterman 2000). For the case study in this investigation, CLDs illustrate the relationship between the economic demand for shale gas and the resultant increase in produced water that will require treatment and/or disposal as its production ramps up. The CLD is a preceding activity and is used as a visual aid on a concurrent basis during the development of the stock and flow diagram and SD model architecture.
7.3 Marcellus and Utica Shale Formation

The Marcellus and Utica Shale Formations include an extensive range of gas plays that follow the Appalachian Basin stretching from the Adirondack Mountain massif in the northeastern part of New York State into northern Tennessee. The formations range in depth from 600 to 2,750 meters (AEO2018). Given the AEO2018 projections, significant infrastructure development will continue to be required to access the substantial subsurface reservoir of natural gas and bring this resource to market. To support this market, upstream development of new infrastructure will consist of access roads, water impoundments, water lines and well pads. Midstream development will include the construction of gathering pipelines, transmission pipelines, compressor stations, metering pads,
and additional access roads. It is also recognized that downstream development will continue to evolve as various industries enter the market due to the abundance of natural gas (Henning and Ladavat, 2014). The current research considers these infrastructure types and asset classifications worthy of further investigations. In order to keep the SD model within reasonable bounds for this investigation, the current study focuses specifically on water reuse at a single well site within a shale gas play of either the Marcellus and Utica Formations.

The subject matter of the system dynamics hypothesis is particularly important because of the nature of hydraulic fracturing at these shale formations. A review of existing literature suggests that shale gas production within these formations will continue for at least the next two decades. AEO2018 forecasts that total natural gas consumption in the U.S. will grow annually from 724.9 billion cubic meters (bcm) in 2012 to 894.8 bcm by 2040. As a result, shale gas production from these formations is forecast to annually increase from 53.8 bcm in 2012 to peak production of 141.6 bcm between 2022 through 2024. During these peak years, natural gas from the Marcellus Shale Formation alone is forecast to provide up to 39% of market demand east of the Mississippi River. Between 2016 and 2040, natural gas production from the Marcellus Shale Formation will exceed market demand for the Northeastern and Mid-Atlantic regions of the United States, requiring other more distant markets to purchase the surplus gas. Current forecasts of gas production from the Marcellus Shale Formation show a continuation of a sustained rate before declining to 130.3 bcm in 2040 (AEO2018).

7.3.1 Water in the Marcellus and Utica Shale Gas Value Chain

Shale gas production within these gas plays is notable for its intensive demand on water resources and the potential negative environmental impacts from contaminated flowback and produced water generated by drilling operations. During hydraulic fracturing operations, millions of liters of
fracturing fluid (mainly water) are pumped into the wellbore under high pressure, thereby fracturing the shale rock formations and increasing the production rate of gas. Horizontal drilling allows for gas production from multiple horizontal wellbores at a single shale site, reducing the capital investment required and improving the efficiency of shale gas production. The combination of hydraulic fracturing techniques and more efficient horizontal drilling technologies has led to an explosive growth in shale gas production. The large amount of water generated from shale gas production is generally classified into either flowback or produced water. Flowback water largely consists of the hydraulic fracturing fluid that returns from the well, immediately after fracturing, during the first 10 to 14 days prior to gas production. Produced water is generated during gas production and lasts for the productive life of the well. The observed combined nominal values for flowback and produced water over the duration of a typical Marcellus shale well range between 3,500,000 to 26,000,000 liters. This has placed high demands on water resources, wastewater treatment and transportation infrastructure and environmental monitoring (Jiang et al. 2014).

7.4 SD Model: Architecture

The current research objective is to investigate the use of SD models for the valuation of complex and exotic real options that traverse infrastructure sectors. To achieve this objective an SD model is developed using the software iThink 10.1.2® and simulates both the processes of shale gas production and the implementation of various water treatment technologies. The SD model is also used to determine the NPV of the real options related to the different kinds of infrastructure assets that are required to treat and reuse the flowback and produced water from UNG operations. It is worth noting that the illustrative case study may inadvertently create ambiguity between common terms used in the domain of SD modeling and their homonyms, which are used to describe the fluid dynamics and physical processes of water usage in the shale gas industry. For example, SD
models utilize stocks and flows, which in the illustrative case study literally represent holding basins, reservoirs and the actual flow of fluids (i.e. flowback and produced water). These same expressions (stock and flows), however, are commonly used terms for describing SD model architecture and to describe accumulations and the transfer of tangible as well as non-tangible elements.

The SD model in the current research is broken down and presented in this paper in four sectors so that each sector can be explained separately. Although the four sectors are presented separately in this paper, the SD model contains mathematical equations embedded within ghost variables and other relationships that connect the various stocks and other elements throughout the entire SD model. The four sectors presented in the shale gas and water model include: (1) Figure 7.7 – Shale Gas Operations, Water Usage and Treatment Infrastructure, (2) Figure 7.8 – NPV Costs for RO, MED, MSF for Wastewater Treatment, (3) Figure 7.9 – NPV for Shale Gas Production and CWTs and Deep Well Injection, and (4) Figure 7.10 – NPVs for Shale Gas Production and Water Reuse Technologies. Figures 7.7 through 7.10 represent the complete SD model that has been developed to capture and simulate the processes of shale gas extraction through a single well site along with its demand on fresh water sources. The SD model also simulates the range of NPVs for the real investments in water reuse technologies (i.e. RO, MED and MSF) as demand for shale gas production ramps up and subsides at the well site. As such, the model simulates the usage of various technologies required to treat the flowback and produced water during the well’s entire lifecycle. The initial nominal values, parameters and equations used for each of the model’s sectors are included as Appendix II to this report.
7.4.1 UNG Operations, Water Usage and Treatment Infrastructure

The model sector representing the bulk of the infrastructure related to shale gas operations and the usage and treatment of water is presented in Figure 7.7. Figure 7.7 includes on the left-hand side the freshwater reservoir and its delivery to the well site. The stock and flow diagram shows that several other sources of water, including reused water from CWTs as well as RO, MED and MSF can supply the well head reservoir before being transmitted and eventually used in hydraulic fracturing operations. Figure 7.7 also includes shale gas production, which draws upon the various sources of water needed for hydraulic fracturing operations and the extraction of shale gas. Flowback and produced water is in turn transmitted back to the various technologies for its reuse (i.e. RO, MED or MSF) or is treated at CWT facilities or disposed through deep well injection. Figure 7.7 also shows how a single SD model can simulate complex processes that traverse water treatment alternatives and shale gas production.
Figure 7.7. Shale Gas Operations, Water Usage and Treatment Infrastructure
7.4.2 NPV of Cumulative Costs for RO, MED, MSF for Wastewater Treatment

Figure 7.8 is the SD model sector where the NPVs are calculated based on the volumetric unit costs for treating produced water through the various technologies (i.e. RO, MED and MSF). The NPVs for each water reuse technology is calculated using the following equation 7.1:

\[ PV = \sum_{t=1}^{T} \frac{CF_t}{(1 + i)^t} \]  

(7.1)

where \( CF_t \) denotes the cash outflow for the duration of the shale gas well and \( i \) = discounted rate accounting for the effects of both interest and inflation. For purposes of this study, the capital costs associated with the implementation of each technology is negligible and is included in the volumetric unit cost. Figure 7.8 includes the SD model sector that enables the quantities of water treated under various methods to be expressed in NPVs and used for the valuation of real options in water reuse technologies. NPVs are based on the volumetric unit costs included in Table 7.1 consistent with Gao and You (2015). The volumetric unit costs for produced water treated through RO, MED and MSF drive the system dynamics hypothesis based on the FILO and LIFO laddering sequence and are taken into consideration when calculating the NPV of each reuse option. Appendix II includes a complete list of the relevant equations, time steps and initial nominal values that are found within the numerical equations embedded in the stock and flow diagram.
Figure 7.8 NPV Costs for RO, MED, MSF for Wastewater Treatment

7.4.3 NPV of Cumulative Costs for Shale Gas Production and CWTs and Deep Well Injection

Figure 7.9 is the model sector that represents the cumulative costs for the shale gas production. The SD model sector shown in Figure 7.9 is also used to calculate the NPV for treating water at CWT facilities as well as its disposal through deep well injection. The NPVs for shale gas production, CWTs and deep well injection is calculated utilizing the same formula as the NPVs for the cumulative costs for water reuse technologies. More importantly, Figure 7.9 includes the SD model sector that enables the production costs for shale gas operations to be factored into the valuation of real investments in water reuse technologies.
Figure 7.9 NPV for Shale Gas Production and CWTs and Deep Well Injection

7.4.4 NPVs for Shale Gas Production and Water Reuse Technologies

Figure 7.10 represents the model sector where NPVs are calculated for the cumulative net revenue for shale gas production. The SD model calculates the NPV for shale gas production based on the cumulative revenue, which is a function of the well head price for shale gas over the twelve-month duration production lifecycle for the shale gas well less the cumulative costs for operations and also for the treatment of water through the real investments made in RO, MED and MSF. The NPVs for the production of shale gas is calculated using the following equation 7.2:
\[ NPV(iN) = CC_0 + \sum_{t=1}^{T} \frac{NCF_t}{(1+i)^t} \] (7.2)

Where \( CC_0 \) denotes the capital costs for setting up well head and drilling rig at time 0; \( NCF_t \) denotes the net cash flow for the twelve-month duration of the shale gas well and \( i \) = discounted rate accounting for the effects of both interest and inflation. Figure 7.10 includes the SD model sector that calculates the NPVs for shale gas production under various scenarios, which are directly used for the valuation of real investments in each water reuse technology investigated in the current research (i.e. RO, MED and MSF).

![Figure 7.10 NPVs for Shale Gas Production and Water Reuse Technologies](image)

7.5 Calibration and Validation of the SD Model

The current investigation builds upon these previous bodies of research and expands the SD model that was constructed to simulate water usage and treatment in shale gas production. The SD model presented in this doctoral report has been expanded to include the valuation of two real options related to wastewater treatment alternatives. During its development the current model was
consistently calibrated and underwent multiple validation processes. The following sections highlight key calibration and validation processes.

7.5.1 Calibration of the SD Model for the Valuation of Exotic Options in Real Investments

The SD model presented in this report was calibrated based on various sources of information from the existing body of knowledge related to water resource management in the shale gas value chain. Much of the data was taken from the existing body of knowledge obtained through an extensive literature search. In some cases the data was verified by site visits to shale gas operations in the Marcellus gas plays in the U.S. states of Ohio, Pennsylvania and West Virginia. Of particular importance for this illustrative case study and to achieve the research objective, the SD model was calibrated based on historical and current industry data in terms of the following:

1. Forecast duration of an active well site in the Marcellus Shale gas play;
2. Anticipated quantities and durations for flowback and produced water at a shale gas well;
3. Unit costs for treating and/or disposing of water produced during shale gas extraction; and
4. Well head revenue based on current (and constantly changing) wholesale price of natural gas.

To begin, the SD model was calibrated consistent with values included in Jiang et al. (2014) where an average of 15,000 cubic meters of water is required to hydraulically fracture a well in the Marcellus shale formation. The SD model in the illustrative case is also consistent with Keister (2014), which states the quantity of produced water from a single shale gas well site ranges between 1,514 to 15,142 liters per day (lpd) and lasts for the life of the gas well. Lifecycles of active shale gas wells vary, and the SD model in the illustrative case is calibrated to reflect the real-world system according in part to Chace (2014). In accordance with literature, the SD model was calibrated for a one-year life with 20 liters of produced water created for every 1,000 liters of shale gas that is extracted. As discussed in the following section of this report, the SD model was
also calibrated so simulation runs show that produced water is generated for the duration of the active well while flowback water initially surges but dissipates within weeks of completing the initial fracturing process.

In order to value the real options related to water reuse technologies, the SD was calibrated based on the well head price for natural gas. The well head price for natural gas continuously changes, but the SD model presented in this report includes a volumetric unit rate of $.14 per liter for the well head price of shale gas. The SD model also includes unit costs for water reuse technologies consistent with Gao and You (2015) shown in Table 7.2.

<table>
<thead>
<tr>
<th>Onsite Treatment Method</th>
<th>Unit Cost ($ / liter water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Osmosis (RO)</td>
<td>.03</td>
</tr>
<tr>
<td>Multi-effect Distillation (MED)</td>
<td>.034</td>
</tr>
<tr>
<td>Multistage Flash (MSF)</td>
<td>.041</td>
</tr>
</tbody>
</table>

In order to effectively use the SD model for the intended research objective (i.e. valuation of real options), each treatment technology is given a theoretical maximum capacity. By limiting each process with a maximum capacity, reuse methods are shown to be used in tandem with one another and on a partially concurrent basis as the quantity of produced water steadily increases during simulation runs. Table 7.2 shows the maximum capacity of each reuse technology.
Finally, the SD model’s architecture allows it to readily shut off any reuse option while other water technologies remain active. As discussed in the next two sections, this feature of the model serves two purposes:

1. Validation of the SD Model, and
2. Valuation of Real Options.

Appendix II includes a complete list of the relevant equations, time steps and initial nominal values that are found within the numerical equations embedded in the stock and flow diagram.

### 7.5.2 Validation of the SD Model

The development of the SD model presented in this illustrative case study began with Fitch et al. (2016), in which a system lexicon is presented and a problem statement is defined. Consistent with Sterman (2000) and Borshchev (2012) this effort was necessary to initiate a validation process and select the appropriate level of abstraction to model water resource management in the shale gas industry. In successor follow-on work Fitch et al. (2017) presents an SD model that forecasts the amount of produced water created at a single shale gas well site. The SD model is also used to forecast how the quantities of treated and/or disposed water are anticipated to shift among several alternatives in response to various exogenous and endogenous factors. To expound upon the theory of real options, however, certain elements within that original SD model are no longer necessary.
However, other new sectors are required for the valuation of real options related to water reuse technologies and, thus, have been added in this.

For example, in the previous versions of the model, the quantities and theoretical sources of fresh water used during shale gas operations are included in the model’s simulation results. In the current research the source and quantity of fresh water continues to be included in the model. This element however is not required for the valuation of real options related to the reuse technologies related to the produced water that occurs naturally as a byproduct of shale gas production. At the same time, the SD model’s stock and flow diagram continues to include CWT facilities and deep well injection as alternative processes for treating and disposing of water. By including these and other elements, a structural assessment of the SD model validates that it is consistent with the descriptive knowledge of the system, which has been identified through an extensive literature review and in-situ observations.

The SD model is further validated with two tests and in a manner consistent with Barlas (1996). The SD model is validated by performing two direct structure tests and two structure-oriented behavior tests. These tests are particularly relevant for the valuation of real options in the illustrative case study. The SD model is validated through a direct structure test by comparing the simulation results with the knowledge of the real system structure of a shale well site. Figure 7.11 is a graphical representation of the physical processes related to the production of shale gas along with flowback and produced water. Figure 7.11 shows that the structure of the SD model allows it to simulate the real-world causal relationships and accurately reflects the processes based on notional and empirical data. Figure 7.11 shows that produced water (line 1) is generated for the duration of the active well while flowback water (line 2) initially surges but dissipates within
weeks. Furthermore, Figure 7.11 shows that the production of shale gas following hydraulic fracturing (line 3) surges but begins to taper off and lasts for approximately twelve-months.

![Figure 7.11. Shale Gas Operations & Produced Water](image)

As part of another direct structure test, simulation results are required to validate the model in terms of its ability to simulate water reuse through the various technologies under examination. Figure 7.12 shows that the SD model effectively simulates the FILO and LIFO sequences for employing all three water reuse technologies. In this sense, the SD model captures the dynamic hypothesis for the current research, which is represented in the reference modes included in Figure 7.5. Figure 7.12 shows that RO technology (line 1) is utilized for the duration of the active well site as a result of its lower unit cost. Hence, the SD model captures the FILO behavior of the RO technology. Figure 7.12 also shows that when RO reaches maximum capacity, the process with the next lowest volumetric unit cost, MED (line 2) commences to be utilized or is knocked-in as a barrier option. Figure 7.12 also shows in the same manner that MSF with the greatest volumetric
unit cost is the last option to be *knocked-in* as both a *barrier* and *compound* option. At this point all three water reuse technologies (RO, MED and MSF) are working in tandem. Lastly, Figure 7.12 shows that as a result of its higher unit cost, MSF technology is the first option to be eliminated or *knocked-out* as the quantity of produced water dissipates. Hence, the SD model also captures the LIFO behavior of the MSF technology. Subsequently, MED is *knocked-out* as the quantity of produced water further dissipates while RO technology continues to be utilized.

**Figure 7.12. FILO & LIFO of Water Treatment Methods**

The model is further validated by running several structure-oriented behavior tests. The SD model’s architecture allows it to readily shut off any reuse option while other reuse technologies remain active. Figure 7.13 shows the simulation results when both RO and MSF are inactive and MED is the only water reuse technology in operation. Figure 7.13 shows that no water is treated through RO and MSF (lines 1 and 3) while MED (line 2) is the only active reuse technology. In a similar manner, Figure 7.14 shows simulation results when RO and MSF are used in tandem and
MED is inactive. Figure 7.14 shows that no water is treated through MED (line 2) with all produced water being treated with RO and MSF technology.
7.5.3 Alternative SD Model Architecture for Exotic Options

The current research objective is to demonstrate how the SD model is used to value MSF and MED technology as both barrier and compound options. The SD model is not used to calculate the value of RO as a standalone technology. The dynamic hypothesis for this case study requires at least one technology (i.e. RO) be active in order to support shale gas production. It should be noted that the SD model could have been constructed instead to simulate an expansion option for RO that would have allowed this technology to have greater capacity. Under this scenario the SD model architecture would include an initial maximum capacity or barrier where the RO treatment process is met. The SD model architecture would also include a knock-in point for an expansion option to increase capacity of the RO water treatment process after maximum capacity had been met. The strike price for the expansion option would be a function of the capital costs required to implement expanded capacity and would be offset by the additional revenue generated through further gas production.

Alternatively, the SD model architecture could be constructed to include a switching option, which would facilitate alternating between water treatment technologies (i.e. water reuse vs. CWT facilities vs. deep well injection). The SD model architecture would include a knock-in point for the switching option to alternate between water treatment process after maximum capacity had been met for the first alternative. Again, the strike price would consider the capital costs required to exercise the switching option, which would be offset by the additional revenue generated through additional gas production. The current research is purposefully based on a combination of barrier and compound options rather than on an expansion option for a single system or switching options between treatment methods. The current SD model is constructed to simulate a combination of barrier and compound options so it simulates the FILO and LIFO sequences. By
doing so, this research is more robust in that it simulates not only a *knock-in* behavior but also the *knock-out* behavior for the combination of *barrier* option (i.e. MED) and for a *barrier and compound* option (i.e. MSF).

### 7.6 Case Study Simulation – Real Option Valuation

The SD Model is used to determine the NPV of two out of three real options for water reuse technology: MED and MSF. Once again it is noted that the NPVs for MED and MSF technologies are based on the distributing sequence presented in the reference mode in Figure 5 and shown in the SD model validation results in Figure 7.12. Figure 7.12 captures the FILO and LIFO laddering stacks that are a function of each technology’s maximum capacity and its respective volumetric unit cost (See Table 7.2 and Table 7.3).

#### 7.6.1 Valuation Methodology for RO, MED and MSF

In order to value the water reuse technologies (i.e. MED and MSF) as both a *barrier* and as a *barrier and compound* option, the NPV must take into account the well head net revenue. The valuation process of the two options (i.e. MED and MSF) begins with calculating the value of the option with the greatest volumetric unit cost. It is noted that MSF is the last-in and first-out (LIFO) technology because it is the option with the greatest volumetric unit cost. MSF technology is considered both a *barrier* option as well as a *compound* option because it is an option upon another option. The NPV for MSF is determined only after RO and MED are used in tandem and maximum capacity of both systems have been met.

In order to value MSF as a both a *barrier* and *compound* option, the NPV is first calculated for the well head net revenue when all three reuse technologies (i.e. RO, MED & MSF) are utilized in tandem. The current SD model’s architecture allows all three water reuse technologies to be
utilized. As a result, the well’s NPV when all three technologies are active takes into account their total volumetric unit cost along with the well head net revenue over the lifecycle of the active site. The SD model’s architecture also allows it to shut off MSF as the LIFO option and determine the cumulative combined NPV for the well head net revenue when only the remaining two processes (RO and MED) are working in tandem. The net-NPV for MSF as the LIFO technology and as the *compound-barrier* option is determined by equation 7.3.

\[
\text{Value of MSF as a Compound and Barrier Option} = \text{NPV for Gas Production when RO, MED & MSF are Active} - \text{NPV for Gas Production when only RO & MED are Available} \quad (7.3)
\]

In a similar manner, the value of MED as a simple *barrier* option is determined by subtracting the well’s NPV when RO is used as a standalone technology from the well’s NPV when RO is used in tandem with MED as a *barrier* option as shown in equation 7.3. Again, the current SD model’s architecture allows it to shut off MED as an option and to directly calculate the well’s NPV when only RO is utilized as standalone technology.

\[
\text{Value of MED as a Barrier Option} = \text{NPV for Gas Production when RO & MED are Active} - \text{NPV for Gas Production when only RO is Available} \quad (7.4)
\]
7.6.2 Baseline Case – Water Reuse Technologies: RO, MED & MSF (Knock-in & Knock-out options)

Figure 7.15 NPV of Gas Production with RO, MED & MSF

For the baseline case Figure 7.15 shows the cumulative costs for each water reuse technology (RO, MED and MSF). Figure 7.15 also shows the well’s NPV which is the net result between the cumulative well head revenue less operation costs for utilizing all three water reuse technologies (i.e. RO, MED and MSF) in tandem and on a partially concurrent basis over the twelve-month duration of the active well site. The well’s NPV when all three reuse technologies (i.e. RO, MED and MSF) are available is $2,213,969. The well’s NPV when utilizing all three water reuse technologies is the basis for valuing MSF as both a barrier and compound option.
As stated above, the current SD model’s architecture allows it to readily shut off MSF as the LIFO technology and as the compound option. By doing so, the SD model is used to determine the NPV of shale gas production while the remaining two water treatment processes (RO and MED) are utilized in tandem and on a partially concurrent basis. Figure 7.16 captures the SD model simulation results for the FILO and LIFO sequence when MSF technology is not available. Note in Case B, MED becomes the single barrier option and MSF technology is not available.
Figure 7.17 NPV of Gas Production with RO & MED

Figure 7.17 shows the cumulative costs for both water reuse technologies (RO and MED). Figure 7.17 also shows the NPV for gas production less the cumulative operating costs for using RO and MED for the duration of the active well site. The well’s NPV when only two water reuse technologies (i.e. RO and MED) are available is $2,199,212. As noted in the baseline case, the well’s NPV when all three reuse technologies (i.e. RO, MED and MSF) are available is $2,213,969. The difference between the well’s NPVs when all three technologies (i.e. RO, MED and MSF) are utilized and when only two processes (RO & MED) are available is the value of MSF as both a barrier and compound option. Hence, the value of MSF as both a barrier and compound option is $14,757.
7.6.4 Case C – Only RO Technology Available

Figure 7.18 shows the results for the cumulative cost for using RO as a standalone water reuse technology. Figure 7.18 shows the NPV for gas production which is the net result between the well head revenue less the cumulative operating cost for using RO as a standalone technology. The well’s NPV when only RO is used is $2,072,099. As noted in the Case B, the well’s NPV when two processes (i.e. RO and MED) are available is $2,199,212. As a result, the difference between the well’s NPVs when two technologies (RO and MED) are utilized and when only the RO process is the value of MED as a simple barrier option. Hence, the value of MED as a barrier option is $127,113 at a single shale gas well site within the Marcellus Shale gas play.

7.6.5 Case Studies Summary

Table 7.4 includes the value of MED at a simple barrier option as well as MSF as both a compound and as a barrier option.
Table 7.4 Valuation of Real Options

<table>
<thead>
<tr>
<th>Onsite Treatment Method</th>
<th>Type of Option</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-effect Distillation (MED)</td>
<td>Barrier Option</td>
<td>$127,113</td>
</tr>
<tr>
<td>Multistage Flash (MSF)</td>
<td>Compound Barrier Option</td>
<td>$14,757</td>
</tr>
</tbody>
</table>

Within the financial services industry, the term *moneyness* is used to express the relative position of the current or future price of an underlying asset (e.g., a stock) with respect to the strike price of its derivatives including call or a put options (Neftci, 2008). In the current research, the *moneyness* of real options to utilize one or more water reuse technologies is represented by each process’s NPV relative to the underlying asset (i.e., well head price for natural gas) as well as its relative position to other existing water reuse options. Figure 7.19 shows the values for the single *barrier* option (i.e., MED) and for the *compound* and *barrier* option (i.e., MSF) used in tandem and on a partially concurrent basis with RO and on a contemporaneous basis with the production of gas.
The values or *moneyness* for the water reuse options are based on the SD model’s simulation outputs over the 12-month duration of an active well site. The *moneyness* of MED as a *barrier* option is the difference between the well’s NPV when MED is used in tandem with RO and when RO is used as a standalone technology. Similarly, the *moneyness* for MSF as both a *barrier* and *compound* option is equal to the difference between the well’s NPV when MSF and MED are used in tandem with RO and the well’s NPV when only MED is used in tandem with RO technology. The model’s results suggest that the *moneyness* of MED as a simple *barrier* option is substantially greater and is sustained for the duration of the well compared with the *moneyness* of MSF acting as both *barrier* and *compound* option. The case study results also suggest that although the value of both options increases with production of natural gas, the NPV for MED as a *barrier* option is significantly higher than MSF acting as both a *barrier* and *compound* option (i.e. $127,113 versus $14,757).
CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The last two phases of research presented in this report demonstrate how SD models can simulate the real-world causal relationships related to: (a) the economic impact of quantifiable variables on lifecycle costs and revenues for a transportation project procured through the P3 delivery method presented in Chapter 6 and (b) the processes of shale gas extraction through a single well site along with the economic demand for water reuse technologies presented in Chapter 7. By doing so, a relatively new and vanguard approach for the valuation of real options is presented in both chapters where simulation results from SD models can be used to value real options both “on” project finance structures and “in” the technical design of an infrastructure system. Successor follow-on research involved with the SD modeling method will continue to be aimed at assisting decision-makers tasked with procuring infrastructure through various delivery methods and making real investments that traverse across other types of assets. In addition, other future investigations will include developing SD models aimed at valuing investments “in” technological pursuits and “on” project finance structures within the domain of research and development. Furthermore, future investigations will not be limited to using SD models as a standalone simulation method. Other ongoing and follow-on investigations will be expanded to encompass other modeling methods used in tandem with system dynamics to validate results, calibrate models and create multifaceted approaches that result in more robust analyses of real-world causal relationships. Of particular importance, current ongoing investigations use SD models in tandem with the integer programming (IP) modeling method. In other planned research, SD models will be used in conjunction with econometric models. The following is a narrative of an ongoing current investigation that explores SD models used in tandem with IP modeling method.
8.1 Multi-Method Model & Infrastructure Portfolio Management

In pursuit of this follow-on successor research, Fitch et al. (2018) presents a multi-method model to assist decision-makers in managing existing infrastructure on the concurrent basis of procuring new assets. The purpose of that research is to advance the economic sustainability of infrastructure procurement by hedging the risks of financial loss to private equity sponsors and commercial lenders. To achieve this primary goal, the research objectives of that investigation are threefold. The first objective is to construct an integer programming (IP) model used to optimize a portfolio of infrastructure assets by meeting a set of economic and financial constraints while ensuring all user demands are met. The second objective is to construct an SD model to simulate the causal effects related to asset deterioration, rehabilitation processes, cost accumulation and inflexibility of resources across a portfolio of infrastructure assets. By jointly considering the first two objectives, a third and primary objective will be to present a multi-method model that optimizes decision-making during the procurement of new assets while managing a portfolio of existing infrastructure. The decision-making process is part of an overarching management plan that incorporates economic and financial targets while ensuring all user demands are met. The objective of this evolving research is to develop a multi-method model to manage a portfolio of assets that also includes the valuation of real options “on” project finance structures and “in” the technical design across the portfolio of infrastructure.

8.1.1 Research Methodology

The investigation presented in this first part of a series of research papers is intended to present an SD model that can be used to manage a portfolio of infrastructure assets from multiple perspectives. The methodology outlined in this report is intended to be adaptable and used by various stakeholders during the infrastructure procurement process. For practicing civil engineers
and concerned governments, the SD model will be used essentially as a facility management plan. The modified SD model is also intended to be used by equity sponsors and commercial lenders for optimizing the economic return and mitigating financial risk arising from a portfolio of infrastructure investments.

Furthermore, Fitch et al. (2018) identifies the best management practices (BMP) from the perspective of credit rating agencies can be mathematically modeled within an IP. While the model is based on municipal credit rating in the U.S., the research goal is to investigate and demonstrate how IP and SD models can be constructed and used in tandem to manage a portfolio of infrastructure investments that are subject to a variety of optimizing constraints.

This IP model, presented in this report and originally presented in Fitch et al. (2018), includes an objective function to minimize all costs of managing and operating a portfolio of infrastructure assets while ensuring all user demands are met. The objective function is also subject to a set of financial constraints that are considered highly favorable from the perspective of the credit rating agencies. The investigation presented in Fitch et al. (2018) will be followed by an investigation that presents an illustrative case study showing how the objective function can be optimized. By doing so, the O&M of existing assets and the procurement of new infrastructure can be prioritized as a function of user demands subject to the constraints included in the IP model. The third and final stage of the research will integrate the optimization results into a system dynamics framework of an “aging chain” SD model, which is presented in cursory form in this report. In follow-on research simulation results from the SD model will be used to analyze how the portfolio of infrastructure performs in meeting all user demands while satisfying the optimization constraints.
8.1.2 Management Impact on Credit

The financial constraints included in the IP model are based on Larkin (2002) in which BMPs are identified as highly favorable to concerned governments and other issuers of debt. Table 1 includes those BMPs and indicates their respective constraints within the IP model that captures the mathematical representation of each practice.

Table 8.1 Management Practices and Integer Programming Model Constraints

<table>
<thead>
<tr>
<th>Management Practice</th>
<th>Constraint No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fund balance reserve policy &amp; working capital reserves</td>
<td>No. 4</td>
</tr>
<tr>
<td>Multiyear financial forecasting</td>
<td>No.’s 4, 5, 6, &amp; 7</td>
</tr>
<tr>
<td>Contingency planning policies</td>
<td>No.’s 4, 5, 6, &amp; 7</td>
</tr>
<tr>
<td>Policies regarding nonrecurring revenue</td>
<td>No. 5</td>
</tr>
<tr>
<td>Depreciation of general fixed assets</td>
<td>No. 6</td>
</tr>
<tr>
<td>Debt affordability reviews and policies</td>
<td>No.’s 4, 5, 6, &amp; 7</td>
</tr>
<tr>
<td>Pay-as-you-go capital funding policies</td>
<td>No. 4</td>
</tr>
<tr>
<td>Five-year capital improvement plan integrating operating costs of new facilities</td>
<td>No. 6</td>
</tr>
<tr>
<td>Rapid debt retirement policies (greater than 65% of debt retired in 10 years)</td>
<td>No. 7</td>
</tr>
</tbody>
</table>

8.1.3 INTEGER PROGRAMMING MODEL

The IP modeling method is concerned with optimization problems in which some of the variables are required to take on discrete values. Rather than allow a variable to assume all real values in a given range, only predetermined discrete values within a prescribed range are permitted within the optimization model. In most cases, these values are integers, giving rise to the name of this class of models (Jensen and Bard 2003). Fitch et al.,(2018) presents an IP model that mathematically represents the BMPs from the perspective of municipal credit rating agencies in the U.S.
8.1.4 IP Model for BMPs

The following IP model is presented in Fitch et al. (2018) and includes constraints 1, 2 and 3, which are required to establish that all user demands are met and to account for annual O&M costs dedicated to a portfolio of existing facilities on a concurrent basis with significant upgrades and the construction of new projects.

The integer programming model follows:

\[ X_{ijk} = \begin{cases} 1 & \text{If calendar year } j \text{ is the } k^{th} \text{ year of upgrading or constructing an asset } i \\ 0 & \text{Otherwise} \end{cases} \]  

(8.1)

Where \( c_{ijk} \) equals the cost in year \( k \) for upgrading an existing infrastructure asset or a procuring new facility \( i \) in calendar year \( j \).

Plant \( i \) take on values of A, B, C, D, etc.

For a facility management plan of \( N \) years starting in year 1: \( 1 \leq j \leq N \).

Let \( S \) be the set of variables defined as the following:

\( X_{Aj,1}, \ldots, X_{Aj,k} \) for all \( j \)
\( X_{Bj,1}, \ldots, X_{Bj,k} \) for all \( j \)

For A, B, C, D, etc.

The objective is to minimize the total cost subject to the requirements that all demands be met subject to the capacity of current and future assets contained within the infrastructure portfolio.

\[
\text{Minimize } \sum_{i} \sum_{j} \sum_{k=1}^{K(i)} c_{ijk} \ X_{ijk(i)}
\]  

(8.2)

Where \( K(i) \) equals the number of years to operate and maintain or upgrade existing facilities or construct and add new assets into the infrastructure portfolio; subject to the following constraints:
Constraint No. 1 – All demands must be met over N years.

\[ \sum_{j}^{N} X_{ijk} = d_i \]  
\[ (8.3) \]

Constraint No. 2 – For upgrading and/or constructing infrastructure asset i in n number of years, the nth year follows nth – 1 year etc.

\[ X_{i,j+1,2} \geq X_{i,j+1} ; X_{i,j+2,3} \geq X_{i,j+2} ; X_{i,j+3,4} \geq X_{i,j+3} etc. \]  
\[ (8.4) \]

Constraint No. 3 – For each infrastructure asset i and each calendar year j, j is at most 1 year of operations and maintenance and/or new construction.

\[ X_{i,j,1} + X_{i,j,2} + X_{i,j,3} + X_{i,j,k(i)} \leq 1 \]  
\[ (8.5) \]

Constraint No. 4 – Maintaining a fund balance reserve policy and working capital reserves.

\[ \sum_{i} \sum_{j} \sum_{k=1}^{k(i)} c_{ijk} X_{ijk(i)} \leq U_j + \sum y_j \]  
\[ (8.6) \]

Where \( U_j \) is defined as the upper bound defined by conservatively forecasted revenue less the amount placed into working capital reserves and pay-as-you-go capital funding policies and \( y_j \) is defined as the sum of allowable debt for year \( j \).

Constraint No. 5 – A policy in place regarding nonrecurring revenue.

\[ \sum_{j} (c_{k,j} X_{k,j,1} + c_{k,j,2} X_{k,j,2} + c_{k,j,3} X_{k,j,3}) \leq non\text{-}recurring\text{ revenue} + % U_j + % \sum y_j \]  
\[ (8.7) \]

Constraint No. 6 – Implementation of a five-year capital improvement plan integrating operating costs.

For each year j the \( \sum c_{l,j,k} X_{l,j,k} \leq U_j + \sum y_j \)  
\[ (8.8) \]
Constraint No. 7 – A policy for the rapid retirement of debt with at least 65% of debt retired in the next 10 years.

\[ .65 \sum y_j \geq \sum y_j \text{ in year } j + 10 \quad (8.9) \]

8.1.5 System Dynamics Models

Of relevance to the future research is the work of Rashedi and Hegazy (2015), in which a SD model simulates the “aging chain” of the deterioration and rehabilitation processes as part of an infrastructure management plan. A Markovian process along with a transition probability matrix (TPM) is used to capture the nonlinear progression of infrastructure assets evolving toward worsening states of condition before receiving major rehabilitation or being completely replaced. The SD model is used to preclude budget shortfalls on a concurrent basis with the preservation of existing infrastructure. The TPM is formulated as follows:

\[
TPM = \begin{bmatrix}
    P_{11} & P_{12} & 0 & 0 & 0 \\
    0 & P_{22} & P_{23} & 0 & 0 \\
    0 & 0 & P_{33} & P_{34} & 0 \\
    0 & 0 & 0 & P_{44} & P_{45} \\
    0 & 0 & 0 & 0 & 1
\end{bmatrix} \quad (8.10)
\]

Where \( P_{ii} \) is the probability of an asset in state \( i \) remaining in state \( i \) while \( P_{ij} \) is the probability of the same asset deteriorating to state \( j \) (\( P_{ii} + P_{ij} = 1 \)).

The current research begins to construct the SD model (Figure 8.1) consistent with Rashedi and Hegazy (2015). The stock and flow diagram presented within this research was developed with the computer software iThink 10.1.2® in order to demonstrate how a facility management plan can be developed within a SD model platform.
In the future research the SD model will include a rate of deterioration based on a time constant between states. The time constant will capture the nonlinear progression of infrastructure assets evolving toward worsening states of condition before receiving major rehabilitation or being completely replaced. Figure 8.2 shows an example of 100 assets in state 1 (which could be interpreted as a newly constructed state), wherein the rate of deterioration is exponential for transitions between each successor state. Figure 8.3 shows a reduced rate of deterioration after a rehabilitation process is introduced, which transitions assets from state 3 to the original state 1. In the follow-on research the costs for rehabilitating assets back to earlier states of condition will be constrained by the optimization results from the IP model’s objective function.
8.2 Conclusion and Further Research

The research presented first presented in Fitch et al. (2018) and included this report identifies BMPs that have been determined to improve a government credit rating. An improved credit rating translates into a lowered cost of capital, which in turn makes future projects more feasible. The primary objective of this research is to construct a multi-method model that can be used to manage a portfolio of infrastructure assets while meeting these BMPs. This investigation is a first step to facilitate a more manageable and streamline SD model. This initial step includes the construction of an IP model in which the objective function is to minimize all costs for maintaining a portfolio of assets while meeting all user demands subject to BMPs. Follow-on research will include solving the IP model and optimizing the objective function at the appropriate level of abstraction. The
appropriate level of abstraction will classify infrastructure assets by type and ensure all user demands are met within the framework of the SD model. The objective of this evolving research is to develop a multi-method model to manage a portfolio of assets that can also be used for the valuation of real options “on” project finance structures and “in” the technical design across the portfolio of infrastructure. In doing so, the research presented in this report makes sustainable procurement of infrastructure in terms of economics a more attainable goal for decision-makers, government owners and the civil engineering profession.
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(March 1, 2017)


### APPENDIX I - Initial Nominal Values, Parameters and Equations for P3 Cape Cod Canal Crossing SD Mode Presented in Chapter 6

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Type</th>
<th>Units</th>
<th>Equation (or base case initialization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV debt payments</td>
<td>stock</td>
<td>USD</td>
<td>0 (initial value)</td>
</tr>
<tr>
<td>NPV O&amp;M costs</td>
<td>stock</td>
<td>USD</td>
<td>0 (initial value)</td>
</tr>
<tr>
<td>NPV toll operation costs</td>
<td>stock</td>
<td>USD</td>
<td>0 (initial value)</td>
</tr>
<tr>
<td>NPV toll revenue summer</td>
<td>stock</td>
<td>USD</td>
<td>0 (initial value)</td>
</tr>
<tr>
<td>NPV toll revenue off season</td>
<td>stock</td>
<td>USD</td>
<td>0 (initial value)</td>
</tr>
<tr>
<td>disc debt payments per month</td>
<td>flow</td>
<td>USD per month</td>
<td>principal_and_interest_payments*discount_factor</td>
</tr>
<tr>
<td>disc O&amp;M costs per month</td>
<td>flow</td>
<td>USD per month</td>
<td>O&amp;M_costs*discount_factor</td>
</tr>
<tr>
<td>disc toll operation costs per month</td>
<td>flow</td>
<td>USD per month</td>
<td>toll_operation_costs*discount_factor</td>
</tr>
<tr>
<td>disc toll revenue per month</td>
<td>flow</td>
<td>USD per month</td>
<td>NORMAL(toll_traffic_flow_summer, mean_excursion_summer<em>toll_traffic_flow_summer)<em>vehicle_toll</em>CCB_capacity_factor</em>discount_factor</td>
</tr>
<tr>
<td>disc toll revenue per month off season</td>
<td>flow</td>
<td>USD per month</td>
<td>NORMAL(toll_traffic_flow_off_season, mean_excursion_off_season<em>toll_traffic_flow_off_season)<em>vehicle_toll</em>CCB_capacity_factor</em>discount_factor</td>
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<tr>
<td>construction spend schedule</td>
<td>table function</td>
<td>USD per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>design spend schedule</td>
<td>table function</td>
<td>USD per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>O&amp;M costs</td>
<td>table function</td>
<td>USD per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>toll operation costs</td>
<td>table function</td>
<td>USD per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>toll traffic flow summer</td>
<td>table function</td>
<td>vehicles per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>toll traffic flow off season</td>
<td>table function</td>
<td>vehicles per month</td>
<td>see model file and Appendix</td>
</tr>
<tr>
<td>CCB project NPV</td>
<td>converter</td>
<td>USD</td>
<td>NPV_toll_revenue_summer + NPV_toll_revenue_off_season - NPV_debt_payments - NPV_O&amp;M_costs - NPV_toll_operation_costs</td>
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<td>discount factor</td>
<td>converter</td>
<td>nondim</td>
<td>1/((1+WACC)^(TIME-STARTTIME+DT))</td>
</tr>
<tr>
<td>time step value</td>
<td>converter</td>
<td>month</td>
<td>TIME-STARTTIME+DT</td>
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<td>converter</td>
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<td>mean excursion off season</td>
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<td>converter</td>
<td>USD per vehicle</td>
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<td>Model parameter</td>
<td>Type</td>
<td>Units</td>
<td>Equation (or base case initialization)</td>
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<td>------------------------------</td>
<td>-----------</td>
<td>-------------------</td>
<td>--------------------------------------------------------------</td>
</tr>
<tr>
<td>toll revenue summer</td>
<td>converter</td>
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<td>disc_toll_revenue_per_month_summer/discount_factor</td>
</tr>
<tr>
<td>toll revenue off season</td>
<td>converter</td>
<td>USD per month</td>
<td>disc_toll_revenue_per_month_off_season/discount_factor</td>
</tr>
<tr>
<td>WACC</td>
<td>converter</td>
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<td>0.088/12</td>
</tr>
</tbody>
</table>
APPENDIX II - Initial Nominal Values, Parameters and Equations for Water Treatment
Alternative present in the SD Model Included in Chapter 7

central_wastewater_treatment_capacity(t) = central_wastewater_treatment_capacity(t - dt) +
(flow_from_river_or_other_freshwater_source + trucking_flowback_and_produced_water_to_CWT -
CWT_flow_to_interim_storage - offtake_from_CWT_for_reuse -
treated_water_return_to_river_or_other_surface_water) * dt
INIT central_wastewater_treatment_capacity = 0

INFLOWS:
flow_from_river_or_other_freshwater_source =
IF(central_wastewater_treatment_capacity < CWT_capacity_max) THEN nominal_river_offtake
ELSE 0

trucking_flowback_and_produced_water_to_CWT =
IF(central_wastewater_treatment_capacity < CWT_capacity_max) THEN
fraction_of_FW_to_CWT_flowback & produced_water_storage * time_constant_for_trucking
FPW_to_CWT ELSE 0

OUTFLOWS:
CWT_flow_to_interim_storage =
IF(CWT_interim_storage_capacity < CWT_interim_storage_max) THEN
fraction_of_CWT_offtake_to_interim_storage * central_wastewater_treatment_capacity / time_constant_for_CWT_offtake_to_reuse ELSE 0

offtake_from_CWT_for_reuse =
fraction_of_CWT_offtake_to_reuse * central_wastewater_treatment_capacity / time_constant_for_CWT_offtake_to_reuse

class_II_deep_well_injection_volume(t) = class_II_deep_well_injection_volume(t - dt) +
(trucking_flowback_and_produced_water_to_DWI) * dt
INIT class_II_deep_well_injection_volume = 0

INFLOWS:
trucking_flowback_and_produced_water_to_DWI = IF(class_II_deep_well_injection_volume <=
DWI_volume_limit) THEN
fraction_of_FW_to_DWI * flowback & produced_water_storage * time_constant_for_trucking
FPW_to_DWI ELSE 0

CWT_cumul_cost(t) = CWT_cumul_cost(t - dt) + (CWT_monthly_cost) * dt
INIT CWT_cumul_cost = 0

INFLOWS:
CWT_monthly_cost =
trucking_flowback_and_produced_water_to_CWT * CWT_unit_cost * discount_factor

CWT_interim_storage_capacity(t) = CWT_interim_storage_capacity(t - dt) +
(CWT_flow_to_interim_storage - offtake_from_CWT_interim_storage_for_reuse) * dt
INIT CWT_interim_storage_capacity = 0

INFLOWS:
CWT_flow_to_interim_storage =
IF(CWT_interim_storage_capacity < CWT_interim_storage_max) THEN
fraction_of_CWT_offtake_to_interim_storage * central_wastewater_treatment_capacity / time_constant_for_CWT_offtake_to_reuse ELSE 0

OUTFLOWS:
offtake_from_CWT_interim_storage_for_reuse =
CWT_interim_storage_capacity / time_constant_for_CWT_storage_offtake

drilling_water(t) = drilling_water(t - dt) + (drilling_water_recharge - drilling_water_recycle) * dt
INIT drilling_water = drilling_water_init

INFLOWS:

drilling_water_recharge =
(drilling_water_draw_fraction * wellhead_freshwater_and_reuse_reserve / drilling_water_recharge
 * time_constant

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OUTFLows:

- \( \text{drilling\_water\_recycle} = \text{IF(FFW\_storage\_max - flowback\&_produced\_water\_storage)\leq 0.05 \text{ THEN 0 ELSE}} \)
  \( \text{drilling\_water\_recycle\_fraction} \times \text{drilling\_water\_drilling\_water\_recycle\_time\_constant} \)

- \( \text{DVI\_cumul\_cost(t)} = \text{DVI\_cumul\_cost(t - dt)} + (\text{DVI\_monthly\_cost}) \times dt \)

INIT DVI\_cumul\_cost = 0

INFLOWS:

- \( \text{DVI\_monthly\_cost} = \text{flowback\&\_produced\_water\_to\_DVI\_DVI\_unit\_cost\_discount\_factor} \)

- \( \text{flowback\&\_produced\_water\_storage(t)} = \text{flowback\&\_produced\_water\_storage(t - dt)} + \text{flowback\_produced\_water\_flow} \times \text{trucking\_flowback\_and\_produced\_water\_to\_CWT} \times \text{wastewater\_flow\_to\_MSF} \times \text{wastewater\_flow\_to\_MED} \times \text{wastewater\_flow\_to\_RO} \times dt \)

INIT flowback\&\_produced\_water\_storage = 0

INFLOWS:

- \( \text{flowback} = \text{IF(FFW\_storage\_max - flowback\&\_produced\_water\_storage)\leq 0.05 \text{ THEN 0 ELSE flowback\_recovery\_fraction} \times \text{DELAY(FFW\_water\_flowback\_time\_constant, 0.5)}} \)

- \( \text{produced\_water\_flow} = \text{IF(FFW\_storage\_max - flowback\&\_produced\_water\_storage)\leq 0.05 \text{ THEN 0 ELSE produced\_water\_per\_unit\_water\_produced} \)

- \( \text{drilling\_water\_recycle} = \text{IF(FFW\_storage\_max - flowback\&\_produced\_water\_storage)\leq 0.05 \text{ THEN 0 ELSE}} \)
  \( \text{drilling\_water\_recycle\_fraction} \times \text{drilling\_water\_drilling\_water\_recycle\_time\_constant} \)

OUTFLows:

- \( \text{trucking\_flowback\_and\_produced\_water\_to\_DVI} = \text{IF(class\_IL\_deep\_well\_injection\_volume \leq DVI\_volume\_limit) \text{ THEN}} \)
  \( \text{fraction\_of\_FFW\_to\_DVI\_flowback\&\_produced\_water\_storage\_time\_constant\_for\_trucking\_FFW\_to\_DVI} \times 0 \)

- \( \text{trucking\_flowback\_and\_produced\_water\_to\_CWT} = \text{IF(central\_wastewater\_treatment\_capacity\_CWT\_capacity\_max) \text{ THEN}} \)
  \( \text{fraction\_of\_FFW\_to\_CWT\_flowback\&\_produced\_water\_storage\_time\_constant\_for\_trucking\_FFW\_to\_CWT} \times 0 \)

- \( \text{wastewater\_flow\_to\_MSF} = \text{IF(((MED\_off\_MED\_capacity\_max - onsite\_wastewater\_treatment\_MED) \leq 0.01) OR (onsite\_wastewater\_treatment\_MED \geq (MED\_off\_MED\_capacity\_max + 0.01))) AND ((RO\_off\_RO\_capacity\_max - onsite\_wastewater\_treatment\_RO) \leq 0.05) OR (onsite\_wastewater\_treatment\_RO \geq (RO\_off\_RO\_capacity\_max + 0.01))) \text{ THEN IF((MSF\_off\_MSF\_capacity\_max - onsite\_wastewater\_treatment\_MSF) \leq 0.01) OR (onsite\_wastewater\_treatment\_MSF \geq (MSF\_off\_MSF\_capacity\_max + 0.01))) \text{ THEN 0 ELSE}} \)
  \( \text{flowback\&\_produced\_water\_storage - RO\_off\_RO\_capacity\_max} \times MED\_off\_MED\_capacity\_max\_time\_constant\_for\_FFW\_to\_onsite\_treatment} \)

- \( \text{wastewater\_flow\_to\_MED} = \text{IF((RO\_off\_RO\_capacity\_max - onsite\_wastewater\_treatment\_RO)\leq 0.01) OR (onsite\_wastewater\_treatment\_RO \geq (RO\_off\_RO\_capacity\_max + 0.01))) \text{ THEN IF((MED\_off\_MED\_capacity\_max - onsite\_wastewater\_treatment\_MED) \leq 0.01) OR (onsite\_wastewater\_treatment\_MED \geq (MED\_off\_MED\_capacity\_max + 0.01))) \text{ THEN 0 ELSE}} \)
  \( \text{flowback\&\_produced\_water\_storage - RO\_off\_RO\_capacity\_max\_time\_constant\_for\_FFW\_to\_onsite\_treatment} \)

- \( \text{wastewater\_flow\_to\_RO} = \text{IF((RO\_off\_RO\_capacity\_max - onsite\_wastewater\_treatment\_RO)\leq 0.01) OR (onsite\_wastewater\_treatment\_RO \geq (RO\_off\_RO\_capacity\_max + 0.01))) \text{ THEN 0 ELSE}} \)
  \( \text{flowback\&\_produced\_water\_storage - wastewater\_flow\_to\_MSF\_time\_constant\_for\_FFW\_to\_onsite\_treatment} \)

INFLOWS:

- \( \text{freshwater\_reservoir}(t) = \text{freshwater\_reservoir}(t - dt) + (\text{freshwater\_recharge - pipeline\_freshwater\_flow\_to\_wellhead\_trucking\_freshwater\_flow\_to\_wellhead}) \times dt \)

INIT freshwater\_reservoir = freshwater\_reservoir\_init

INFLOWS:

- \( \text{freshwater\_recharge} = \text{IF(freshwater\_surplus > 0) THEN}} \)
  \( \text{freshwater\_reservoir\_time\_constant\_for\_freshwater\_recharge} \times 0 \)
OUTFLOWS:
- pipeline_freshwater_flow_to_wellhead = (1-fraction_of_transfer_by_truck)*freshwater_demand
- trucking_freshwater_flow_to_wellhead = IF(trucking_fleet_max_capacity-fraction_of_transfer_by_truck)*freshwater_demand THEN fraction_of_transfer_by_truck*freshwater_demand ELSE 0

\[ HF_{water}(t) = HF_{water}(t-\Delta t) + (-flowback - unrecovered_{HF_{flow}}) \times \Delta t \]
INIT HF_{water} = HF_{water}_{init}

OUTFLOWS:
- flowback = IF((FPW_storage_max - flowback & _produced__water_storage) < 0.05) THEN 0 ELSE (flowback_recovery_fraction*DELAY(HF_{water}_{flowback_time_constant}, 0.5)
- unrecovered_{HF_{flow}} = (1-flowback_recovery_fraction)*HF_{water}_{unrecovered_{HF_{flow_time_constant}}}

\[ MED_{wastewater_{treatment_{cumul_cost}}}(t) = MED_{wastewater_{treatment_{cumul_cost}}}(t-\Delta t) + (MED\_monthly\_cost) \times \Delta t \]
INIT MED_{wastewater_{treatment_{cumul_cost}}} = 0

INFLOWS:
- MED_{monthly\_cost} = IF(MED_{on\_off} = 1) THEN 0 ELSE MED_{water_{flow_to_MED_{treatment_{unit_cost}}}}*discount\_factor

\[ MSF_{wastewater_{treatment_{cumul_cost}}}(t) = MSF_{wastewater_{treatment_{cumul_cost}}}(t-\Delta t) + (MSF\_monthly\_cost) \times \Delta t \]
INIT MSF_{wastewater_{treatment_{cumul_cost}}} = 0

INFLOWS:
- MSF_{monthly\_cost} = IF(MSF_{on\_off} = 1) THEN 0 ELSE MSF_{water_{flow_to_MSF_{treatment_{unit_cost}}}}*discount\_factor

\[ onsite_{wastewater_{treatment_{MED}}}(t) = onsite_{wastewater_{treatment_{MED}}}(t-\Delta t) + (wastewater_{flow_to_MED} - MED\_treated_{wastewater_{return_{for_resuse}}}) \times \Delta t \]
INIT onsite_{wastewater_{treatment_{MED}}} = 0

INFLOWS:
- wastewater_{flow_to_MED} = IF(((RO_{off} * RO_{capacity_{max}} - onsite_{wastewater_{treatment_{RO}}}) < 0.01) OR ( onsite_{wastewater_{treatment_{RO}}}= (RO_{off} * RO_{capacity_{max}} + 0.01)) THEN IF( ((MED_{off} * MED_{capacity_{max}} - onsite_{wastewater_{treatment_{MED}}}) < 0.01) OR ( onsite_{wastewater_{treatment_{MED}}}= (MED_{off} * MED_{capacity_{max}} + 0.01)) THEN 0 ELSE (flowback & _produced__water_storage - RO_{off} * RO_{capacity_{max}}/time_constant_for_FPW_to_onsite_{treatment} ELSE 0

OUTFLOWS:
- MED\_treated_wastewater_{return_{for_resuse}} = onsite_{wastewater_{treatment_{MED}}}/MED_{wastewater_{time_constant}}

\[ onsite_{wastewater_{treatment_{MSF}}}(t) = onsite_{wastewater_{treatment_{MSF}}}(t-\Delta t) + (wastewater_{flow_to_MSF} - MSF\_treated_{wastewater_{return_{for_resuse}}}) \times \Delta t \]
INIT onsite_{wastewater_{treatment_{MSF}}} = 0

INFLOWS:
- wastewater_{flow_to_MSF} = IF(((MED_{off} * MED_{capacity_{max}} - onsite_{wastewater_{treatment_{MED}}}) < 0.01) OR ( onsite_{wastewater_{treatment_{MED}}}= (MED_{off} * MED_{capacity_{max}} + 0.01)) AND ((RO_{off} * RO_{capacity_{max}} - onsite_{wastewater_{treatment_{RO}}}) < 0.05) OR ( onsite_{wastewater_{treatment_{RO}}}= (RO_{off} * RO_{capacity_{max}} + 0.01)) THEN IF( ((MSF_{off} * MSF_{capacity_{max}} - onsite_{wastewater_{treatment_{MSF}}}) < 0.01) OR ( onsite_{wastewater_{treatment_{MSF}}}= (MSF_{off} * MSF_{capacity_{max}} + 0.01)) THEN 0 ELSE (flowback & _produced__water_storage - RO_{off} * RO_{capacity_{max}}/MED_{off} * MED_{capacity_{max}}/ time_constant_for_FPW_to_onsite_{treatment} ELSE 0

OUTFLOWS:
- MSF\_treated_wastewater_{return_{for_resuse}} = onsite_{wastewater_{treatment_{MSF}}}/MSF_{wastewater_{time_constant}}
onsite_wastewater_treatment_RO(t) = onsite_wastewater_treatment_RO(t - dt) +
(wastewater_flow_to_RO - RO_treated_wastewater_return_for_resuse) * dt
INIT onsite_wastewater_treatment_RO = 0
INFLOWS:
  → wastewater_flow_to_RO = IF(RO_off*RO_capacity_max - onsite_wastewater_treatment_RO
  <= 0.01) OR ( onsite_wastewater_treatment_RO >= (RO_off*RO_capacity_max + 0.01) ) THEN 0
  ELSE(flowback & _produced_water_storage - wastewater_flow_to_MED -
  wastewater_flow_to_MSF) / time_constant_for_FPW_to_onsite_treatment

OUTFLOWS:
  → RO_treated_wastewater_return_for_resuse =
  onsite_wastewater_treatment_RO / RO_wastewater_time_constant

RO_wastewater_treatment_cumul_cost(t) = RO_wastewater_treatment_cumul_cost(t - dt) +
(RO_monthly_cost) * dt
INIT RO_wastewater_treatment_cumul_cost = 0
INFLOWS:
  → RO_monthly_cost = IF(RO_on_off = 1) THEN 0 ELSE
  wastewater_flow_to_RO / RO_treatment_unit_cost * discount_factor

shale_gas_cumul_production(t) = shale_gas_cumul_production(t - dt) + (shale_gas_production) * dt
INIT shale_gas_cumul_production = 0
INFLOWS:
  → shale_gas_production = IF( (FPW_storage_max - flowback & _produced_water_storage)<=
  0.05) THEN 0 ELSE DELAY(shale_gas_well_reservoir/shale_gas_production_time_constant
  0.5)

shale_gas_cumul_wellhead_revenue(t) = shale_gas_cumul_wellhead_revenue(t - dt) +
(shale_gas_wellhead_revenue_generation) * dt
INIT shale_gas_cumul_wellhead_revenue = 0
INFLOWS:
  → shale_gas_wellhead_revenue_generation =
  shale_gas_production * shale_gas_wellhead_price * discount_factor

shale_gas_production_cumul_cost(t) = shale_gas_production_cumul_cost(t - dt) +
(shale_gas_monthly_production_cost) * dt
INIT shale_gas_production_cumul_cost = 0
INFLOWS:
  → shale_gas_monthly_production_cost =
  shale_gas_production / shale_gas_production_unit_cost * discount_factor

shale_gas_well_reservoir(t) = shale_gas_well_reservoir(t - dt) + (shale_gas_reservoir_rampup -
shale_gas_production) * dt
INIT shale_gas_well_reservoir = 0
INFLOWS:
  → shale_gas_reservoir_rampup = STEP(shale_gas_volume_init, 0) -
  STEP(shale_gas_volume_init, 0.5)
OUTFLOWS:
  → shale_gas_production = IF( (FPW_storage_max - flowback & _produced_water_storage)<=
  0.05) THEN 0 ELSE DELAY(shale_gas_well_reservoir/shale_gas_production_time_constant
  0.5)

wellhead_freshwater_and_reuse_reserve(t) = wellhead_freshwater_and_reuse_reserve(t - dt) +
(pipeline_freshwater_flow_to_wellhead + trucking_freshwater_flow_to_wellhead +
offtake_from_CVT_for_reuse + offtake_from_CVT_interim_storage_for_reuse +
MED_treated_wastewater_return_for_resuse + RO_treated_wastewater_return_for_resuse +
MSF_treated_wastewater_return_for_resuse - drilling_water_recharge -
freshwater_and_reuse_draw_for_HF) * dt
INIT wellhead_freshwater_and_reuse_reserve = 0
INFLows:
- pipeline_freshwater_flow_to_wellhead = (1-fraction_of_transfer_by_truck)*freshwater_demand
- trucking_freshwater_flow_to_wellhead = 
  IF(trucking_fleet_max_capacity > fraction_of_transfer_by_truck * freshwater_demand) THEN 
  fraction_of_transfer_by_truck * freshwater_demand ELSE 0
- offset_from_CWT_for_reuse = 
  fraction_of_CWT_offset_to_reuse * central_wastewater_treatment_capacity / time_constant_for_CWT_offset_to_reuse
- offset_from_CWT_interim_storage_for_reuse = 
  CWT_interim_storage_capacity / time_constant_for_CWT_storage_offset
- MED_treated_wastewater_return_for_reuse = 
  onsite_wastewater_treatment_MED / MED_wastewater_time_constant
- RO_treated_wastewater_return_for_reuse = 
  onsite_wastewater_treatment_RO / RO_wastewater_time_constant
- MSF_treated_wastewater_return_for_reuse = 
  onsite_wastewater_treatment MSF / MSF_wastewater_time_constant

OUTflows:
- drilling_water_recharge = 
  drilling_water_draw_fraction * wellhead_freshwater_and_reuse_reserve / drilling_water_recharge_time_constant
- freshwater_and_reuse_draw_for_HF = HF_water_time_constant / for_HF_draw

- annualized_WACC = 0.038
- capacity_per_truck = 19000
- CWT_capacity_max = 6000000
- CWT_interim_storage_max = 10000000
- CWT_unit_cost = 0.024
- discount_factor = 1 / ((1 - WACC) * (TIME * STARTTIME + DT))
- drilling_water_draw_fraction = 0.03
- drilling_water_init = 300000
- drilling_water_recharge_time_constant = 24
- drilling_water_recycle_fraction = 0.8
- drilling_water_recycle_time_constant = 2
- DWI_unit_cost = 0.01
- DWI_volume_limit = 1000000
- flowback_recovery_fraction = 0.12
- flowback_time_constant = 3
- FPW_storage_max = FPW_storage_max_INIT - RO_on_off * RO_capacity_max
- FPW_storage_max_INIT = 600000
- fraction_of_CWT_offset_to_interim_storage = 0.3
- fraction_of_CWT_offset_to_reuse = 1 - fraction_of_CWT_offset_to_interim_storage
- fraction_of_CWT_returned_to_river = 0.6
- fraction_of_FPW_to_CWT = 0
- fraction_of_FPW_to_DWI = total_fraction_of_FPW_to_CWT_or_DWI - fraction_of_FPW_to_CWT
- fraction_of_FPW_to_MED = MED_split * (1 - total_fraction_of_FPW_to_CWT_or_DWI - fraction_of_FPW_to_RO)
- fraction_of_FPW_to_MSF = (1 - MED_split) * MED_split * fraction_of_FPW_to_MED
- fraction_of_FPW_to_RO = UNIFORM(R0min, 1 - total_fraction_of_FPW_to_CWT_or_DWI)
- fraction_of_transfer_by_truck = 0.2
- freshwater_demand = freshwater_and_reuse_draw_for_HF + drilling_water_recharge
○ freshwater_level_lower_limit = 1000000000
○ freshwater_reservoir_init = 500000000
○ freshwater_surplus = freshwater_reservoir - freshwater_level_lower_limit
○ HF_water_init = 100000000
○ MED_capacity_max = 2000000
○ MED_off = IF(MED_on_off = 1) THEN 0 ELSE 1
○ MED_on_off = 0
○ MED_split = 0.5
○ MED_treatment_unit_cost = 0.034
○ MED_wastewater_time_constant = treated_wastewater_time_constant
○ MSF_capacity_max = 150000
○ MSF_off = IF(MSF_on_off = 1) THEN 0 ELSE 1
○ MSF_on_off = 1
○ MSF_treatment_unit_cost = 0.041
○ MSF_wastewater_time_constant = treated_wastewater_time_constant
○ nominal_river_offtake = 500000
○ NPV_net_revenue_for_shale_gas_production = shale_gas_cumu_consumption - RO_wastewater_treatment_cumul_cost - MED_wastewater_treatment_cumul_cost - MSF_wastewater_treatment_cumul_cost - shale_gas_production_cumul_cost
○ number_of_trucks = 150
○ produced_water_per_unit_gas_produced = 20/1000
○ R0_min = 0.9
○ R0_capacity_max = 150000
○ R0_off = IF(R0_on_off = 1) THEN 0 ELSE 1
○ R0_on_off = 0
○ R0_treatment_unit_cost = 0.03
○ R0_wastewater_time_constant = treated_wastewater_time_constant
○ shale_gas_production_time_constant = 3.5
○ shale_gas_production_unit_cost = 0.021
○ shale_gas_volume_init = 400000000
○ shale_gas_wellhead_price = 0.14
○ time_constant_for_CWT_offtake_to_reuse = 4
○ time_constant_for_CWT_storage_offset = 3
○ time_constant_for_FPW_to_onsite_treatment = 1.0
○ time_constant_for_freshwater_recharge = 12
○ time_constant_for_HF_draw = 0.5
○ time_constant_for_treated_water_return_to_river = 4
○ time_constant_for_trucking_FPW_to_CWT = 1
○ time_constant_for_trucking_FPW_to_DWI = 2
○ total_fraction_of_FPW_to_CWT_or_DWI = 0.9
○ treated_wastewater_time_constant = 1.5
○ trucking_fleet_max_capacity = number_of_trucks*capacity_per_truck*truck_roundtrips_per_month
○ truck_roundtrips_per_month = 15
○ unrecovered_HF_flow_time_constant = 2
○ WACC = annualized_WACC/12
○ wastewater_onsite_treatment_cumul_cost = RO_wastewater_treatment_cumul_cost+MED_wastewater_treatment_cumul_cost+MSF_wastewater_treatment_cumul_cost