Improved Methods for Managing Megaprojects

by

Paolo Minelli

B.S., Energy Engineering, Politecnico di Milano (2012)
M.S., Nuclear Engineering, KTH Royal Institute of Technology
and ENSTA ParisTech (2014)

Submitted to the Department of Nuclear Science and Engineering
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY IN NUCLEAR SCIENCE AND ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2020

Author . . . .
Paolo Minelli
Department of Nuclear Science and Engineering
October 11, 2019

Certified by . . . .
Michael W. Golay, Ph.D.
Professor of Nuclear Science and Engineering
Thesis Supervisor

Certified by . . . .
Jacopo Buongiorno, Ph.D.
TEPCO Professor of Nuclear Science and Engineering and
Director of the Center for Advanced Nuclear Energy Systems (CANES)
Director of Science and Technology of the Nuclear Reactor Laboratory at MIT
Thesis Reader

Certified by . . . .
James M. Lyneis, Ph.D.
Visiting Senior Lecturer at MIT
Thesis Reader

Accepted by . . . .
Ju Li, Ph.D.
Battelle Energy Alliance Professor of Nuclear Science and Engineering and
Professor of Materials Science and Engineering
Chairman, Department Committee on Graduate Theses

Improved Methods for Managing Megaprojects

by

Paolo Minelli

Submitted to the Department of Nuclear Science and Engineering
on October 11, 2019, in partial fulfillment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY IN NUCLEAR SCIENCE AND ENGINEERING

Abstract

Nuclear power is in danger of fading away as a significant source of energy supply in some parts of the world unless it becomes more competitive. The cost of nuclear energy largely depends on capital cost because nuclear power plants are very expensive to design and build and relatively cheap to operate. The capital cost of nuclear power plants is literally dominated by factors other than those of physical equipment, such as project preparation, site preparation, engineering, planning, installation, and management. Interestingly, project planning, monitoring, execution and management is where too often the nuclear industry has failed in the past. As of 2014, the average time and cost overrun for nuclear projects worldwide are 64% and 117.3%, respectively. There is evidence showing that there is something that we fundamentally do not understand (or represent) in project planning and management.

This work is based on the premise that nuclear projects are megaprojects. As such, they are complex systems that are (1) constantly changing, (2) tightly coupled, (3) governed by feedback, (4) non-linear, (5) history-dependent, (6) self-organizing, (7) adaptive, (8) characterized by trade-offs, (9) counter intuitive, (10) policy resistant. Hence, traditional project management methods alone are insufficient. An alternative approach to reduce cost and uncertainties of nuclear projects is to turn them into more standard projects, in terms of scope, complexity and capital at risk. For example, the nuclear industry is pursuing the development of micro-reactors, a type of plug-and-play nuclear batteries that would be two orders of magnitude smaller in physical size, wholly manufactured and fueled in a factory, and transported to the site within standard-size freight containers, requiring minimal site excavation and preparation.

This work develops an improved framework for managing megaprojects, estimating their value, and making project/design decisions involving numerous stakeholders, multiple competing objectives, and substantial uncertainty. The framework is built on two pillars: a System Dynamics (SD) model and a probabilistic Discounted Cash Flow (DCF) model. The former focuses on design and construction, while the latter focuses on operations. These two models are consistent with each other and they are run sequentially.

To demonstrate its feasibility and appreciate its benefits, the SD-DCF approach is applied to a real-world case study, e.g. an ongoing project in North America based on a marine nuclear power plant entirely built in a shipyard and towed to the site upon completion. A multi-objective decision making problem is framed to illustrate the importance of a solid decision management process in megaprojects. 270 different projects are derived from the combination of six high-level design/project choices: plant's capacity, deployment concept, flexibility, overlap between design and construction, level of effort spent on FEED, size and availability of management team. The projects are simulated using the SD and DCF models, represented on trade spaces and finally evaluated against success objectives to derive general policy insights.

This framework represents a synthesis of management methods that was not practically available before. This work documents the development of the models, it shows why they should be used, it applies them to an actual case study hence providing a real-world application, and it makes the method credible, publicly available and convenient to adopt.

Thesis Supervisor: Michael W. Golay, Ph.D.
Title: Professor of Nuclear Science and Engineering

Thesis Reader: Jacopo Buongiorno, Ph.D.
Title: TEPCO Professor of Nuclear Science and Engineering and
Director of the Center for Advanced Nuclear Energy Systems (CANES)
Director of Science and Technology of the Nuclear Reactor Laboratory at MIT

Thesis Reader: James M. Lyneis, Ph.D.
Title: Visiting Senior Lecturer at MIT

Acknowledgments

I am sincerely grateful to my supervisor Professor Michael Golay, who has provided me with technical and moral support during my Ph.D. studies. He has always given me complete freedom in my research, which was both challenging and incredibly valuable. He once told me something I will always keep in mind: “Don’t be too logical about the future”.

I would like to thank the rest of my thesis committee - Professor Jacopo Buongiorno and Professor Neil Todreas - for giving me the opportunity to work in their group in the first place and for their precious feedback in these years. Thank you also to Professor Matteo Bucci for chairing my Ph.D. defense. This work would have been impossible without their support.

Special thanks to Dr. James Lyneis for being an excellent technical advisor and a fantastic mentor. His input along the journey has been especially insightful. His kindness, humility, sense of duty and the passion for his work will inspire me forever.

Many thanks to Dr. Mathias Trojer for giving me the opportunity to work on the offshore small nuclear power plant design. Many thanks for the feedback, for all the coffee breaks and the long hours spent discussing the future of the project.

Thank you to the NSE faculty for being a source of inspiration and support. I am also indebted to Brandy Baker, Heather Barry, Carolyn Carrington, Peter Brenton, and the rest of the NSE staff for making every administrative aspect of my life here smooth and simple.

I would like to acknowledge *all* the good friends I met along the way. Very special thanks to Riccardo, Andrea, Gianpaolo, Stefania, Gherardo, Bartolomeo, Martina, Sara, Simone, Lorenzo and the rest of MITaly. I am grateful to my NSE colleagues, especially Shikhar, Pablo(s), Patrick, Enrique, Dan, Stephen, Guillaume, Abdulla and Sam. Many thanks to Juan, Rami, Giulia, Giancarlo, Javi and Anita for their support during the first years. Many thanks to my current and past housemates: Albano, Ana, Charlene, Pauline, Francesco, Elina, Marthe, Maddie, Fleur, Jamie, James, Colin, Kevin, Anwoy and Jie. Many thanks to Aristeidis, Enrique, Ferran, Alex, Manon and the rest of the legendary HSA basketball team for the many battles we fought on the court and the five titles we won together. Many thanks to the members of the MIT Global Startup Workshop for the great work we did together and the terrific trips to Chile and Thailand. Looking back, I have got a lot of amazing memories.

I am thankful to my family for their continuous and unparalleled love, help and support. Special thanks to my parents Tiziana and Marco for their words in *those* key moments. Many thanks to

my brothers Luca and Giorgio, my sisters-in-law Medina and Federica, and my nephews Matilde, Elia, Filippo and Niccolò (only one in four was there when I started!).

Finally, my sincere gratitude goes to Benedetta for being there when I needed her the most: I feel privileged. This is only the beginning!

“[...] E ora che ne sarà
del *mio* viaggio?
Troppo accuratamente l’ho studiato
senza saperne nulla. Un imprevisto
è la sola speranza. Ma mi dicono
ch’è una stoltezza dirselo.”

Eugenio Montale (“Prima del Viaggio”)

To my parents.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Research motivation

The recent construction performance on reactor projects in Europe and the United States has reduced confidence in the industry and cast doubt about the ability of nuclear energy to contribute further to achieve decarbonization. The widespread loss of faith in nuclear power is unfortunate as the technology has long proven itself to be safe, reliable and one of the fastest and most effective options for decarbonising electricity supply [1].

After the 1973 oil crisis and the subsequent nuclear golden age, the nuclear industry started to suffer some stagnation - a condition that lasts until today. According to the MIT study *The Future of Nuclear Energy in a Carbon-Constrained World* the main problem of nuclear energy is cost [2]. From the first wave of nuclear reactors constructed back in the late 1960s and 1970s to the most recent projects in Finland, France and the United States, huge delays and cost overruns have slowed down the deployment of nuclear power and damaged its reputation. Other generation technologies have become cheaper in recent decades, while new nuclear plants have only become costlier. Nuclear power competitiveness heavily depends on its capital cost because nuclear power plants are relatively inexpensive to operate but extremely expensive to build. Thus reducing costs and project times is crucial. According to the same MIT study, at least three things need to happen: access to cheap financing should be facilitated, regulatory barriers should be lowered, and industry should improve its performance. As nuclear engineers, improving industry performance is the factor we can control the most. The MIT report suggests that this can be achieved by:

1. Focusing on using proven project/construction management practices to increase the proba-

bility of success in the execution and delivery of new nuclear power plants.

2. Shifting away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants [2].

Project planning, monitoring, execution and management is where too often the nuclear industry has failed in the past. Rather than developing improved reactor designs, this work provides a framework to increase the success probability of nuclear projects delivery (addressing point 1). The case study is an actual, ongoing project in North America. The project is based on a marine nuclear power plant entirely built in a shipyard and towed to the site upon completion (addressing point 2).

1.2 Historical overview of nuclear projects performance

1.2.1 Brief history of nuclear power

Nuclear plants use the energy released by the fission of certain elements to generate nuclear power. In a typical plant the exothermic fission reaction is used to heat up the working fluid of a Rankine cycle (i.e. water), produce steam, and drive the turbines that generate electricity.

Fission was discovered at the end of 1938 and theoretically explained in 1939. During World War II the field of nuclear energy developed and research focused on producing bombs [3]. In the 1950s, after years of war and the traumatic bombing of Hiroshima and Nagasaki, the attention turned to commercial power generation as a peaceful application of the new promising technology. In this first stage of the “atomic era” nuclear power was promoted as the epitome of progress and modernity. There was a widespread sense of nuclear optimism and the idea that everything would use a nuclear power source of some sort in a positive way started to emerge. All sorts of applications were advanced: nuclear medicine, food irradiation, water desalination, deep space exploration, nuclear houses, nuclear powered artificial hearts, plutonium heated swimming pools for SCUBA divers and much more [4], [5]. It seemed that all of this was just a few years of work away. In 1946 Congress created the Atomic Energy Commission (AEC) “to foster and control the peacetime development of atomic science and technology” [6]. The Experimental Breeder Reactor 1 was built in Idaho shortly after. It generated the first electricity from nuclear energy on December 20, 1951 [7]. In 1953 President Eisenhower launched the “Atoms for Peace” program, which reoriented significant research effort towards electricity generation and set the course for civil nuclear energy development in the USA [8]. The first commercial electricity-generating plant powered by nuclear energy was located in Shippingport, Pennsylvania (Figure 1-1). It was a Light Water Reactor (LWR) and it reached its full design power in 1957. The nuclear power industry grew rapidly in the 1960s. Everything foreshadowed that the future would be atomic.

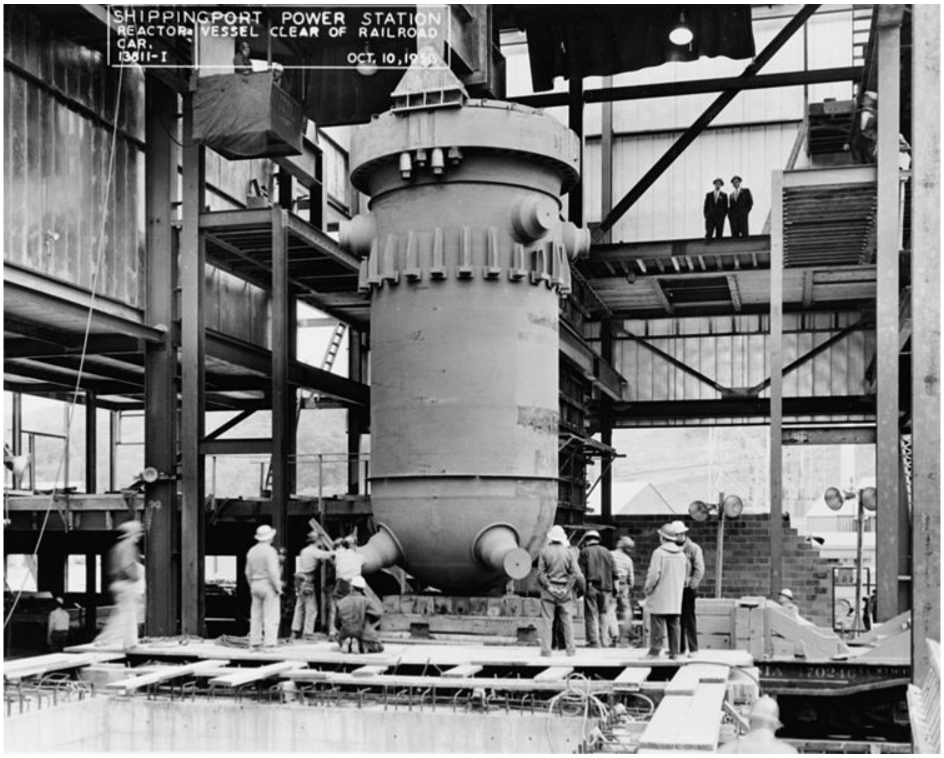


Figure 1-1: Shippingport reactor vessel clear of railroad car, Ohio River, 25 miles Northwest of Pittsburgh, October 10, 1956 [9].

Nuclear power turned out to be very complicated and expensive to translate from physics on paper to reality. The reasons behind this include:

- *Complexity of engineering problems.* Nuclear power plants are inherently difficult to build. When most units were built, the technology was relatively new and many technical problems were fundamentally ignored until construction. As for the most recent units, the loss of construction know-how and the need to re-build a reliable, competent nuclear supply chain after years of stagnation has been also identified as a major problem.

- *Uniqueness of designs.* Each reactor is built in a unique combination of natural, political, regulatory environment. This makes standardization hard to achieve even when the reactor technology is the same.

- *Strict regulatory framework* built to protect the people and the environment from the harmful effects of radiation;
- *Antinuclear movement.* Until the mid 1960s, the opposition to nuclear power was relatively limited. As opposition increased, the number of stakeholders involved (and their interests) grew significantly. In the United States, the movement was at its strongest in the early 1970s when many nuclear projects were being launched or were under construction, matched in strength by protests of the Vietnam War, from which the antinuclear movement drew many of its tactics and participants [10].

In addition, it soon became clear that complex and capital intensive nuclear projects were very risky investments. For example, the discount rate in the United States increased exponentially from the 1950s to the beginning of the 1980s (Figure 1-2). Being one of the major factors determining the economic viability of nuclear power plants (see Section 4.4.10), the discount rate played an important role in the cost escalation of the first units[1].

Despite all these challenges, the promise of clean, reliable and high-density energy (and sometimes the intent of developing nuclear weapon programs) motivated some countries to keep investing in nuclear. In 1973 the members of the Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo, which was targeted at nations perceived as supporting Israel during the Yom Kippur War [12]. The "oil crisis" caused the oil prices to skyrocket worldwide. The prospect of being independent from oil and gas imports revived the interest in nuclear power. Governments and private companies began to invest at an impressive rate in many parts of the world. Indeed most reactors we have today were built between 1970 and 1985, the nuclear golden years.

This situation did not last long and just a few years after the oil crisis the nuclear industry started to suffer some stagnation. In the late 1970s electricity demand decreased and concerns grew over the controversial points of nuclear, such as reactor safety, waste disposal, and other environmental considerations, especially after the Three Mile Island accident in 1979 [7]. The Chernobyl (1986) and Fukushima (2011) disasters highlighted additional flaws in the way power

---

[1] Depending on the context, the term "discount rate" might refer to either the interest rate that the Federal Reserve Bank charges banks and other financial institutions for short-term loans, or the interest rate used in DCF analysis to determine the present value of future cash flows. The cost of capital is a combination of the cost of debt (which is a function of the interest rate shown in Figure 1-2) and the cost of equity weighted by the mix (see Section 4.4.10). Figure 1-2 is just meant to reflect the increasing cost of capital in the U.S. and the data shown are considered a sufficient argument as the cost of equity would also follow a similar pattern.

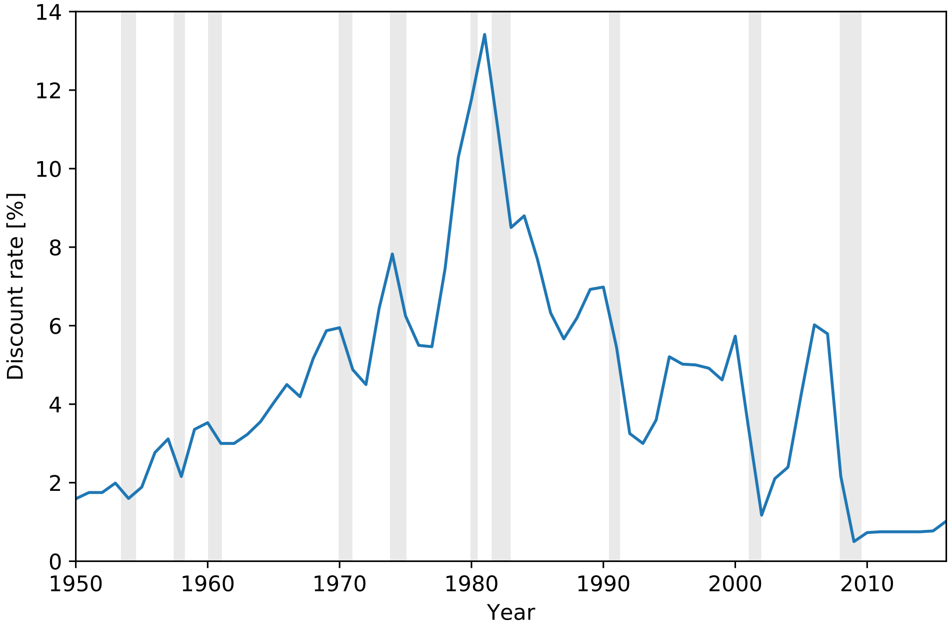


Figure 1-2: Annual average discount rates for the United States from 1950 to 2016. Shaded areas indicate United States recessions (adapted from the Federal Reserve Economic Data (FRED) [11]).

plants were designed and operated. These events had an enormous psychological impact on the society, and the resulting polarization of the public opinion explains why nuclear-related decisions are often so politicized. In response to these accidents, nuclear regulators worldwide became much more cautious to trust other parties to do things correctly. The regulators' unwillingness to risk their reputations resulted mainly in time escalations. On the one hand the safety performance of reactors improved, on the other hand nuclear costs escalated significantly, especially for the reactors that were under construction at the time of an accident.

In the new century several factors combined to revive the prospects for nuclear power. First was the realisation of the scale of projected increased electricity demand worldwide, but particularly in rapidly-developing countries. Secondly was the awareness of the importance of energy security. Thirdly was the need to limit carbon emissions due to concerns about climate change [8]. However, the so called "nuclear renaissance" stalled following the financial crisis of 2007-2008 and the Fukushima events of 2011 posed an end to it (at least temporarily, at least in the Western democracies).

1.2.2 Nuclear power today

Currently 449 nuclear power plants distributed over 30 countries provide 397,650 MW_e of total net installed capacity. This corresponds to about 11% of the World's electricity and a meager 5% of the global primary energy production [13], [2].

In 2017 thirteen countries produced at least one-quarter of their electricity from nuclear. France got 71.2% of its electricity from nuclear energy; Hungary, Ukraine and Slovakia get more than half from nuclear; Sweden, Belgium, Switzerland, Slovenia, Bulgaria, Czech Republic, Finland get one-third or more. The United States gets 19.3% of its electricity from 97 nuclear units (and two are under construction). Japan is used to relying on nuclear power for more than one-quarter of its electricity and may return to somewhere near that level [3].

Since most units were built in the 1970s-80s the current average age of a power plant is about 30 years (Figure 1-3). These plants were originally designed to operate for 40 years. This means that today many countries are faced with a choice: extending the operational licenses for the ageing reactors (upon satisfaction of the safety requirements), replacing them, or moving away from nuclear power towards other technologies such as fossil fuels, renewables, hydro and biomass.

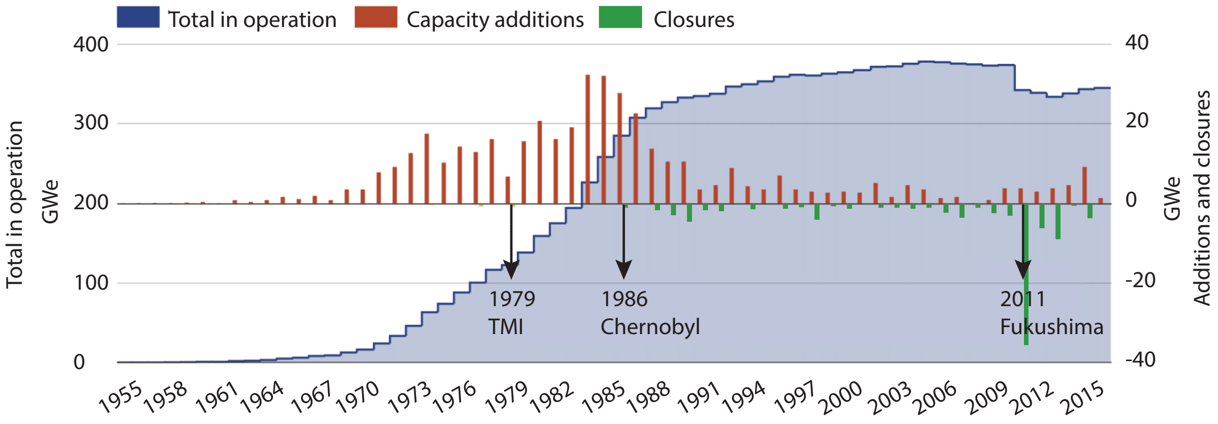


Figure 1-3: Cumulative nuclear capacity worldwide between 1955 and 2016 (blue area, left axis), capacity additions (red bars, right axis), reactor shut downs (yellow bars, right axis). Adapted from [14], [13].

54 reactors are currently under construction worldwide, corresponding to 14% of the existing capacity. Most of them are in fast growing countries such as China and India. After the Fukushima accident several nuclear plants/projects were temporarily shut down and some countries even opted for a nuclear phaseout. Nevertheless, the global nuclear generation has been rising since 2012. In 2018 nuclear plants supplied 2,563 TWh of electricity, almost matching the pre-Fukushima

levels [13]. The need for new nuclear generating capacity is motivated by the increased electricity demand in many countries, the raising concerns about fossil fuels and their negative effects on the environment.

1.2.3 Global nuclear construction cost trends

Nuclear cost escalation has been widely studied in the United States and in France given their role as industry pioneers. In 2016 Lovering et al. conducted a comprehensive investigation of historical construction costs of early and recent reactors in seven countries [15]. The study covers plants completed as of 2015 (it does not reflect, for example, the experience of the EPRs in Europe and the AP1000s in the United States).

The analysis shows that the overnight costs of the last U.S. reactors were about 7 times greater than those of the first non-demonstration reactor. As for France, a previous cost assessment done by Grubler pointed out that the units installed in 1974 were 3.5 times less costly, in constant Euros, than the post-1990 installed reactors [16]. The revised analysis by Lovering et al. was done after the release of reactor-specific costs from the Cour des Comptes in 2012 [17], and it shows that the overnight costs of the most recent French reactors were about 1.5 to 2 times greater than that of the first unit. The cost trends in Canada, Germany, Japan and India are comparable to the French experience, the overnight cost of the recent units being between 1.5 and 2 times greater than the first one. These findings led to the thinking that cost escalation is inherent in nuclear power, given that even under the best conditions, as prevailing in France (i.e. centralized decision making, high degree of standardization and regulatory stability), the construction costs have also risen significantly [18].

South Korea has managed to keep a lid on build times and has limited cost increases. South Korea reported to have reduced costs as its experience has grown, with the last reactors costing as little as half than the first one. Some analysts question cost data for South Korea, arguing it is in any case an exception to the trend of rising costs [14]. The 2012 “Korean nuclear scandal” [19] involving about 100 people, replacement parts and fake documents, casts some doubt on whether we can trust these data.

1.2.4 Recent nuclear construction experience in the United States

The last nuclear power plants built in the United States are Watts Bar 1 and 2. They both started construction in 1973 and did not begin commercial operation until 1996 and 2016 respectively [13].

Since 1973, only four reactors started construction in the United States: two units at the Vogtle site in Georgia, and two units at the V.C. Summer site in South Carolina. Cost overruns were so severe that Westinghouse, who supplied the four reactors, filed for Chapter 11 bankruptcy protection on March 29, 2017. In 2018, Westinghouse was acquired by Brookfield Business Partners [20].

The Vogtle plant site (Burke County, GA) hosts two Westinghouse PWRs (units 1 and 2), whose construction was completed respectively in 1987 and 1989. In April 2008, Georgia Power Company reached a contract agreement for two Westinghouse AP1000, which are currently under construction (units 3 and 4). Each reactor will have a net electric output of 1,117 MW_e. Unit 3 started construction in March 2013 and it was expected to enter operations in 2016. Unit 4 started construction in November 2013 and was expected to enter operations in 2017 [13]. Within a few months of obtaining the operating license in 2012, many reports indicated that the project was already behind schedule and over budget. Currently, the expected completion dates are November 2021 and November 2022 [21]. The factors that contributed to such a low performance include regulatory policy changes, poor planning and project management, the bankruptcy of Westinghouse, the loss of construction know-how and the absence of a robust nuclear supply chain. In February 2010 the expected building cost for the two reactors was \$14 billion [22], [23]. In 2018 costs were estimated to be about \$25 billion [24].

The V. C. Summer nuclear power plant (Fairfield County, SC) has one Westinghouse 3-loops PWR (unit 1) that has received approval of a 20 years license extension from 2022 to 2042. On the same site two Westinghouse AP1000 power plants (units 2 and 3) started construction in March and November 2013. The new reactors, virtually identical to those at Vogtle, were expected to go online in 2019 and 2020, respectively. In December 2015 the project was already 18 months late [25]. The placement of the CA-01 large module was especially complicated. The CA-01 module is a massive and big structure within the containment housing some principal components. Its installation was long delayed due to both regulatory body interventions and manufacturing hurdles [26]. On May 27, 2008 the president of the South Carolina Electric & Gas Company (SCE&G) signed the agreement with Westinghouse for the new AP1000 reactors. The construction overnight cost forecast was \$9.95 billion for the two units. In December 2015 the cost projection was already \$12.6 billion [25]. In 2017, shortly after Westinghouse filed for Chapter 11 bankruptcy, the V.C. Summer nuclear project was abandoned.

1.3 Why focusing on design and construction?

1.3.1 The four challenges of nuclear power

Reducing the capital cost of nuclear power plants is crucial to revitalize this industry. But why focusing on construction and power plant delivery in general? In the first place, why focusing on cost? The debate about benefits and risks of nuclear power is a long-running controversy. Leaving the benefits aside, the nuclear community face four major challenges: safety, radioactive waste disposal, nuclear weapons proliferation and cost[2].

Safety and the risks of nuclear accidents have been a topic of debate practically since the first nuclear reactors were constructed [27]. Over the years experts have produced designs with smaller accident initiating event probabilities, and designed advanced solutions to mitigate the consequences of potential accidents. Nuclear plants have come to reach excellent levels of safety performance. In comparison to any other source of power, nuclear power is the safest per TWh generated, accounting for all the risks from mining to production to storage. This holds even after the inclusion of nuclear catastrophes like Fukushima as the vast amount of energy generated in the long term offsets these events [28], [29], [30].

Nuclear waste is the radioactive by-product from nuclear power generation, nuclear weapons and medical isotope production. Its high radioactivity (that decreases with time) requires that it be safely isolated from humans and the environment until it no longer poses a hazard [31]. Civil nuclear waste has been managed without a significant environmental release for over six decades. The mass of waste to be disposed is small. One person's total lifetime volume of high level radioactive waste, if they were to use nothing but nuclear energy for the whole life, would fit in a small cup [32]. Waste management practices vary across countries. Robust technical options are available for storing spent fuel in dry casks and in permanent geological repositories, as well as for reprocessing it. The challenges of dealing with nuclear waste are not technical but rather of social and political nature.

The problem with nuclear proliferation is that the civilian nuclear fuel cycle can be used, and in certain cases has been used, to obtain weapons grade materials. Since some facilities (enrichment and reprocessing) can be used in the production of weapons, the International Atomic Energy Agency (IAEA) have put safeguards and treaties in place, which are effective at policing these. It is key to control the fissile materials, U_{235} and Pu_{239}, from cradle to grave to make the civilian fuel

---

[2] In reality, the discussion about safety, nuclear waste and proliferation is not this simple, but it goes beyond the scope of this work.

cycle an unattractive path to proliferation. Also in this case, several technical and political options exist: regional enrichment centers, fuel banks, fuel take back centers [32].

The fourth and last challenge of nuclear power is cost. While initially cost was expected to be one of the technology's advantages, nowadays it is arguably its main drawback [33]. In many parts of the world nuclear power plants are increasingly uncompetitive due to the availability of cheap natural gas and the falling costs for renewable energy coupled with flat electricity demand due to decreasing overall energy consumption. As a result, the owners have shut down some units in the last years or announced plans to close them well before their operating licenses expire. Capital cost is the determining factor of nuclear competitiveness: nuclear power plants are relatively cheap to operate but can be very expensive to build. The first generation of nuclear plants in the United States proved so costly to build that half of them were abandoned during construction. Those that were completed saw huge delays and cost overruns. Because a power plant does not earn income and currencies can inflate during construction, longer construction times translate directly into higher finance charges. In 1985 Forbes labeled the U.S. nuclear power program "the largest managerial disaster in business history" [34]. In recent years the industry has failed to prove that things will be different: soaring, uncertain costs continue to plague nuclear power in the 21st century [33]. In summary, compared to the other three, the problem of cost is still fundamentally unsolved. This answers the question "why cost?". Section 1.3.2 illustrates why we shall focus on improving design and construction methods.

1.3.2 Nuclear capital cost breakdown

Figure 1-4 shows the structure of the nuclear cost of energy as well as the capital cost breakdown for a generic new nuclear power plant (such as a Westinghouse AP1000) [35]. The cost of nuclear energy is dominated by capital cost. The overall cost structure does not vary significantly across countries and reactor technologies [2], [36].

Nuclear Island Equipment includes cost of containment, fuel handling equipment and the Nuclear Steam Supply System (NSSS) components. *Turbine Island Equipment* includes cost of turbine generator and the other power conversion systems. *Yard, Cooling, and Installation* includes total plant labor cost, costs for civil works to prepare the site, including excavations and foundations, the ultimate heat sink (cooling towers or river cooling), other equipment, and the installation of plant components. *Engineering, Procurement, Contsruction Management* are related to indirect engineering, quality assurance (QA), and supervisory costs for engineering, procurement, and con-

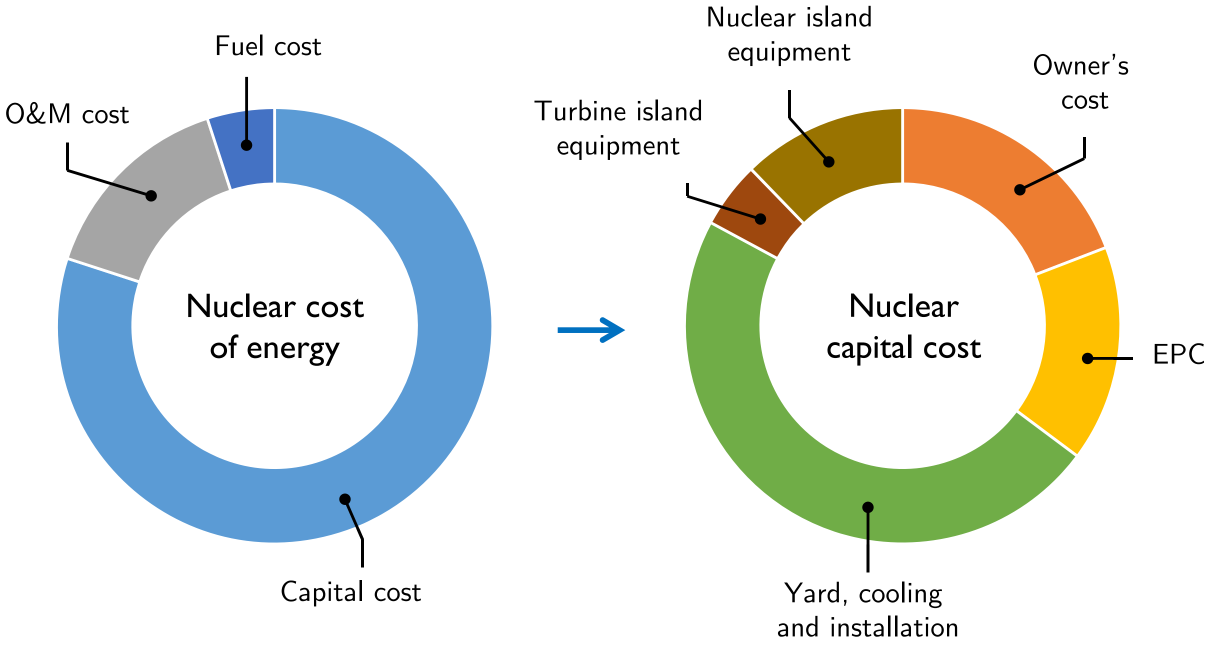


Figure 1-4: Nuclear cost of energy structure and capital cost breakdown for a typical nuclear power plant. The contributions are expressed in percentages (adapted from [2]).

struction (EPC) [2]. *Owner's cost* includes owner's project management, owner's site construction management, bid document preparation, fees and permits, taxes, owner's engineering costs, and costs for spare parts and commissioning.

The capital cost of nuclear power plants is literally dominated by factors other than those of physical equipment. Project preparation, site preparation, engineering, planning, installation, and managment are the major contributors to cost. The reactor and turbine represent a mere 17.5% of the overnight cost. If interest during construction is included, the fraction of total cost associated with the nuclear reactor and turbine islands is even smaller because long construction times result in significant interest payments [2].

1.4 Research objective and thesis structure

Nowadays cost is arguably the main drawback of nuclear power. The main contributors to nuclear cost are those associated with power plant development, construction and delivery, rather than components, materials, neutronics and thermohydraulics. This work aims at developing an improved framework for managing megaprojects, adapting to changes, estimating their value, and making project/design decisions involving numerous stakeholders, multiple competing objectives, and substantial uncertainty. The framework is based on two models:

1. A System Dynamics (SD) model that allows to simulate the design and construction project of a nuclear power plant (up to commissioning).
2. A probabilistic Discounted Cash Flow (DCF) model that focuses on operational profitability (from commissioning to decommissioning).

The points of connection/consistency between the two models are overnight cost and construction time. The power of this framework is that it covers the entire lifetime of the nuclear power plant, from the initial idea to decommissioning. More details about structure, benefits and limitations of this framework are illustrated in Section 2.4.

Chapter 2 reviews the project management methods most commonly used in system engineering, focusing on their benefits and shortcomings (Section 2.1). Section 2.2 gives a definition of a nuclear project based on its systemic characteristics. Section 2.3 shows why standard methods alone are insufficient to manage "megaprojects", justifying the effort to develop an improved method. Advantages and limitations of the new framework are introduced conceptually in Section 2.4.

Chapter 3 focuses on the first part of the framework: the System Dynamics (SD) model of a nuclear design and construction project. Section 3.1 illustrates the basics of SD, a mathematical and computational technique to model complex systems. Some successful applications are also discussed. Section 3.2 presents project dynamics, the branch of SD focusing on projects. The key concepts of rework cycle, controlling feedback processes and side-effect feedbacks are introduced. Section 3.3 describes structure and assumption of the SD model of a nuclear project. In Section 3.4 the simulation of an actual, realistic nuclear project is built incrementally starting from the ideal case. Then, model validation and calibration are also discussed. Section 3.5 illustrates through an example the potential of using the SD model as a stand-alone application, independently from the greater framework.

Chapter 4 focuses on the second part of the framework: the probabilistic Discounted Cash Flow (DCF) model of a nuclear project. Section 4.1 recognizes the crucial role of uncertainties in making forecasts in projects extending 50-60 years in the future. Structure, main variables and assumptions of our DCF model are presented in Section 4.4. The benefits of modeling real options, decisions made in the future in response to uncertain events, is discussed in Section 4.5. Section 4.6 illustrates through an example the potential of using the DCF model as a standalone application, independently from the greater framework.

Chapter 5 discusses the importance of a solid decision management process in the context of megaprojects, including nuclear projects. Stakeholders' value definition, the key concepts of multi-objective decision making, trade spaces analysis, Pareto frontier, definition of success objectives and measures are illustrated in this chapter.

Chapter 6 demonstrates that the overall framework is not only valuable but also feasible through a case study: the design, construction and operations of a small modular marine nuclear power plant. Project background and motivation are presented in Sections 6.1.1 to 6.1.4. A set of 6 high level decisions (3 design and 3 project management decision) is selected to test the framework (Section 6.1.5). These decisions are translated into a SD and DCF simulations (Section 6.1.6), then all their allowable combinations (in total 270) are simulated, represented on trade spaces, and evaluated against project success objectives to derive general policy insights (Section 6.2).

Chapter 7 concludes this work, summarizing important findings, contributions and benefits of the proposed framework. Model limitations are identified and future directions of research are advanced.

Chapter 2

Management, Control and Evaluation of Projects

2.1 Approaches to project management

The modern discipline of Project Management (PM) emerged in the late 1920s to collect management principles, methods, and tools to effectively plan and implement successful system and product development projects [37].

Several methods have been developed over the years, each varying in terms of objectives and applications. The methods commonly used by systems engineering managers include: Work Breakdown Structure (WBS), Program Evaluation and Reviewing Technique (PERT), Critical Path Method (CPM), Design Structure Matrix (DSM), Earned Value Method (EVM), Gantt Chart, System Dynamics (SD) and Discounted Cash Flow (DCF) analysis. WBS is used for project planning, PERT, CPM and Gantt charts are used for project scheduling, DSM is used for project planning and product design, EVM is used for project control, SD is used for dynamic control, and DCF is used to estimate the present value of an investment. These methods are the most referenced PM methods in systems engineering handbooks sources [38]. The rest of Section 2.1 provides a brief description of these approaches, with their benefits and shortcomings. SD and DCF are discussed separately in Chapters 3 and 4, respectively.

2.1.1 Work Breakdown Structure (WBS)

A Work Breakdown Structure (WBS) is a method that breaks a project down into a hierarchy of manageable deliverables, tasks, and subtasks. The Project Management Body of Knowledge Guide (PMBOK®) [39] defines WBS as "a hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables". A WBS is typically performed at the beginning of the project to define its scope because it forces planners to think through what is needed to be done to deliver the product. A WBS also facilitates the process of assigning responsibilities and allocating resources.

Figure 2-1 illustrates a WBS of the first three levels of a typical aircraft system (adapted from [40]). WBSs can be deliverable-oriented as well as activity-oriented, and they are now required by the US Government as part of any Statement of Work (SOW).

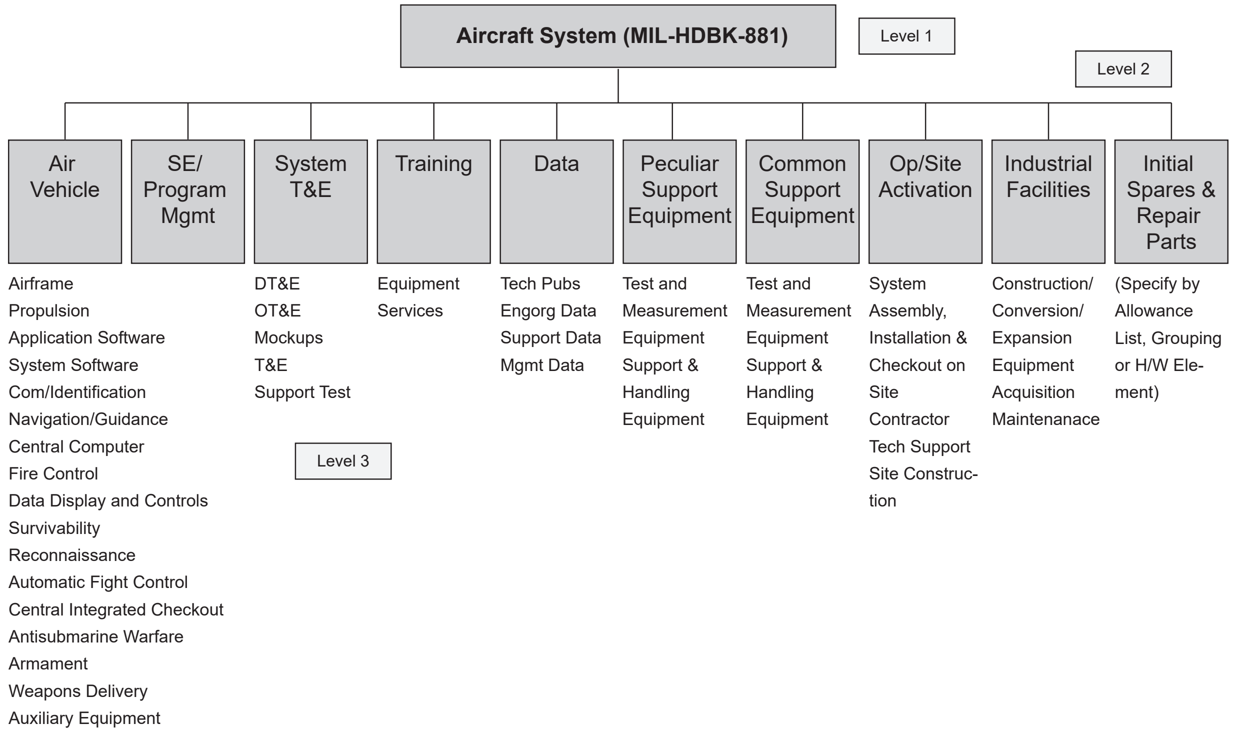


Figure 2-1: Example of Work Breakdown Structure (WBS): first three levels of a typical aircraft system (adapted from [40]).

A WBS highlights the "terminal elements" of the project and it is useful during early stage to create a list of tasks to do. However, the WBS approach have some shortcomings: WBSs are static snapshots of the project at a given point in time, so they are not adequate for managing changes; they do not capture interactions between tasks and elements; in complex systems such as nuclear projects not all tasks are known ahead of time; large-scope projects must be broken into smaller WBSs with maximum 100-200 terminal elements each, so detailed management is complicated; WBSs can have demarcation problems; they show activities in no particular order; they do not show what parts of the projects are critical; they focus on single parts of the network, ignoring the overall structure of the project.

2.1.2 Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT)

The Critical Path Method (CPM) represents a project as a network of tasks using graph theory. CPM was developed in the 1950s by DuPont for management of maintenance projects in industrial factories [38]. A critical path analysis is a diagrammatic representation of what needs to be done and when, and what is the cost of performing a job that requires particular resources.

The method depicts tasks, their duration, their logic (dependencies) and the slack time for each activity. Time in a CPM chart is deterministic, resulting in a fixed estimate of the time required to complete the project [38]. A CPM analysis identifies the critical path(s) of a project. The Project Management Body of Knowledge Guide (PMBOK®) defines the critical path as "the sequence of scheduled activities that determines the duration of the project" [39]. It is the longest sequence of tasks in a project plan that must be completed on time in order for the project to meet its deadline. Thus, a delay in a job on the critical path delays the entire project. A project can have multiple critical paths. CPM assumes that jobs are ordered as a sequence of activities in series and parallel, and that the project is concluded when all tasks are completed. The main steps to perform a CPM analysis are: (1) specify each activity; (2) establish dependencies (activity sequence); (3) draw the network diagram; (4) estimate activity completion time; (5) identify the critical path(s). Figure 2-2 illustrates the CPM diagram of the Unmanned Aerial Vehicle (UAV) case project presented in [41]. The diagram shows several tasks (23 nodes), slacks (boxes), and relationships (arrows). The three critical paths are denoted by solid lines.

The Program Evaluation and Reviewing Technique (PERT) was developed in the late 1950s as part of the U.S. Navy's Polaris project [42]. Unlike CPM, it is a probabilistic network model. Similarly to CPM, PERT depicts tasks along with dependency information and duration. This allows for assigning parametric probabilities to task completion times in accordance with optimistic, pessimistic, and likely estimations [38]. In general, any probability distribution function (pdf) can be used. Conceptually, the main difference between CPM and PERT is that the former is concerned with *activities*, whereas the latter is concerned with *events (i.e. milestones)*. So, with CPM the activities are the network's nodes and the milestones are the arrows connecting them. On the contrary, with PERT milestones are represented by nodes and activities by arrows.

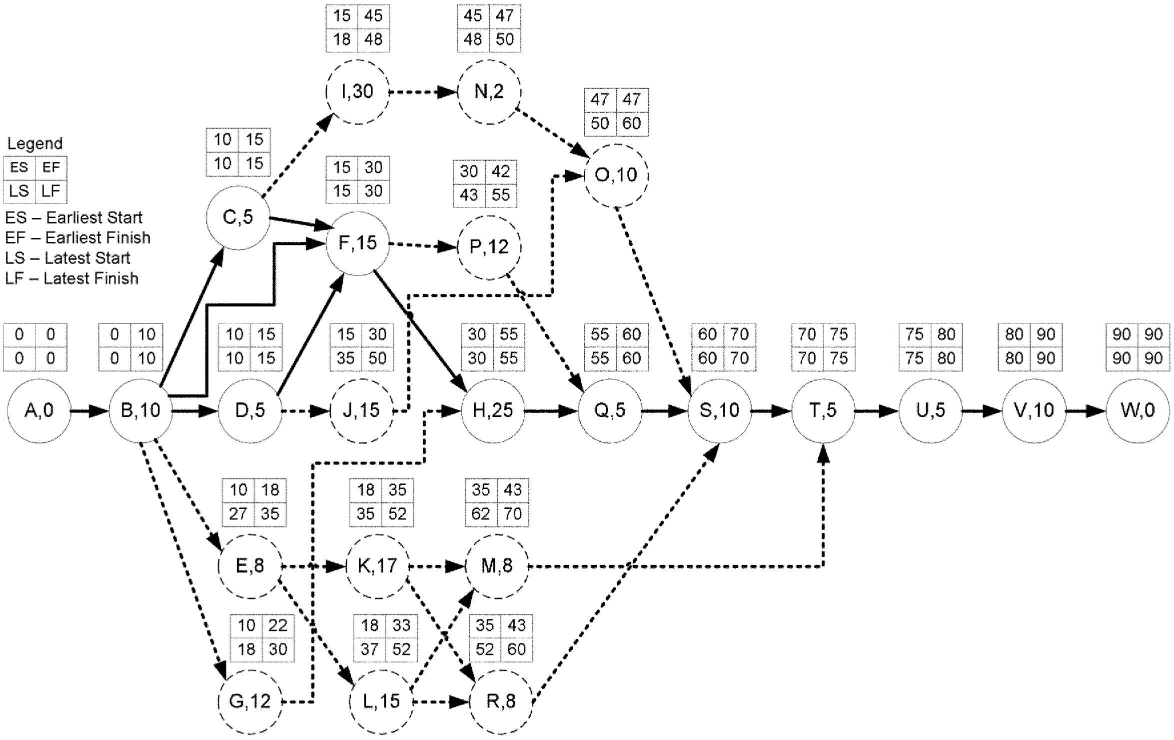
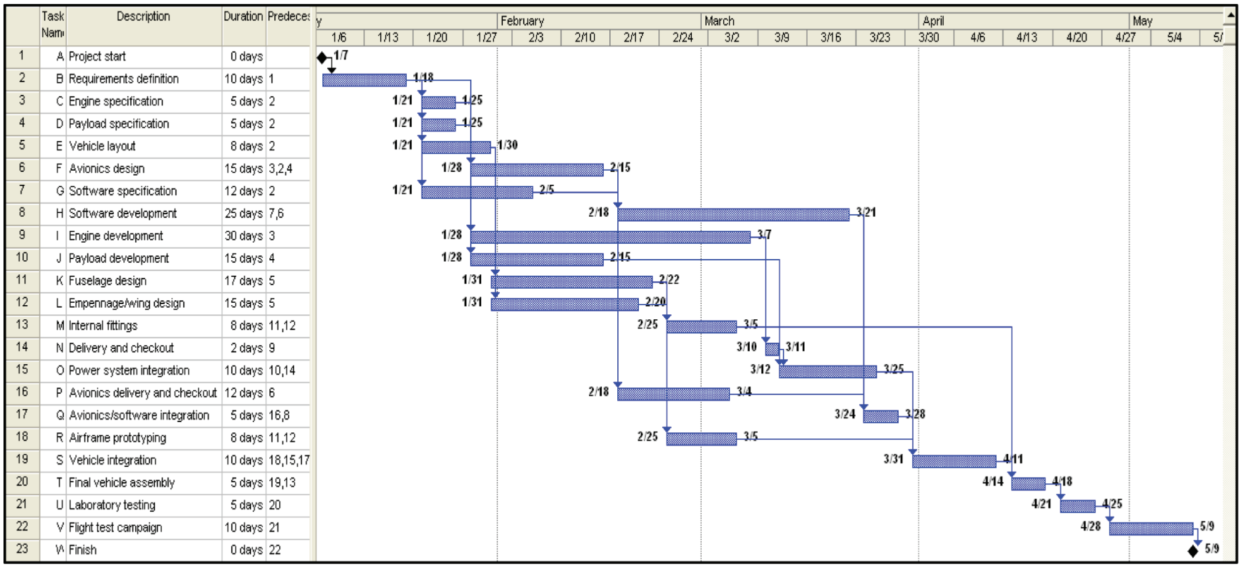


Figure 2-2: Example of Critical Path Method (CPM) application: Unmanned Aerial Vehicle (UAV) (adapted from [38])

CPM and PERT facilitate the identification of critical paths, and they make tasks dependencies explicit and visible. However, it is difficult to track the project progress using these network diagrams; they are inadequate if the project cannot be broken into discrete activities with known completion times (which might be hard to estimate, especially if the project is novel); handling changes and resource shifting is inconvenient as diagrams must be always adjusted; understanding the project's big picture is almost impossible, as there can be thousands of activities and individual dependency relationships; CPM and PERT do not account for soft human factors, political and strategic matters; they are linear models, they ignore iterations and rework, which in turn can affect other parts of the system.

2.1.3 Gantt chart

The Gantt chart is probably the most popular PM tool. It was introduced by the American engineer Henry Gantt (1861-1919) at the beginning of the twentieth century as a way to represent graphically the schedule of a project. In its original form the Gantt chart was a simple horizontal bar chart with time flowing from left to right, showing both sequence and duration of project tasks. Modern Gantt charts include dependency relationships between activities (for example start-to-start and finish-to-start links), current schedule status, and they can be coupled with network-based models such as CPM and PERT. Figure 2-3 shows the Gantt chart of the Unmanned Aerial Vehicle (UAV) case project discussed in [41]. Gantt charts are intuitive, easy to understand and to communicate. They provide an overview of the project's activities and the (expected) time needed to complete them.



	Task Nam	Description	Duration	Predeces
1	A	Project start	0 days	
2	B	Requirements definition	10 days	1
3	C	Engine specification	5 days	2
4	D	Payload specification	5 days	2
5	E	Vehicle layout	8 days	2
6	F	Avionics design	15 days	3,2,4
7	G	Software specification	12 days	2
8	H	Software development	25 days	7,6
9	I	Engine development	30 days	3
10	J	Payload development	15 days	4
11	K	Fuselage design	17 days	5
12	L	Empennage/wing design	15 days	5
13	M	Internal fittings	8 days	11,12
14	N	Delivery and checkout	2 days	9
15	O	Power system integration	10 days	10,14
16	P	Avionics delivery and checkout	12 days	6
17	Q	Avionics/software integration	5 days	16,8
18	R	Airframe prototyping	8 days	11,12
19	S	Vehicle integration	10 days	18,15,17
20	T	Final vehicle assembly	5 days	19,13
21	U	Laboratory testing	5 days	20
22	V	Flight test campaign	10 days	21
23	W	Finish	0 days	22

Figure 2-3: Example of Gantt chart application: Unmanned Aerial Vehicle (UAV) (adapted from [38])

Unfortunately, too often Gantt charts alone have proven inadequate because: they have a linear structure and cannot handle feedback loops and iterations; they are hard to manage in large projects comprising thousands of activities; they indicate the time but not the effort needed to complete tasks; they are static representations of the project at a given point in time; updating Gantt charts to reflect project changes is time consuming; they focus only on tasks, ignoring that complex projects are much more than a linear combination of those (see Section 2.2).

2.1.4 Design Structure Matrix (DSM)

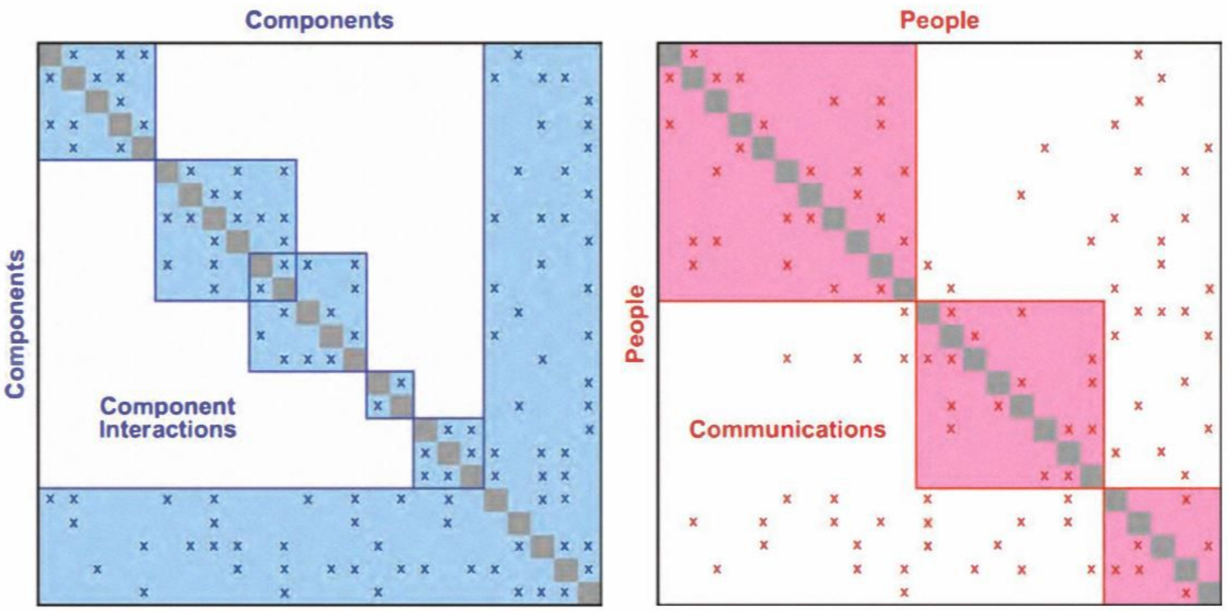
The Design Structure Matrix (DSM) is a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture (or designed structure). The term DSM was coined in the 1970s by Professor Don Steward of California State University, Sacramento, even though a branch of graph theory had long used square precedence matrices to depict relationships among nodes in a digraph [43].

Eppinger and Browning [43] suggest four primary types of DSM, depending on the type of system being modeled (Figure 2-4): (a) product architecture DSM; (b) organization architecture DSM; (c) process architecture DSM; (d) multi-domain MDM. The cells along the diagonal of the matrix represent the system elements (the nodes of a CPM or PERT chart). Each diagonal cell has inputs entering from its left and right sides and outputs leaving from above and below. Matrix elements can be ordered to reflect the sequence of tasks. More in general, the display of the matrix can be manipulated to emphasize certain features of the process flow. DSMs have been applied in many fields such as construction, real estate development, semiconductors, automotive, photographic, aerospace, telecommunication, small-scale manufacturing, factory equipment, and electronics industry, as well as in many projects sponsored by government agencies [43].

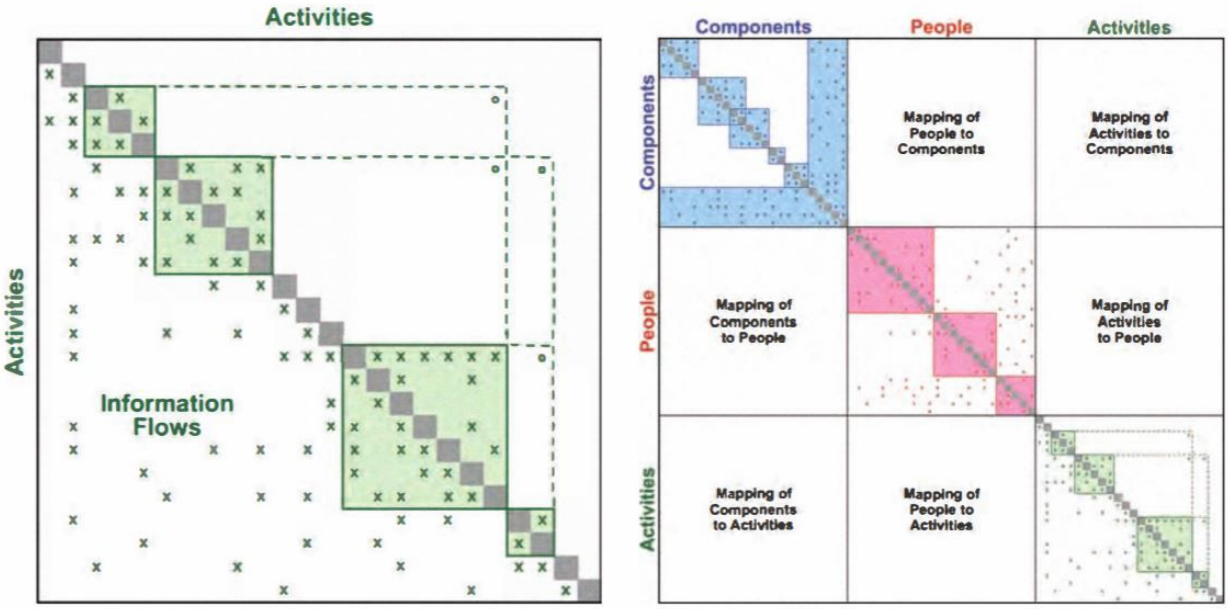
Compared with other PM methods, the main benefit of DSM is the use of a matrix format, which is an intuitive, compact, and easy to explain representation of the system. DSMs facilitate the visualization of the effect of changes on other activities. Most importantly, unlike CPM and PERT, DSMs are able to show iterations (appearing above the diagonal), which are an unavoidable part of any project. DSMs are useful operational tools. However, they are not able to show the dynamic behavior of a project. In addition, the only allowed type of connection between elements is binary (two elements are either linked or not) and the causal relationship between them is fundamentally ignored. Finally, DSMs cannot capture parallel task sequences (these are only implied) and hence they are indifferent to possible task sequences [44].

2.1.5 Earned Value Management (EVM)

The Earned Value Management (EVM) method is used to measure performance and progress of projects, combining the key concepts of scope, time and cost. Recent research studies have shown that the principles of EVM are positive predictors of project success [45]. The basic version of the method was introduced back in the 1960s by the U.S. Department of Defense. The theoretical



(a) Product Architecture DSM (b) Organization Architecture DSM



(c) Process Architecture DSM (d) Multidomain MDM

Figure 2-4: Four primary types of Design Structure Matrix (DSM) according to [43]

formulation of EVM has become increasingly solid, and it is now an ANSI standard [38]. Its popularity has grown in recent years beyond government contracting, especially in the construction industry.

Essential features of any EVM implementation include: (1) a project plan that identifies work to be accomplished; (2) a valuation of planned work, called planned value (PV) or budgeted cost of work scheduled (BCWS); (3) pre-defined "earning rules" (also called metrics) to quantify the accomplishment of work, called earned value (EV) or budgeted cost of work performed (BCWP). EVM implementations for large or complex projects include many more features, such as indicators and forecasts of cost performance (over budget or under budget) and schedule performance (behind schedule or ahead of schedule). However, the most basic requirement of an EVM system is that it quantifies progress using PV and EV [46].

The foundational principle of EVM is that a true understanding of cost performance and schedule performance relies on measuring technical performance objectively [46]. EV can only be calculated after a project has started, and it is always defined in reference to a specific control point in time [38]. The major benefit of EVM is that it displays on the same graph information about time, scope and cost. Figure 2-5 shows four different projects and their performance in terms of PV, actual cost, and EV. Schedule Variance (SV) and Cost Variance (CV) are also indicated. Their signs determine whether the projects are beyond/behind schedule and under/over budget. Top-left and bottom-right projects are respectively the worst and best cases scenarios.

EVM is a powerful tool for monitoring projects. However, it has several shortcomings: its efficacy is very limited in the management of continuous business operations [47]; it can be used only after the project has started and not during planning phases; earned value can be problematic to measure, and it is assigned at discrete levels (e.g. when a given deliverable is x% complete); it is not a planning tool; it provides insights about the performance of a project but not about its nature; it does not help understanding the cause of cost and schedule deviations.

2.2 What are nuclear projects?

A project is a combination of tasks with a specific objective to be achieved within certain specifications, with a defined schedule and constrained resources. Nuclear projects include pre-project activities, engineering, licensing, financing, procurement of equipment and material, manufacturing of components, construction, management, quality assurance, commissioning, and many other tasks. These activities are not executed as a linear sequence of actions and a nuclear project is much more than a combination of them.

Nuclear projects are megaprojects. According to the Oxford Handbook of Megaproject Management, "megaprojects are large-scale, complex ventures that typically cost $1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are trans-

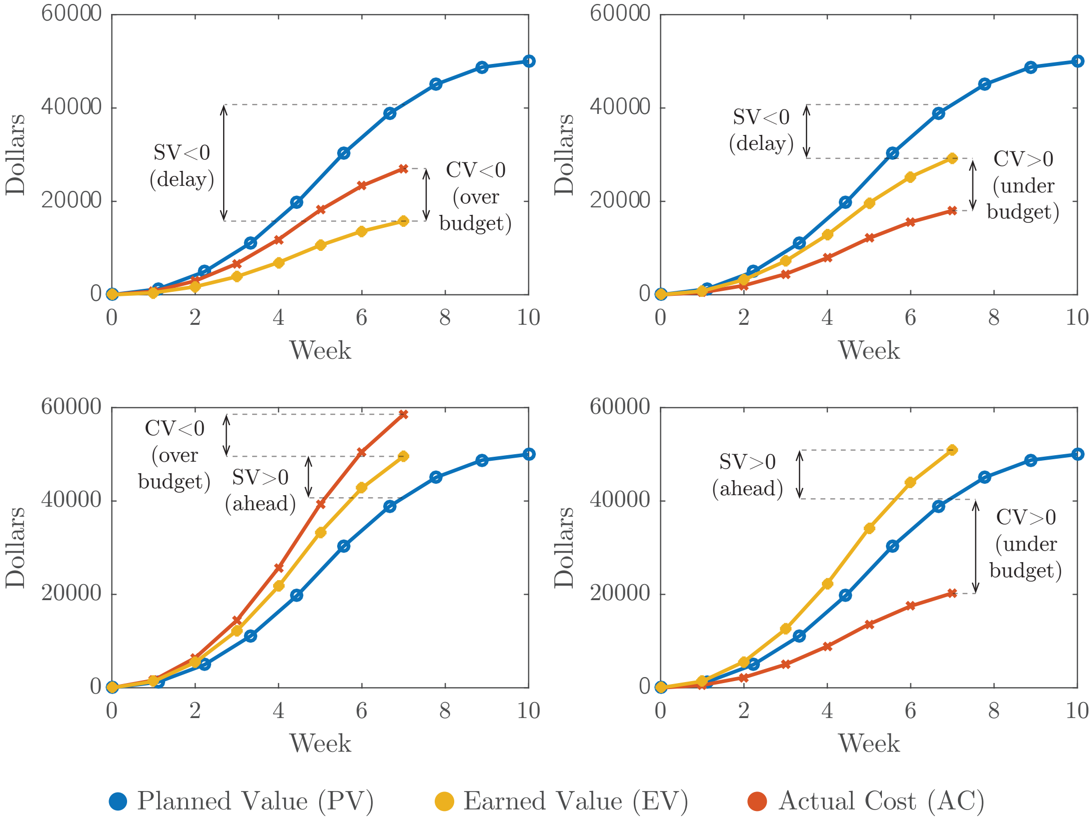


Figure 2-5: Representation of four different projects according to the EVM method. From the top-left and moving clockwise: delayed and over budget project, delayed and under budget project, ahead and over budget project, ahead and under budget project.

formational, and impact millions of people" [48].

Depending on the specific application, megaprojects are driven by a combination of technological, political, economic, aesthetic needs, or just a pure societal need [49]. Megaprojects include large infrastructures, airports, railways, hydroelectric facilities, aerospace projects and large IT systems. Predictable side effects of megaprojects are:

1. Megaprojects are inherently risky due to long planning horizons and complex interfaces [50].
2. Often projects are led by planners and managers without deep domain experience who keep changing throughout the long project cycles that apply to megaprojects, leaving leadership weak [49].
3. Decision-making, planning, and management are typically multi-actor processes involving multiple stakeholders, public and private, with conflicting interests [51].

4. Technology and designs are often non-standard, leading to "uniqueness bias" amongst planners and managers, who tend to see their projects as singular, which impedes learning from other projects [49].
5. Frequently there is overcommitment to a certain project concept at an early stage, resulting in "lock-in" or "capture", leaving alternatives analysis weak or absent, and leading to escalated commitment in later stages. "Fail fast" does not apply; "fail slow" does [52], [53], [54].
6. Due to the large sums of money involved, principal-agent problems and rent-seeking behavior are common, as is optimism bias [55], [56], [57].
7. The project scope or ambition level will typically change significantly over time [49].
8. Delivery is a high-risk, stochastic activity, with overexposure to so-called "black swans", i.e., extreme events with massively negative outcomes. Managers tend to ignore this, treating projects as if they exist largely in a deterministic Newtonian world of cause, effect, and control [58].
9. Statistical evidence shows that such complexity and unplanned events are often unaccounted for, leaving budget and time contingencies inadequate.
10. As a consequence, misinformation about costs, schedules, benefits, and risks is the norm throughout project development and decision-making. The result is cost overruns, delays, and benefit shortfalls that undermine project viability during project implementation and operations [49].

In summary, nuclear projects are complex, uncertain, adaptive systems, continuously recreated through the ongoing choices, actions and interactions among numerous entities across a dense network. As all complex systems, they are (1) constantly changing, (2) tightly coupled, (3) governed by feedback, (4) non-linear, (5) history-dependent, (6) self-organizing, (7) adaptive, (8) characterized by trade-offs, (9) counter intuitive, (10) policy resistant.

It is the nature itself of nuclear projects that make them challenging to plan, monitor and manage. They are complex sociotechnical problems, with a vital technological component but also an important social factor. Applying traditional management models alone to such complex problems have proven insufficient. Developing improved methods is necessary to reduce construction delays and thus financial risk, and ultimately revive the nuclear industry.

2.3 Traditional models alone are insufficient

We are taught to think linearly: there is a cause and there is an effect, there is a beginning and there is an end. This approach is sometimes convenient because it reduces the degree of complexity of problems and produces models that the human brain is able to process easily. Most project management methods employed in the nuclear industry are based on linear cause-and-effect models. Linear models [1] work adequately in some situations. As the wind speed increases (cause), the sail boat moves faster (effect). However, the real world is made of intricate relationships and circumstances that these models are not able to capture. As a matter of fact conventional linear approaches have not been able to cope with all problems that can affect projects. Projects still fail across various industries, with overruns ranging from 40% to 200% being common [59]. In most cases, the root causes for these failures are to be found in areas *not* addressed by conventional tools: soft human factors, feedbacks, political and strategic matters, all of systemic nature. Conventional tools are based on a bottom-up approach where the focus is on controlling the individual elements of a project, with little emphasis on their systemic interactions [60]. Complexity theory tells us that a complex problem is not a function of any part of the system. Instead, it is a product of how the system is structured. Oversimplification limits our understanding of nuclear projects and it can drive to easy-to-get, but wrong, conclusions.

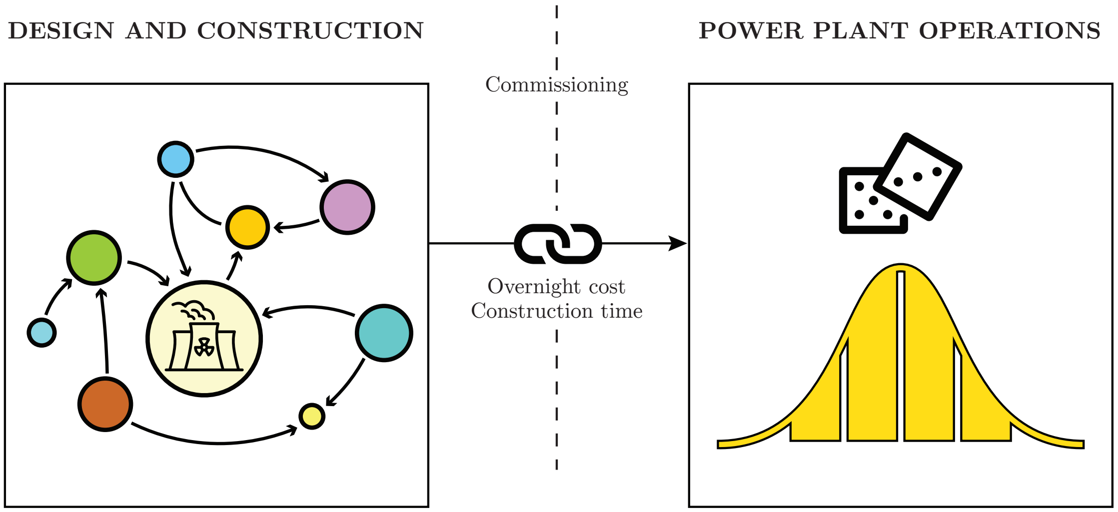
Nonlinear models are preferred when dealing with complexity. They provide the means to conceptualize the interaction of the multiple components that make up a system and focus on their interrelations. Nonlinear models use feedback loops to express that when a signal is introduced in a system, then it *stays* there and it does not disappear. It travels through a chain of causal relations to re-affect itself. Nonlinear methods recognize that the structure of any system – the many circular, interlocking, sometimes time-delayed relationships among its components – is often just as important in determining its behavior as the individual components themselves [61]. Examples are chaos theory and social dynamics. Since there are often properties of the whole which cannot be found among the properties of the elements, in some cases the behavior of the whole cannot be explained in terms of the behavior of the parts alone [62].

---

[1] In this context linear models are intended as those where events are modeled as linear processes: begin/end, cause/effect, rise/fall, action/reaction. On the contrary, nonlinear models are intended as those based on interrelations, iterations and feedbacks. The terms "linear" and "nonlinear" do not refer to the degree of the equations in the models.

2.4 Proposed framework

This work aims at developing an improved framework for managing megaprojects, estimating their value, and making project/design decisions involving numerous stakeholders, multiple competing objectives, and substantial uncertainty. The framework is built on two pillars: a System Dynamics (SD) model and a Discounted Cash Flow (DCF) model. The conceptual representation of the framework is shown in Figure 2-6. The SD model is a virtual "lab" that allows us to simulate the course of a design and construction project (Chapter 3). SD was selected because it allows one to represent delays, feedbacks and interrelationships between variables. The DCF model is used to estimate the present value of the nuclear project as an investment based on its future cash flows (Chapter 4). The two models are run sequentially and not in parallel, they are consistent with each other, and connected mainly through overnight cost and construction time (outputs of the SD model and are input for the DCF model). Each model can also be run individually as a standalone application.



- **Methodology:** System Dynamics (SD)
- **Treatment of uncertainties:** scenario analysis
- **Output:** project cumulative effort, total project time, construction time, etc.

- **Methodology:** Discounted Cash Flow (DCF)
- **Treatment of uncertainties:** Monte Carlo
- **Output:** NPV distributions

Figure 2-6: Conceptual representation of the framework and the connection between SD and DCF models.

The outcome of this method is a set of practical and project-specific recommendations that should minimize the likelihood of project delays and cost overruns. The proposed framework is a powerful addition to the current nuclear design, construction and management standard because:

- It covers the entire lifetime of the nuclear power plant, from the initial conceptual idea to decommissioning. So the scope of the project is broader than is usually defined.
- No matter how much time is spent on planning all details, surprises will occur due to the many uncertainties that are present. Thus, having a way that allows to *control* changes and *adapt* to a new set of conditions is extremely valuable. This framework allows to do so;
- This framework puts together two models that have been specifically developed and calibrated for nuclear projects. This work demonstrates that the idea of using these techniques is not only valuable but also feasible.
- Lyneis and Ford [63] propose three approaches to increase SD application in project management: (1) publishing more success stories, particularly in project management literature; (2) making SD models easier and less expensive to develop; (3) attempting to better integrate SD models with traditional project management tools. This framework address all of these.

The main limitations of this framework are:

- Both models take time to develop. They are applicable to a generic nuclear project. However, we recognize that every project is different: host country, number of units being built, reactor technology, type of contract, etc. A certain degree of adaptation will always be necessary, but it will not take as much time as developing the models from zero.
- One of the major critiques against SD models is that they are difficult to validate. Validation and calibration are even more complicated in the context of nuclear construction projects because of the scarcity of historical data and/or the reluctance of contractors to release them.
- This framework cannot do what other project management tools do. For example, in the SD model tasks are treated as packages of work that a person can do in one month. This fits well with the scope of a SD model but it is just a high level representation of the project. At some point a more practical list of tasks, such as a Gantt chart, is necessary to shift from high level planning to operational planning.

Chapter 3

System Dynamics Model of a Nuclear Project

3.1 System Dynamics

3.1.1 Overview of system dynamics

System Dynamics (SD) is a computer-aided mathematical modelling technique. It is a branch of system theory used to frame, understand and discuss the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays [64]. SD applies to any complex, dynamic systems that is tightly interdependent, non linear, adaptive, characterized by mutual interaction, information feedback, and circular causality [65]. It was developed at MIT in the 1950s by Prof. Jay Forrester to help corporate managers to improve their understanding of industrial processes. Forrester's pioneering book *Industrial Dynamics* is still a significant statement of philosophy and methodology in the field [66]. Within few years from its introduction, SD grew from corporate and industrial problems to applications in many other fields such as healthcare, economy, population studies, politics, climate change, urban dynamics, energy systems, food systems, education, transportation, blockchain. Projects have proven challenging to plan and manage. This is largely because project conditions and performance evolve over time as a result of feedback responses, many involving nonlinear relationships, and to accumulations of project progress and resources. This has made the application of system dynamics to project management a fertile and productive field of study [63]. In most industries, projects encounter chronic delays and cost overruns, despite the rigorous application of project management expertise and techniques. Some surveys suggest that overruns of 40-200% are common [67], and applying SD to projects (e.g. project dynamics) is a useful tool to understand why this happens and to improve responses to them.

The basis of the method is the recognition that the structure of any system – the many circular, interlocking, sometimes time-delayed relationships among its components – is often just as important in determining its behavior as the individual components themselves [61]. A system is a set of parts that are interrelated to perform some collective functions. What distinguishes a set of parts from a system is causal relations. SD focuses on understanding the connections between elements and changing them to get the emergence of new, macro-level structures. Compared to traditional PM methods, SD is particularly suitable for modeling not only tasks, costs, duration and precedence, but also project's features with a systemic nature, such as relationships between stakeholders, political and human factors, rework, customer changes, procurement delays, resources availability. SD is a way to engineer a problem that is not only technical.

The concept of *feedback* is at the heart of the SD approach [65]. Feedback is the process through which a signal travels through a chain of causal relations to re-affect itself [68]. Whatever action a player in the project takes, it does not disappear. On the contrary, it affects the system, which will evolve and re-affect the cause.

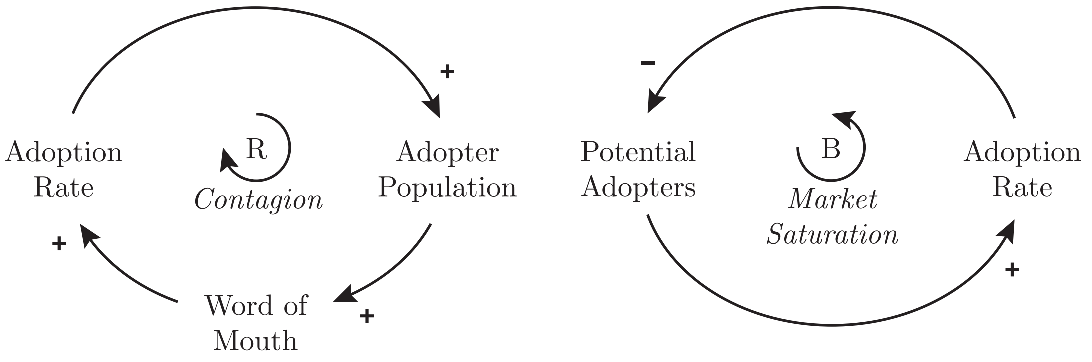
3.1.2 Feedback loops, time delays, accumulations, causal loops, and stock & flow diagrams

Feedback loops, time delays, and accumulations are the building blocks of SD. Causal loop diagrams and stock and flow diagrams are tools used to develop and explain models. Feedback loops capture the interactions between the parts and how they lead to a certain overall pattern of behavior over time. Feedback loops can be either positive or negative. A causal link from one element A to another element B is positive (that is, $+$) if either (a) A adds to B or (b) a change in A produces a change in B in the *same* direction everything else being the same. A causal link from one element A to another element B is negative (that is, $-$) if either (a) A subtracts from B or (b) a change in A produces a change in B in the *opposite* direction everything else being the same. The sign of a loop is the algebraic product of the signs of its links [69]. Positive feedback loops are also called *reinforcing* loops (usually denoted by the letter R) because they reinforce change with even more change, leading to rapid exponential growth. Since in reality exponential behaviors cannot endure forever, reinforcing loops are typically associated with unstable processes (for example the stock prices in an economy of financial bubbles). Negative feedback loops are also called *balancing* loops (denoted by the letter B) because they stabilize the system. If the current level of the variable of interest is above the goal, then the balancing loop structure pushes its value down, while if the current level is below the goal, the loop structure pushes its value up [69]. Figure 3-1 shows two examples of positive feedback loop (top-left, contagion loop) and negative feedback loop (top-right, market saturation loop) in the context of a new product being launched on the market. The positive feedback loop indicates that the more people have already adopted the new product, the more people will reference it (word of mouth effect). In turn more references will cause more people to buy the new product. This reinforcing process alone should generate sales that grow indefinitely, which is obviously unrealistic. The negative feedback loop shows that the larger the number of adopters, the smaller the pool of potential adopters (market saturation).

Causal loop diagrams are just the combination of multiple feedback loops whose primary purpose is to identify the feedback processes which cause dynamic behavior in a system [70]. Causal loop diagrams reflect our understanding of the system, its complexity and the causal relationships among its parts. All feedback loops act simultaneously, but at different times and they may have different strengths. If positive loops are associated with exponential growth and negative loops with oscillations, combining many feedback loops allows the modeler to obtain virtually any type of dynamic profile, for example: goal seeking behavior, S-shaped growth, growth with overshot, overshot and collapse (Figure 3-2).

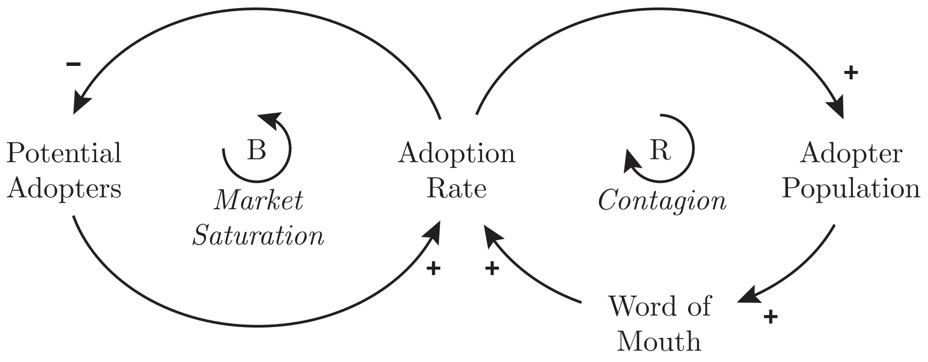
When we simulate real-world systems both size and intricacy of causal loop diagrams increase quickly as we try to capture all relevant phenomena affecting their dynamic behavior. This proves that the complexity of the system is not being ignored. Guessing the qualitative dynamics of a simple causal loop diagrams can be relatively easy. For example, in Figure 3-1(c) one might expect growing sales in the initial years, and then declining sales in the later years [62]. However, in more realistic systems, the human mind is unable to make sense of the intricacies that link numerous elements of a system to one another and how these links unfold in time. For example, Figure 3-3 illustrates the causal loop diagram representing the endogenous dynamics of the housing market cycle [71]. The many feedback loops, interconnections and delays (denoted by two short lines across the link) make it fundamentally impossible to guess the dynamic behavior of each variable.

To perform a quantitative analysis, a causal loop diagram is transformed into a stock and flow diagram. As with a causal loop diagram, the stock and flow diagram shows relationships among variables which have the potential to change over time. Unlike a causal loop diagram, a stock and



(a) Positive feedback loop

(b) Negative feedback loop



(c) Combination of positive and negative feedback loops

Figure 3-1: Positive and negative feedback loops and their combination in the context of new product launch on the market.

flow diagram distinguishes between different types of variables [69]. Stocks are all entities (state variables) that accumulates and depletes over time (people, cash, tasks, grams of CO_2, water levels, material inventories, etc.). Stocks are the memory of a dynamic system. Flows are rates of change in the stocks (birth/death rate, adoption rate, production rate, etc.). They are the sources of a system's disequilibrium and dynamic behavior. Stock and flows can be written in derivative and integral formats:

$$S(t) = \int_{t_0}^{t} (Inflow - Outflow) dS + S_0$$

$$\frac{dS}{dt} = Inflow - Outflow$$

Figure 3-4 shows a stock and flow diagram for the new product launch example introduced above. Stocks are indicated with rectangular boxes and flows with valves. In summary, using stock

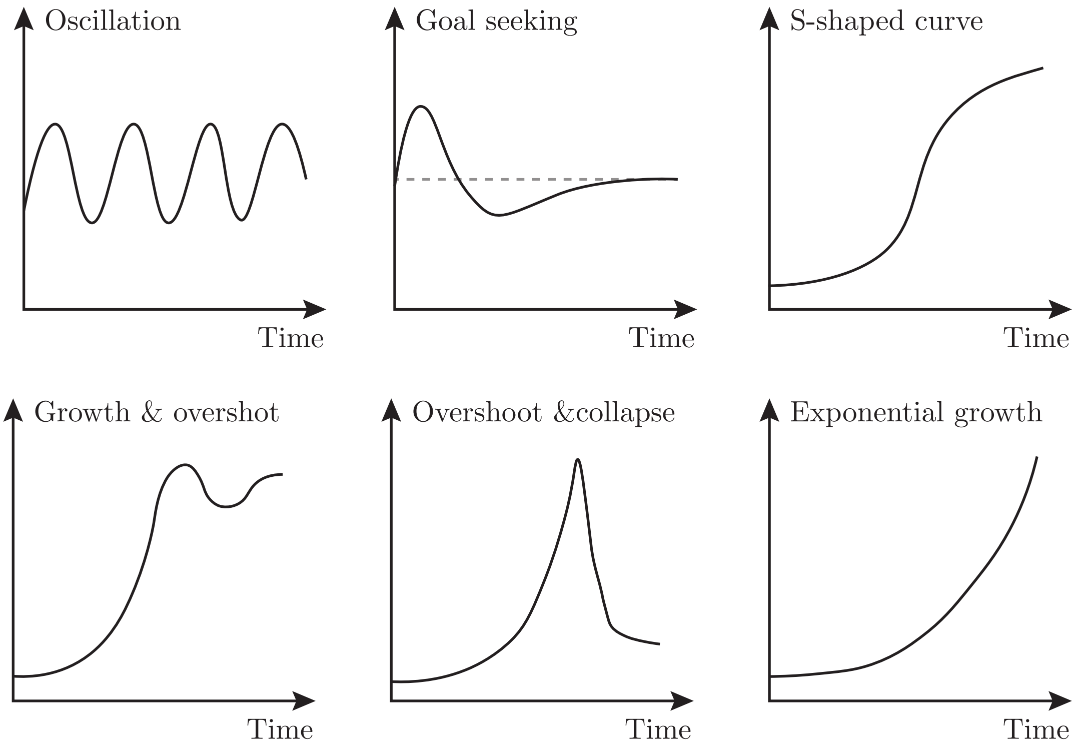


Figure 3-2: Possible dynamic behaviors in a system/process.

and flow diagrams the complex system (e.g. the nuclear project) is translated into a large system of differential conservation equations built and simulated using a computer software such as Vensim® [72]. In addition to the model, there are "changes" files that specify the parameter changes for each simulation scenario. Changes files can have any extension, but in Vensim® they default to .cin if no extension is specified.

3.1.3 Successful applications of system dynamics

The following examples intentionally focus on successful applications of *project dynamics*, the branch of SD that deals with projects (see Section 3.2). An example of SD successfully applied to a large-scale project is the Peace Shield Program, which is described by Lyneis et al. in *Strategic Management of Complex Projects: a Case Study Using System Dynamics* [73]:

"The Peace Shield Weapon System was a program undertaken by Hughes Aircraft Company for the U.S. Air Force on behalf of the Kingdom of Saudi Arabia. Hughes, now a part of Raytheon

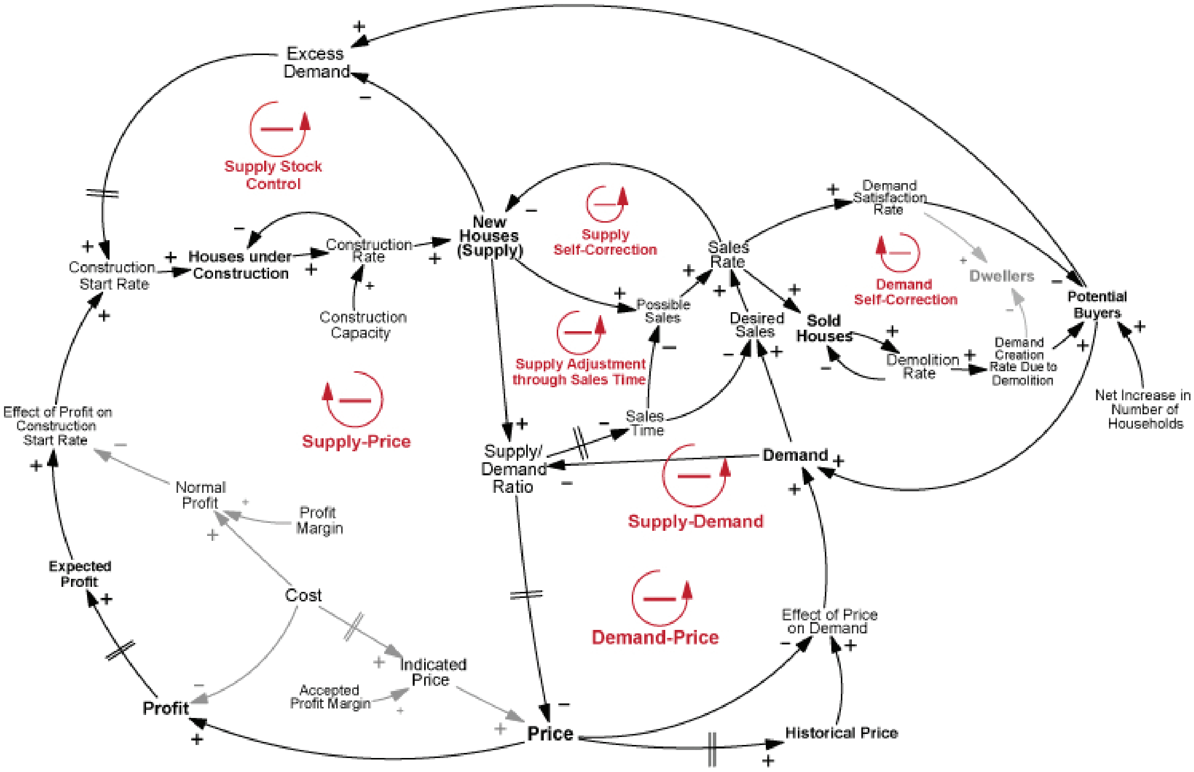


Figure 3-3: Examples of causal loop diagram representing the endogenous dynamics of the housing market cycles (adapted from [71]).

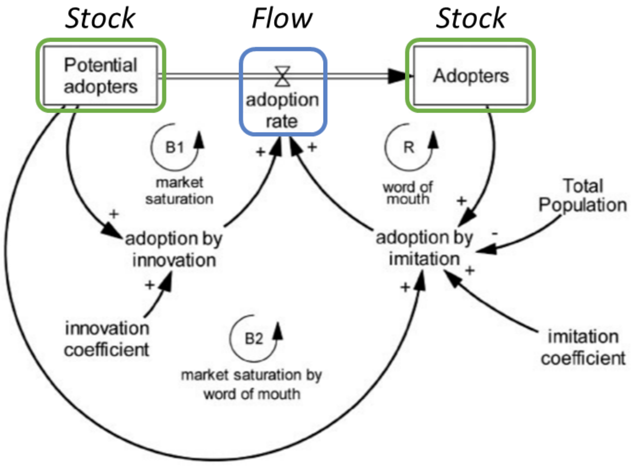


Figure 3-4: Stock and flow diagram for a new product launch on the market.

Corporation, won a competitive bid for the program after the Air Force terminated another contractor for default. The estimated value of the contract was more than $1 billion with final delivery scheduled for 3 January 1996. This schedule required a 54-month design, development, and testing *effort. While many people in the Air Force considered this schedule to be impossible, with some estimates as high as 116 months, Hughes contracted for the 54 months with a $50 million bonus should Hughes achieve a three-months-early delivery. The Peace Shield program involved both hardware and software. It "required delivery of a nationwide ground-air defense and command, control, and communications system to the Saudi Air Force. Key elements included 17 radar installations, a central command operations center, five sector command and operations centers, nationwide communications links, interfaces with all agencies having a role in national defense, and communications centers to contact and control civil and military aircraft". The Peace Shield program was not the first program of this type for Hughes. During the 1980s, the company had developed similar systems for NATO (Northern European Command and Control System) and Egypt. Pugh Roberts/PA Consulting used a system dynamics model to advise Hughes during several periods on the Peace Shield project. [...] The Peace Shield project finished in month 47, six months and 13 days ahead of schedule. It was viewed by all as highly successful. "In my 26 years in acquisitions, this is the most successful program I have ever been involved with, and the leadership of the U.S. Air Force agrees", said Ms. Darleen Druyun, Acting Assistant Secretary of the Air Force for Acquisition."*

A second example of SD successful application is the Change Impact Assessment tool used at Fluor Corporation. Fluor Corporation is an American multinational engineering and construction company. With headquarters in Irving, Texas, Fluor ranks 164 on the Fortune 500 list with revenue of $ 19.2 billion in 2018 and has more than 53,000 employees worldwide [74]. After Fluor had identified and quantified the business need for improving the practice of project change management, two external consultants designed, built, tested, and implemented a SD model to aid project management. The model is set up for and tailored to each engineering and construction project. The model is able to compute staffing needs, work progress, productivity, rework and its key determinant. It is used to foresee future cost and schedule effects of project changes, and most importantly, test ways to avoid the consequences. This Change Impact Assessment system has now been used on well over 100 different Fluor projects, a number that is growing rapidly each year. Hundreds of project managers and planners have been trained in the ongoing internal use of the system. In addition to providing a better understanding of the project-wide effects of changes, the cost savings for Fluor and its clients has now grown beyond $ 1.3 billion [75].

A third example is the Litton case, which was the first large-scale modeling of a complex project. Program overruns, contract disputes, and legal confrontation between defense contractors and the government escalated seriously over the 1970s [76]. The Litton simulation was crucial to resolve a multi-million shipbuilder claim against the U.S. Navy. The model introduced some key concepts of project dynamics such as the rework cycle (see Section 3.2) and it was used to diagnose the causes of cost and schedule overruns on two multi-billion-dollar shipbuilding programs. Ingalls Shipbuilding used the model to quantify the costs of disruption stemming from Navy-responsible delays and design changes; in June 1978, the Navy agreed out of court to pay $ 447 million of the claim [77]. This unprecedented use of SD in support of a legal dispute provided the defense and legal communities with a means by which adversary relationships can be avoided and equitable settlements of contract cost disputes achieved [76].

Apart from this anecdotal evidence, making a cost-benefit analysis of applying SD to projects is possible but certainly difficult. A person involved with the use of SD for many years provided some values for the benefits of project dynamics modeling[1], distinguishing between proactive applications and dispute resolutions. In proactive applications simulations are used to support project management, to avoid problems and improve cost and schedule performance:

- Project dynamics has been used in more than 250 proactive applications and more than $ 25 millions in consulting fees;
- Project dynamics conservatively saved clients $ 10 billion on cost and schedule performance.

Thus, for every dollar invested in project dynamics about $ 10 billions / $ 25 millions = $ 400 are saved. Moreover, about $ 10 billions / 250 = $ 40 millions per project are saved on average. In legal disputes project dynamics can provide an objective, transparent view of a complex, emotional situation. The same source of information stated that:

- Project dynamics has been used in more than 50 contract disputes, for a total value of more than $ 4 billions;
- The average dispute recovery is about 75% vs. about 40% with traditional methods;
- Project dynamics is a recognized and accepted approach in dispute resolution.

In the United States hiring a consulting company for a typical proactive assignment costs between $ 250,000 and $ 500,000[2]. So for the Litton case, for example, the benefits were between $ 900 and $ 1,800 per dollar spent. For a legal dispute, it would depend on how close to trial the

---

[1] These estimates date back to 2005.

[2] These estimates refer to the 1995-2005 period.

intervention is required. Reasonably, it would be double to triple the proactive estimate. When companies decide to engage directly with the model, providing internal analysts and support, these costs would be reduced to a fraction of about 10 plus the \$ 100,000 annual license for the software. Assuming an *initial* estimated capital cost of \$ 6 to \$ 9 billions to build a new reactor, and conservatively assuming that in 2019 hiring a consulting company to support the project costs \$ 1 million per year for 10 years, the total modeling cost would be only about 0.01% of the capital cost!

3.1.4 Limitations of system dynamics

Despite many successful applications, SD somehow failed to become part of the management consulting profession's standard toolbox. Specifically in the field of project management, a relatively small percentage of projects have used SD [63]. SD potentially offers a valuable insurance against project catastrophes and financial disasters. Then why are managers and planners inclined towards acting against their own interests? The answer is a combination of factors:

- SD models are complex. As mentioned in Section 3.1.2, real-world systems require large and intricate causal loop diagrams (ignoring complexity would be wrong). There exist other engineering disciplines that are far more complex. For example, Computational Fluid Dynamics (CFD)[3] solves engineering problems in extreme detail, routinely using grids with 1-100 million nodes, far more than the variables of any SD model [79]. However, the complexity of SD models is real and it takes a significant amount of resources (time, money, people) to develop them.

- Sometimes SD models are cumbersome to use. It takes many resources to transition from a model to another. For example, adapting a single unit model to a new project where two units are built in parallel requires the skills of an expert developer. However,

- The problems that SD typically tackles are inherently challenging. These problems are often not only technical in nature. On the contrary, they involve soft variables that are difficult to model and measure. Compared with engineering laws, behavioral/social laws are more complicated to test, describe and validate.

---

[3] Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows [78].

- There is a lack of understanding of the value of SD. Rumeser et al. identify four major causes for this: (1) lack of SD awareness, (2) one time use of SD, (3) perception that SD is impractical, (4) lack of a sense of belonging with the model [80].
- Lack of confidence in the system dynamics model. Rumeser et al. identify three major causes for this: (1) lack of the SD model transparency, (2) prior beliefs, (3) political issues [80].
- SD models cannot be used as a simple operational tool. They are more strategic tools. The incentive to use SD should come from high management levels, who are more involved in the overall project's performance, and less in the daily operational problems.
- It is difficult (but not impossible) to measure the benefits of SD. In a construction project, for example, developing and implementing a SD model is a cost item that is not easily linked to a revenue item.

Despite this, today SD is taught around the world and used by corporations, nonprofits, schools, and governments to respond to real world challenges that are becoming increasingly complex and interrelated.

3.2 Project dynamics

Nuclear projects have proven challenging to plan and manage and this makes SD an effective tool to understand them and increase their success probability. Project dynamics is the branch of SD focusing on projects. Most traditional project management tools focus on project elements (resources, tasks, staff, scope, etc.) and their architecture (dependencies, roles, breakdown structures, etc.). This static view of projects ignores that variables (productivity, work quality, stakeholder attitude, etc.) are constantly evolving and tightly coupled. Project dynamics, in contrast, describes how elements and architecture interrelate via project processes to determine the project's behavior over time [70]. Project processes include: accomplishment of work (productivity), making mistakes (fraction of work correct), detecting and handling errors, dependence (precedence, coupling, coordination), monitoring (gathering and processing information), forecasting, making decisions.

Several specific accumulation and feedback processes link project elements, project architecture, and project processes to form a theory of the structure of projects that create that dynamic behavior. That theory has developed over nearly 50 years of the application of dynamic modeling to the study of projects, both in academia and in practice [63]. These four components are the drivers of that theory [70]:

1. A *rework cycle*, in which the accumulation processes of accomplishing work, making mistakes, and detecting and handling errors capture the accomplishment of work and rework on a project;
2. *Feedback processes* within the rework cycle, that result from dependence and interaction between work tasks (e.g., error propagation, out-of-sequence work, communication, etc.), and from the decisions made by individuals and teams on how to spend time;
3. *Controlling Feedback processes*, wherein management monitors and forecasts project performance, and attempts to bring a project which has fallen behind schedule, or over budget, back on track, or adjusts the targets (e.g., adding staff, working overtime, exerting schedule pressure, cutting scope, sacrificing fraction correct);
4. *Side-effect feedbacks*, reinforcing (here vicious circles) feedbacks, which circumvent efforts at project control (e.g., skill dilution from hiring staff; fatigue from overtime; “haste makes waste” loop from schedule pressure).

3.2.1 Rework cycle: the core of project dynamics

Virtually all project dynamics models build on the ground-breaking consulting work by Pugh Roberts Associates in the 1970s. At the heart of all these models is the rework cycle. The rework cycle recognizes that the completion of a project task may be flawed, resulting in a need for rework. Rework can itself be flawed, requiring further rework in a recursive cycle that can extend project duration and work load far beyond what is originally conceived. In the absence of the rework cycle, project completion is a function of the number and scope of tasks, the available resources and their productivity [81]. The recursive nature of the rework cycle, in which rework generates more rework that generates more rework, etc., creates problematic behaviors that often stretch out over most of a project’s duration and are the source of many project management challenges [63].

Figure 3-5 illustrates a typical rework cycle. Various versions have been developed over the years. The rework cycle used in our simulations is more complex, and it includes other stocks and flows. However, the basic idea is always the same. There are four stocks: `Original Work to Do`[4], `Work Done`, `Undiscovered Rework`, and `Rework to Do`. Work (tasks) is the quantity

---

[4] The `typewriter` font is used for all SD variables.

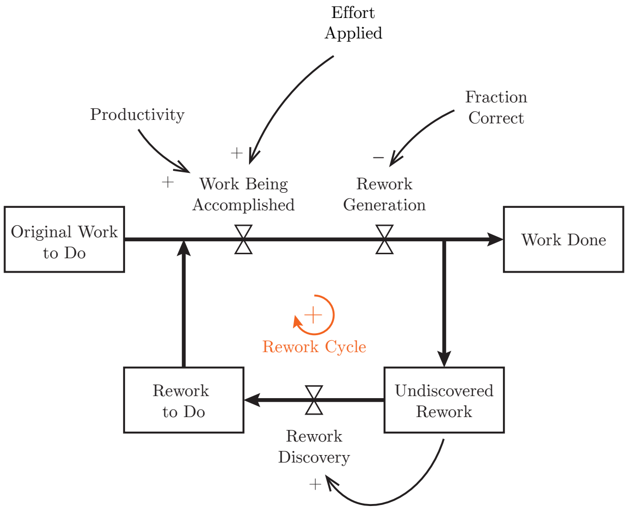


Figure 3-5: Basic structure of the rework cycle (adapted from [70])

that accumulates and depletes over time. Tasks are treated here as equivalent packages of work (work that a person completes in a unit of time). The flow of tasks from one stock to another is controlled by three flow variables: `Work Being Accomplished`, `Rework Generation`, and `Rework Discovery`. `Original Work to Do` represents the initial project scope, which is decreased by `Work Being Accomplished` (tasks per unit time). Tasks that are performed correctly flow into the `Work Done` stock. The rest (controlled by `Rework Generation`) flows into the `Undiscovered Rework` stock. Errors are discovered with some delay. `Rework Discovery` controls this delay and moves flawed tasks into the stock of `Rework to Do`. In this simple form of the rework cycle `Work Being Accomplished` is just a function of `Productivity` and `Effort Applied`. Figure 3-5 shows that there is a positive causal link between these variables: if either `Productivity` or `Effort Applied` increase, then progress rate increases. `Rework Generation` is a function of `Fraction Correct`. Finally, `Rework Discovery` is a function of `Time to Discover Rework` (not shown here) and the stock of `Undiscovered Rework` (the more undiscovered rework, the more tasks needing rework are discovered).

3.2.2 Direct and indirect effects

The rework cycle is the fundamental building block of any project dynamics simulation. Obviously, real projects are more complicated and there are many phenomena and circumstances affecting the variables shown in Figure 3-5. As SD practitioners, our role is to identify all important factors driving a project, to understand how they connect to the rest of the system, and what is the causal nature of these links. Each factor (e.g. effect) is then translated into a causal loop diagram, *which might not be the perfect representation of the phenomenon, but it reflects our best understanding of it.* The causal loop diagram is then translated into a detailed stock and flow diagram with associated equations, the computer model (here in Vensim$^{®}$). The overall model is then a map of the complex sociotechnical system (in this case a nuclear project) that should represent our most up-to-date interpretation of it. In this sense, the model can be viewed as an encyclopedia of nuclear projects, containing all variables driving progress and performance as well as their causal links. As any other collection of information, the model should be made available to the nuclear industry, and it should be updated as new information (experience) is gained.

As we *connect* effects (i.e. structures, loops) to the original rework cycle, both size and intricacy of the model grow relatively fast. Nuclear projects are complex, so having complex models is perfectly normal. In order to understand cost and schedule overruns on nuclear projects, we distinguish between direct and indirect factors. Direct effects add effort (man-hours) to the project directly. They reduce work product fraction correct and/or productivity independently of whether other effects happen or not. Indirect effects are generated as a consequence of other effects being realized. Indirect effects cannot exist independently. According to [70], the cost of indirect effect in complex projects is about 2-4 times larger that of direct effects. As we will see, direct effects are typically more complicated to avoid. As a result, there is significant leverage for improvement from understanding and managing project dynamics.

The nuclear project model presented here is adapted from the *“Lyneis model”* [70], which incorporates a huge experience derived from many real world applications, gained over many years in the consulting industry. The model, which is adjusted for a nuclear project, includes but is not limited to the following effects:

- Error propagation (indirect);
- Out-of-sequence work (indirect);
- Coordination of tasks and people (indirect);
- Uncertain requirements (direct);
- Novelty (direct);
- Level of effort spent on Front End Engineering and Design (FEED) phase (direct);

- Overlap between project phases (both direct and indirect);
- Size and availability of management and technical leadership team (indirect);
- Suppliers problems and suppliers coordination (both direct and indirect);
- Scope growth and external factors (both direct and indirect).

In Section 3.3 we explain how these effects are combined and replicated to produce the SD model of a nuclear project.

3.3 System dynamics model of a nuclear project

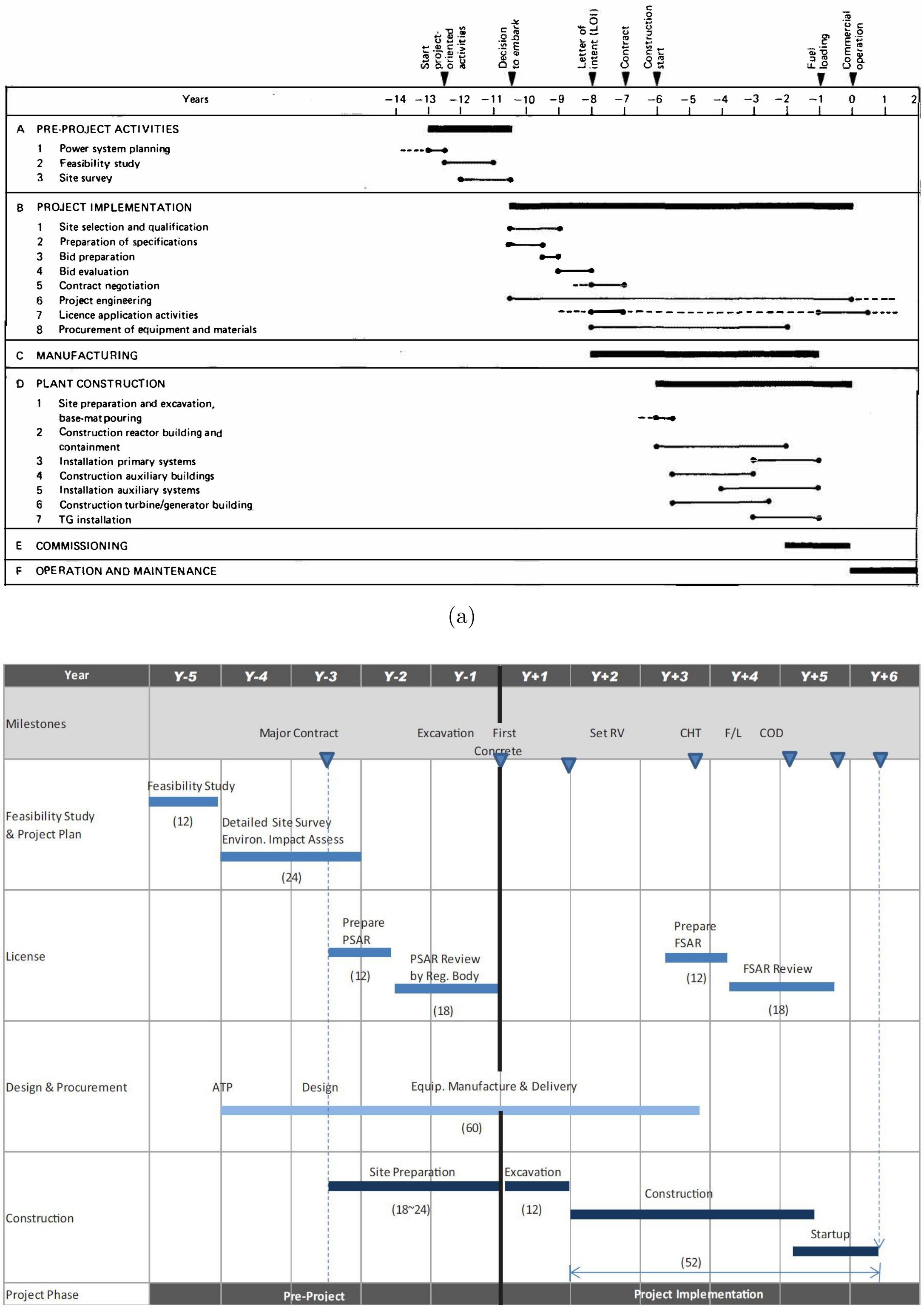
In this section we first illustrate the overall *modular* structure of the model. Then, we describe how all direct and indirect effect come together to form each module.

3.3.1 Overall model architecture

To build the model we need to know the duration of all phases as well as how much they overlap. Figure 3-6 illustrates two versions of the Gantt chart of a typical nuclear project according to the International Atomic Energy Agency (IAEA). The chart on the top (Figure 3-6a) is dated 1980 [82], the chart on the bottom (Figure 3-6b) is a more recent version dated 2012 [83]. We notice that:

- There is a remarkable overlap between all phases. Very large capital costs incentivize parallelization of activities to shorten construction times. For example, major equipment such as reactor vessels, steam generators, reactor coolant pumps and turbine generators are long lead items, so if pre-project conditions are favorable an ATP (Authorization to Proceed) can be issued to the selected main contractors even before the contract is awarded so as to shorten the overall construction schedule [83].
- Considering overlaps between phases, an average nuclear project *plan* (from pre-project activities to start of operations) is about 10 to 15 years long.

The SD model of a nuclear design and construction project must capture its complexity. In principle, one could build a sub-model for each task shown in Figure 3-6 separately, and then merge everything into a larger model where all activities interact with each other. In practice, to keep



(a)

(b)

Figure 3-6: Typical high-level Gantt charts of a nuclear project (adapted from [82],[83]) the model manageable, we divide the project into three phases only: *FEED & Licensing*, *Design & Procurement*, and *Build & Commissioning*.

- *FEED & Licensing (F&L)*[5] includes all pre-project activities: power system planning, feasibility study, site selection and acquisition, development of environmental impact assessment, stakeholders' analysis, identification of requirements, evaluation of conceptual designs, infrastructure development planning, establishment of project management organization, development of long-term reactor deployment strategy, plant information management, integration management, communications management, definition of organizational structure, roles and responsibilities. *F&L* includes also licensing and regulation activities.
- *Design & Procurement (D&P)* includes preparation of the construction project, determination of project specific conditions, detailed design of the system, building layout combination and site general arrangement, civil and architectural design, project engineering, construction infrastructure development, project detailed scheduling, selection of suppliers and sub-suppliers, procurement of equipment and material.
- *Build & Commissioning (B&C)* includes manufacturing of equipment and components, plant construction, plant commissioning, construction inspection, training of personnel and operators.

Figure 3-7 shows a conceptual view of the three project phases[6]. In reality the model is much more complex, but the figure is intentionally simplified and schematic. Each phase includes the structures necessary to model rework cycle, rework discovery, productivity, fraction of work correct, task precedence, downstream impact, management control, system engineering, staff allocation, external impact, scope growth, project cost and schedule, and all other effects discussed earlier. *F&L*, *D&P*, and *B&C* are nearly identical in structure, the only differences being those necessary to represent interactions between the phases, and any parametric differences. In Figure 3-7 the work *phases* are represented in series, but note that *tasks* within and outside each phase are also done in parallel since we model overlap. Nuclear projects in general are also decomposed into parallel phases. For example, design may be broken down into sub-components or functional areas. This model is modular and so we can easily adapt it to the scenario we want to simulate. For example,

---

[5] Other sources define FEED (Front-End Engineering Design) slightly differently.

[6] Figure 3-7 combines causal loop diagrams and stock and flow diagrams, and it is just a conceptual representation of the three portions of the model.

a large nuclear program in which multiple units are built could be modeled through a single *F&L* block and single *D&P* block, followed by multiple *B&C* blocks in parallel. In practice, while greater disaggregation is possible, three phases of work and single reactor unit is a good starting point for this dynamic analysis.

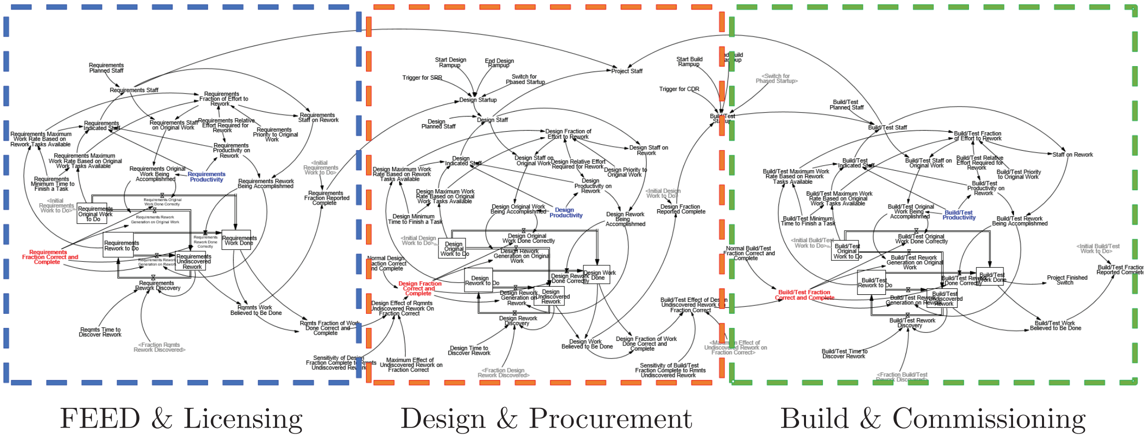


Figure 3-7: Schematic representation of 3-phase model.

3.3.2 Error propagation

The first feedback loop that we introduce is caused by the propagation of errors in upstream work products to downstream tasks [70]. The loop is illustrated in Figure 3-8. If the number of mistakes increases, `Undiscovered Rework` level increases, then the probability that downstream tasks contain rework also increases. This induces a decrease in `Fraction Correct`, which in turn causes `Rework Generation` and `Undiscovered Rework` to increase. Thus, error propagation is a positive (reinforcing) loop that obviously tends to diverge. The error propagation loop, like the rework cycle loop itself, increases the total number of tasks done, the effort (man-hours), and it delays project completion.

In a real project, the error propagation loop gain (sensitivity) depends on the level of tasks dependency. Dependency is the degree to which information or deliverables from other upstream tasks are required to accomplish downstream tasks. Dependency creates task precedence constraints and error propagation. A simple project might have limited, nearly one-on-one dependence between an upstream task and a downstream task as indicated by the blue arrows in Figure 3-9. Snakes of independent sets of parallel tasks are created. On more complex projects, however, the parallel snakes may in fact depend on information from upstream tasks in other parallel snakes, as indi-

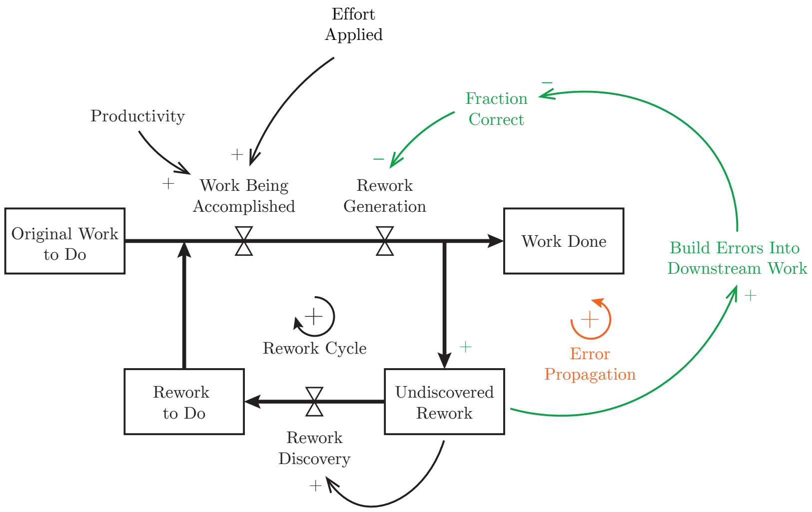


Figure 3-8: The error propagation feedback loop (adapted from [70])

cated by the red arrows (which might continue beyond Tasks 7, 8, and 9 to further tasks in the parallel snakes). The more connections between upstream and downstream tasks, the greater the dependency at a given stage in a project. A final kind of dependency, indicated by the bold arrows, is coupling. Tasks being done in parallel need information from each other [70].

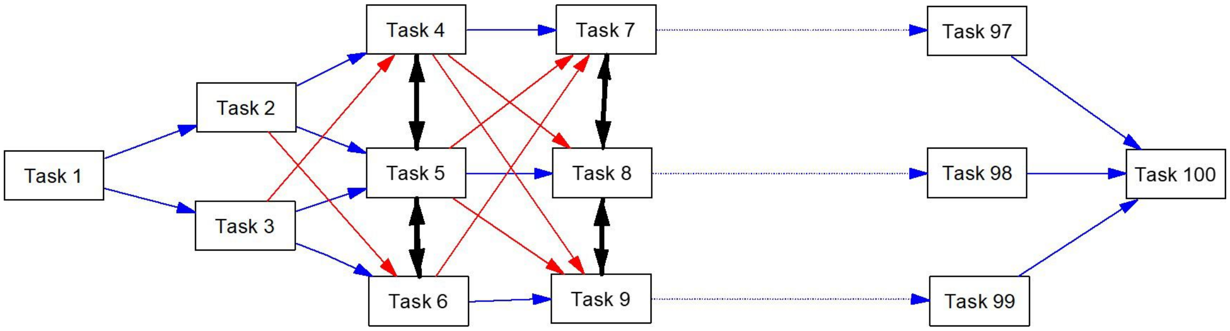


Figure 3-9: Different degrees of task interdependency (adapted from [70])

3.3.3 Out-of-sequence work

Ibbs et al. [84] define out-of-sequence (OOS) work as “a condition in which the originally planned, and probably most efficient and logical, work sequence is interrupted and changed”. This change could be in terms of changes in the specifications, plans, design, equipment, materials, used technology, temporary facilities, time of performance, personnel, construction method, and external conditions. Changes are the norm rather than the exception in construction projects. Rearranging the work to accommodate change without fully contemplating the project's interrelated feedbacks leads to productivity loss and added costs [85].

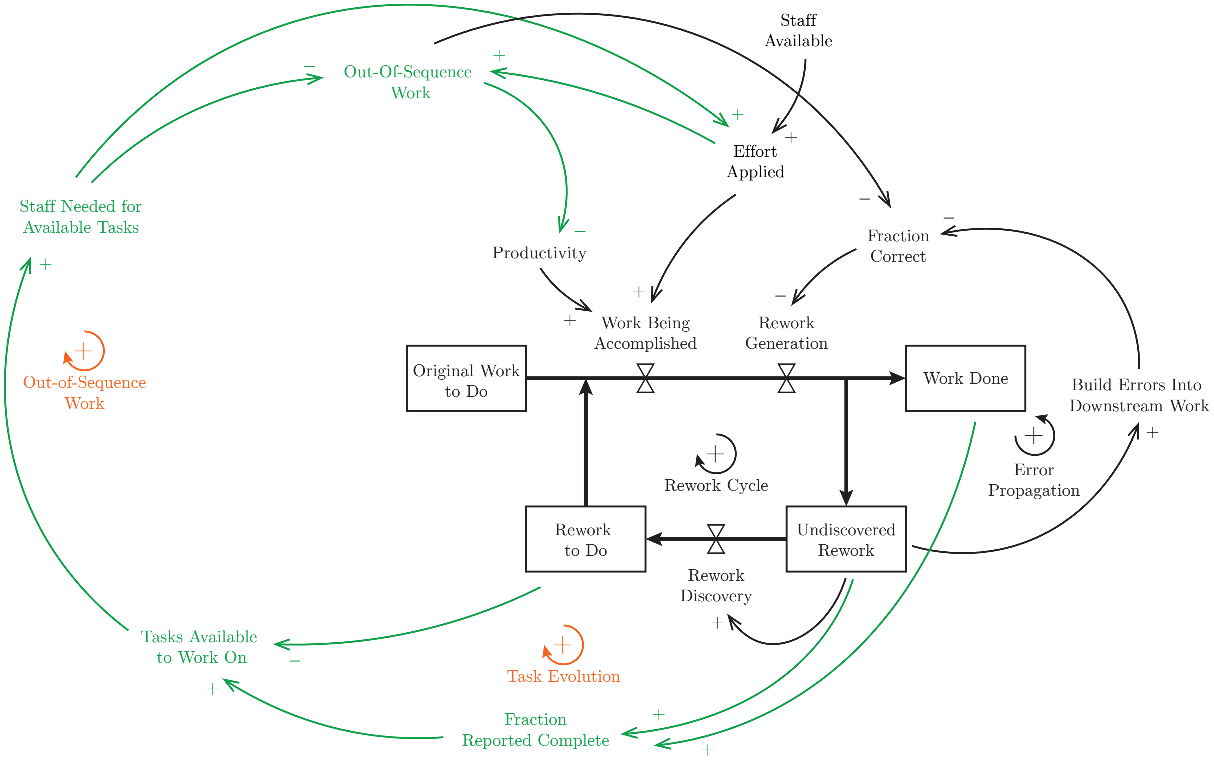


Figure 3-10: Out-of-sequence work and task evolution loops (adapted from [70])

The new structure, comprising task evolution loop and OOS work loop, is shown in green in Figure 3-10. The former is normally a benign loop reflecting the evolution of the project through the planned sequence of tasks as specified by the project task sequence and dependencies of the project architecture [70]. The sum of `Work Done` and `Undiscovered Rework` determines how much work is reported to be complete and consequently the number of tasks on which staff can work. `Tasks Available to Work On` in turn determines `Staff Needed for Available Tasks` based on productivity. Then, `Staff Needed for Available Tasks` is compared with `Effort Applied` (expressed in number of people) and if they are equal, the project proceeds as planned and no OOS is generated. On the contrary, if `Effort Applied` is greater than `Staff Needed for Available Tasks`, the extra effort can either remain idle (reducing `Productivity`) or further downstream tasks can be worked but out of the proper sequence (therefore reducing `Fraction Correct`).

OOS work can be caused not only by the dynamics of the rework cycle itself, but also by forces outside the rework cycle (schedule pressure, exceptional external events, etc.), which are captured by `Staff Available`. For simplicity, the predecessors of `Staff Available` are not shown here. Discovering errors in upstream tasks can also generate OOS work. This is indicated by the negative causal link between `Rework to Do` and `Task Available to Work On`. When tasks are found to contain errors, they suddenly become unavailable to work on until they are reworked. Thus, the project continues but following a formal sequence that is different from the original plan.

3.3.4 Coordination

Coordination needs depend on the number of activities being executed at any point in time and by the interdependency between those activities inherent in the project architecture. Figure 3-11 shows a simplified version of the coordination loop (in green).

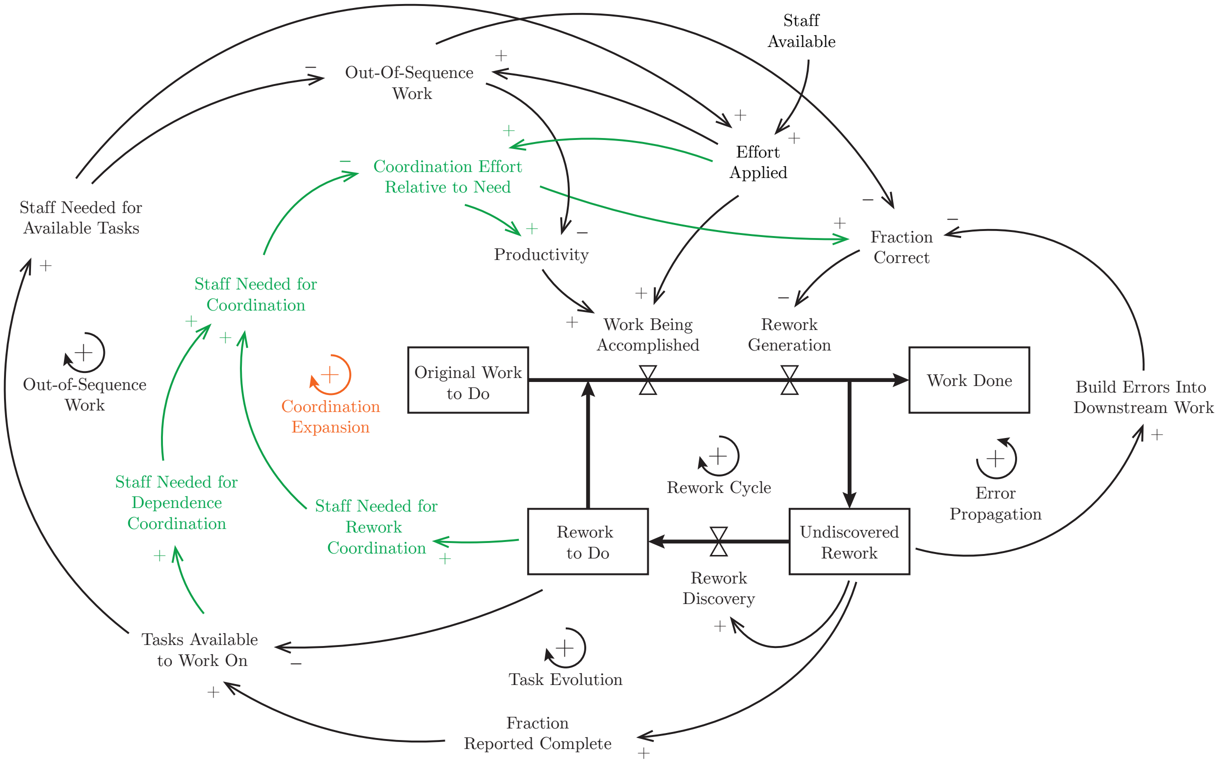


Figure 3-11: Coordination loop (adapted from [70])

`Staff Needed for Coordination` is the sum of `Staff Needed for Dependence Coordination`, proportional to `Tasks Available to Work On`, and `Staff Needed for Rework Coordination`. The staff available for coordination (which is a function of the level of priority assigned to coordination by the management) is compared with `Staff Needed for Coordination`. In case of shortage, the modeler chooses the mix between (1) giving priority to coordination and (2) giving priority to task accomplishment. In the first case, the project would be slowed down. In the second case, `Fraction Correct` would suffer.

3.3.5 Uncertain requirements

Stakeholders are legitimate sources of requirements. The set of requirements defined during early stage development reflects the stakeholders' state of knowledge about the project up to that moment. The initially defined requirements cannot be perfectly accurate because: (1) that initial state of knowledge is not perfect; (2) a project is intrinsically subject to changes; (3) new stakeholders can join the project with other requirements, some can leave; (4) stakeholders can change their opinion and/or their internal management structure (decisional structure); (5) boundary conditions can vary resulting in a change of project scope or stakeholders' attitude. For example, following a Fukushima-like event, an undergoing nuclear project could loose political support. The introduction of a new technology or process, such as hydraulic fracturing (or "fracking"), could disrupt the energy market. In both cases some stakeholders would probably change their opinions about the project.

Capturing as many correct requirements as possible early in the project is crucial. However, no matter how much we improve recall and precision of requirements identification, there will always be changes. SD is useful to learn how to *react* to such changes. Uncertain customer requirements are "known unknowns": we are nearly certain that some rework will be created by these factors, but we are not sure of how much. If we had data from (and modeled) prior projects, we might be able to determine a likely range for the uncertain requirements effect on different types of project. We might then use the average of the historical ranges, or a worst case, depending on how we wanted to plan and set targets for the project [70].

The effect of uncertain requirements is meant to capture the consequences of uncertainties in stakeholders requirements in early stage development (with subsequent propagation to later design and construction). Even with an optimal level of effort spent on *F&L* (Section 3.3.7), it is possible that the nature of the product or the stakeholders can cause uncertainty in the exact focus and requirements of the project. The buyer may not know exactly what is wanted until a product (or prototype) is built and operated; or seeing it for the first time may stimulate changes and/or new requests. This effect is intended to be in addition to, and separate from, the impact of inadequate

F&L scope on `Productivity` and `Fraction Correct` in each phase. Inadequate *F&L* scope may further contribute to a poor understanding of customer requirements.

The effect of uncertain requirements is expressed through two parameters, a magnitude and a timing (Figure 3-12). The magnitude is a constant (between 0 and 1) indicating by how much `Fraction Correct` is reduced. Timing is a function of `Fraction of Original Work Complete`. Figure 3-13 illustrates three examples of possible timing profiles. The modeler can use any curve depending on the characteristics of the project. The y axis is a multiplier for `Magnitude of Effect of Uncertain Requirements on Fraction Correct`. In all cases, it seems reasonable that the effect starts at one (e.g. `Fraction Correct` is reduced by `Magnitude of Effect of Uncertain Requirements on Fraction Correct`), then it decreases progressively. Note that we make the assumption that uncertain requirements do not have a direct effect on `Productivity`, which is affected only indirectly through the action of uncertain requirements on `Fraction Correct`.

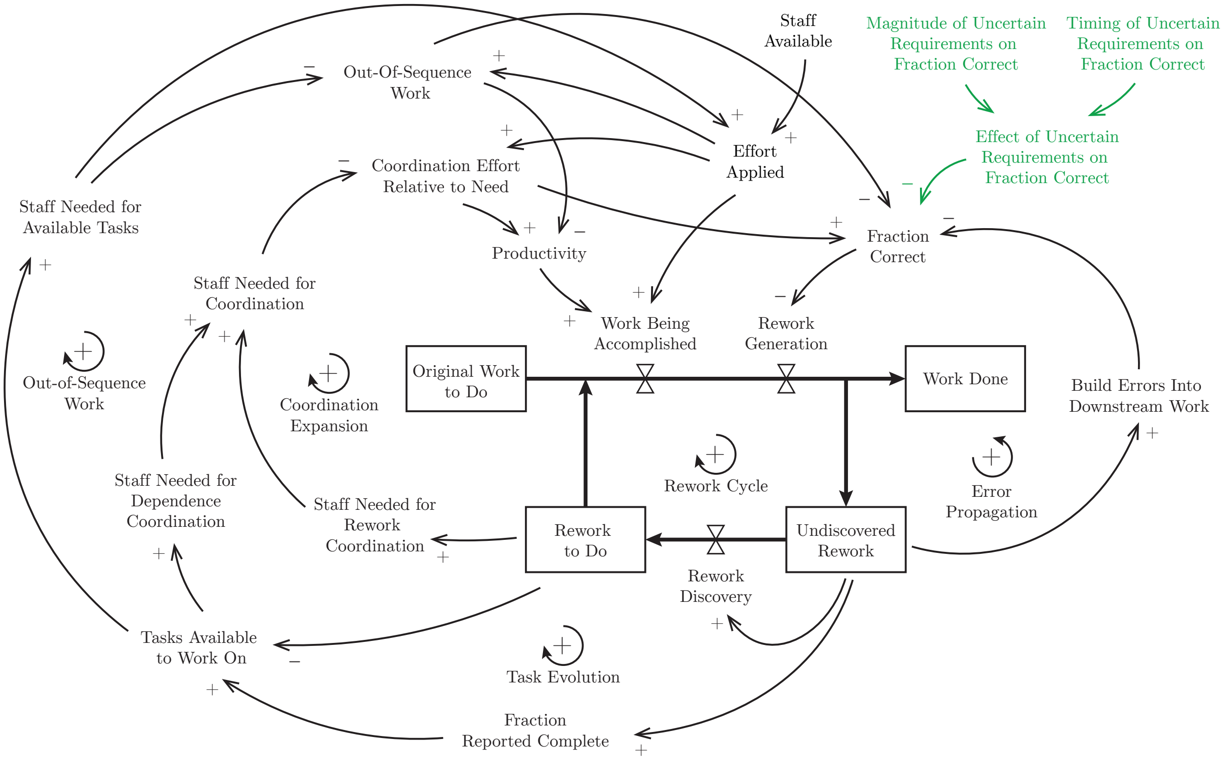


Figure 3-12: Uncertain requirements effect on fraction correct.

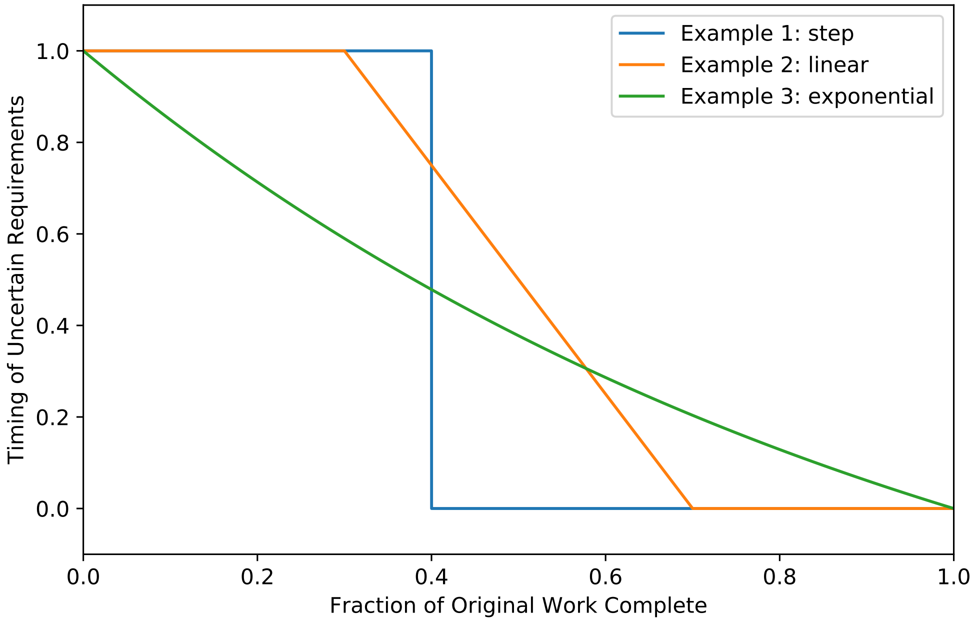


Figure 3-13: Timing effect of uncertain requirements effect.

3.3.6 Novelty

This structure is meant to capture the effect of technical novelty and/or complexity on the *F&L* and *D&P* effort (with subsequent propagation to build). Even with optimal *F&L* scope, it is possible that the newness and/or complexity of the product can cause downstream rework. For example, we may not know if a new technology, or combination of technologies, will work until built and tested. This effect is intended to be in addition to, and separate from, the impact of inadequate FEED scope on productivity and fraction correct in the project (Section 3.3.7). Note that it is also possible, perhaps likely, that novelty will also lead to an increase in tasks to do as downstream progress discovers "known unknowns" that need to be addressed. This is captured by the scope growth effect (Section 3.3.11).

The effect of novelty operates similarly to the effect of uncertain requirements: novelty is modeled through `Magnitude of Effect of Novelty on Fraction Correct` and `Timing of Effect of Novelty`. These values can be varied to compare the dynamics of projects based on already built versus newly designed reactors. Also in this case, it is reasonable to assume that the effect of novelty is large early in the project and then phases out as `Fraction of Original Work Complete` increases. In reality, both magnitude and effect of novelty are coupled with other variables, such as the amount of effort spent on pre-project activities.

3.3.7 Level of effort spent on FEED

While error propagation, rework discovery, and task precedence are the major categories of interconnection between project phases, FEED presents a special case[7]. We assume that for detailed design and build phases, the scope of work is largely fixed and dictated by the conceptual design of the project. While the scope of work may not be precisely known for these phases, and may change as a result of external factors, or be reduced in response to schedule pressures, the scope of work can be taken as a given at any point in time on the project.

In contrast, FEED scope of work is much more flexible. FEED includes all pre-project activities: power system planning, feasibility study, site selection and acquisition, development of environmental impact assessment, stakeholders' analysis, identification of requirements, evaluation of conceptual designs, infrastructure development planning, establishment of project management organization, development of long-term reactor deployment strategy, plant information management, integration management, communications management, definition of organizational structure, roles and responsibilities. While some effort must be directed to all of these activities, the amount of that effort can vary widely from project to project. Each activity can be done more or less thoroughly. Other things being equal, the more thorough the FEED effort, the longer it will take. The pressure to get started on the "real" project can often lead to a shortchanging of the FEED effort; similarly the attitude that we have done this before and "know" what to do. While reducing FEED effort will allow the detailed design phase to get started earlier, there can be adverse consequences in doing this [70].

FEED is a subset of the System Engineering (SE) activities. SE is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. SE uses an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem [86]. According to Honour [87], SE comprises the following activities: (1) mission definition; (2) require-

---

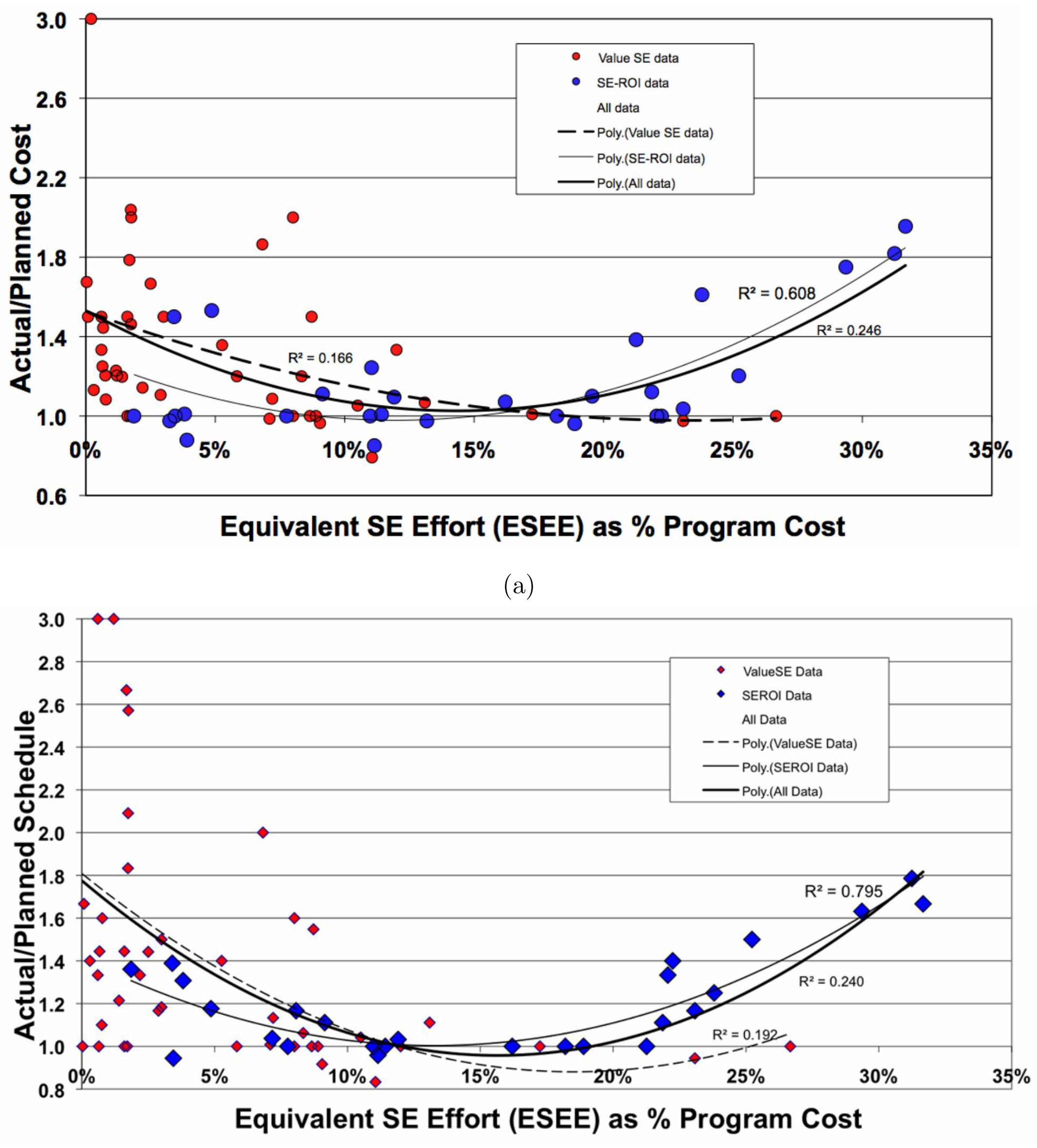
[7] The content in Sections 3.3.7 to 3.3.11 was developed jointly with Dr. James M. Lyneis and it appears both in this work and in *Project Dynamics: Understanding, Modeling and Managing the Internal Drivers of Cost and Schedule Growth*, available on ***name of the website when available***.

ments engineering; (3) system architecting; (4) system implementation; (5) technical analysis; (6) technical management; (7) scope management; (8)verification and validation. According to this classification, FEED would be the sum of (1), (2), (3), and (5), corresponding to about 40% of SE expenditure [87]. Honour analyzed a set of projects to understand how their costs and delays change as a function of more or less SE effort. His work suggests the existence of an "optimum" level of SE, which is around 15% of the program cost (Figure 3-14). Thus, the optimum FEED level (excluding licensing) would be about $15\% \cdot 40\% = 6\%$ of the total program cost. This statistic is based on 92 projects based in United States, Australia and Israel (only Western cultures), with program total costs ranging between \$ 600,000 and \$ 5.6 billions, and program duration ranging between 2 months and 12 years. These projects include: Navy shipbuilding programs, security control systems development, shipboard control systems development, avionics systems development, aircraft power systems development, Army ground systems development, military intelligence systems development, commercial production control systems development, operational training devices systems development, communications systems development, space systems development programs. Compared to these projects, nuclear constructions are different in terms of cost, duration and nature. So the optimum indicated above might not be the right number. Still, there are no reasons why nuclear projects should not have a similar qualitative behavior (e.g. have an optimum).

We recognize that at least in theory there exist an "ideal" amount of effort to be put on the list of FEED activities above. By thoroughly addressing the tasks above, the ideal/optimal FEED effort minimizes errors in downstream tasks, minimizes uncertainty in downstream tasks, and it depends on technical complexity, uncertainty, novelty, regulatory and political environment.

Doing more than optimal FEED work might also be detrimental to the project. At a minimum, doing more work adds hours of work with little or no improvement in downstream work quality. But to the extent that extra FEED effort leads to bureaucratic increases in procedures and documentation, it may also reduce the productivity of downstream work. In summary, the level of FEED effort relative to the assumed "optimal" has an effect on both `Fraction Correct` and `Productivity`. These effects differ from error propagation and task precedence effects from FEED to downstream tasks. Even if the optimal FEED scope is done, there could be undiscovered errors in that work which propagate to following project phases. The task precedence effect represents the availability of needed upstream information, and can be active regardless of the level of FEED effort relative to optimal [70].

Figure 3-15 shows the causal model of the effect of FEED effort level on *D&P* productivity and



(a)

(b)

Figure 3-14: Actual versus planned program (a) costs and (b) schedule as a function of System Engineering (SE) effort as a percentage of program cost (adapted from [87]).

fraction correct. The same effect in *B&C* (not shown here) has a similar structure but with different parameters. `FEED Effort Relative to Optimal Effort` is at the center of the figure. Above it are the variables upon which it depends. Below it is the effect on productivity and fraction correct. `FEED Effort Relative to Optimal Effort` is normally determined by `FEED Initial Work to Do` (e.g. the FEED planned scope) divided by `FEED Optimal Effort`. `FEED Initial Work to Do` is specified as a multiple of `FEED Optimal Effort`. This structure is adopted for easy policy

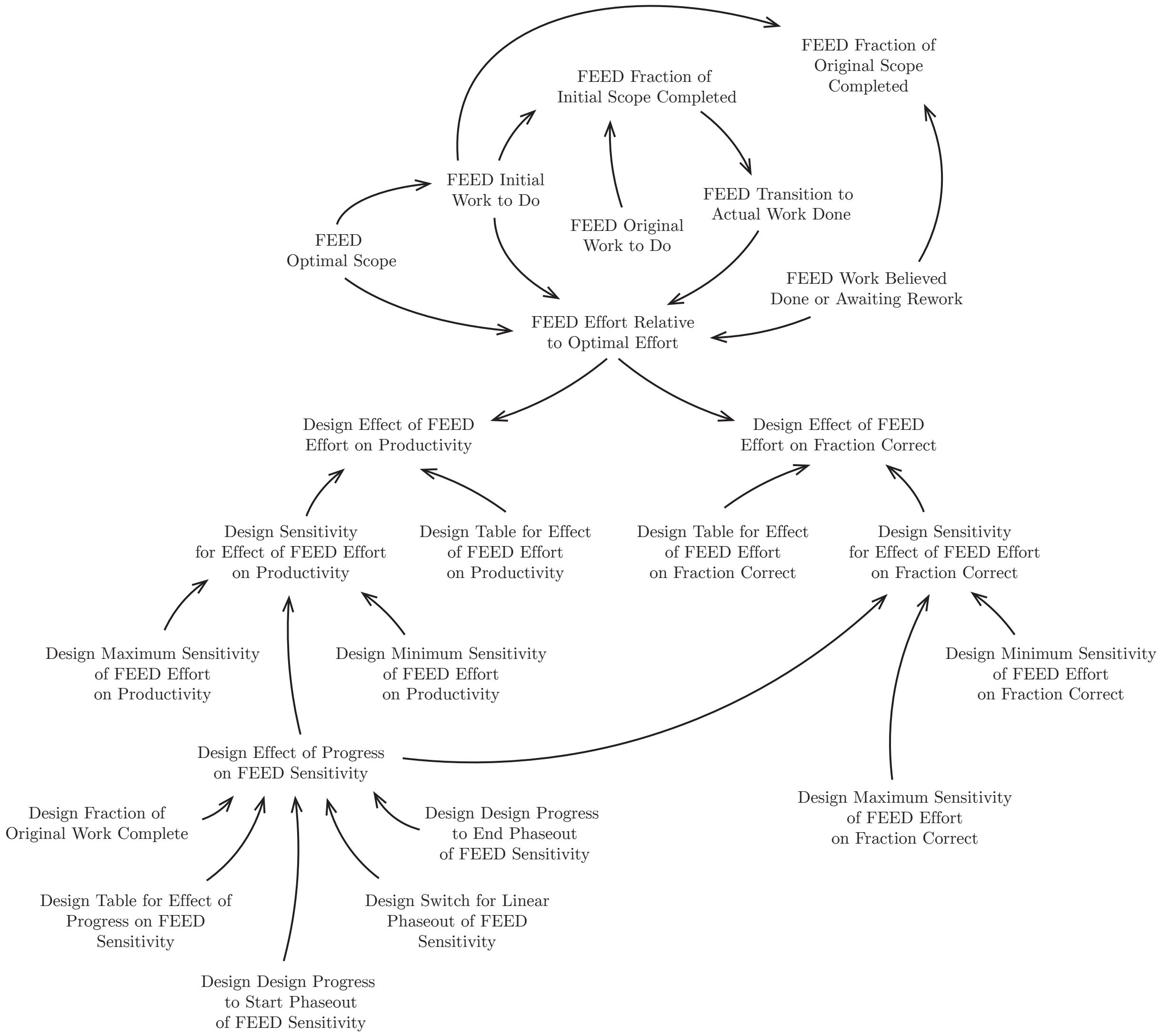


Figure 3-15: Causal structure of the effect of level of FEED effort.

testing as it allows easy changes in scope relative to optimal. Since in some situations the project might not achieve the planned scope, other variables such as `FEED Transition to Actual Work Done` are needed to switch from calculating the ratio using the FEED planned scope to using the actual FEED work done [70].

The effect of FEED effort on productivity is expressed through `Effect of FEED Effort on Productivity` and `Sensitivity for Effect of FEED Effort on Productivity`. The former is a multiplier expressing how much productivity is reduced as a function of the level of FEED effort relative to optimal. A profile that seems reasonable is shown in Figure 3-16. The x axis is the FEED effort relative to optimal. Productivity is less than 10% of the nominal value for zero effort spent on FEED activities. Then, it grows (in this case linearly) reaching the maximum in correspondence of the optimal FEED effort. As discussed earlier, productivity can decrease if too much effort is spent on FEED. The sensitivity variable allows the graphical function in Figure 3-16 to be easily adjusted. This sensitivity is a value between 0 and 1. A sensitivity of 1 yields the input curve shown in the figure; a sensitivity of 0 causes the curve to be flat at 1 (no effect). Sensitivity changes over the course of the project. For example, it might be high at the beginning of design when the FEED information is most critical, especially about requirements, but then reduce as design progresses and the current design is building more from early design products than from FEED products. The dynamic behavior (phaseout) of sensitivity over time can be input either as a lookup table or as linear function. In the latter case, the user specifies maximum and minimum sensitivity values as well as start and end times.

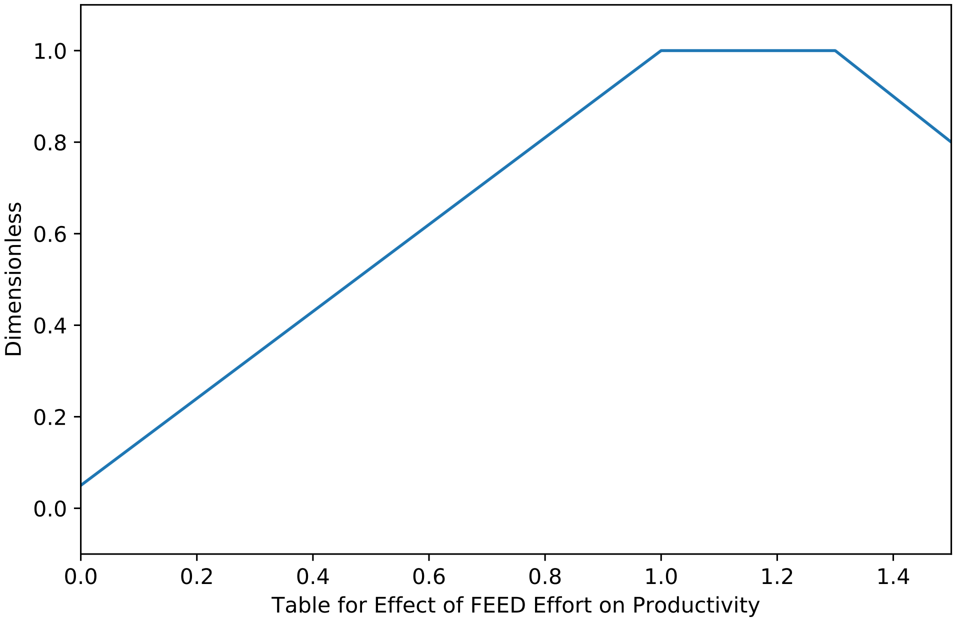


Figure 3-16: Example of table for effect of FEED level relative to optimal.

The effect of FEED effort on fraction correct has an equivalent structure, as shown at the bottom right side of Figure 3-15. `Table for Effect of FEED Effort on Fraction Correct` is similar to Figure 3-16 but we assume that it remains always flat and equal to 1 for FEED effort relative to normal greater than 1.

3.3.8 Overlap and interconnections between project phases

In our model work is conducted in phases (Section 3.3.1). Phases are nearly identical in structure, the only differences being those necessary to represent interactions between phases, and any parametric differences. One important management question is that of when to start downstream work relative to progress on upstream work. Other things remaining equal, the earlier that downstream work is started, the earlier the project will finish. Unfortunately, other things rarely remain equal. There are three important factors that determine the cost-effectiveness of starting downstream work earlier:

1. *The quality of upstream work products* (how much undiscovered rework is contained in the work products which are believed to be completed). The earlier that downstream work starts using upstream work products, the greater is the likelihood that there will still be errors in those work products, and the more likely that those errors will be built into the downstream work products. What determines the optimal start from an upstream work quality perspective?

    - The higher the inherent quality of the upstream work (i.e. due to familiar technologies, experienced staff) and the stability of the design, the higher will be the quality of the upstream work products.
    - Without other factors, the optimum would be reached when starting downstream work earlier generates sufficient extra rework to negate the benefits of the earlier start (in terms of extra cost and delayed finish).

2. *The degree to which upstream rework can be discovered by further upstream work versus downstream work.* If further upstream work, for example further reviews, can discover upstream rework, then delaying the start of downstream work may be cost-effective. However, if upstream rework cannot be discovered until various downstream work tasks are completed, then further upstream work may not be cost-effective. For example, whether or not a particular technology or technology combination actually works as designed may not be known until the product is built and tested – no amount of design review can discover that. Similarly, whether a product meets customer needs may not be known until the customer sees the product. What determines the optimal downstream start from a rework discovery perspective?

    - Rework discovery may occur in two phases: early in the downstream work (e.g., whether or not the parts fit together – "connectivity"); later in upstream work when testing occurs. It may be possible to discover the early rework in the upstream phase by early experimentation and/or teaming of design with build engineers.

- Novel technical products and novel customer relationships may have a higher fraction of rework which is only discoverable by downstream work. For products which are similar to those made before, many of the possible errors might be discovered by experienced staff through review and checking.
- On novel products, it may be desirable to design the project so as to discover these technical/customer uncertainties as soon as possible (e.g., through targeted prototypes or mockups).
- Other things being equal, the optimal downstream start would lie between when all upstream rework discoverable by upstream work was discovered at the latest, and when starting downstream work earlier would create sufficient extra rework to negate the benefits of the earlier start.

3. *The ability to execute downstream tasks given the status of upstream work products.* For some phases of work, there may be a physical constraint on starting downstream work until some upstream work is finished (e.g., testing cannot be started until a prototype is completed; a higher floor of a building cannot be started until the lower floor is completed). For other types of work, it may just be information that is needed – e.g., designs from which to build. Here the constraint may be less absolute than a physical constraint – (educated) guesses could be made to allow starting downstream tasks before the necessary upstream work is ready.

    - It does not seem that it would ever make sense to start downstream work before physical constraints are removed. Similarly for information constraints if the downstream staff were unable to accomplish any usable work. Let this situation be described by Curve A in Figure 3-17 (the curve does not need to be linear, and may reach unity before all upstream work is complete, i.e. point R). By assumption, any staff "working" on downstream tasks earlier than the Curve A completeness point operates at zero productivity.
    - At the other extreme, if schedule were a priority, it would not make sense to delay the start of downstream work (and the ramp-up of staff) beyond the point where all necessary upstream work were completed for the downstream tasks being done. Call this Curve B in 3-17 (the curve does not need to be linear).

- In between the two extremes, an earlier downstream start would mean that downstream progress is being made, but based on only partial information. Partial information increases the number of assumptions which must be made, and the chance for errors and rework. Presumably as the earlier downstream starts from the point Q and moves toward the point P, the greater the number of errors. This is called "out-of-sequence" work. As more work is performed out-of-sequence, the more errors are made.

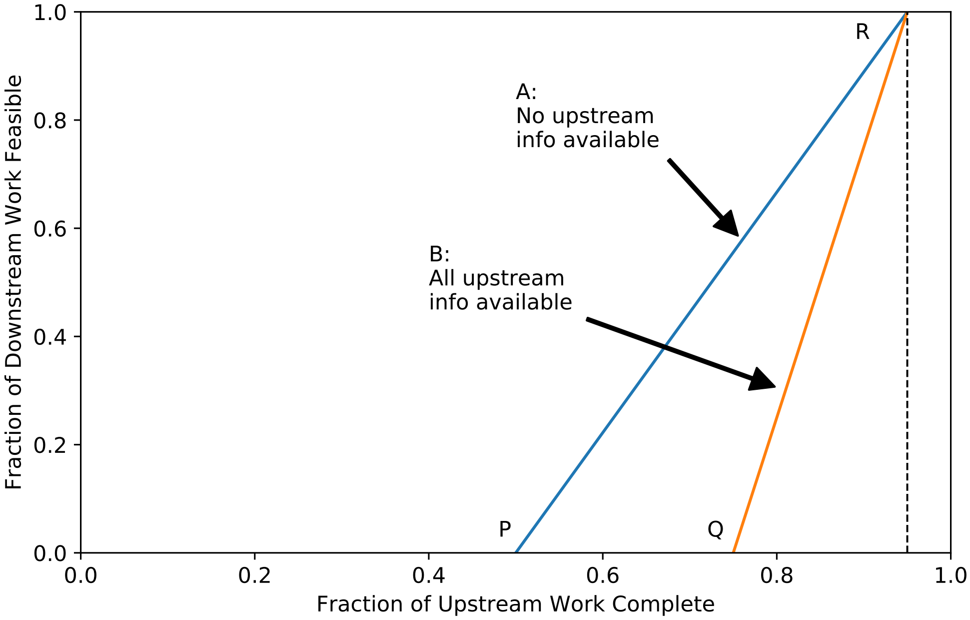


Figure 3-17: Conceptual representation of fraction of downstream work feasible as a function of upstream work completed.

In summary, the optimal start of downstream work seems to be between curves A and B in the diagram. Ramping up staff faster than that dictated by curve A would never make sense. Ramping up staff slower than indicated by curve B would only make sense if doing so would allow the upstream work quality to be improved enough to offset the effects of a delayed downstream start. In between curves A and B, the optimal strategy would depend on the quality of upstream work products and the need for downstream work to discover upstream errors.

In order to analyze the effects of different levels of overlap between phases of a project, we need to model the interconnections between those phases. Specifically, we need to specify:

1. Effect of upstream work quality on downstream work quality (error propagation).

2. Effect of downstream progress on upstream rework discovery.

3. Effect of upstream progress on the availability of information to downstream tasks.

4. Effect of downstream overlap placing demands on upstream resources.

The first three of these interconnections are shown in Figure 3-18. In most cases we assume that connections exist between the adjacent phases.

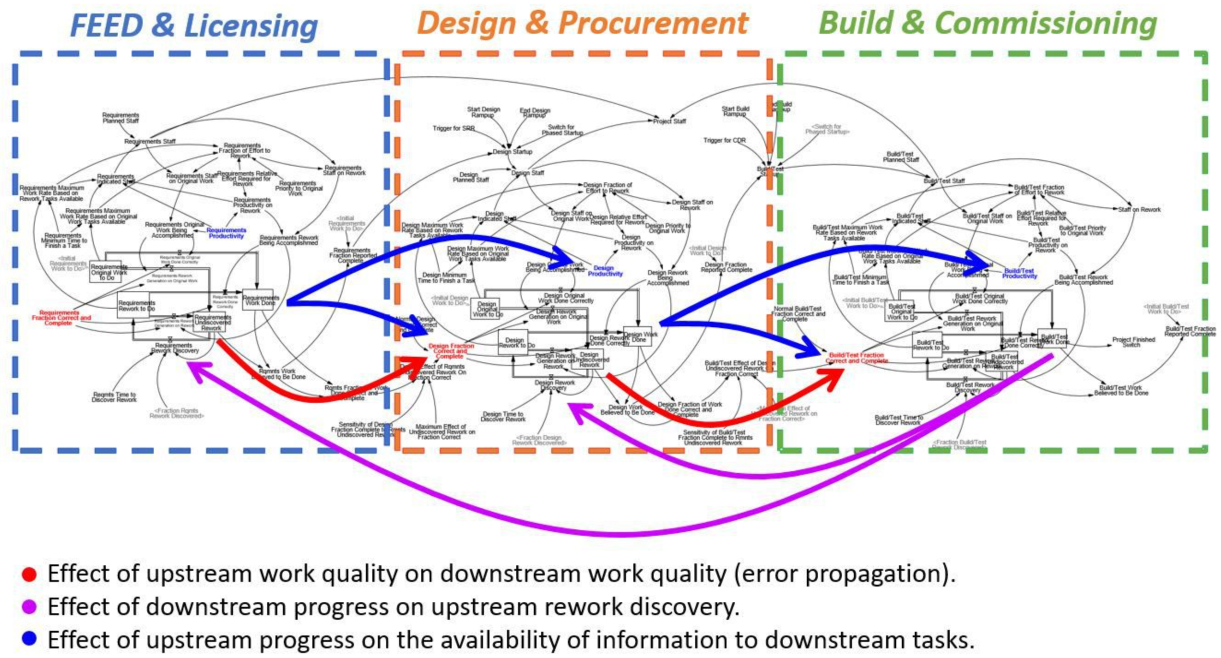


Figure 3-18: Effects of interconnections between phases.

Effect of upstream work quality on downstream work quality

Upstream errors can propagate to cause errors in downstream phases. As for error propagation within a phase of work, error propagation from upstream to downstream phases is a function of the amount of undiscovered rework in the upstream work. Undiscovered rework in the upstream phase affects the downstream phase's fraction correct. This effect is captured through (1) `Normal Effect of Undiscovered Rework on Fraction Correct` and (2) `Sensitivity of Fraction Correct to Undiscovered Rework` in the upstream phase. The former is a graphical function of the fraction of work correct in the upstream phase. The multiplicative effect is here taken as a linear function (with the provision that the effect does not go to 0). If fraction of undiscovered rework in the upstream phase is equal to 0, then the input to the graphical function is unity, and the output is unity. The sensitivity is time dependent (we assume it reduces as the project progresses) and it is expressed through a maximum and a minimum value. If sensitivity is 0, upstream errors do not propagate. If unity, upstream errors propagate in direct proportion to their fraction of upstream work done. For example, if 50% of the upstream work contains undiscovered rework, then 50% of the downstream tasks being done will have an error, other factors being equal.

Effect of downstream progress on upstream rework discovery

In a multi-phase model, rework discovery can occur as a result of work within a phase as well as work in a downstream phase. Here, *F&L* rework discovery can occur because of downstream *F&L* work, because of downstream *D&P* work, and/or downstream *B&C* work. *D&P* rework discovery can occur because of downstream *D&P* work and/or downstream *B&C* work. Unfortunately, representing this process is actually somewhat complicated, involving "co-flows". In models with only one phase, `Rework Discovery` (tasks per unit time) is:

$$\texttt{Rework Discovery} = \frac{\texttt{Undiscovered Rework} \cdot \texttt{Fraction of Rework Discovered}}{\texttt{Delay in Discovering Rework}}$$

where `Fraction of Rework Discovered` is a graphical function of work progress [8].

In our three-phase model, rework discovery is driven by the same forces. The difference is that in each phase `Fraction of Rework Discovered` is split into the multiple contributions. So, for example rework discovery in *F&L* has three components: `Fraction of F&L rework discovered by F&L, by D&P, and by B&C`; rework discovery in *D&P* has two components: `Fraction of D&P rework discovered by D&P, and by B&C`; rework discovery in *B&C* has one component: `Fraction of B&C rework discovered B&C`. The dynamic behavior of rework discovery in each phase is input by the modeler through a graphical function that depends on the project's characteristics such as novelty, complexity, tasks sequence, testing and validation procedures. Figure 3-19 illustrates an example of how upstream phase (in this case *F&L*) rework discovery depends on downstream phase progress (in this case *D&P*). For each phase, the modeler specifies the maximum fraction of rework discoverable in each other phase, which is also a function of the project's characteristics. Each phase can discover up to as much rework defined by the maximum, regardless of anything else. Since we assume that by the end of the project there remain no undiscovered rework, the sum of those fractions in each phase must be unity.

---

[8] The effect of work rate is omitted in this discussion for simplicity.

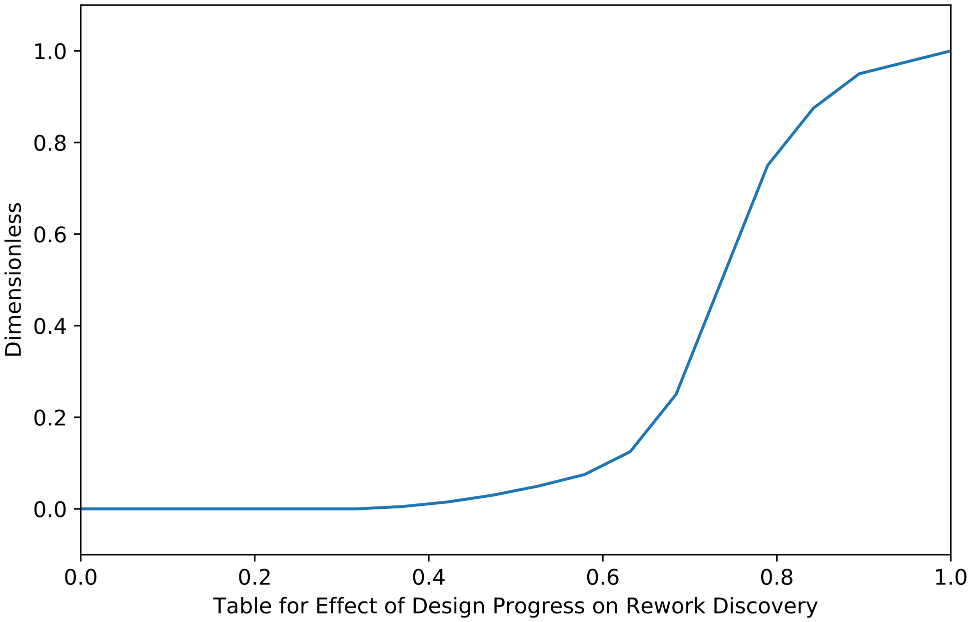


Figure 3-19: Example of effect of *D&P* progress on *F&L* rework discovery.

Implementing the concept of a maximum amount of rework discoverable by each phase requires a somewhat complex "co-flow" structure. Figure 3-20 shows a simplified version of this structure for *D&P*. The word "Design" at the beginning of a variable indicates that it belongs to the *D&P* phase. The other phases are conceptually similar. At the right of the figure, `Design Rework Generation` is split into two flows: `Design Rework Generation to be Discovered by Design` and `Design Rework Generation to Be Discovered by Build`. The split depends on `Maximum Fraction of Design Rework Discoverable by Design Work`. The corresponding stocks `Design Undiscovered Rework Discoverable by Design` and `Design Undiscovered Rework Discoverable by Build` (which sum to `Design Undiscovered Rework`) are then depleted by `Design Rework Discovery by Design` and `Design Rework Being Discovered by Build`. These outflows are constrained by the amount of rework in the stocks, thereby limiting the maximum rework discoverable by design work to the specified limit. It is possible, however, that less than the maximum will actually be discovered by *D&P* work, and therefore the flow `Design Remaining Rework Discovered by Build` depletes any remaining `Design Undiscovered Rework Discoverable by Design`. As in a model with one phase only, the flows of rework discovery equal the associated stock of undiscovered rework multiplied by the fraction of rework discovered, and divided by delay in discovering rework.

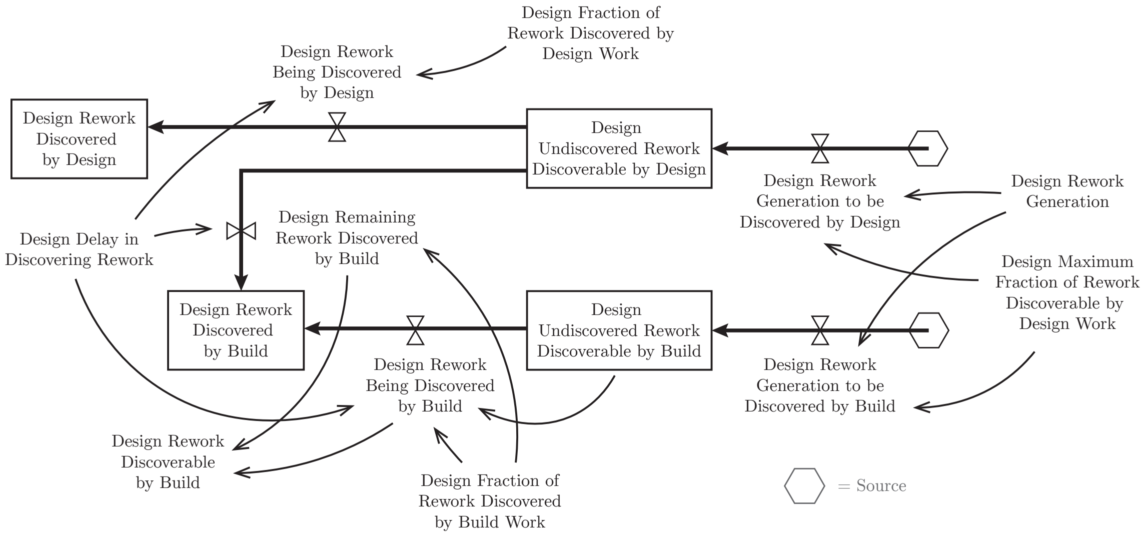


Figure 3-20: Simplified rework co-flow structure for *D&P*.

The structure for *F&L* rework discovery is identical to that for *D&P* rework discovery except that there are three sources of possible discovery rather than two. The *B&C* does not have downstream phases. However, it is possible with sufficient overlap between phases that upstream progress can discover propagated errors to downstream work. A structure to represent these phenomena is shown in Figure 3-21. Again, co-flows are necessary to represent the split of *B&C* undiscovered rework between that attributable to *D&P* (and therefore discoverable by *D&P*), and that attributable to *B&C*. On the right of the figure, `Build Rework Being Generated` is split into two flows based on `Build Fraction of Rework Generation Attributable to Design`. Unlike the prior structures where the split was exogenous, here the split will be calculated based on the source of the rework. Rework discovery from the co-flows is determined on the left by `Build Rework Discovery from Design` and `Build Rework Discovery from Build`.

Effect of upstream progress on the availability of information to downstream tasks

"Precedence" or "availability" effects occur when downstream work gets ahead of the information provided by upstream work progress. Here we illustrate the effect of *D&P* progress on *B&C* progress. The structure for the effect of *F&L* progress on *D&P* progress is identical, but with a different parametrization.

D&P progress can affect both *B&C* productivity and fraction correct if *B&C* gets ahead of the available *D&P*. The effect is determined by `Build Design Shortfall` and illustrated in Figure

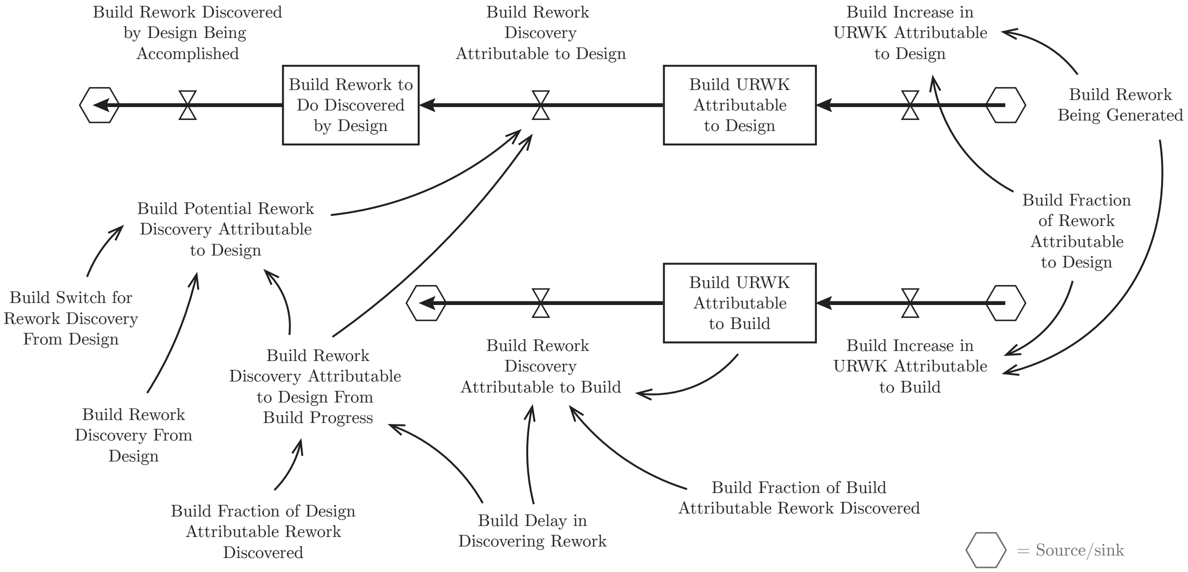


Figure 3-21: Simplified rework co-flow structure for *B&C*.

3-22. `Build Design Shortfall` is a function of `Build Required Design Progress` (the amount of *D&P* work that *B&C* needs at any point) relative to *D&P* actual progress as measured by `Design Fraction Reported Complete`.`Build Required Design Progress` can be input either as a graphical table (function of *B&C* progress) or simply as a linear function. The linear function is defined by the fraction of upstream phase required progress when the downstream phase starts and ends. Figure 3-23 shows an example of how such graphical table could look like: 50% of *D&P* work is needed by the time *B&C* starts. The curve rises relatively quickly during the early stages, then it slows down and it reaches 100% only at the end of *B&C*.

`Build Design Shortfall` then drives the effect on *D&P* productivity and fraction correct. The effect on productivity is expressed by `Build Table for Effect of Design Shortfall on Productivity`, e.g. a graphical function that depends on the ratio between *D&P* shortfall and the *D&P* shortfall required to hit zero productivity.

The extent to which the shortfall affects productivity versus fraction correct is controlled by `Build Managerial Willingness to Charge Ahead of Design`. This variable captures the attitude/strategy of the management team in face of a shortfall. Holding back (not proceeding with *B&C*) in the face of a *D&P* shortfall reduces productivity because some *B&C* staff must remain idle; but at the same time since those tasks are not done, rework is not created but OOS work increases. Charging ahead reduces the effect on productivity because tasks are done, but it increases the effect on fraction correct because without the necessary information from the previous phase those tasks are more likely to include errors.

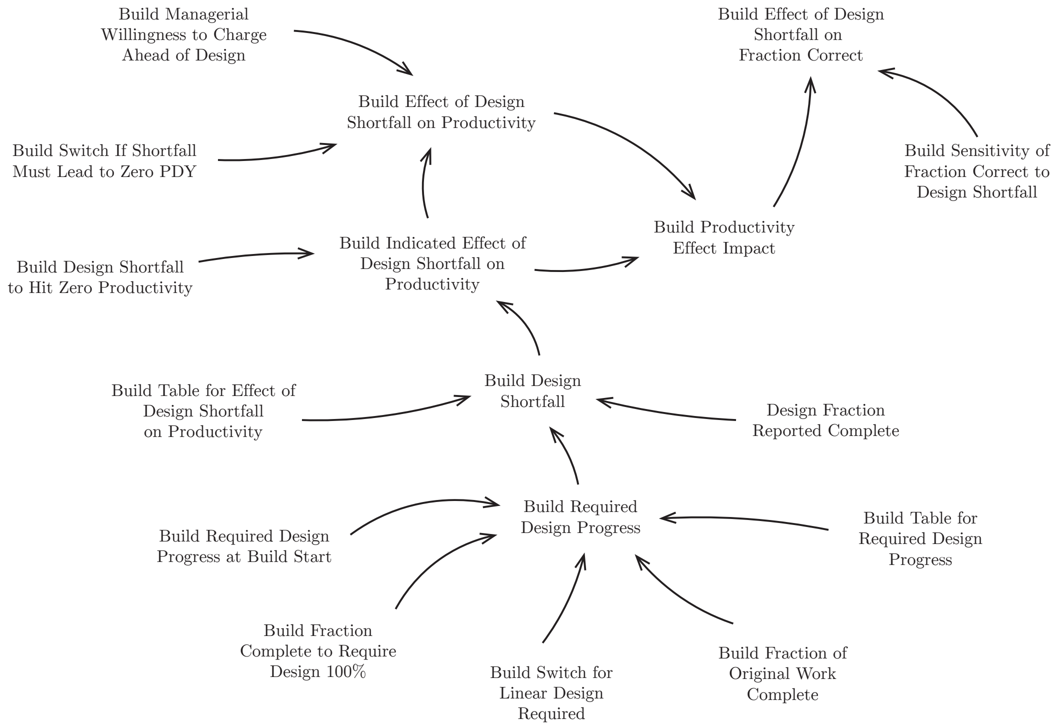


Figure 3-22: Effect of *D&P* progress on *B&C* progress.

The structure for the effect of *F&L* progress on *D&P* progress is identical to the structure described above for the effect of *D&P* progress on *B&C* progress. However, the parameterization is likely to be different.

Effect of downstream overlap placing demands on upstream resources

There are two important effects of downstream work on upstream workload:

- Downstream discovery of upstream workload creates downstream and upstream coordination needs (rework coordination);
- Concurrency between downstream and upstream work can create a coordination workload on upstream staff (concurrency coordination).

Regarding rework coordination, in a one phase model both the discoverer and the fixer of rework come from the same aggregate staff. Therefore, `Relative Effort Required for Rework`

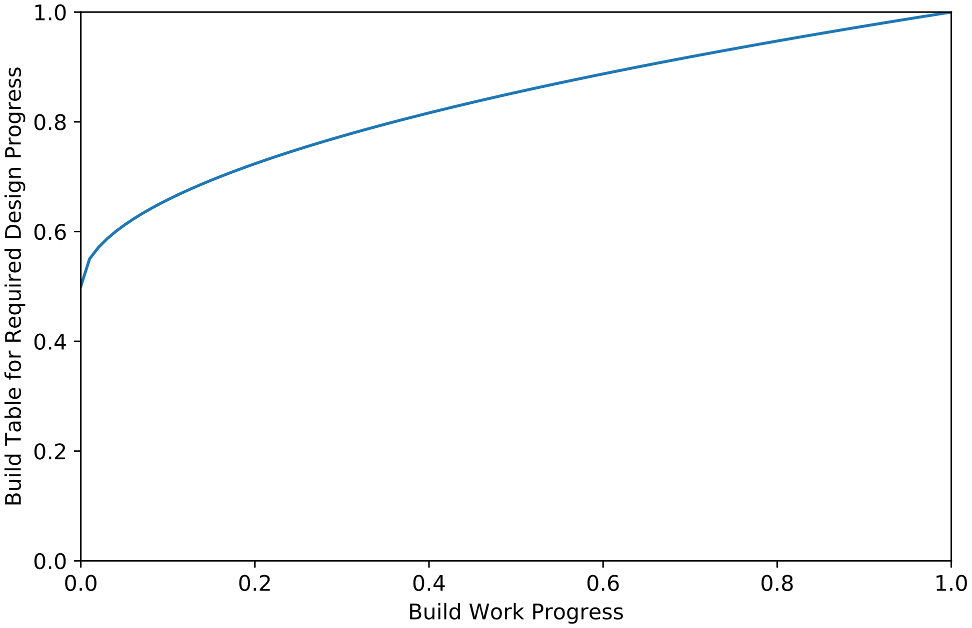


Figure 3-23: Example of required *D&P* progress as a function of *B&C* progress (graphical table).

`Coordination` for tasks discovered within a phase of work is multiplied by a factor two. With a multi-phase model, some rework may be discovered in another project phase, such that the discoverer is now in a different staff category in the model than the doer (assuming each phase of work has a distinct staff). The effort for rework coordination is correspondingly split between different sectors.

Regarding concurrency, the effect is expressed in terms of the amount of work needing extra coordination in the upstream phase, adjusted by a sensitivity factor set by the modeler. All phases have identical structures.

3.3.9 Size and availability of buffer management and technical team

One important activity of SE is ongoing scope management and technical leadership/management. According to Honour [87] in successful projects these activities represent about $20\% \cdot 15\% = 3\%$ of the total program cost. The effort required by these activities ramps up during *F&L*, and it increases even more later in the project. Successful projects are hypothesized to have higher levels of these activities than unsuccessful projects. Figure 3-24 shows the structure capturing the effect of ongoing scope management and technical leadership/management on the project.

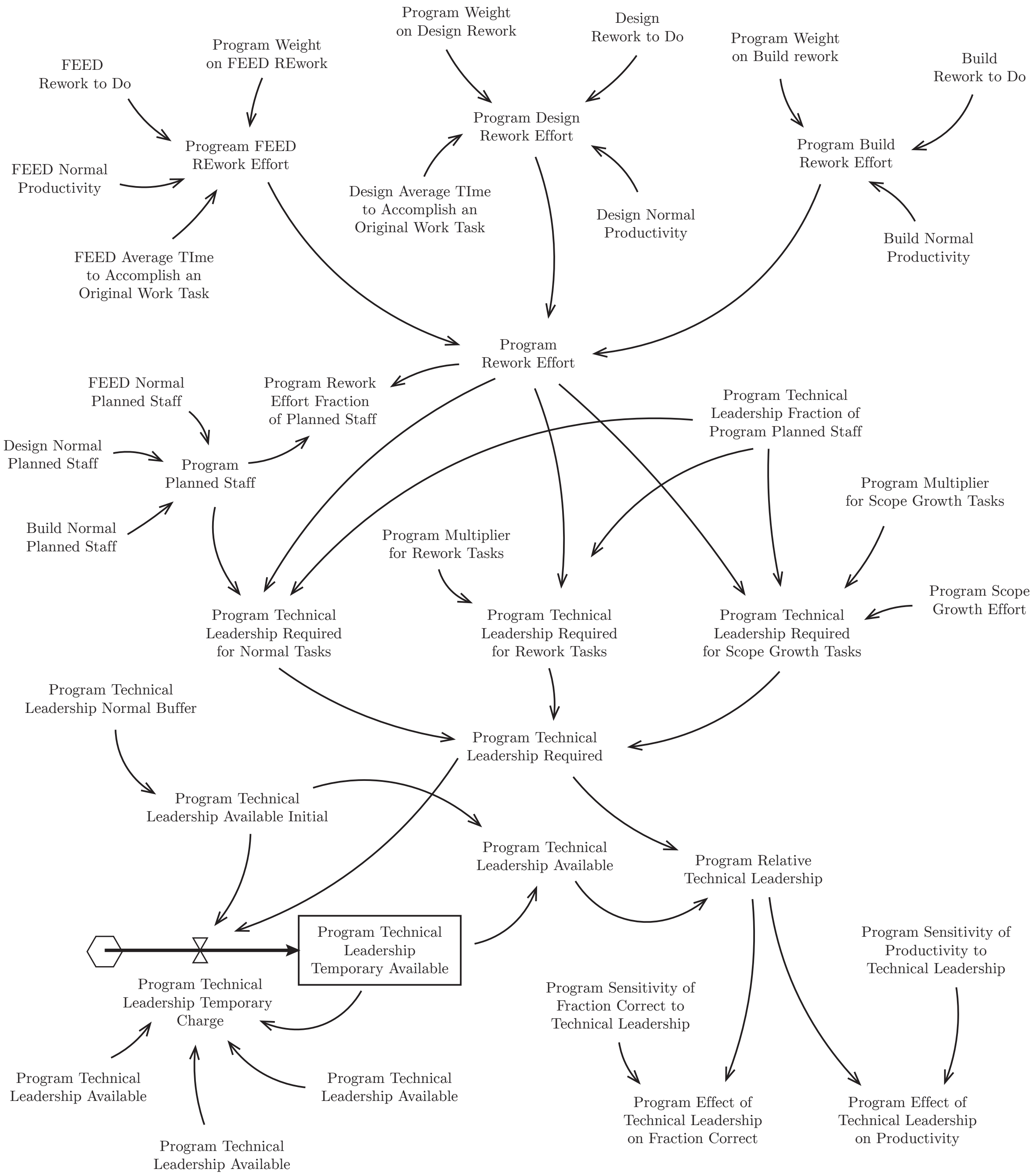


Figure 3-24: Causal structure of the effect of management and technical leadership team requirements.

Scope management and technical leadership/management are here jointly call “Program Technical Leadership”. `Program Technical Leadership Required` (in units of people) is shown at the center. On its left we see that the management/technical leadership team is needed for normal planned work, for rework tasks, and for scope growth tasks. The first is a constant that depends on `Program Planned Staff`. The second depends on the total rework effort and it can be adjusted by `Program Multiplier for Rework Tasks` allowing rework tasks to carry a different weight in leadership requirements. `Program weight on FEED/Design/Build Rework` are used to assign a different weight respectively to *F&L*, *D&P* and *B&C* tasks. The third is a function of the total program scope growth, adjusted by a sensitivity multiplier. The total `Program Technical Leadership Required` is the sum of these three factors multiplied by `Program Technical Leadership Required Multiplier for Project Problems`, which can be used to capture external impacts on the project.

`Program Technical Leadership Available` can be a constant or respond to changes in required leadership. The initial management/technical leadership staff available (for example 5% of the total project staff) is set by the user. The model also includes a management/technicla leadership buffer. This is added for policy testing, and it helps to answer questions such as: "Is it a good idea to have a buffer of management staff that remains idle for some time during the project, and intervenes only in case of excessive rework and/or extraordinary circumstances?".

Besides this "fixed" buffer, the model can also simulate temporary allocation of management/technical leadership staff. This is represented by the stock and flow structure on the right of Figure 3-24. The stock `Program Technical Leadership Temporary Allocation` increases (or decreases) `Program Technical Leadership Available`. The rate of addition of temporary new staff (e.g. `Program Tech Leadership Temporary Change`) is a function of staff required at a given point in time (limited by an upper threshold because in reality we do not add staff indefinitely) and `Program Tech Leadership Change Delay`, which captures the time required to transfer and get up to speed of temporary management/technical leadership staff.

`Program Relative Technical Leadership` (which is the ratio of staff available and required) drives the effect on both program fraction correct and productivity (top right of Figure 3-24), each adjusted by a sensitivity factor. This effect is the same for *F&L*, *D&P*, and *B&C*. However, the consequences of each on the project are different because the number of task in each phase is different.

3.3.10 Suppliers problems and suppliers coordination

Suppliers and subcontractors are often important stakeholders on a project. How can their effect on project dynamics be represented? The first consideration is how significant their role is in the project. There is a difference between *subcontractors* and *suppliers*. We define subcontractors as organizations which take on a major role in the design and perhaps build of the project. There are several ways of representing subcontractors:

- As separate *D&P* and/or *B&C* rework cycle building blocks. Such building blocks would be represented in a multi-phase model as parallel phases of work. For example, *D&P* might be represented as two (or more) parallel phases, one which represents the prime contractors design effort and others representing subcontractor design efforts. Precedence constraints would exist between the parallel phases;
- As a separate source of staff in one rework cycle building block. Staff would be disaggregated into prime contractor staff and subcontractor staff;
- As a simplified supplier entity as discussed below.

Which of these to choose would depend on the relative amounts of work performed by each contractor, the closeness of the working relationships between the contractor teams, and the amount of information and data available.

Suppliers are assumed to be organizations with a more minor roles in the project, ones that do not warrant a full rework cycle building block. For example, they provide a specific component or subsystem to the build process. Suppliers need be represented only if they have a significant effect on the dynamics of the project. Specifically, if their performance affects the productivity and/or fraction correct of the prime contractor. If supplier performance is completely independent of the prime contractor, then their effect on the project can be represented by exogenous inputs. However, if their performance is affected by the prime contractor, then in order to be able to do policy and scenario tests supplier performance will need to be represented endogenously. The effect of the prime contractor will come through progress and work quality of the prime contractor in releasing requirements, designs, and other information to the supplier.

The structure of the effects of suppliers is shown in Figure 3-25. This structure can be used to represent all important suppliers, or it can be duplicated to represent specific suppliers or groups of suppliers. In our model this structure is replicated twice, one for *D&P* and the other for *B&C*. On the top left side of the figure is the flow of work of suppliers. `Supplier Work Released` is the rate at which tasks are assigned to suppliers to work on. It is a function of the time it takes to release work, and the amount of work that is ready to be released. The latter is captured by `Fraction of`

`Supplier Work That Can be Released`. This curve can be input either directly as lookup table that depends on project progress, or as a linear function between two points. In both cases, the shape of the curve depends on the type of project and its construction schedule. `Supplier Work Released` accumulates tasks into the stock `Supplier Work in Progress`, which in turn is depleted by `Supplier Work Rate` (Figure 3-25).

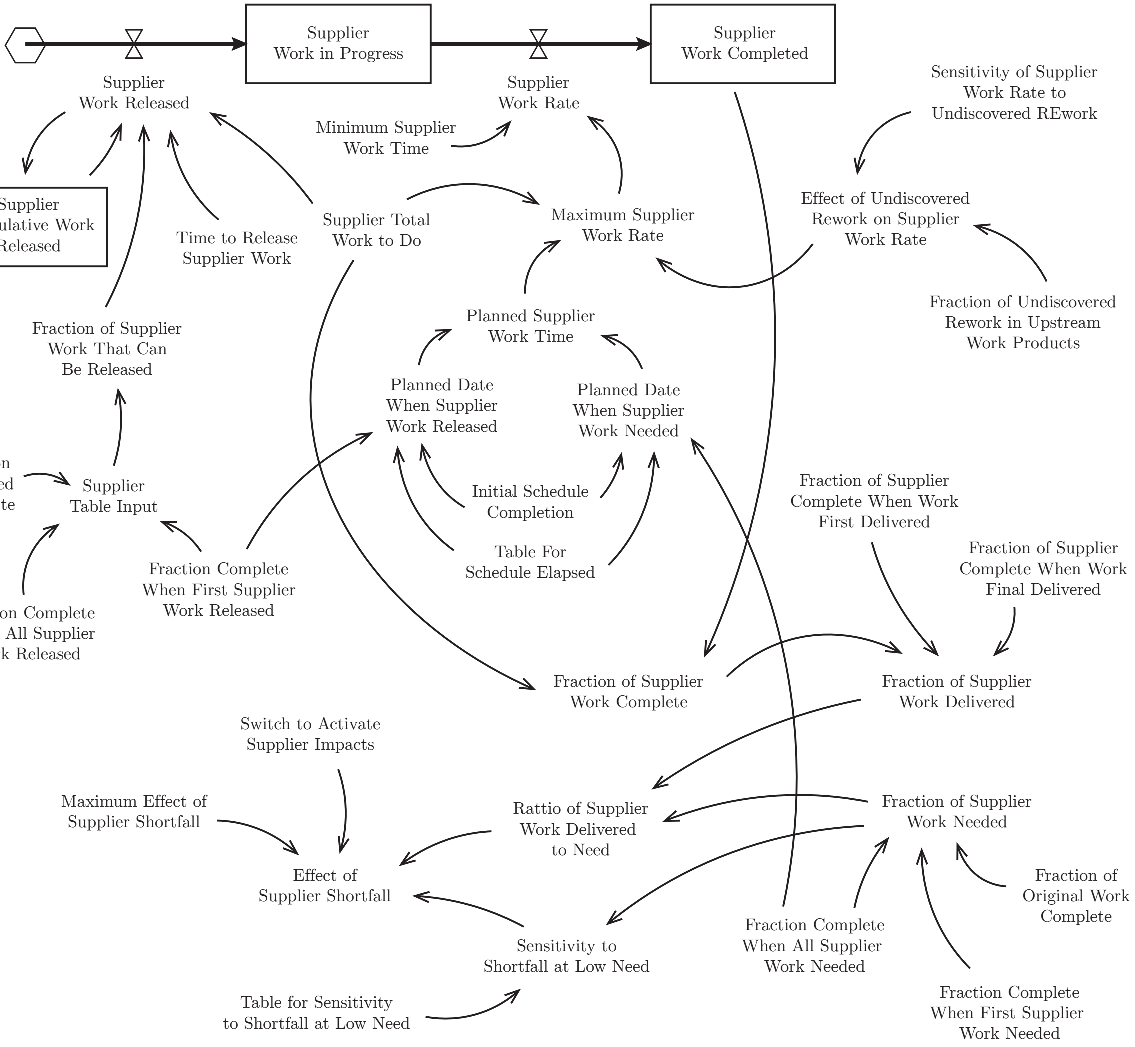


Figure 3-25: Causal structure of the effect of suppliers.

`Supplier Work Rate` is the minimum of two terms: `Maximum Supplier Work Rate` and the ratio between `Supplier Work In Progress` and `Minimum Supplier Work Time`. The first term is the operative work rate; the second term constrains the work rate to avoid negative values for the stock of work in progress, and sets it to zero when the work is done. `Maximum Supplier`

`Work Rate` is nominally `Supplier Total Work to Do` divided by `Planned Supplier Work Time`. In other words, the suppliers work rate is assumed to be constant. However, we use `Effect of Undiscovered Rework on Supplier Work Rate` as a way to represent the effect of design changes on suppliers. Here we assume that `Design Undiscovered Rework` causes the `Supplier Work Rate` to decrease from the maximum. This might occur because of the discovery of errors and the need to rework them, and also because of reductions in productivity from changes in design information from the prime contractor.

`Supplier Work Rate` (tasks per unit time) feeds the `Supplier Work Completed` stock. Then, `Fraction of Supplier Work Delivered` is compared with `Fraction of Supplier Work Needed` at any point in time (Figure 3-25 on the right). A shortage has an effect on productivity and/or fraction correct. The effect is controlled by a sensitivity factor. In particular, `Sensitivity to Shortfall at Low Need` reduces the impact of Supplier shortfalls when the `Fraction of Supplier Work Needed` is low. For example, consider two situations: a 50% shortfall when the needed materials are 100%, and a 50% shortfall when the needed materials are 10%. Arguably, the second situation would produce less of an impact than the first. `Sensitivity to Shortfall at Low Need` is a graphical function of `Fraction of Supplier Work Needed` as shown in Figure 3-26.

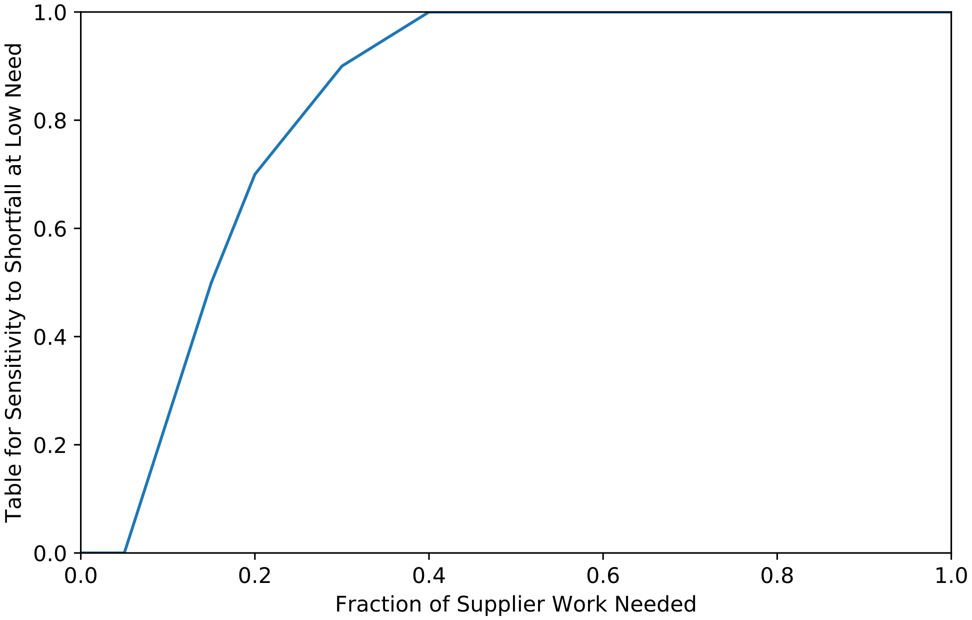


Figure 3-26: Table for sensitivity to suppliers shortfall at low need.

3.3.11 Scope growth and project changes

Scope growth and changes represent an increase in the number of tasks that need to be done on the project. Depending on what causes them, we distinguish between:

- Task growth from scope;
- Task growth from rework;
- Task growth from progress;
- Changes.

The first mechanism, `Task Growth From Scope`, reflects purely exogenous drivers of scope growth on the project, such as from customer or regulatory changes. In the model only one step change in scope is provided independently for each phase of work (*F&L*, *D&P*, and *B&C*). When modeling an actual project, exogenous scope growth is more likely to occur in a series of changes over the course of the project, and so in future model versions either additional step changes will be needed, or a graphical function can be used. In the current version of the model, `Task Growth From Scope` is captured by three variables: `Time of Task Growth`, `Duration of Task Growth` and `Magnitude of Task Growth`. The latter is expressed as a fraction of initial work to do. The three variables define a rectangular function whose height is defined the magnitude divided by the duration.

The second mechanism, `Task Growth From Rework`, reflects that sometimes rework adds scope. Examples of this might include: (1) fixing the error requires removing something already built, thereby adding additional tasks; (2) fixing a software error requires adding code (i.e. fixing error takes more work than effort on the original task). Two variables are used: `New Tasks Created Per Rework Tasks` (the "magnitude" of the mechanism) and `Table for Timing of Rework Based Task Growth` (the dynamic behavior over the project). Both depend on many factors such as type of project, product and team experience. In practice, these are difficult to determine. However, data from prior projects can help define the possible range for this parameters. The project plan can then reflect either an average or a best or worst case. `Task Growth From Rework` is provided independently for each of the three phases.

The third mechanism, `Task Growth From Progress`, depends on downstream progress to recognize additional scope. In many situations, downstream work leads to the recognition of unknown scope. This mostly occurs on technically novel projects, for example if: (1) downstream work identifies tasks that need to be done but were not thought of in initial planning; (2) assumptions in design prove incorrect and the subsystem does not work as thought, which creates additional tasks needed to accomplish required performance. `Task Growth From Progress` is described by two variables: the magnitude of scope growth (in each phase), and a graphical table controlling the timing of task growth from progress (within the phase and in the downstream phases).

`Changes` represent truly exogenous effects which make obsolete work that was previously done correctly and now must be redone. Changes might result from new customer requests, unanticipated market shifts, new regulatory or legal requirements, and so on. Changes are different from rework in that their occurrence cannot be anticipated ("unknown unknowns"). Changes remove work from `Work Done` and move it to `Rework to Do`. We assume that changes do not affect `Undiscovered Rework`, as that work already needs rework. For each phase, the changes are input using three variables: `Time of Change`, `Duration of Change` and `Magnitude of Change`.

3.4 SD Model setup, calibration and validation

3.4.1 Ideal case (no rework)

In the ideal case there is no rework and consequently no delays. Everything goes as planned and the total effort is just the sum of effort required to perform each activity. The ideal case is not realistic. However, building the actual case incrementally, starting from the ideal case should help the reader following the process. The effects of all structures are previously discussed.

The first information needed to set up the ideal project simulation are: scope of each phase (number of tasks to do), planned project schedule (tasks duration and overlap between phases), and staffing information (workforce requirements over time). The IAEA Manpower Development for Nuclear Power Guidebook [82] suggests approximate staffing levels for each activity separately as a function of project progress. Each curve is normalized to the peak number of people. Table 3.1 shows these activities and their peak staff values. One of such curves is shown in Figure 3-27. On the x axis are the years before start of commercial operations. Below the x axis is an approximate indication of duration and overlap of the sub-activities. On the y axis is the expected number of people required. The peak manpower for manufacturing equipment and components is about 3,000 people (Table 3.1).

Both the shape and the staff levels characterizing these staffing curves are project-specific. In

Activity	**Approximate number of people at peak (100%)**
Pre-project activities	30
Project management	100
Project engineering	370
Procurement of equipment and materials	30
Quality assurance and quality control	100
Manufacturing of equipment and components	3000
Plant construction	2000
Plant commissioning	200
Plant operation and maintenance	220
Licensing and regulation	50

Table 3.1: Manpower loading (peak) for nuclear project activities (adapted from [82]).

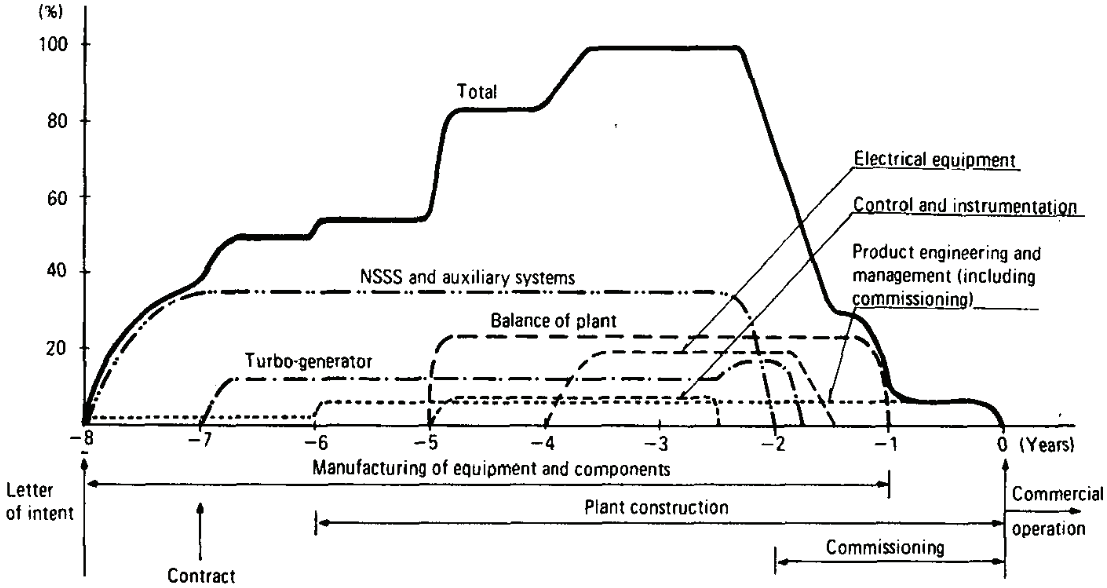


Figure 3-27: Staff requirements for manufacturing of equipment and components (adapted from [82]).

fact, the IAEA specifies that:

- The tables are meant to provide guidance of general applicability for the assessment by each particular country and organization of its own manpower requirements on the basis of its needs and resources;

- For nuclear power project-oriented activities, the tables refer to a single unit in the size range of 600 to 1300 MW_e;

- Manpower requirements are usually presented as a range with upper and lower values. Here the numbers should be interpreted as indications of orders of magnitude.

These data are limited to the IAEA member states up to 1980, when the document was published and most U.S. nuclear plants just finished construction. We processed and combined all these data in Figure 3-28. A logarithmic scale is used for the y axis. Figure 3-28 shows three interesting features. First, there is a significant overlap between all activities. Second, most people are required in the second half of the project.

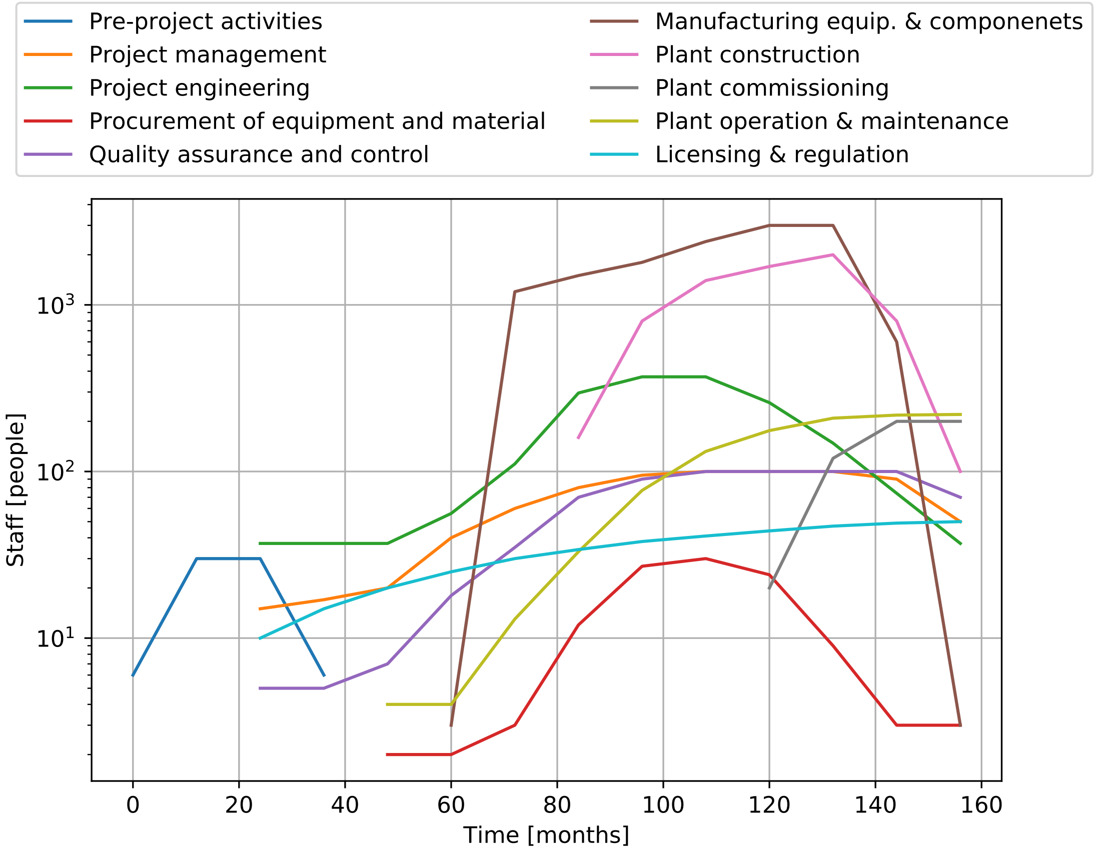


Figure 3-28: Staff requirements divided by project activities (adapted from [82]).

Our model does not treat each activity separately. Instead, activities are assigned to either of the three model phases: *F&L*, *D&P*, or *B&C*.

- *F&L*: pre-project activities, licensing and regulation;
- *D&P*: project engineering and procurement of equipment and materials;
- *B&C*: manufacturing of equipment and components, plant construction, plant commissioning and plant operation and maintenance training (only up to start of operations).

Staff required for project management, quality assurance and quality control are excluded because the model accounts for them separately. Figure 3-29 shows the resulting staffing curves of each phase. Note the significant overlap between *D&L* and *B&C*, as well as the relatively little effort planned for FEED as opposed to the rest of the project. The area under each curve represents the required effort (person-month) for that phase.

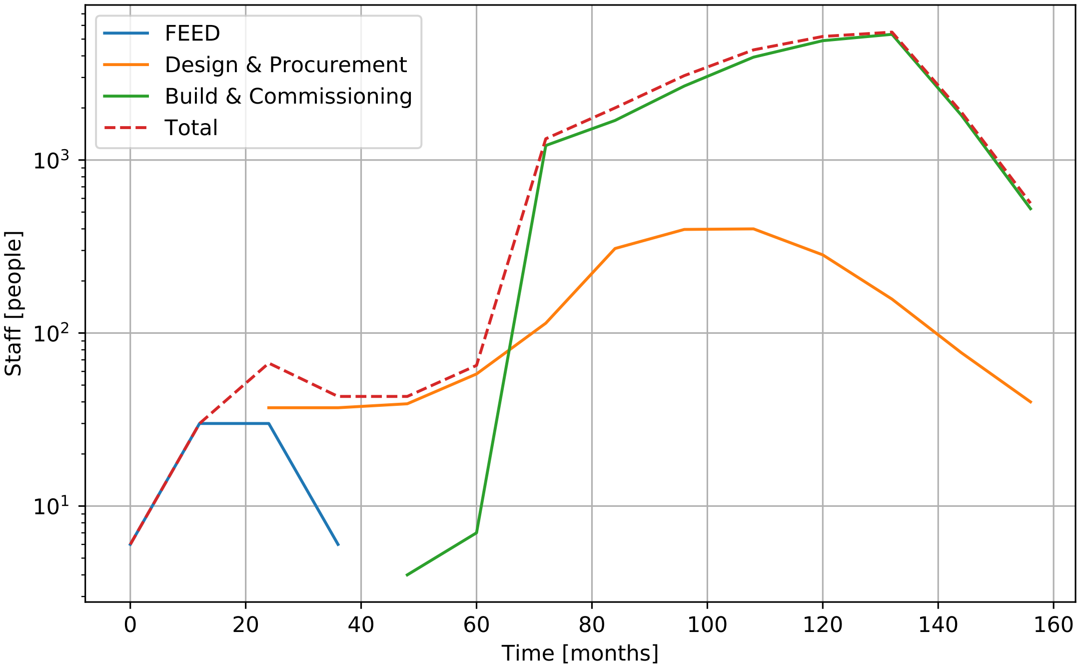


Figure 3-29: Staffing profiles by nuclear project phase.

Planned project schedule (tasks duration and overlap) and staffing information can be extracted from these figures. In the ideal case all sources of rework are set to zero: it is assumed that all tasks are performed correctly the first time. Then, the model is tuned in order to fit the planned staff profiles. The main time variables are:

- `Final Time` = 320 [months], i.e. about twice the total project duration (156 months);
- `Time Step` = 0.0625 [months].

Work is defined in terms of *tasks*, where a task is the amount of work that one person can do in a month. Therefore, in the ideal case `Productivity` is one task per person per month. Scope, staff, duration and productivity must be consistent for each of the three phases. So for example if a generic phase lasts 10 months and scope is 300 tasks, then phase staff must be set to 30 people (assuming level-loaded staff and productivity equal to one task/month/person). However, the curves in Figure 3-29 are far from being rectangular functions, so it was necessary to develop structures allowing for staff ramp-up and ramp-down. It is assumed that task sequence and staff profile are coordinated: we ramp-up staff with the increase in tasks available to work on, and ramp-down staff with the decrease in tasks available at the end of the project. Figure 3-30 shows the parametrization of staff ramp-up and ramp-down.

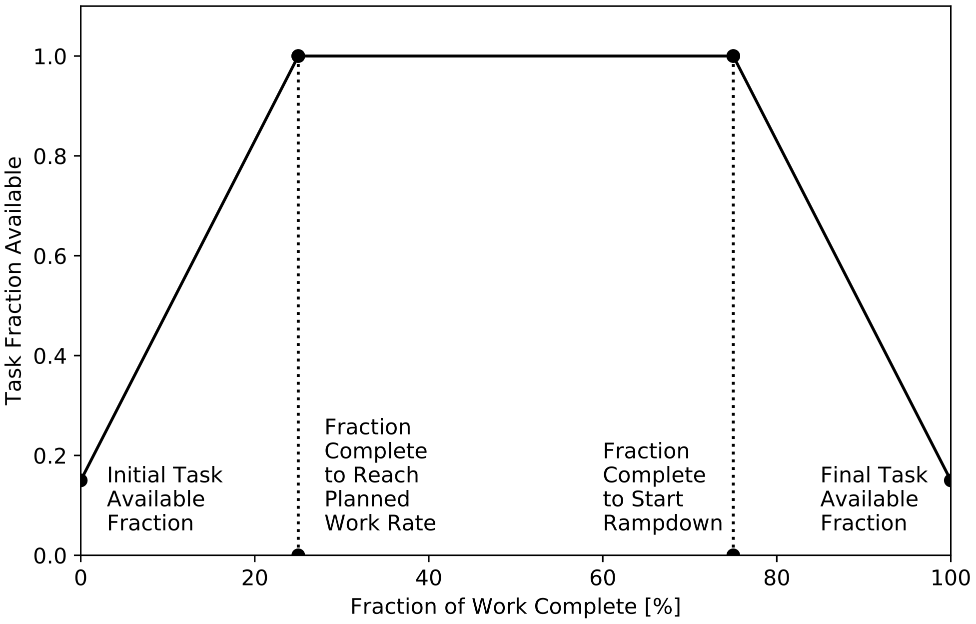


Figure 3-30: Parametrization of staff ramp-up and ramp-down.

The linear ramp-up in Figure 3-30 is in fact somewhat exponential when simulated. This is the result of linear input table in combination with continuous simulation, which creates a reinforcing feedback slightly accelerating the rate at which `Planned Work Rate` reaches its maximum. Progress (`Fraction Reported Complete`) increases `Task Rampup`, which is just a multiplier for the work rate. `Task Rampup` in turn increases progress, further accelerating `Task Rampup`. The opposite applies to ramp-down, where the exponential behavior draws out the end of the project. Progress reduces staff, which slows the rate of progress, but since it is still increasing staff is reduced further.

Since staff profiles are neither rectangular nor trapezoidal it is somewhat complicated to calculate their integrals, which are proportional to scope. Iteration was necessary to ensure consistency between scope, staff, duration and productivity. R is the ratio between the integrals of simulated staff curve and IAEA data curve. Ideally, this should be equal to unity, but excessive precision is not justified as the IAEA values are just approximations. Figure 3-31 compares the simulated total project staff (sum of *F&L*, *D&P* and *B&C*) with the reference IAEA data. The calibration is satisfactory: the model has enough degrees of freedom to reproduce the non-linear complex curves and R is within a few percentages away from the target. Note the exponential character of ramp-up and ramp-down mentioned above. The project finishes on time (156 months) because there is no rework in the ideal case. Project effort increases slowly for about 60 months, then *D&P* and *B&C* kick in, and the effort starts growing faster following a S-shape behavior, as expected.

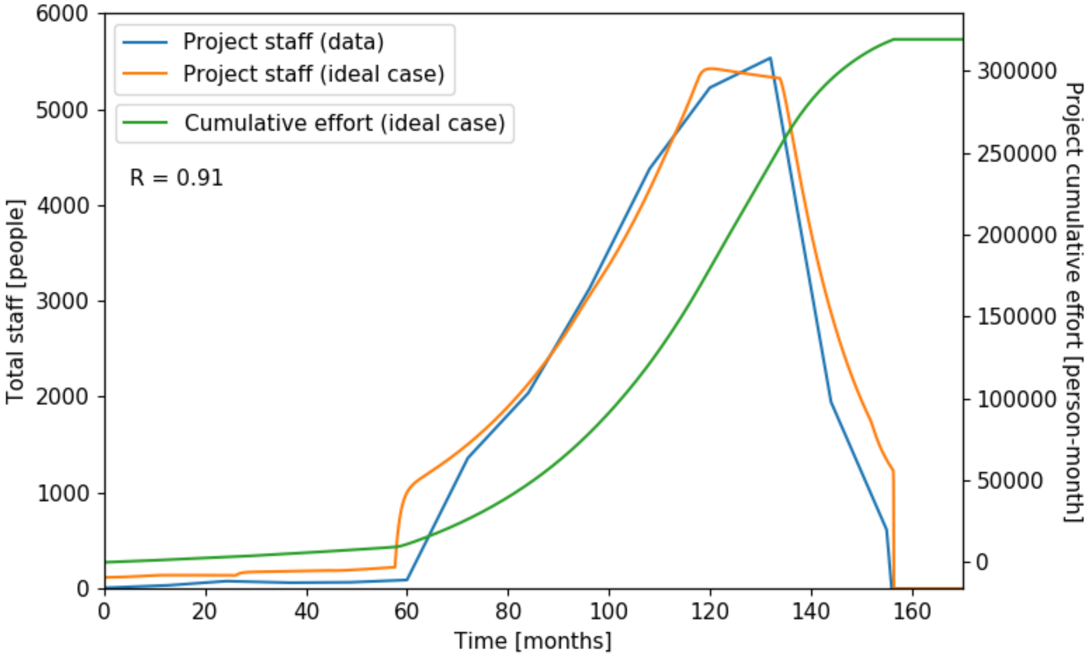


Figure 3-31: Comparison of simulated project total staff profile and IAEA reference data [82].

3.4.2 Standard project plan (adding contingencies)

In this section we build the project plan: the project as it has been historically *planned* in past nuclear projects. This is the second step of the path from ideal to actual case.

According to the IAEA Guidelines on Nuclear Plant Project Construction [83], the planned or target budget is set up for all project partners along with the project contracts and it is refined at the start of project execution. It is recognized that usually some cost increases can occur, but the treatment of these cost items is rather generic: *"[...] One common source of errors in overall project estimates can be the failure to appreciate that additional costs are bound to rise as a result of design errors, manufacturing mistakes, logistic errors, material or component failures. Contingencies in the budget are used to account for these possibilities. The degree to which these must* *be added depends on many factors: soundness of engineering concepts, reliability and experience of project partners, contractual conditions, etc. [...] For proven product and contractual model, the total contingency allowance might be set at 5% of the project scope. [...] If the figure exceeds 15% perhaps the utility should consider whether the partners or contractual decisions are acceptable.*

In our SD model these generic sources of error are captured by `Fraction of Work Correct`. The IAEA documentation makes no differentiation between different causes of error and it ignores less familiar sources of rework such as OOS work, design novelty, coordination effects, insufficient FEED effort. Indeed, the indicated range of effort increase (5-15%) seems rather low and difficult to reconcile with what we typically observe in reality.

In the standard project plan simulation, rework is introduced through `Fraction of Work Correct`. This is consistent with the IAEA treatment of contingencies just discussed. `Fraction of Work Correct` is reduced from the ideal value of one to a new value that causes a 10% effort increase (between 5 and 15% as indicated above). It is assumed that errors are split equally between the three work phases (i.e. equal decrease of `Fraction of Work Correct`). After a few iterations we find that `Fraction of Work Correct` in each phase must equal 0.911. Out of 10 tasks, about 9 are correct and complete when performed the first time. This might seem too optimistic but note that it does not include yet the effects discussed in Section 3.3 (coordination, overlap, availability of emergency buffer staff, out-of-sequence work, effort spent on FEED phase, external factors, suppliers etc.).

Figure 3-32 compares the project staff in the ideal case and the standard project. The qualitative behavior is the same but rework causes the standard project simulation to finish approximately 9 months later. The figure shows also `Project Cumulative Effort`, which is a proxy for overnight cost.

Figure 3-33 shows when *D&P* rework is generated and discovered over time. The other phases are conceptually similar. `Design Rework Being Generated` follows `Design Staff`. This makes sense because task sequence and staff profile are coordinated. Rework generation is proportional to staff because rework is only generated through `Fraction of Work Correct` (for now). The magnitude of rework generation in each phase is also a function of the amount of error propagation from upstream work containing undiscovered errors to current work. This is determined by the amount of upstream work containing such errors and `Sensitivity of Fraction Correct to Undiscovered Rework`. `Rework Discovery` happens with some delay. `Rework Discovery` is a function of `Delay in Discovering Rework`. Amount and timing of rework discovered in each

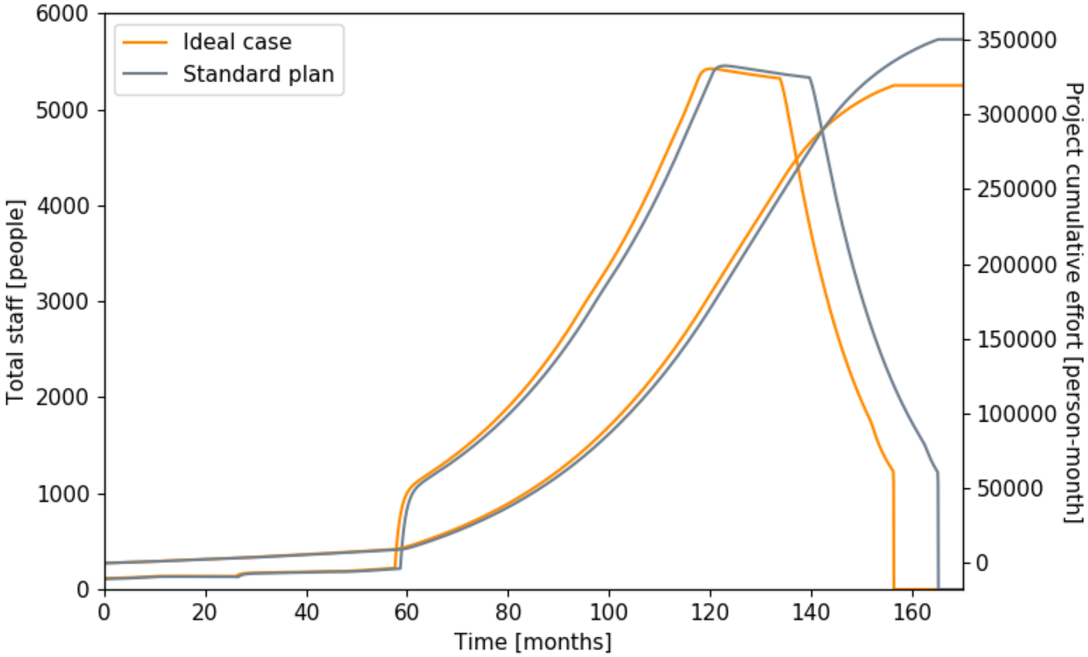


Figure 3-32: Comparison between staff profiles in the ideal case and the project plan.

phase is set by the modeler and should reflect the behavior observed on similar projects; rework discovery is typically low early in a phase and accelerates as downstream progress is made (note that rework discovery in a phase of work is impacted both by progress in the phase of work, and by progress on downstream phases. In the model the amount of rework discoverable is expressed through a maximum and a minimum value in each phase. The timing is expressed through a lookup table, which is a function of the downstream phase progress. The pattern of `Rework Discovery` is therefore primarily a function of the product of this timing table and the undiscovered rework. `Rework Discovery` peaks when `Undiscovered Rework` is high and the timing curve is rising. According to Lyneis [70], the peak tends to occur when the phase progress is between 50% and 75%, not at 100% (e.g. the peak of `Rework discovery` in Figure 3-33 is skewed to the left).

3.4.3 More sources of delays and cost overruns

Nuclear projects are complex and have often required effort increases much more than 10%. Causes of delays and cost overruns in nuclear construction projects are discussed extensively in the literature. However, these analyses tend to focus on a few factors without looking at how they influence each other and in turn the overall system. For example, increasing the degree of design completion before construction start has been suggested as a way to control project schedule and cost (in our

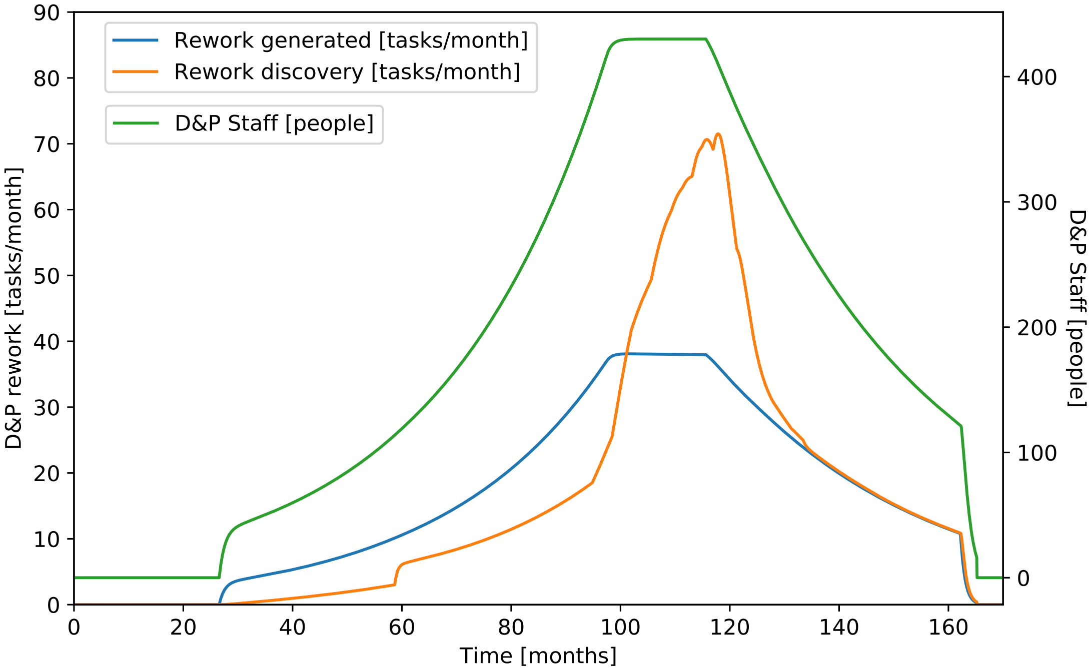


Figure 3-33: *D&P* staff in shown in grey; rework generated and discovered are shown in black. All curves are for the standard plan simulation.

model this is equivalent to reducing the overlap between *D&P* and *B&C*). But is this always possible? Does it always make sense? What happens for different project sizes or degrees of novelty? Slowness or inability to respond to exogenous unpredictable events have also been indicated as a vulnerability in past nuclear projects. But how can we react to these dynamic changes if we rely on tools that are static, linear and ignore the effects on other variables?

The standard plan staff curve is qualitatively similar to the ideal case, with a 9 months shift to the right (Figure 3-32). This 6% schedule increase is not consistent with the industry performance worldwide, where the difference between planned and actual results is much more pronounced. Figure 3-34 compares average estimated with realized construction times of 75 U.S. nuclear plants (categorized by year of construction start) [88]. The figure shows the gap between initially estimated (0% progress) and actual (100% progress) construction times, and how this forecast evolves in time. The thick black line is an average weighted on the number of plants. The average construction time increases by about 93%. Figure 3-34 reflects only the construction experience in the United States, which is particularly bad for a number of reasons. The 10% cost increase is too optimistic, also if compared with the worldwide performance, which was generally better. Delays are tightly coupled with cost overruns. Figure 3-35 shows the average estimated and realized overnight construction costs for the same fleet of U.S. reactors. The average increase is 215%. Figures 3-34 and 3-35 show that:

- Our ability to predict problems does not improve over the course of a single project: we predict poorly delays and costs until the very last stages of the project (the slope does not decrease);
- Our ability to predict problems does not improve over time (no learning effect);
- Estimated and actual construction times and overnight costs increased over time.

This suggests that there is something that we fundamentally do not understand (or represent) in project planning and management. Hence, the need for tools to understand the dynamics of projects.

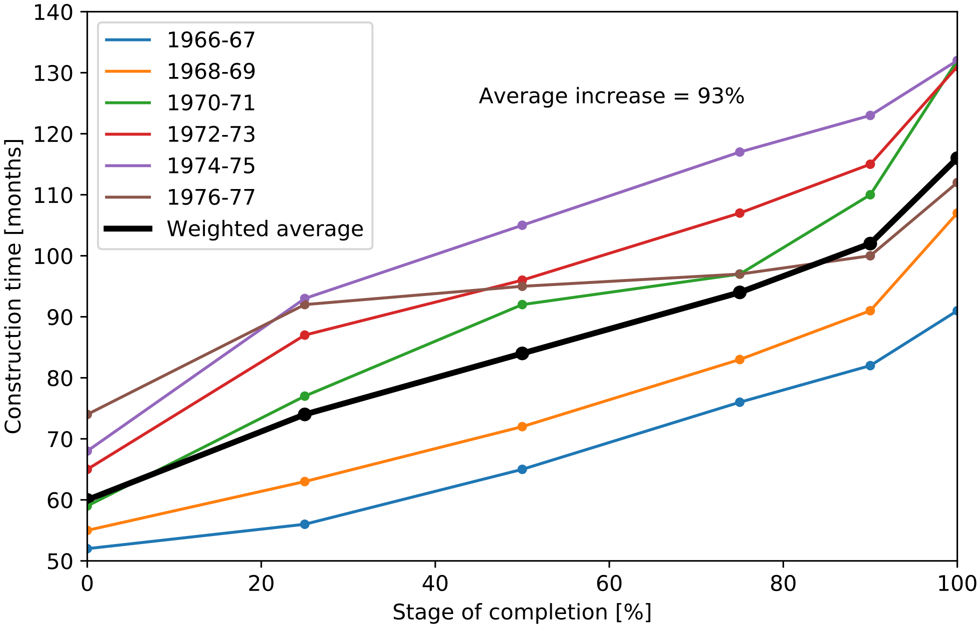


Figure 3-34: Average estimate and realized nuclear construction times in the U.S. grouped by year of construction start (adapted from [88]).

The "generic contingencies" approach does not explain the low performance of nuclear projects. Our SD model considers error propagation, OOS work, coordination, uncertainty requirements, novelty, level of FEED effort, overlap between project phases, availability and size of management/technical leadership team, suppliers problems, task growth. Adding these effects changes

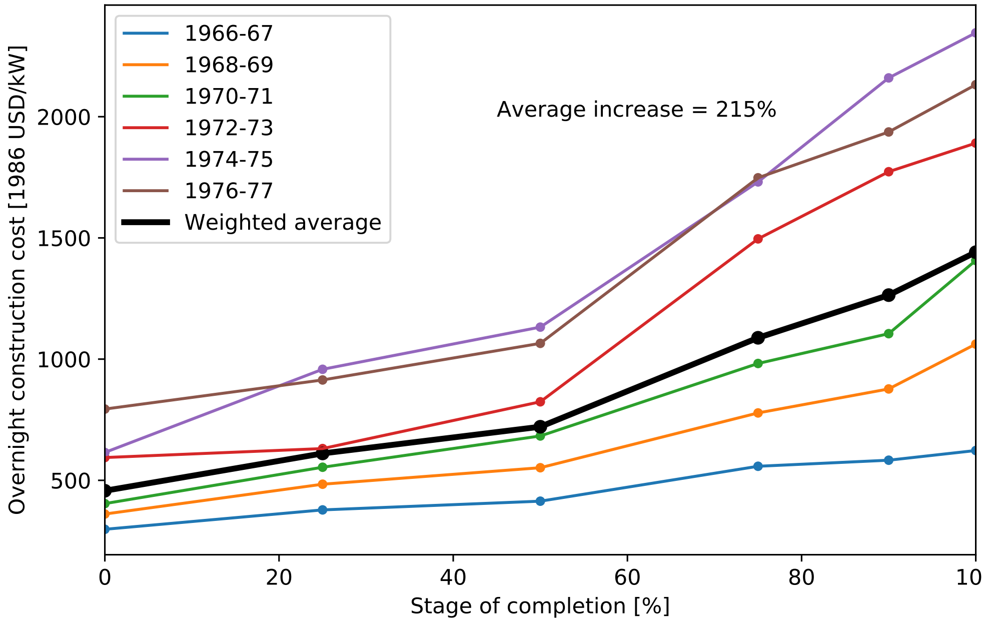


Figure 3-35: Average estimate and realized nuclear overnight construction costs in the U.S. grouped by year of construction start (adapted from [88]).

drastically the simulated project performance, as shown in Figure 3-36. The project takes 304 months to finish, corresponding to a construction time increase of about 95% (not too far from what Figure 3-34 suggests). Project cost is about 2.1 relative to plan (i.e. a 110% cost increase). This is lower than what Figure 3-35 suggests. However: (1) in our model cost is just that of effort, and for now other cost items such as delay fees, inflation, etc. are not considered; (2) the early-years experience in the United States (Figure 3-35) is exceptionally negative.

This simulation is named “slip schedule” because it assumes that no actions are taken during the project to bring schedule and budget back on track. In other words, this simulation assumes that management is passive/absent. For example, no extra staff are added to the project, which explains why the three curves in Figure 3-36 peak at the same level.

3.4.4 The actual case (adding management control)

Projects rarely evolve as planned and troubles arise for many reasons: initial schedule is too aggressive, work scope is underestimated, the regulator requires design revisions, suppliers do not deliver on time. In these cases, the management team takes actions to control changes and the effects of unfolding uncertainty on schedule and cost. Management control entails monitoring progress,

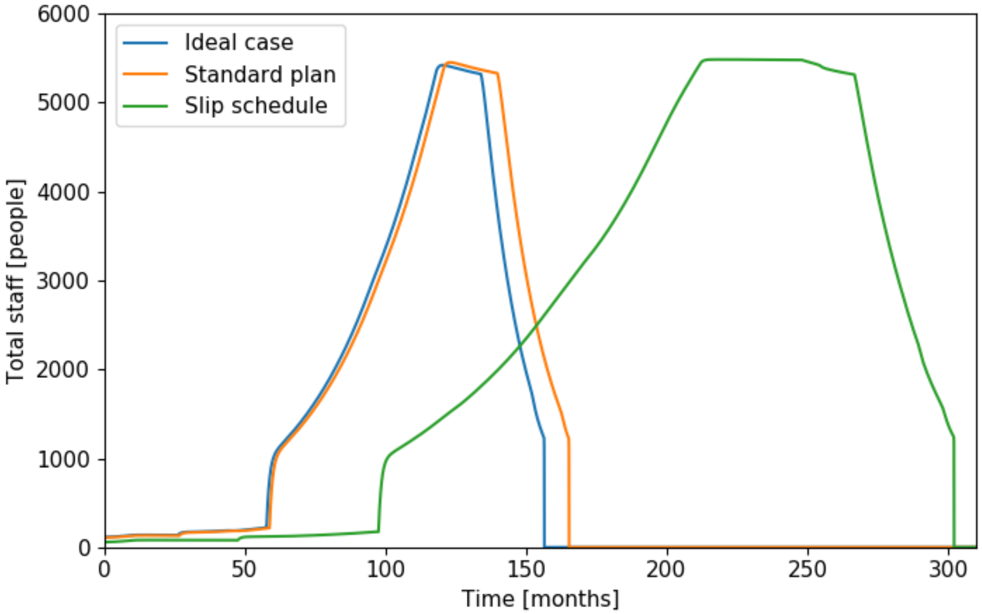


Figure 3-36: Project staff profiles in ideal case, standard plan, and slip schedule case.

forecasting performance, comparing forecast to targets, and taking corrective actions. In order to set up the model to represent a specific project, we need to specify (1) plan targets, (2) forecasting assumptions, (3), management control actions, (4) strength of side effect feedbacks [70].

Figure 3-37 shows how management control works at a high level. At each time step, management compares current forecast for completion to current schedule[9]. The current forecast is determined by estimating `Known Work Remaining` and dividing by current staff levels. The sum of `Original Work to Do` and `Rework to Do` is the `Known Work Remaining`. `Effort Needed` is computed on the base of `Known Work Remaining`, which is performed by a certain number of people working at a certain level of productivity depending on time remaining. If `Known Work Remaining` is more than can be completed in `Time Remaining`, that is if the project is behind schedule, management can decide to add resources. In our model we consider two common actions that can be taken to correct a forecasted missing of a deadline: (1) hiring additional staff; (2) working overtime. In either case, adding resources increases the effort applied on the project, which increases progress and closes the gap between planned and actual schedule. Adding resources forms balancing feedback loops (see section 3.1.2) that tend to stabilize the system. These loops are named “Add People” and “Work More” in Figure 3-37. In reality there are two loops in each case, one through

---

[9] Other targets such as cost and quality can also be monitored.

`Original Work to Do` and one through `Rework to Do`.

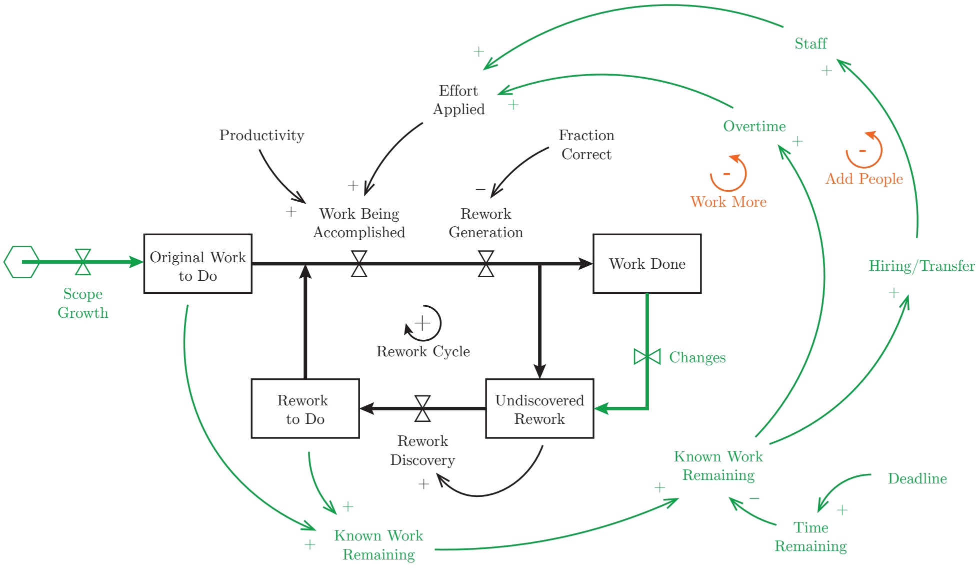


Figure 3-37: High level causal loop of management control process.

In practice, actions taken to close a gap between project performance and targets have unintended side effects that reduce productivity and fraction correct. These side effects create reinforcing feedback loops which can cause significant overruns in cost and schedule. The side effects typically create two such loops, one through productivity and one through fraction correct [70].

Hiring new staff creates two unintended feedback loops: "Experience Dilution" and "Too Big to Manage" (Figure 3-38). There are in fact four reinforcing loops, two through `Productivity` and two through `Fraction Correct`. Hiring reduces average staff `Experience`. `Fraction Correct` is penalized because workers with less skill and/or less familiarity with the project are brought on. `Productivity` is also reduced because new workers require experienced developers to divert time to training instead of doing development. Hiring also increases congestion and communication problems. This in turn reduces `Productivity` and `Fraction Correct`, increases `Known Work Remaining`, increases `Effort Needed` and in turn additional staff is hired, completing the "Too Big to Manage" loops. "Experience Dilution" and "Too Big to manage" are positive reinforcing loops because as productivity decreases and rework increases, the gap between planned and actual project performance broadens, additional staff is hired and consequently more experience dilution and congestion problems are generated.

Sustained overtime causes two side effect feedback loops, one through `Productivity` and one

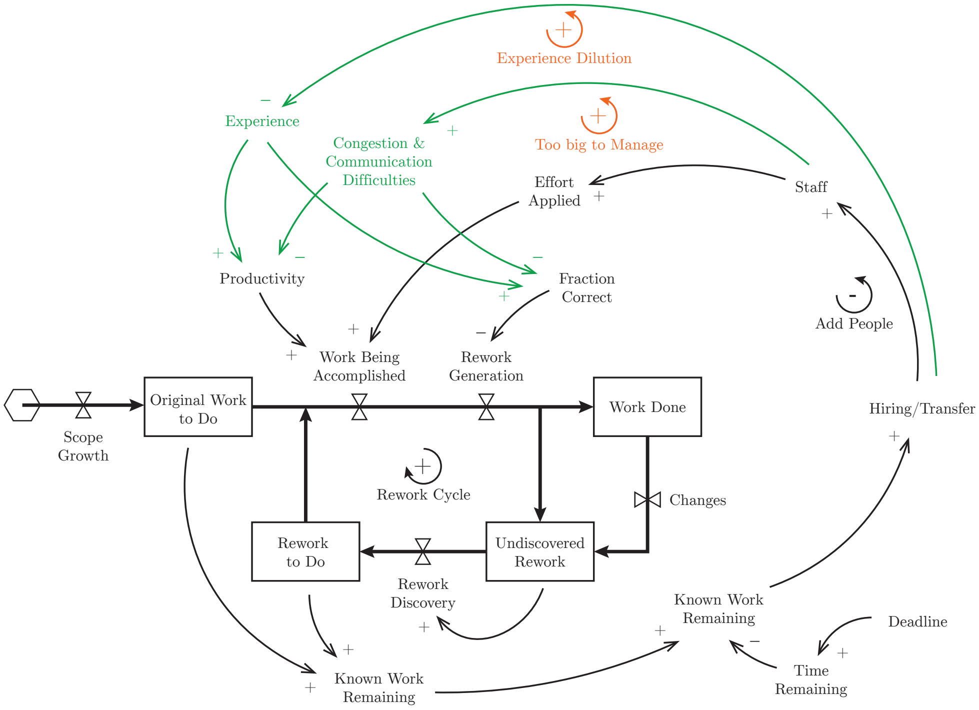


Figure 3-38: Unintended ripple effect loops of hiring additional staff or transferring in staff from other projects.

through `Fraction Correct`. These "Burnout" loops are shown in Figure 3-39. Working overtime for too long increases `Fatigue`, which reduces `Productivity` and `Fraction Correct`. These are also reinforcing loops. In reality, the structures of "Experience Dilution", "Congestion and Communication Problems" and "Burnout" loops are more complicated but we decide to omit the details here. All these loops exacerbate the rework cycle and can generate significant harmful dynamics, including additional out-of-sequence work, coordination, error propagation, and morale problems.

In each of the three phases, both management policy and mix of added resources can be controlled through the following:

- The balance between `Willingness to Add resources` vs. `Willingness to Slip Schedule`, which depends on management policy and stakeholders preferences. These vary between 0 and 1 and they must sum to 1 in each phase independently. For example, a value of 0 for `Willingness to Slip Schedule` means no schedule slip, hiring and overtime are used to get the project done; a value of 1 means slip the schedule as indicated to allow the current staff to get the job done (as in Section 3.4.3).

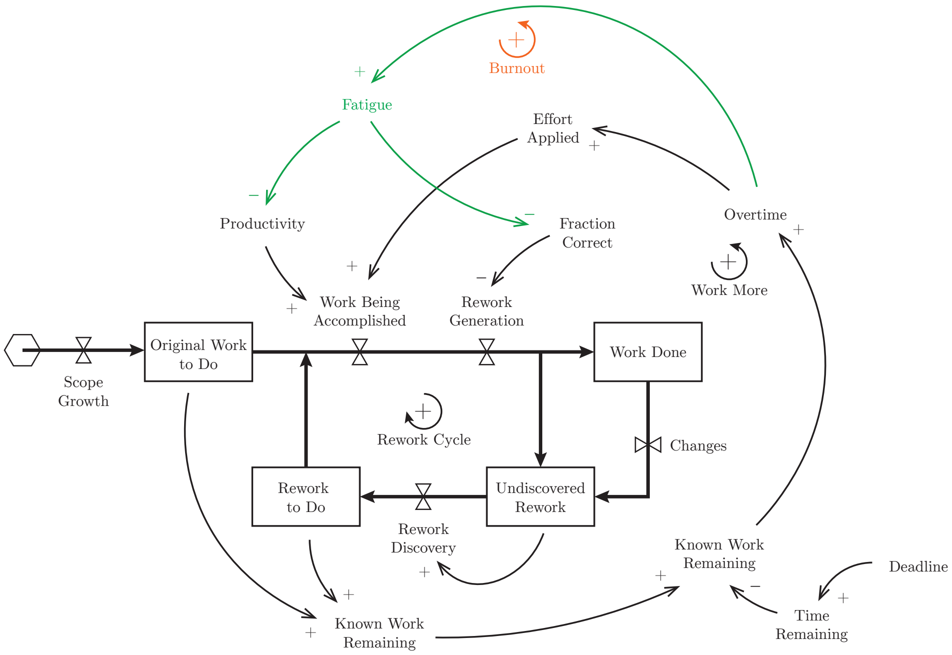


Figure 3-39: Unintended ripple effect loops of working overtime.

- If extra resources are used, they are added in the proportion established by `Fraction of Additional Resources from Staff` vs. `Fraction of Additional Resources from Overtime`. These vary between 0 and 1 and they must sum to 1 in each phase independently. If `Fraction of Additional Resources from Staff` is 1, then all extra resources are added as new staff and vice versa.

- Other variables such as `Time to Slip Schedule`, `Hiring Delay`, `Min and Max Staff Multiple of Planned Staff`, `Min and Max Overlap`, and `Time to Perceive Indicated Completion`. All are defined independently in each phase.

Adding resources generates side effects. Their strength is a function of many variables, such as `Relative Experience of New Staff`, `Time to Gain Experience`, `Fraction of Experienced Staff Time Required Per New Staff`, `Sensitivity of Performance to Organizational Size`, `Time for Fatigue to Build`, `Sensitivity of Productivity to Overtime`, `Sensitivity of Fraction Correct to Overtime`. These values are chosen to obtain delays and cost overruns that are reasonably close to the values found in the literature (fitting models to data is discussed in the next section). Figure 3-40 shows the total project staff profile when management control is introduced. This is the realistic case (we call it the "actual case") because the management team takes corrective actions in face of schedule deviations. This simulation assumes that `Willingness to Add Resources` is 75% and `Willingness to Slip Schedule` is 25%. The fraction of resources from hired staff is 70% and the fraction from working overtime is 30%. Total staff peaks at a higher level because workers are added to bring the project on track and finish on time. In fact, Figure 3-40 shows that "Management Control" finishes about 24 months earlier than "Slip schedule". But at what cost? Figure 3-41 shows project cumulative effort in the ideal case, standard plan, slip schedule case, and management control case. Effort is proportional to cost, so management actions cause costs to increase. Cost is sacrificed to achieve the project scope in the scheduled time. This is the typical first response on any project as nobody wants to admit they cannot get the job done on the original schedule, and often time to market is the primary objective [70]. "Management control" cost increases by about 174% with respect to "Standard plan". This is reasonable: it is right between the value of 215% experienced in the United States between the 1970s-80s (Figure 3-35), and 117.3%, the world average nuclear cost overrun updated to 2014. More about calibration and the plausibility of results is discussed in the following sections.

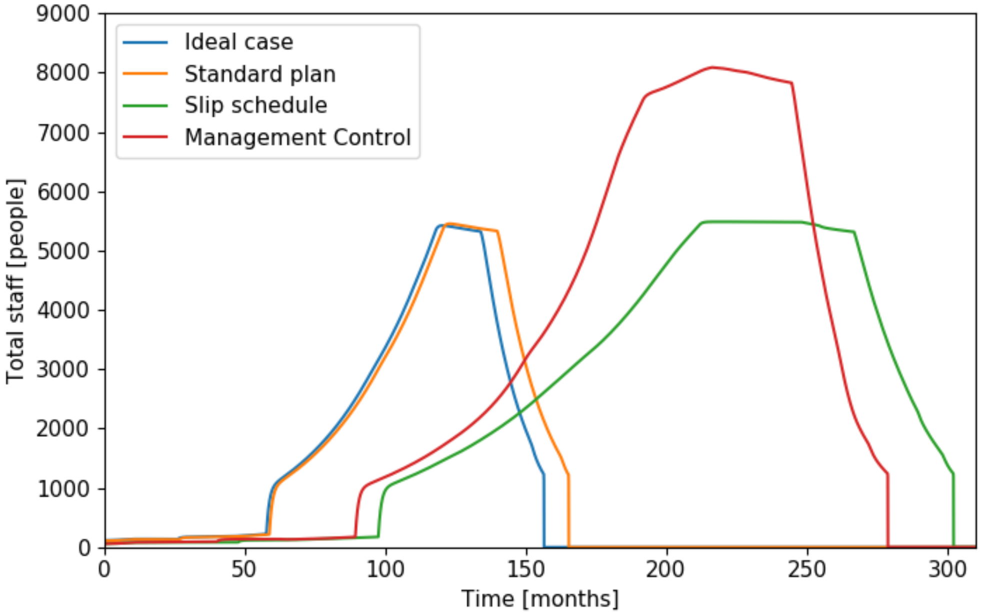


Figure 3-40: Project staff profiles in ideal case, standard plan, slip schedule case, management control case.

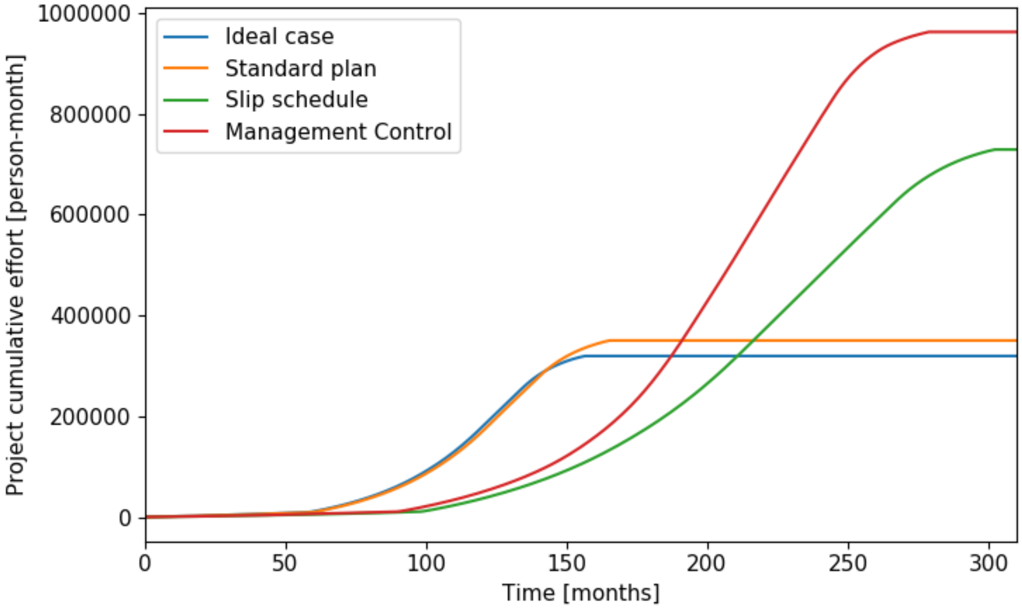


Figure 3-41: Project cumulative efforts in ideal case, standard plan, slip schedule case, management control case.

3.4.5 What is validation in the context of system dynamics?

Validation is the task of demonstrating that the model is a reasonable representation of the actual system: that it reproduces system behavior with enough fidelity to satisfy analysis objectives [89]. Validity of results in a SD model is crucially dependent on the validity of the model [90]. A model must present a simplification of a real world problem and therefore will exclude some variables or structures present in the real world to achieve this. If a model were to be truly correct it would need to be as complex as the real world in every detail and there would be no benefit in modelling [91]. The statistician George Box once wrote that "...all models are wrong, but some are useful" [92].

SD models are built to explore policy implications, management strategies and possible scenarios in extremely complex systems. Thus, validating these models is hard by nature, especially because there is no clear consensus on the concept of validity in the contexts of SD. As a matter of fact, the absence of a formal validation process has been one of the most common critiques against SD. One of the SD authorities, Sterman, even argued that validation of SD models is actually impossible [93].

It is generally recognized that validation of a SD model is a relative concept and it depends on the model's purpose. SD validation can be highly subjective, never conclusive and the level of confidence required in a model's veracity must be a function of its intended purpose [91]. A model used to make decisions in the context of a multi billionaire gas extraction project is likely to have different requirements than a model used to understand how fatigue builds up in a small company. The key issues in SD validation are: (1) to decide if the model fits the purpose for which it was built; (2) to reach a point when modeler and customer place enough confidence in the model, its results and the implications on real world decisions [94]. Figuring out these two points is hard but SD models are not different from other types of models from the perspective that they are all approximations. The equations of classical mechanics for example cannot be used at all scales. Newton's laws are a good model for the macroscopic world, but a wrong model for other purposes.

At least these five things are necessary to trust the nuclear project SD model:

1. To explain the causal relationships and structures used to model the phenomena of interest;
2. To be clear about the model's boundaries (what details are left out);
3. To explain what is the modeling process;
4. To match the results with historical data when these are available;
5. To enhance model's transparency.

The first point encloses the *unavoidable* set of assumptions ad corollaries. As has been said repeatedly, a SD model only reflects the modeler's best understanding of a real-world problem (so it is far from being perfect). Agreeing on the causal relationships among variables at a basic level (i.e. the causal loop diagram) is crucial. This process involves iterations and refinements. If we agree on the fact that when I slide an object on a rough surface there are three forces involved (gravity, friction and my arm pushing), then we can agree on the rest of the results. It is a necessary but not sufficient condition. This is the why Section 3.3 illustrates the model's structure and causal loops.

The second point states what is the range of validity. Just like classical mechanics, also a SD model is not always appropriate. In Section 3.3 we explained that the model can be used for the construction of a single unit traditional nuclear power plant. If one wants to simulate the parallel construction of two units in one site, the model would need to be adjusted.

The third point also involves both modelers and users and it requires iterations. How are real world scenarios translated into different model simulations? What sensitivities analyses are performed and what variables are involved? What results should be monitored in order to derive certain policy implications?

The fourth point deals with calibrating the model using historical data. The concept is simple on paper: the model should be able to reproduce what happened in the past. In practice, some problems arise:

- Detailed data about megaprojects are hard to find. Data about nuclear projects are even harder to find because contractors do not keep this type of information (or they do not share it). Data about nuclear projects in the United States are almost impossible to find because most power plants were built in the 1970s-80s.
- Sometimes "macroscopic" performance indicators are available, such as the total project delay and cost overrun. However, SD models are not 'black box' models. The structure of what is inside the model and how the output is achieved is fundamental to the insights generated from its use. Therefore, having a model output that replicates some reference behaviour is not a true or complete test of model validity [91].

The next section focuses on fitting the model against historical data. Section 3.4.7 focuses on model transparency.

3.4.6 Nuclear project model calibration

Qualitative calibration is done by inspecting the dynamic behavior of rework generation and discovery, fraction of work correct in each phase and relative contributions, productivity in each phase and relative contributions. Quantitative calibration is done for:

- Relative contribution of each delay factor to the total project delay;
- Project total delay;
- Project cost overrun;
- Fraction of rework generated.

The ideal case project (no rework) in Section 3.4.1 is built combining the IAEA data relative to scope, duration, and staff for a single unit in the size range of 600 to 1300 MW_e [82]. Duration of activities, staff level and ramp up/ramp down timing are project specific. What really matters is the order of magnitude, as the overall model's uncertainty does not justify greater precision. The standard plan case is built assuming a 10% cost increase to account for general contingencies. Calibration is rather straightforward up to this point.

Adding other phenomena such as the effect of uncertain requirements, novelty, FEED effort, overlap, changes, task growth, and suppliers' problems, is more complicated because their relative strength is unknown. Their combination produces a specific total time and cost increase, but the model needs to know their relative contributions. Hossen et al. recently developed a method to assess the construction schedule delay risk for international nuclear power plant projects [95]. The method is based on the selection of three levels of delay factors through both literature review and discussion with nuclear industry experts. Figure 3-42 shows the characteristics of the surveyed experts. All main stakeholders' categories are well represented, which reduces bias. All experts have at least 10 years of experience in the field, which increases the study's reliability.

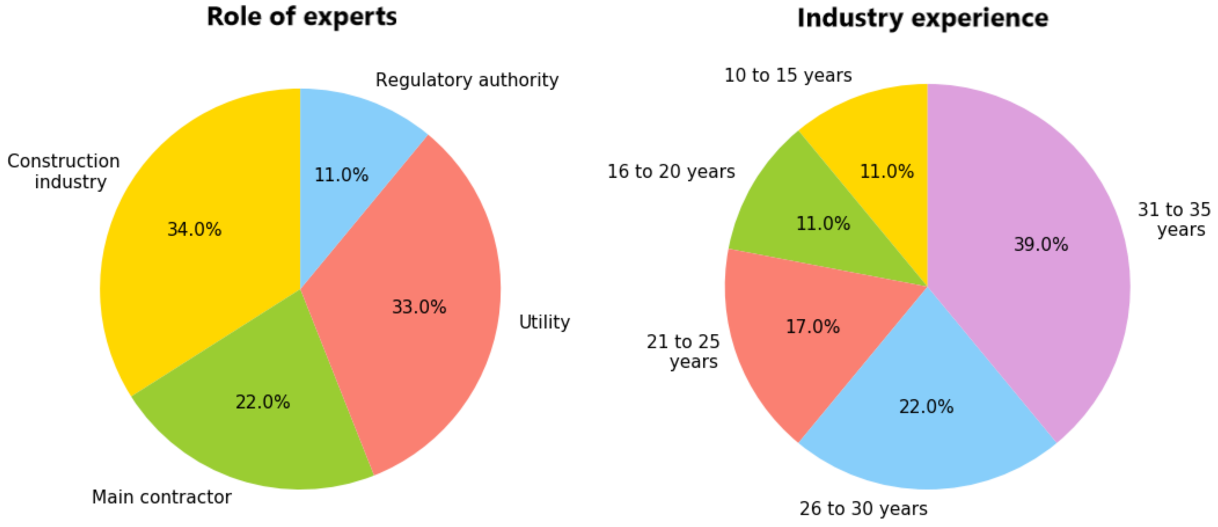


Figure 3-42: Profile of nuclear experts who participated in the assessment of nuclear project delay factors (adapted from [95]).

Construction delay risk is assessed qualitatively and quantitatively on the basis of the Analytic Hierarchy Process (AHP) and Relative Importance Index (RII) methods. The first level of the analysis identifies four main delay initiators: main contractor, utility, regulatory authority, and financial and country factor. The second and the third levels are designed with 12 sub-factors and 32 sub-sub-factors, respectively. All delay factors, their severity and risk values are shown in Table 3.2.

Table 3.2: Nuclear construction delay factors (adapted from [95]).

Level 1	**Level 2 (sub-factor)**	**Level 3 (sub-sub-factor)**	**Severity**	**Frequency**	**Risk**
Main contractor	Inadequate completion of design before start of construction (MC1)	Redesign due to errors in design and design changes (MC11)	0.245	0.704	0.172
		Inadequate drawings and specifications (MC12)	0.178	0.407	0.072
		Shortage of experienced designers (MC13)	0.200	0.370	0.074
	Difficulties in managing the subcontractor chains (MC2)	Inexperienced subcontractor due to lack of nuclear specific practices (MC21)	0.178	0.543	0.097
		Frequent change of subcontractor because of inefficient work (MC22)	0.080	0.444	0.036
	Slow procurement, manufacturing of equipment and delivery to the site for installation (MC3)	Worldwide shortage of qualified and experienced nuclear specific equipment manufacturers (MC31)	0.350	0.420	0.147
		Delayed procurement of equipment and bulk material due to unavailability in the global market (MC32)	0.275	0.395	0.109
	Delayed progress of construction and commissioning related works (MC4)	Shortage of technical professionals due to experienced expert retirement and lack of new competency for advanced construction technologies (MC41)	0.080	0.481	0.038
		Inexperienced construction management team (MC42)	0.125	0.580	0.073
		Rework due to errors and quality control during manufacturing and construction (MC43)	0.155	0.654	0.101

Utility	Improperly organized and delayed licensing application (U1)	Delayed in approval of design documents (U11)	0.223	0.556	0.124
		Delayed licensing application (U12)	0.185	0.481	0.089
	Dealyed supervision of manufacturing, construction and commissioning activities (U2)	Design, materials and sequence of the work changed by the utility (U21)	0.133	0.481	0.064
		Lack of coordination between central office and site office of utility (U22)	0.050	0.432	0.022
		Slow quality control procedures of utility (U23)	0.065	0.407	0.026
	Delay in utility's scope of supply items (U3)	Delay in material supply due to unavailability in the local market (U31)	0.065	0.432	0.028
		Lack of nuclear specific skilled workers (U32)	0.058	0.519	0.030
		Delayed procurement contract (U33)	0.208	0.605	0.126
	Slow decision making and delayed payment (U4)	Slow decision making due to poor project management system, inadequate planning and scheduling (U41)	0.110	0.593	0.065
		Inexperienced project management team (U42)	0.110	0.568	0.062
		Delayed payment by owner due to financial difficulties (U43)	0.080	0.481	0.038
Regulatory authority	Delayed regulatory approval (RA1)	Uncompromising regulatory criteria and licensing documents conflicting with existing regulations (RA11)	0.800	0.457	0.366
		Robust design document review procedure (RA12)	0.725	0.444	0.322

	Regulatory inspection oversight (RA2)	Inexperienced regulatory inspection group (RA21)	0.193	0.457	0.088
		Late changes in the regulatory criteria (RA22)	0.238	0.420	0.100
Financial and country factor	Country factor (FC1)	Policy changes due to political instability and public intervention (FC11)	0.605	0.654	0.396
		Lack of communication and coordination among the parties (FC12)	0.185	0.593	0.110
		Cultural gap and language barrier among the workforce (FC13)	0.170	0.531	0.090
		Unforeseen ground conditions of site due to unexpected weather (FC14)	0.118	0.321	0.038
	Financial matters (FC2)	Poor economic condition (FC21)	0.155	0.531	0.082
		Inappropriate feasibility and economic analysis (FC22)	0.155	0.469	0.073
		Economic crisis (FC23)	0.215	0.457	0.098

The risk level of each factor is proportional to its contribution to the total project delay. The SD model does not treat these 32 items separately. Instead each item is assigned to one or more effects that are modeled explicitly: (1) uncertainty requirements, (2) project novelty, (3) FEED effort, (4) overlap between *F&L* and *D&P*, (5) overlap between *D&P* and *B&C*, (6) size and availability of management team and technical leadership, (7) suppliers problems, and (8) task growth. The strength of each delay factor is then calculated compounding the contributing items weighted by their risk level (Figure 3-43). The eight effects are added to the SD model one at a time (individually) and the resulting incremental delays are fitted to the pie-chart data. After several iterations, the discrepancy between simulated delays and Figure 3-43 is about 3%, which seems satisfactory.

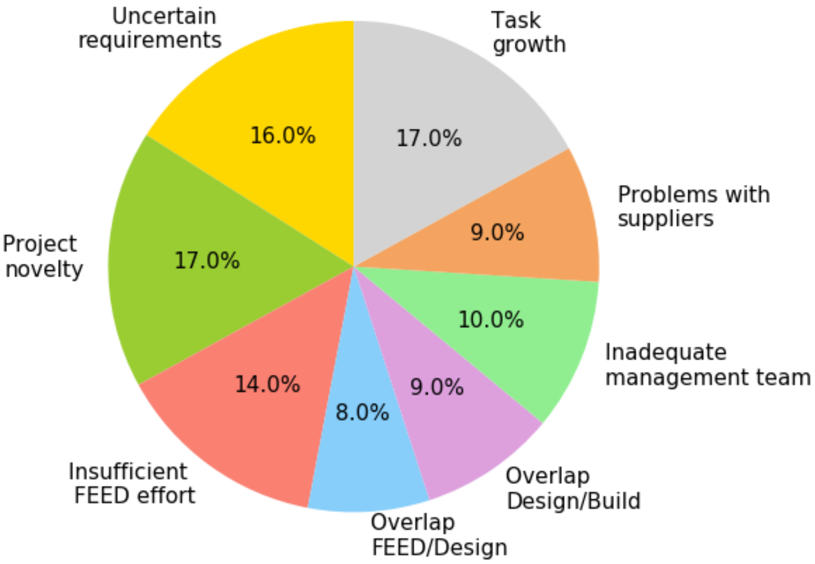


Figure 3-43: Nuclear construction delay contributions of each effect modeled explicitly.

Moving to total project delays, Figure 3-34 shows that the average construction time overrun of 75 U.S. nuclear plants which started construction in the 1970s-80s is about 93% [88]. Such a poor performance was most likely influenced by the Three Mile Island and Chernobyl accidents and the resulting regulatory ratcheting, where safety requirements were significantly altered in the middle of construction periods and regulators became much more cautious. Figure 3-44 shows the average time overrun for energy infrastructure projects worldwide as of 2014, divided by project type [96]. Nuclear and hydroelectric projects have the poorest records, with average construction delays of about 64%. For nuclear projects, the sample consists of 180 reactors with a combined installed capacity of 177,591 MW_e. Only completed projects are considered, and not those canceled or still under construction at the time of the study. This means that many of the "worst" projects, that were simply scuttled prior to completion, are not included. For instance, of 117 privately owned nuclear reactors in the United States that began construction in the 1960s-70s, 48 were canceled, and almost all of them "experienced significant cost overruns" [96]. In summary, it seems reasonable to expect a time overrun ranging between 64% and 93%. After calibration, the simulation produces a construction delay of 78%, right between these values.

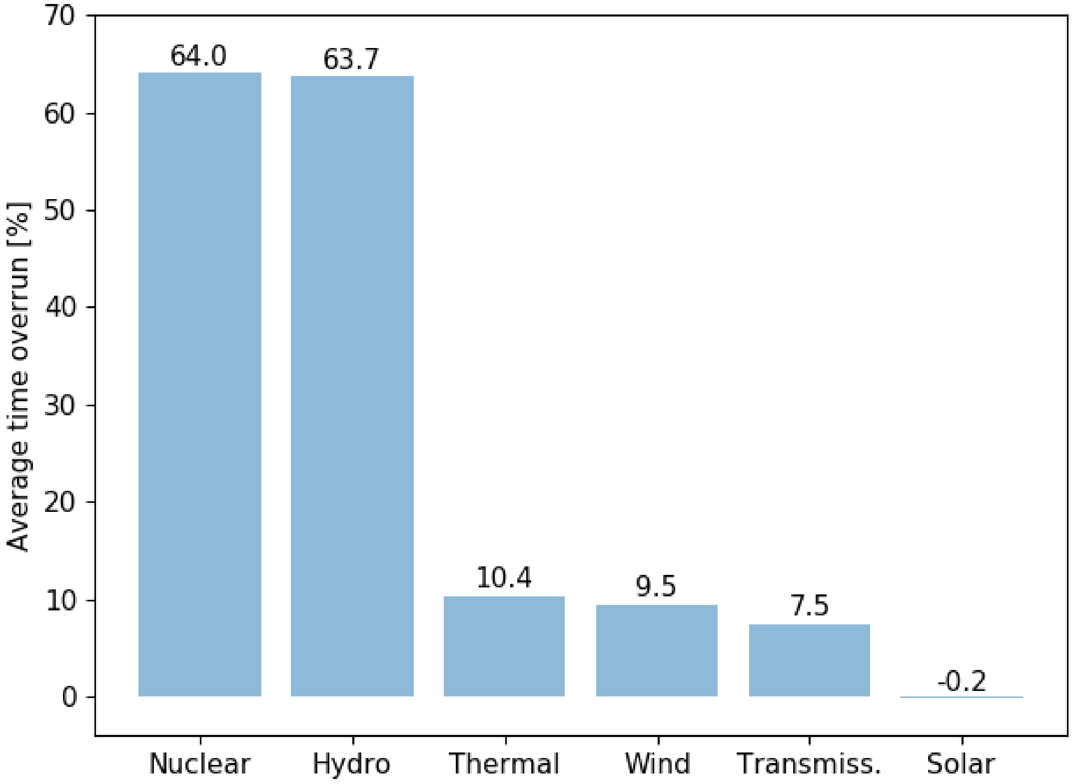


Figure 3-44: Average time overrun for energy infrastructure projects worldwide as of 2014 by project type (adapted from [96]).

Moving to total project cost overruns, Figure 3-35 shows that the average overnight cost overrun of 75 U.S. nuclear plants which started construction in the 1970s-80s is about 215% [88]. Again, the poor performance is influenced by the Three Mile Island and Chernobyl accidents, the politicized safety regulatory process, as well as by the fact that the United States had the industry first mover's disadvantage. The worldwide performance as of 2014 is better, as shown in Figure 3-45. The average time overrun of nuclear projects is about 117%. In summary, it seems reasonable to expect a cost overrun ranging between 117% and 215%. After calibration, the simulation produces a construction delay of 175%, right between these values.

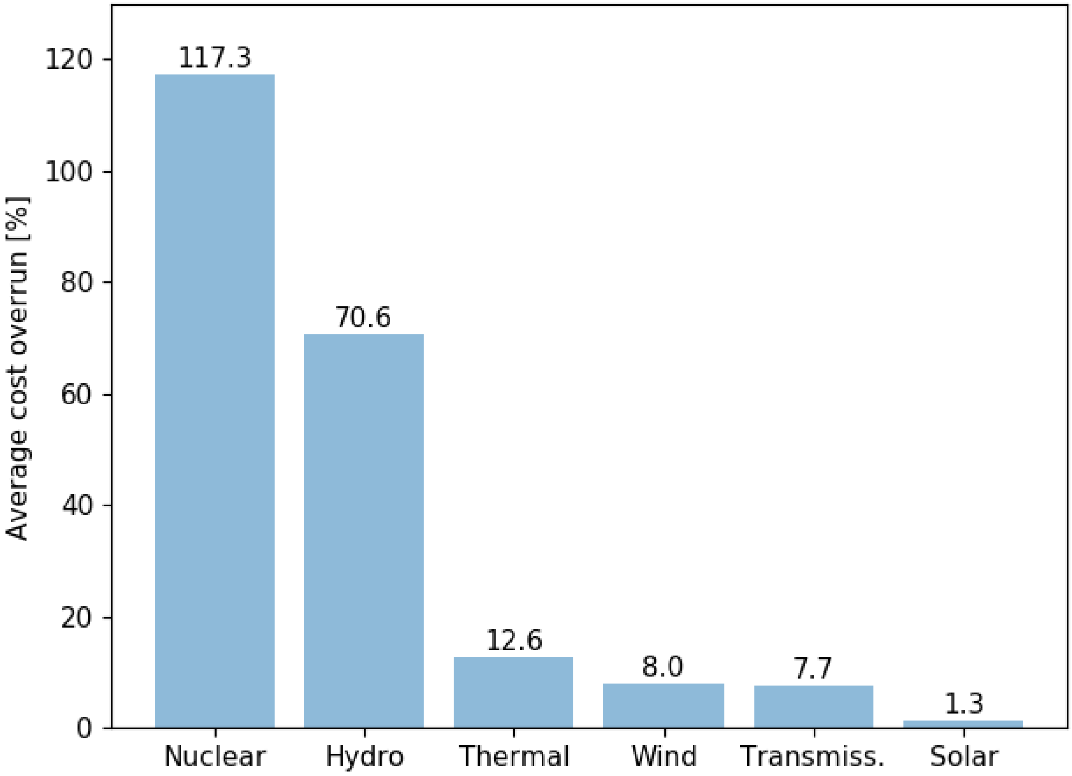


Figure 3-45: Average cost overrun for energy infrastructure projects worldwide as of 2014 by project type (adapted from [96]).

It is harder to find in the literature consistent data regarding rework in large-scale projects. Contractors do not keep records of rework generation and discovery and, even if they did, they probably would not be willing to share them. Rework data vary significantly across industries and projects. In the literature one finds anything between a few percent and 80% rework. For example, Reichelt et al. report some data regarding design and construction phases of a sampling of nine projects in the automotive and aerospace industry [97]. For design, the average percentage of design hours which were rework is 48%, but with slightly more projects in the 20-40% range; for build, the amount of rework is lower, with the average at 24%. Since the amount of effort required for rework is generally less than for original work, the proportion of rework tasks will be higher. If the project is on the uncertain/novel/complex side, rework tasks above 50% would not be uncommon [70]. A survey by Cooper and Mullen looks at the problem in terms of fraction of work correct [98]. Their analysis indicates that the average fraction of work correct and complete in commercial software development products is 68%, with a range of between 40% and 95%. This means that on average every task is done approximately 1.5 times. On state-of–the-art defense projects, which are more similar to nuclear projects, the average is 34% (every task done 3 times), with a range between 10% and 55%. Apart from the wide spectrum of data, it is hard to find a consistent definition of rework. This SD model for instance uses the effects of project novelty and uncertain requirements to generate direct impact through rework. It is possible that others might define such rework as being caused by other sources, such as customer changes or design changes. Something that seems recurrent is that more rework is generated during design than construction. After calibration, the fractions of *D&P* and *B&C* efforts that were rework are respectively 57% and 43% (as expected more rework is generated during *D&P*). The average fraction correct of *D&P* and *B&C* is about 70%. These results seem reasonable and consistent with the literature

3.4.7 An open-source SD model to enhance transparency

Model transparency is increasingly identified as a necessary characteristic of SD models [63], [80]. It is a central element in good modeling practice to enhance understanding and facilitate reproducibility [99]. Sterman even argued that "perhaps the most important pragmatic issue for modelers is documentation" [93]. System dynamicists struggle with how to document their models so that other modelers can examine the elements efficiently and effectively, thus increasing confidence in the model's usefulness [99]. In the past, many practitioners have included text listings of the equations in their papers/reports. In this work we decided to take transparency to a whole new level and make the following material completely accessible to everyone:

- The SD model used to simulate the nuclear design and construction project;
- Supporting model description and analyses.

For this purpose, we built a website[10] where Vensim model and supporting documentation are made available: https://sites.google.com/view/nuclear-pm.

---

[10] A beta version of the website is currently available.

3.5 Example: using the SD model to manage task growth during construction

In this work the SD model is part of a larger framework presented in Section 2.4. However, we think it is important to show the benefits of using the SD model independently, as a stand-alone application.

Managing nuclear projects cannot be seen as the task of optimizing a set of activities. This approach did not work in the past and it will not work in the future[11]. No matter how much time is spent on planning all details, surprises will occur due to the many uncertainties that are present. Thus, having a way that allows one to *control* changes and *adapt* to a new set of constraints is extremely valuable. One of the main benefits of the SD model is that it allows one to handle such changes. In general, a project gets into trouble for many reasons, for example: (1) the original plan may have been infeasible; (2) the project's scope could have been underestimated, or it could have increased because of customer requests; (3) customers can request changes in the design or requirements which cause work previously done correctly to flow into the rework stock; (4) staff cannot ramp up as planned because of hiring delays or the delayed completion of other projects; (5) uncertainties can be resolved in ways less favorable than assumed in the project plan [70]. This section provides a simple example to show how the SD model can be used to manage scope growth during the construction of a nuclear power plant. Note that handling changes with other management tools is much more complicated if not infeasible (Section 2.1).

Suppose that a sudden increase in *B&C* scope (work to do) occurs during construction as a result, for example, of a major new regulatory change. For simplicity, we assume that scope growth can be modeled using a rectangular function defined by three parameters:

- `Build Magnitude of Task Growth`: the magnitude of exogenous scope growth as a fraction of initial work to do;
- `Build Time of Task Growth`: time at which exogenous task growth begins;
- `Duration of Task Growth`: time period over which exogenous task growth occurs.

In principle, it would be possible to consider multiple rectangular functions or even a different

---

[11] Unless nuclear projects are turned into more standard projects, in terms of scope, complexity and capital at risk. For example, the nuclear industry is pursuing the development of micro-reactors, a type of plug-and-play nuclear batteries that would be two orders of magnitude smaller in physical size, wholly manufactured and fueled in a factory, and transported to the site within standard-size freight containers, requiring minimal site excavation and preparation.

function shape. Compared with other management tools (Section 2.1), modeling this change in SD is relatively straightforward and fast. We assume that at `Time` = 200 months (during construction) an unexpected event causes the scope of the project to increase by 15% as a fraction of the original construction work to do. The increase happens over a period of 12 months, as shown in Figure 3-46. The height of the rectangular function is the magnitude of the task growth magnitude divided by the duration of the task growth.

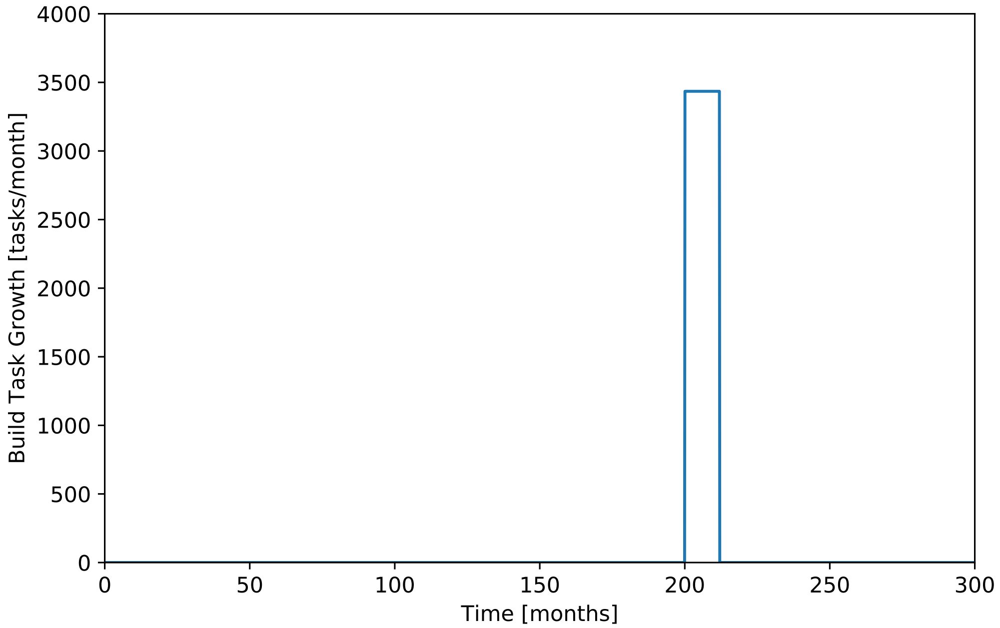


Figure 3-46: Rectangular function representing the task growth during construction.

Figure 3-47 compares the evolution of remaining work to do in a project with no scope growth and a project with the step change in Figure 3-46. As expected, remaining work to do is the same until `Time` = 200 months, when scope growth happens over a period of one year and causes the second project to finish about 16 months later. For now it is assumed that managers are passive and, even in presence of problems, they do not take corrective actions to bring back the project on track. Figure 3-48 shows the total project staff over time. Staff peaks at the same level, confirming that no corrective actions are taken (e.g. no staff is added). The schedule just slips, the project finishes about 1.5 years later and `Project Cumulative Effort` (proportional to cost) is about 11% larger.

Assuming that managers react passively to scope growth is not realistic. In reality, they would intervene to control the project to its cost, schedule, scope and quality objectives. Management

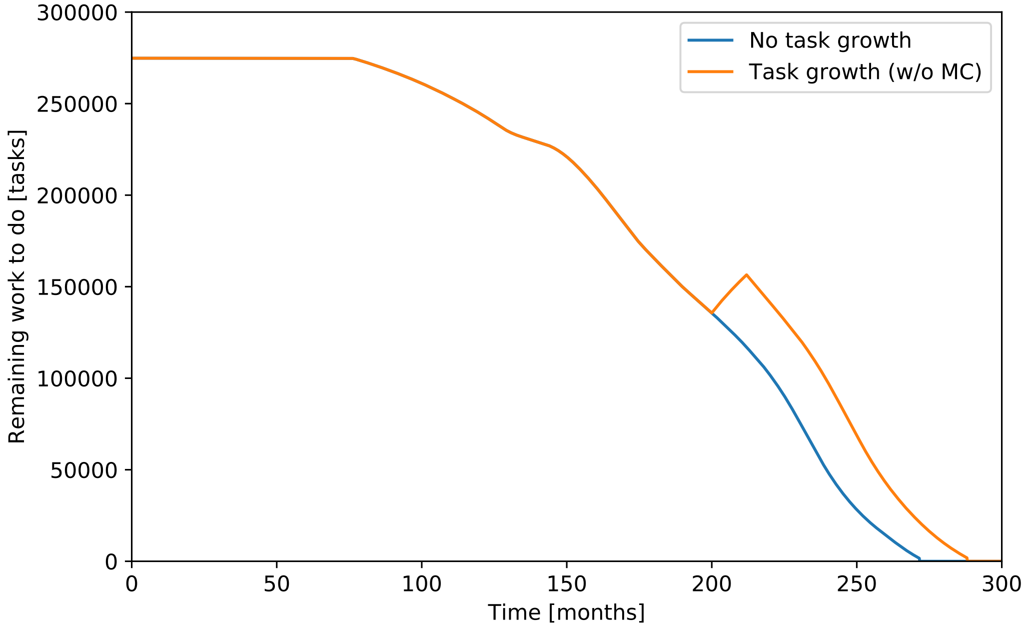


Figure 3-47: Build work to do increases as a result of an unexpected exogenous event.

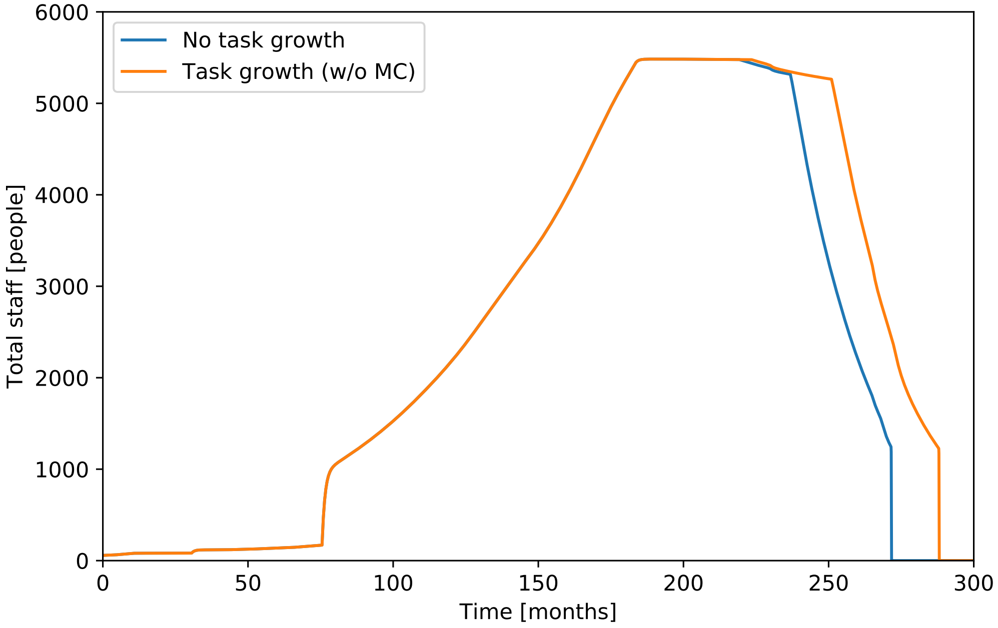


Figure 3-48: The project finishes later as a result of an unexpected exogenous event.

actions involve monitoring performance, forecasting the effort needed to complete the remaining work, and control actions such as adding resources. Control actions form balancing feedback loops

[70] as shown in Figure 3-37. When the project falls behind schedule, management can decide whether to add resources, to what extent, and what types of resources. Typically, three options are considered: (1) to hire or transfer in additional staff; (2) to work overtime; and (3) to work faster or more intensely [70]. For the sake of simplicity, it is assumed here that only the first two options are available. In summary:

- The mix of adding resources versus slipping the schedule is controlled by `Willingness to Add Resources` and `Willingness to Slip Schedule`. These should sum to 1;
- The mix of resources is controlled by `Fraction of Additional Resources From Staff` and `Fraction of Additional Resources From Overtime`. Also these should sum to 1.

The SD model is powerful because when the project deviates from plans (e.g. scope growth), managers can easily test different policies before implementing them in the real world. The green curve in Figure 3-49 represents a project where:

- `Willingness to Add Resources` = 0.75 (thus `Willingness to Slip Schedule` = 0.25);
- `Fraction of Additional Resources From Staff` = 0.7 (thus `Fraction of Additional Resources From Overtime` = 0.3).

As the project falls behind schedule, management adds resources (staff peaks at a higher level and some overtime is introduced). In this example, management adds resources throughout all the project as rework accumulates and not only after the new scope is added, which explains why the green curve deviates from the others for `Time` $<$ 200 months. At `Time` $=$ 200 months staff increases sharply as a result of the rectangular scope growth. The project finishes earlier than if no corrective actions are taken (orange curve). However, adding so many resources is very costly. If introducing scope growth without management control costs about 11% more than the reference case, implementing these management actions (green curve) costs about 65% more. Cost is higher because (1) more people are on the payroll; (2) rework generation is increased; (3) productivity is decreased. In fact, experienced workers must devote a percentage of their time to train the newly added workers. In addition there are increased communication overhead and other costs, such as space constraints, associated with the size of the organization.

If decision makers think that these results are unacceptable, they can use the SD model to explore other options. The red curve in Figure 3-50 represents a project with a different mix of adding resources versus not taking actions (slipping the schedule):

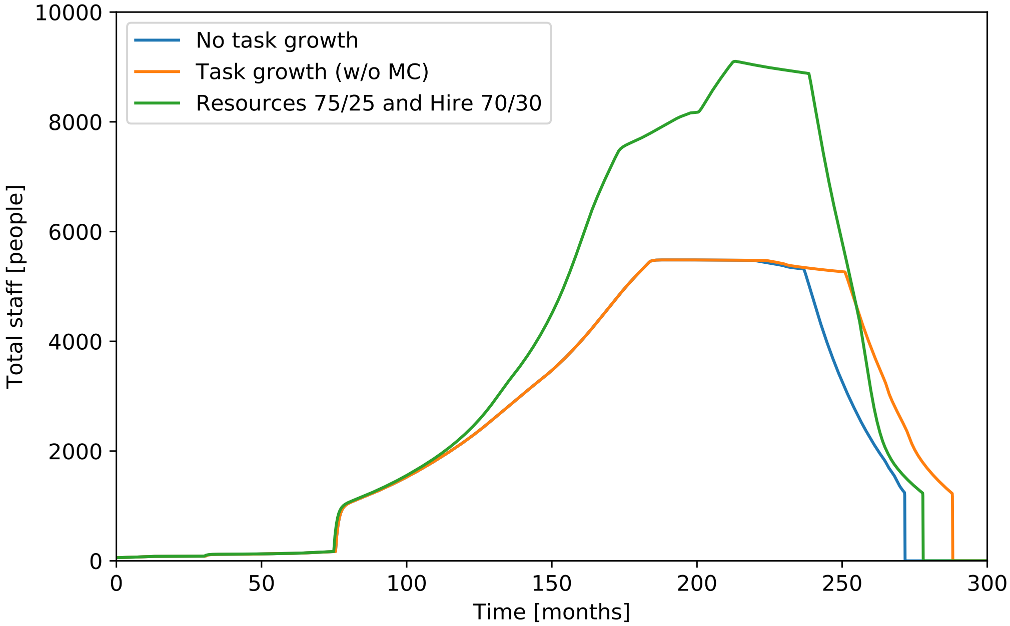


Figure 3-49: Management control is added. Willingness to add resources is 75% and resources added from hiring new staff is 70%.

- `Willingness to Add Resources` = 0.50 (thus `Willingness to Slip Schedule` = 0.50);
- `Fraction of Additional Resources From Staff` = 0.7 (thus `Fraction of Additional Resources From Overtime` = 0.3).

Fewer workers are added and the project finishes later. The red project ends up costing about 23% less than the green one and it finishes only 2 months later, which is not much even considering interests during constructions. So it seems that in some cases it is better to limit management control actions because their negative side effect feedbacks might surpass their benefits.

Finally, the purple curve in Figure 3-51 represents a project with a different mix of resources (staff vs. overtime). In particular:

- `Willingness to Add Resources` = 0.75 (thus `Willingness to Slip Schedule` = 0.25);
- `Fraction of Additional Resources From Staff` = 0.5 (thus `Fraction of Additional Resources From Overtime` = 0.5).

Fewer workers are added and the project is not delayed much compared to the green curve. Nevertheless, the purple project costs almost as much as the green one (98% to be precise). Why?

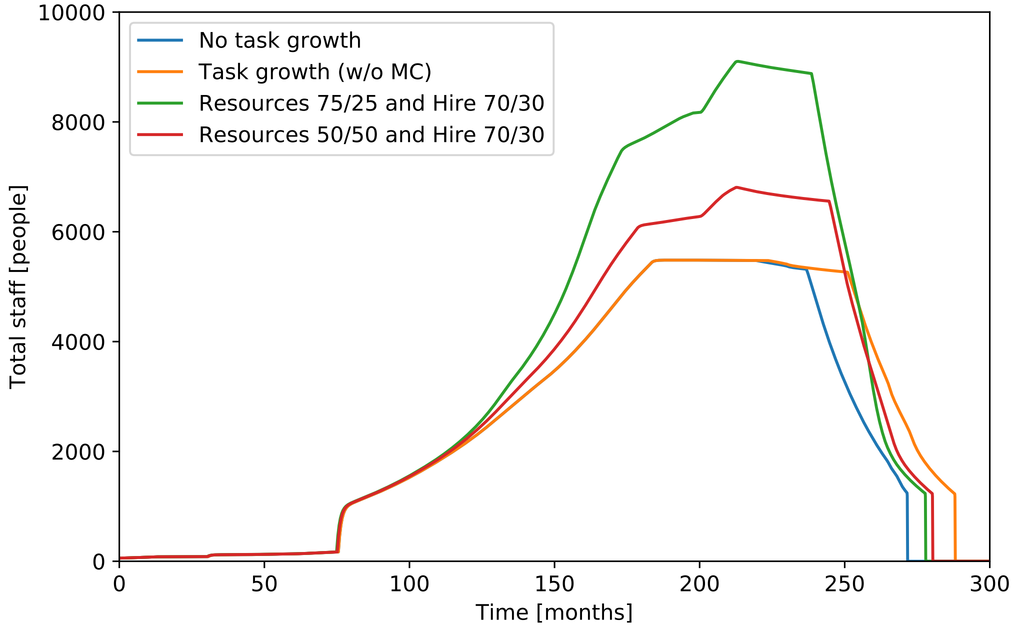


Figure 3-50: Comparison of projects with different willingness to add resources.

The advantage of overtime is that it can be imposed quickly and it does not generate experience dilution. It is effective on the short term. However, if overtime persists, fatigue sets in, which causes slowed progress, decreased productivity and the project may fall further behind schedule, necessitating even more management control. The SD model takes this into account, which explains why the green and purple projects require about the same amount of cumulative effort. Figure 3-52 shows the greater effect of overtime on `Fraction Correct` in the project with more overtime. The negative effect of overlap on `Productivity` has a similar trend.

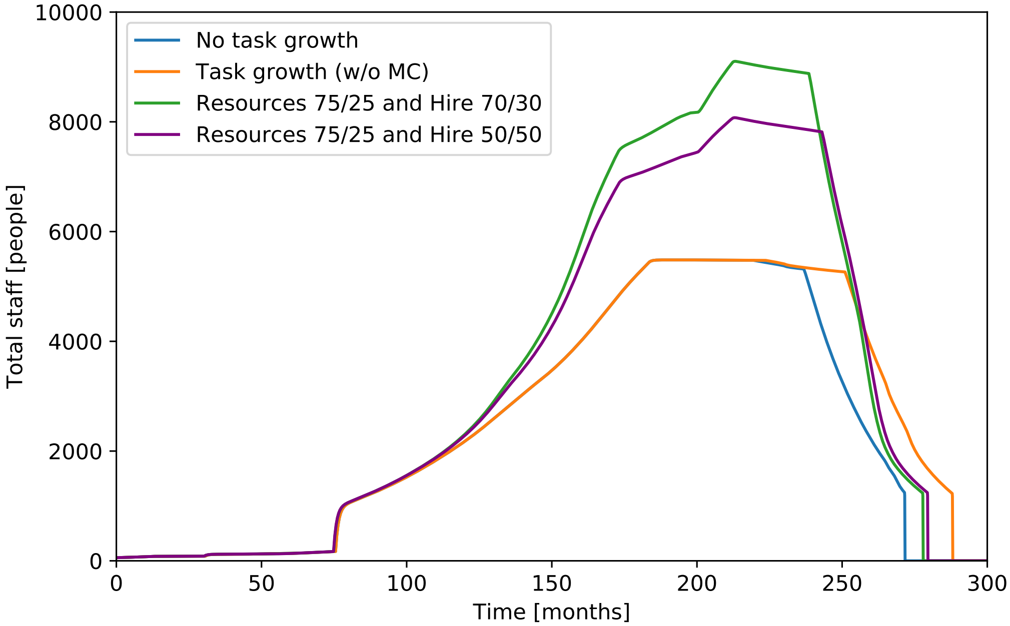


Figure 3-51: Comparison of projects with different mixes of resources (staff vs. overtime).

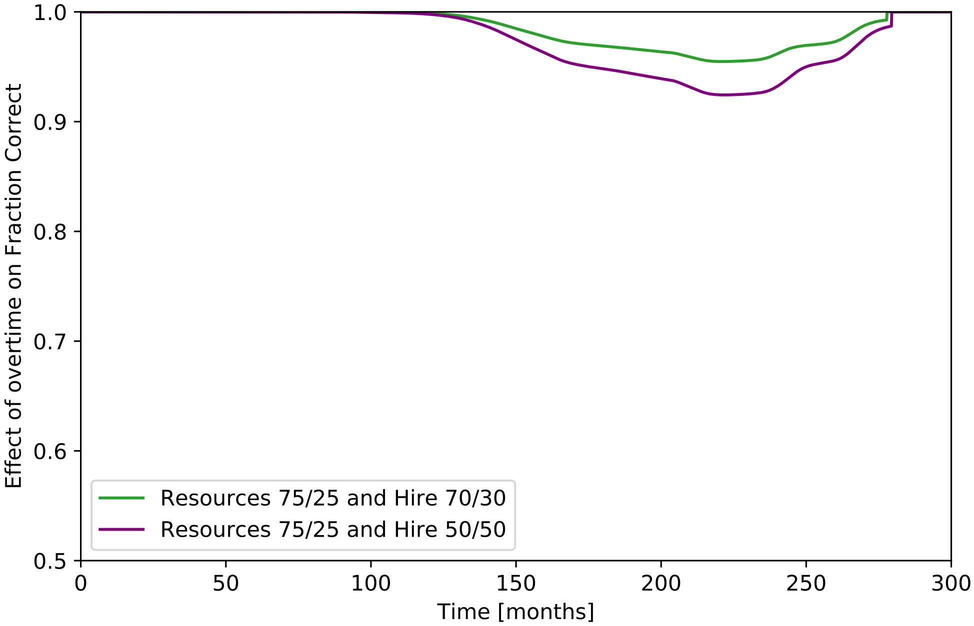


Figure 3-52: Effects of overtime on Fraction Correct of two projects with different mixes of resources (staff vs. overtime).

Chapter 4

DCF Model of a Nuclear Project

4.1 Recognizing uncertainties in nuclear projects

The success of nuclear power plant projects involves considerations of several factors, such as technology specifications, geographical area, political and regulatory framework. In general, it is possible to split the total costs of a generating plant into capital, operating, and external costs. Plant operating costs can be fixed or variable and include the costs of operation and maintenance (O&M), fuel, provisions for funding decommissioning, spent fuel and wastes. Capital costs include expenses associated with site preparation, engineering, construction and installation of components, construction materials, workforce, licensing and financing. The external costs to society from operation are defined as those actually incurred in relation to health and the environment, and could include the costs of dealing with a serious accident, if the insurance limit is exceeded [100].

In nuclear reactors, the initial investment represents the largest cost component over the lifetime of the power plant, and it takes decades to be recovered. In the 2015 update of the Annual Energy Outlook Report, the U.S. Energy Information Administration (EIA) estimated that the capital cost represents about 75% of the total Levelized Cost of Electricity (LCOE) of nuclear power plants [101]. This value, in relative terms, is the largest comparing to all other dispatchable technologies. Nuclear projects are capital intensive, whereas the expenses associated with O&M and fuel are relatively small. Traditionally, the economy of scale drives to the construction of large units, for which the initial investment can be considerable. Consequently, the capital cost is very high not only in relative but also in absolute terms. On the other hand the assumption that a modular approach is beneficial might be valid only if many units are built.

Nuclear projects are complex and they take place in a rigorous regulatory environment, whose potential instability and policy changes may affect the construction process. Project duration is a fundamental parameter. Between the time of the investment and the starting of operations, no power is sold, and consequently there are no revenues. The financial risk increases with increasing number of years required to complete the project. Long construction periods increase the chances that the market conditions and system performance requirements will have evolved adversely between the time of investment and the time at which the plant eventually enters service. For example, materials and labor cost variations can significantly affect the actual investment, and these variations are – in general – rather difficult to predict over an extended period. In a capital intensive and long project, the impact of interest rates is significant, even in the absence of delays.

Beyond the technical difficulties, many costly delays are attributed to poor project management or schedule planning. Some of the large and complex components of a nuclear plant (such as the reactor pressure vessel and the steam generators) can be manufactured only by a few companies around the world. Consequently, these parts have inherently long lead times, and they must be ordered much in advance. Also the regulatory authority has a critical role in the construction phase of the power plant. Regulatory inspections can demand rework or design changes throughout the construction process. Each additional modification can lead to overruns, even if project managers usually plan for appropriate extra time built into the schedule that can allow certain tasks to run overtime without delaying the whole schedule [100]. In addition, there are many critical risk factors that are difficult to summarize with a simple statistic, including changing regulations such as pollution standards for power plants, fuel economy standards for automakers, labor regulations and health insurance rules [102].

In conclusion, there are several “traditional” sources of uncertainties (construction cost, energy demand, construction time, etc.), as well as very important “non-standard factors” for which the uncertainties are more difficult to characterize (political support, social acceptance, etc.). Estimating the value of a nuclear project certainly requires a model that (1) handles both types of uncertainties, and (2) maintains a good balance between accuracy and practicality.

4.2 Discounted Cash Flow (DCF) analysis

All enterprises, including nuclear power plants, have cash flows. These are the net amount of cash and cash-equivalents being transferred into and out of the business. At the most fundamental level, the enterprise’s ability to create value for shareholders is determined by its ability to generate positive cash flows, or more specifically, maximize long-term free cash flow [103]. Calculating the value *today* of future cash flows is complicated because money (or, more generally, assets) has value over time. Indeed the most basic principle of finance is that since money can be invested to earn interest, a dollar today is worth more than a dollar tomorrow. Algebraically, the time value of money is expressed by the discount rate. Net Present Value (NPV) is the *present* value of the difference between cash inflows and outflows over a period of time (Equation 4.1). C_t is the net cash flow at year t, and r is the discount rate that reflects the time value of money and the project's risk. NPV is the amount we can withdraw from the company bank account today (and spend in other ways) so that the end-of-life contribution of the project will allow us to pay back the accrued debt of our withdrawal at the end of the project [104].

$$NPV = C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + ... + \frac{C_T}{(1+r)^T} = C_0 + \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{4.1}$$

The Discounted Cash Flow (DCF) method values the company on the basis of the NPV of its future free cash flows[1] which are discounted by an appropriate discount rate [106]. DCF is the most common methodology for an economic appraisal and comparison of alternative system designs [104]. The NPV decision rules are simple: (1) any project is worthwhile if it generates a positive NPV; (2) design A is preferable to design B if A's net return is larger than B's.

DCF is a powerful and convenient tool because (1) it takes into account the entire life of an investment; (2) it recognizes the time value of money; (3) NPV depends solely on the forecasted cash flows from the project and the opportunity cost of capital (e.g. it does not depend on factors difficult to control such as the manager's tastes, the company's choice of accounting method, the profitability of the company's existing business, or the profitability of other independent projects); (4) projects can be compared and (5) NPVs of different projects can be summed.

The main assumption behind a DCF analysis is that cash inflows and outflows are based on sales and costs *forecasts*. Predictions are difficult to make, especially if transactions happen far in the future (the expected lifetime of a nuclear power plant is at least 40 years). A drawback is that selecting the right discount rate for the analysis is hard (Section 4.4.10). Also, it is assumed that all the capital comes from a single virtual bank account, which is not strictly true but it simplifies the comparison between projects and make these comparisons conceptually independent of the specific financial arrangements [104].

---

[1] The free cash flow is the amount of cash not required for operations or reinvestment [105]

4.3 Monte Carlo method

Monte Carlo simulation is a computerized mathematical technique to model uncertainty and risk in quantitative analyses [107]. Monte Carlo methods solve deterministic problems by a stochastic approach using random numbers. Typically, the problem in question is difficult or even impossible to solve using a deterministic approach. Instead of looking at a limited number of plausible combinations of input variables (single point estimates, three points estimates or sensitivity analyses), a Monte Carlo simulation considers all many possible combinations. It is a virtual experiment where a calculation is repeated hundreds, thousands or millions of times, randomly sampling from probability distribution functions for any input factor that has inherent uncertainty. The number of repetitions depends primarily on the number of variables and their levels of uncertainty. The benefit of using probability distributions is that the full set of outcomes and the likelihood of each outcome can be explored - if desired.

Monte Carlo methods have found applications in many fields such as physical sciences, engineering, mathematics, statistics, finance, business, design and even visual arts. For example, they are widely used in reactor physics to trace the path of individual neutrons as they traverse matter in a reactor. Starting from the source of neutrons, which is predominantly if not entirely the fission source, a first random number is used to select the neutron energy from a probability distribution function. Similarly, other random numbers are generated to determine how far does the neutron travel in space, in which direction, and what is the nature of its next interaction (e.g. collision, fission, absorption). The process is repeated for a large number of neutron histories, and the results are derived from the averaged observation. Figure 4-1 illustrates this process conceptually for three different neutron histories.

In this work, Monte Carlo modeling is used to simulate thousands of possible nuclear project histories (i.e. projections), modeling explicitly the cash flow uncertainty. The result is a range of NPVs along with observations on the average, the distribution skewness, and the likelihood of each outcome (for example that the NPV is greater than zero). Monte Carlo simulation is a powerful tool for making project decisions because it provides more information than a deterministic analysis. Importantly, it is efficient: a laptop computer can examine a financial spreadsheet for thousands of possible outcomes in just a few seconds [104].

While the real world case study is presented in Section 6.1, here we anticipate that this is a marine small modular reactor intended to serve mining operations in the North of Canada.

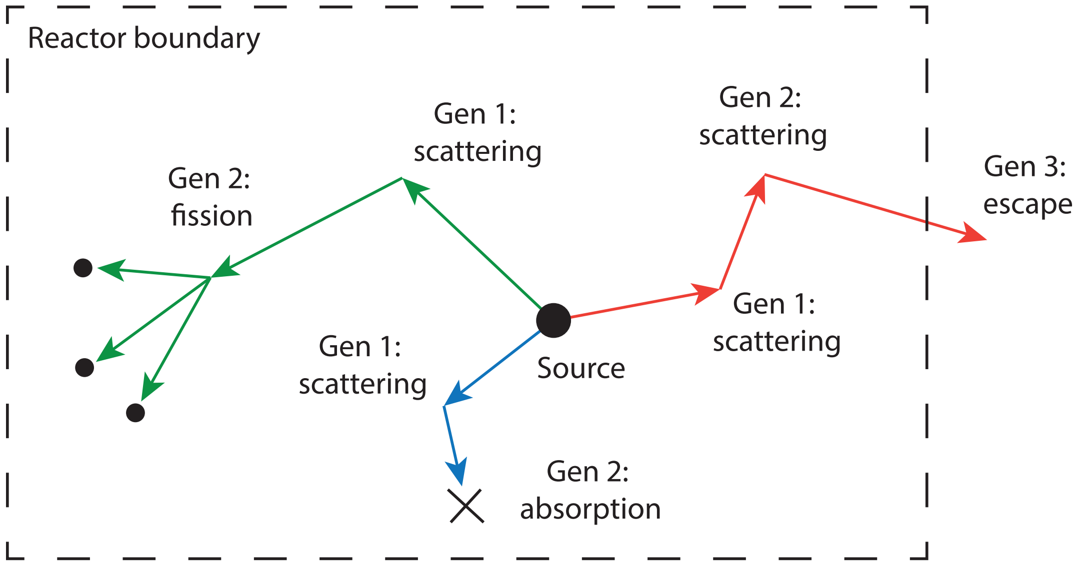


Figure 4-1: Conceptual representation of Monte Carlo simulation of three neutron histories.

This helps illustrating the DCF model structure. Several open source and commercial software packages are available to perform Monte Carlo probabilistic modeling and risk analysis. We use the commercial package @RISK® (Palisade Corporation), an add-in to Microsoft Excel. The spreadsheet comprises about 50 variables, most of which are treated stochastically. Below are the main parameters and assumptions.

4.4 DCF model setup

4.4.1 Power rating

The nominal power rating of the power plant is a constant value. The nominal power is expressed in MW_e. Assuming a generic integral small modular reactor we assumed a total net power output between 50 and 60 MW_e.

4.4.2 Capacity factor

Nuclear power plants are at the high end of the range of capacity factors, ideally reduced only by the availability factor, i.e. maintenance and refueling. Outages management in power plants has reached extremely high levels of efficiency [100]. Uncertainty about the plant's realized capacity factor is one of the critical risks facing an investor in a nuclear project. Historically, realized capacity factors have shown great variation. Nevertheless, typical investor's cash flow models use projected capacity factors of 85% or more. Having a more realistic capacity factor model is crucial to improve predictions. Du and Parsons [108] developed a stochastic model for the dynamic structure of nuclear capacity factor risk, based on the IAEA's PRIS database [13]. They calculated mean and variance of capacity factors from the database, expressing the values conditionally to the previous year. Figures 4-2 and 4-3 show sample and fitted[2] mean and variance of PRIS capacity factors. Note that:

- The expected capacity factor increases through the life of the reactor;
- The variance decreases through the life of the reactor. Power plants performing at high capacity factor tend to maintain a good performance with relatively low variability;
- Reactors performing at low capacity factor at any given year tend to exhibit more variable performance in the following year.

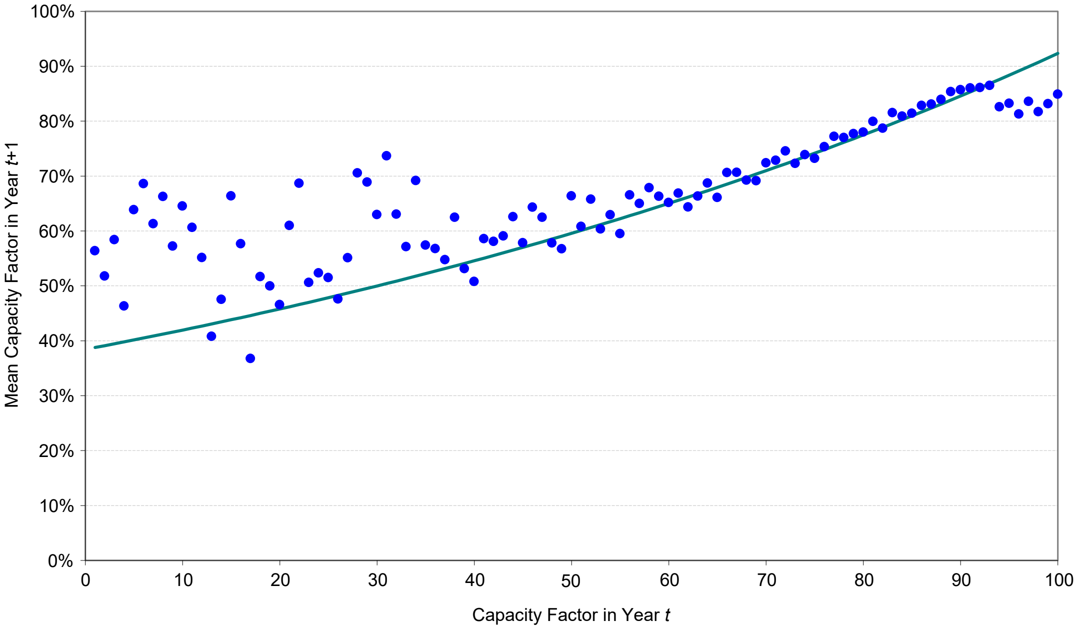


Figure 4-2: Sample and fitted mean of capacity factors, PRIS database (adapted from [108]).

Du and Parsons also show that the unconditional variance starts from values as large as about 10%, then it decreases rapidly within the first few years of operations, finally it stabilizes around 4% (Figure 4-4). The results presented in Figures 4-2, 4-3 and 4-4:

---

[2] OLS regression with robust standard errors was used to account for the fact that there are more observations at high capacity factors.

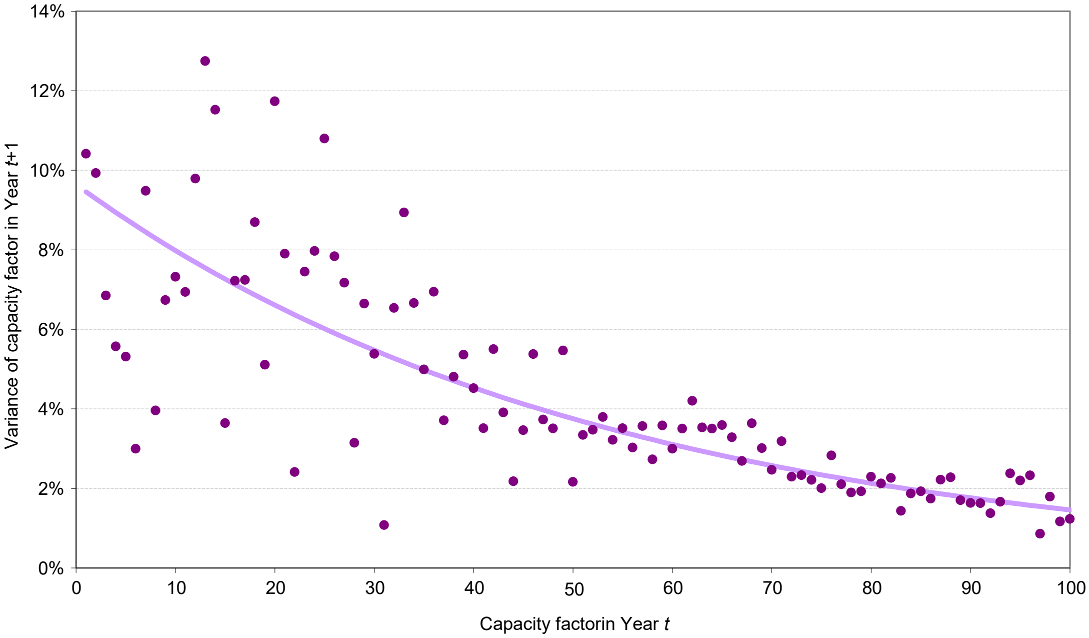


Figure 4-3: Sample and fitted variance of capacity factors, PRIS database (adapted from [108]).

- Include all types of reactors (also unusual and experimental designs);
- Include reactors managed in very diverse institutional settings;
- Cover a large time window;
- Ignore life-cycle patterns;
- Include shutdowns that are not purely exogenous.

For the purpose of the nuclear project financial model, the following refinements are made:

- Only PWR, BWR and PHWR are considered (the ONPP is likely based on a PWR);
- Only reactors with power rating larger than 300 MW_e are considered. In this way, small research/experimental reactors are excluded.
- Voluntary shutdowns are excluded;
- Only OECD reactors are considered (the ONPP is likely to be sited in Canada);
- Only reactors operating after the year 2000 are considered.

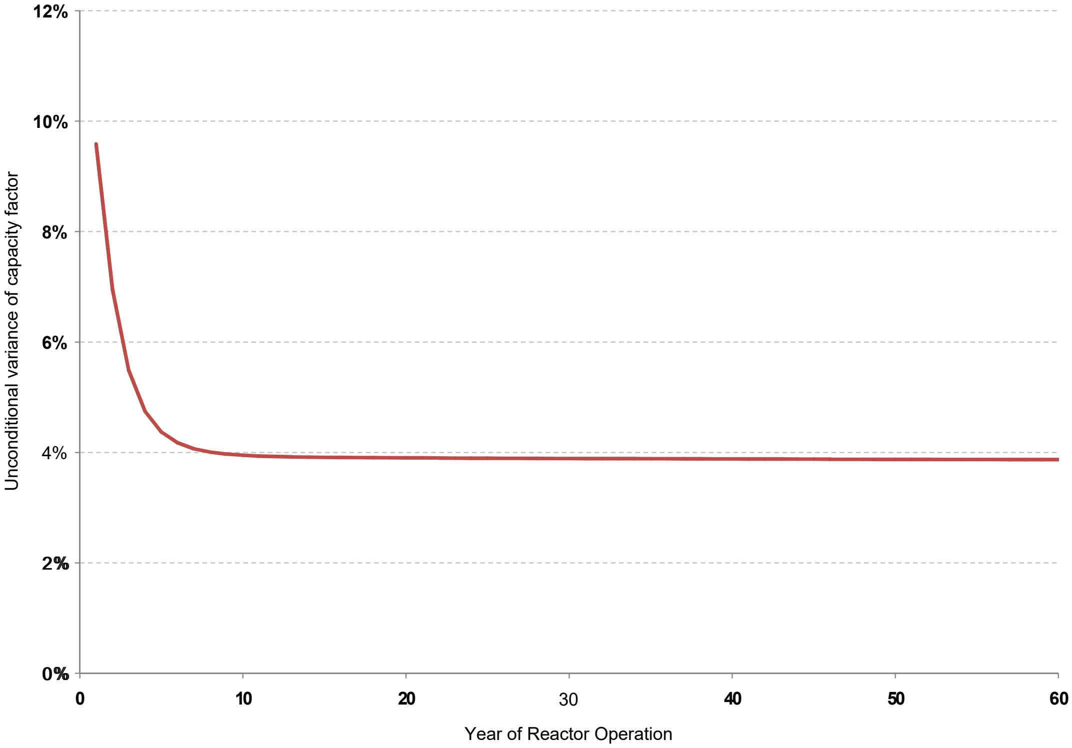


Figure 4-4: Unconditional variance of the nuclear capacity factor through the life of the reactor (adapted from [108]).

Under these assumptions, the variance shows a similar behavior in the first years of operations but its asymptotic value is much lower and stabilizes around 0.4%. In the nuclear project financial model the modeler selects a value for the "nominal" (asymptotic) mean capacity factor, μ_n. Then the capacity factor in year t is modeled using a normal distribution. Since the range of a normal distribution is $[-\infty; +\infty]$, the distribution is truncated below 0% and above 95%.

$$CF_t \sim (\mu, \sigma^2)$$

Using the variance values from [108], then the model input for the capacity factor is:

$$CF_t = \begin{cases} CF_{t=1} \sim N(0.5 \cdot \mu_n, 0.097) & \text{for} \quad t = 1 \\ CF_{t=2} \sim N(0.6 \cdot \mu_n, 0.018) & \text{for} \quad t = 2 \\ CF_{t=3} \sim N(0.7 \cdot \mu_n, 0.006) & \text{for} \quad t = 3 \\ CF_{t=4} \sim N(0.8 \cdot \mu_n, 0.005) & \text{for} \quad t = 4 \\ CF_{t\geq 5} \sim N(1.0 \cdot \mu_n, 0.004) & \text{for} \quad t \geq 5 \end{cases} \tag{4.2}$$

4.4.3 Price of electricity

The price at which the electricity is sold depends on several parameters such as capital cost, operation costs, competition, contractual agreement, demand profile. Predicting the electricity prices 50 years from now is not easy. It is assumed that electricity is sold through a Power Purchase Agreement (PPA). A PPA is a legal contract between an electricity generator (provider) and a power purchaser (in this case the mine). Contractual terms may last anywhere between 5 and 20 years, during which time the power purchaser buys energy, and sometimes also capacity and/or ancillary services, from the electricity generator [109]. The tax status of Canadian nuclear power plants changes after 21 years of operations, after which lower electricity prices can be offered.

The model uses a latent variable for market price of electricity. The user sets the initial price of electricity (e.g. 15 $cents/kWh$) and the time interval t_r for PPA price renegotiation (e.g. 10 years). Initial price and time interval are decided initially during contractual phase, so they are not uncertain variables. Every t_r years the electricity price "jumps" to the renegotiated value, which is assumed to match the market price of that year.

The market price (latent variable) is modeled as a random walk. This is the standard discrete stochastic process model for stock prices, and works well also for electricity prices [102].

$$p(t_n) = p(t_0) \cdot \mathrm{e}^{n \cdot \epsilon} \quad n = 1, 2, \ldots, N \tag{4.3}$$

Where $\epsilon \sim (\mu, \sigma^2)$, the growth rate from one year to the next, is sampled every year from a normal distribution. μ and σ are selected by the modeler. The random walk model reflects that the uncertainty of electricity price forecasting grows over time. This is shown qualitatively in Figure 4-5, where a simple Monte Carlo simulation is used to obtain 20 different electricity price histories. Figure 4-6 shows 20 PPA electricity prices histories with renegotiation time interval of 10 years, and tax status change at year 21. A multiplicative factor $c \leq 1$ is used to control the effect of tax status change.

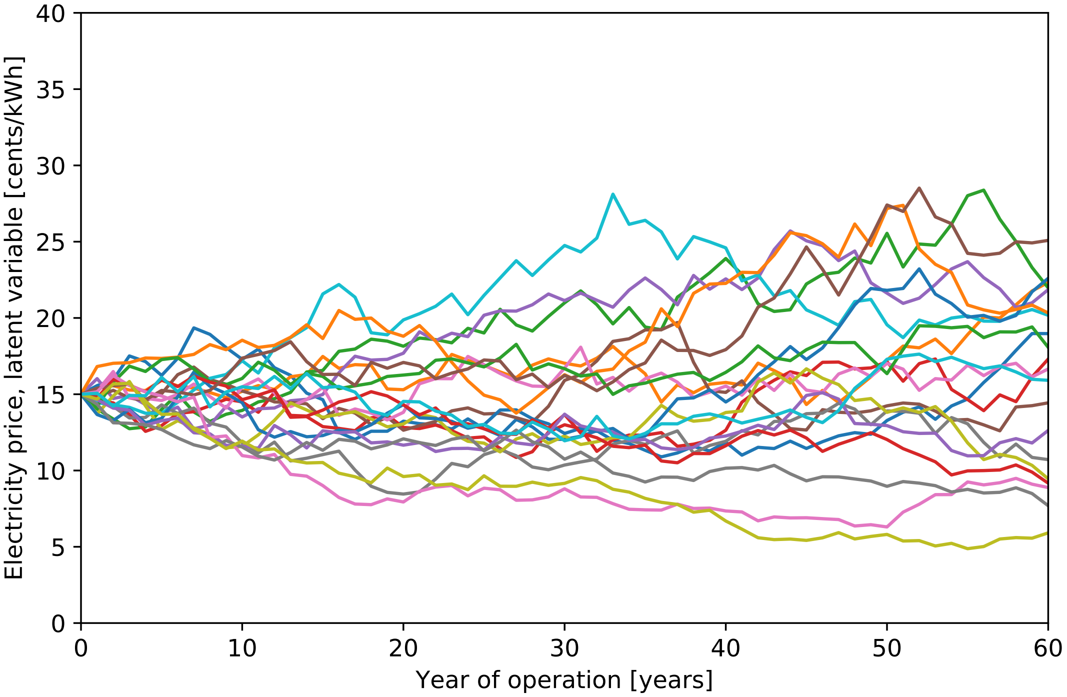


Figure 4-5: 20 electricity prices histories obtained with a Monte Carlo simulation

4.4.4 Construction time and delayed construction fees

Portugal-Pereira et al. evaluated overnight construction time escalation of nuclear power construction projects from 1955 to 2016. To this end, they studied a comprehensive database of commercial Light Water Reactors (LWR). Their statistical analysis shows that the probability distribution function of nuclear construction time can be adjusted to lognormal functions. Although a high concentration of values can be found around the average, the positive long tail on the right shows a high dispersion of the database. This distribution shape represents energy projects with highly risk parameters, such as nuclear reactors [110].

In the DCF model construction time is drawn from a lognormal distribution with adjusted parameters (Figure 4-7). Truncation limits are introduced so that construction time can never be less than 3.5 years nor larger than 15 years. 3.5 years is a reasonable lower bound reflecting the most optimistic case; projects that take more than 15 years to build would be abandoned before so it would not be fair to include them in the Monte Carlo simulation. Selecting for instance $\mu = 6$

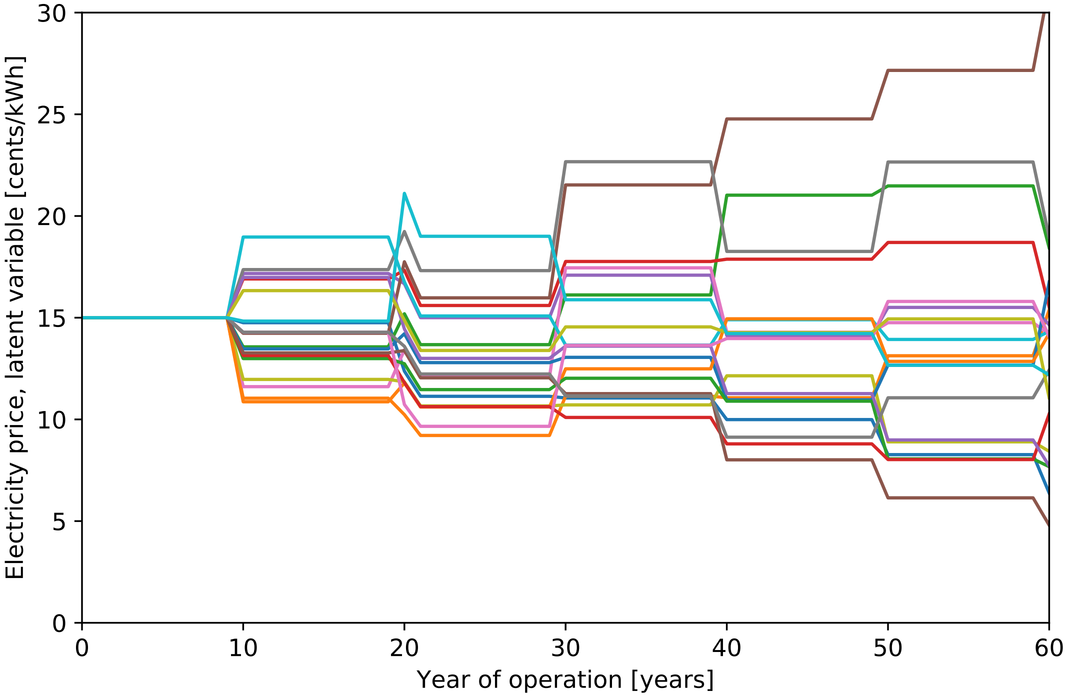


Figure 4-6: 20 PPA electricity prices histories obtained with a Monte Carlo simulation.

years and $\sigma = 25$ years and $shift = 3.5$ years, then 5^{th} and 95^{th} percentiles are respectively 3.6 and 11.5, which seems reasonable. The distribution is very skewed to the right, so for example the probability of building the plant in less than 8 years is 72%. For simplicity, construction time is always rounded to the closest integer.

When contractors encounter a owner caused (excusable/compensable) delay they are typically entitled under the contract to recover both the time resulting from the delay as well as delay damages [111]. There are several methods to calculate these costs. In our model we simply add a constant cost item for every year of delay.

4.4.5 Capital cost

Capital cost is composed of two parts: (a) the "overnight cost", which refers to the cost of building the plant, including equipment, construction materials, and labor, independent of how long it takes to actually build the plant (hence the term "overnight") and (b) the cost of interest on funds raised to build the plant (either as loans-debt or stock-equity) [2].

Figure 4-8 show that the overnight cost of historic LWRs ranges between about $2,000$ and

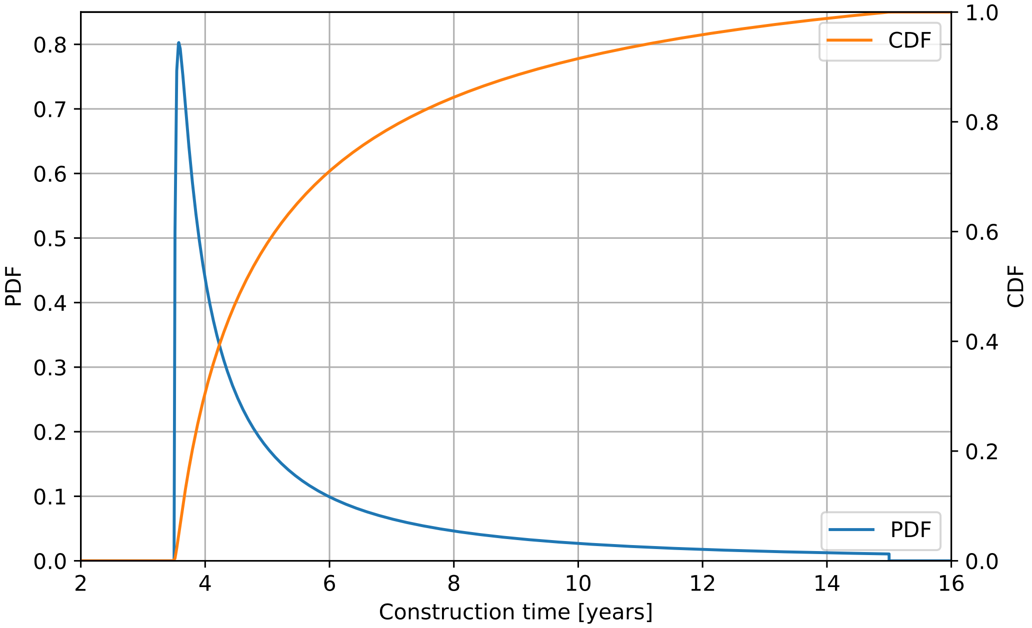


Figure 4-7: Construction time cumulative distribution function assuming $\mu = 4$, $\sigma = 15$, shift$= 3.5$, truncation limit $= 15$ years.

$12,000\,\$/kW_e$ in the United States and between $2,000$ and $5,000\,\$/kW_e$ in the the rest of the world (France, India, South Korean and Japan). Recently completed, proposed or under construction reactors have an overnight cost ranging between $2,500$ and $9,000\,\$/kW_e$ [2].

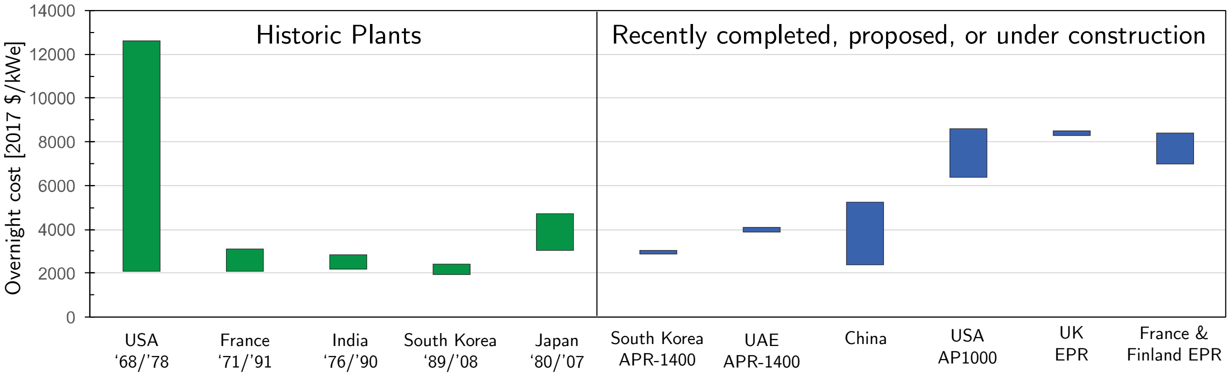


Figure 4-8: LWR overnight costs around the world (adapted from [2]).

In the DCF model the overnight cost is drawn from a lognormal distribution with adjusted parameters as suggested by Portugal-Pereira et al. [110]. Truncation limits are introduced so that overnight cost is in the range $2,000$ to $12,000\,\$/kW_e$. Figure 4-9 shows the overnight cost PDF and CDF assuming $\mu = 4,000$, $\sigma = 1,575$, truncation limits $= 2,000$ and $12,000\,\$/kW_e$.

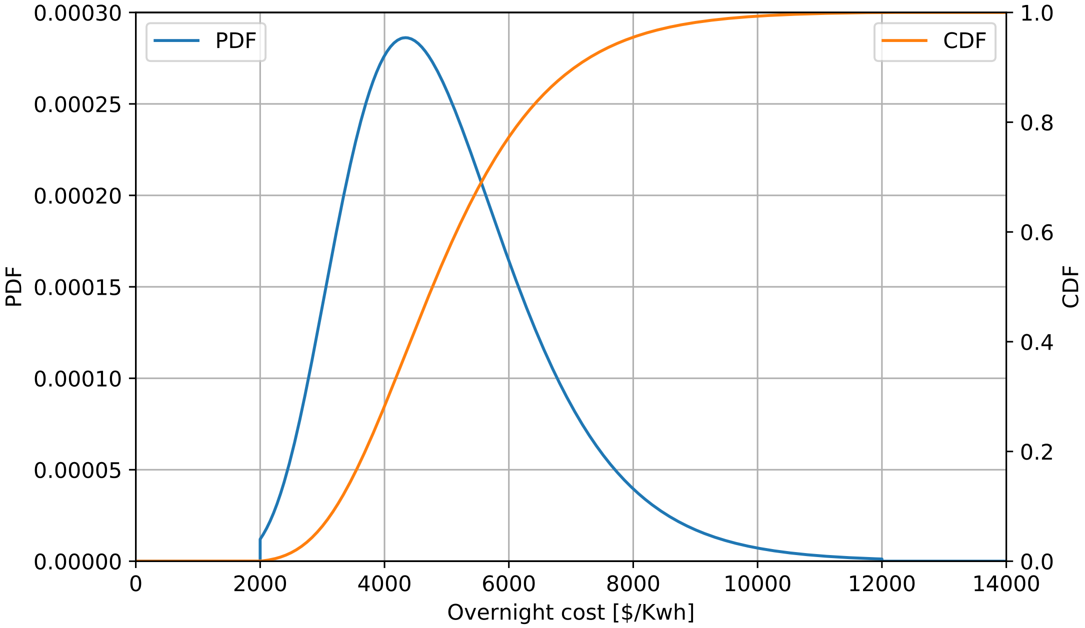


Figure 4-9: Overnight cost cumulative distribution function assuming $\mu = 4,000$, $\sigma = 1,575$, truncation limits $= 2,000$ and $12,000\$/kW_e$.

Interest costs are affected by construction time and the interest rate that applies to the borrowed money, which is known as “interest during construction” (IDC) or “accumulated funds during construction” (AFDC) [2]. IDC is calculated as follows:

$$IDC = 1 + \frac{N \cdot x}{2} \tag{4.4}$$

N is the construction time in years and x is the interests rate. Figure 4-10 shows how interests during construction vary as a function of construction time for different interests rates. The median construction time required for nuclear reactors worldwide from 1981 to 2017 is about 7 years [13], thus the median IDC is about 20-30% of the overnight cost!

4.4.6 Fuel costs, O&M costs and fixed (overhead) costs

Apart from the cost of fuel, the cost of operating and maintaining the power plant, also a provision for funding the costs of treating and disposing of used fuel and wastes is typically included. High fuel, O&M and fixed (overhead) costs are often offset by advantages in other areas, and vice versa.

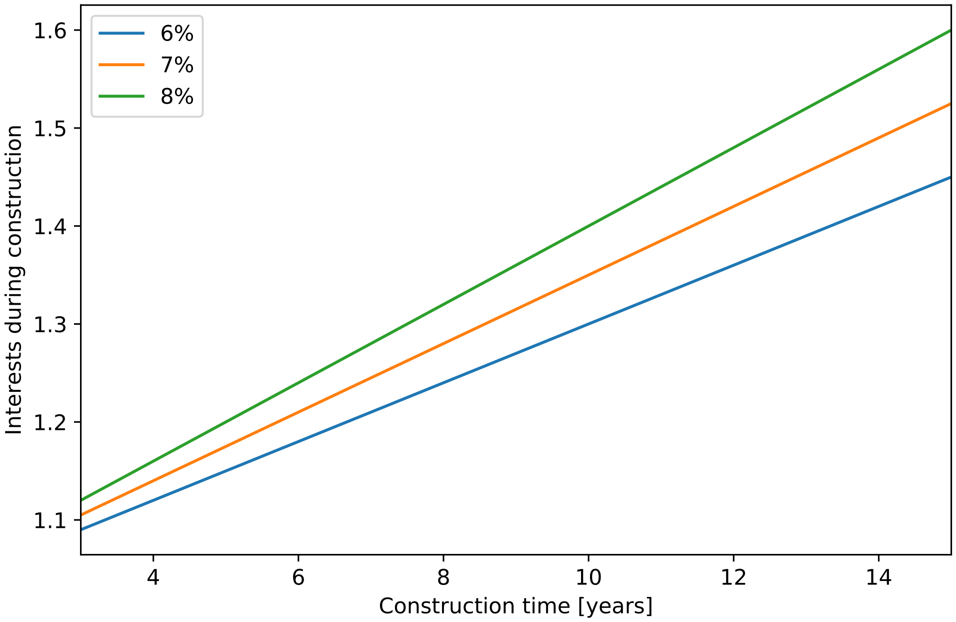


Figure 4-10: Interests during construction (as a multiplier of overnight cost) as a function of construction time for interests rates of 6%, 7% and 8%.

Normally these costs are expressed relative to a unit of electricity (for example, $\$/MWh$) to allow a consistent comparison with other energy technologies.

Fuel, O&M and fixed (overhead) costs vary widely between different forms of power generation. Nuclear power plants are expensive to build but relatively cheap to operate. Depending on the plant, fuel and O&M costs account respectively for only 5% and 15% of the total cost of energy [2]. Once the plant is built, O&M costs depend on the personnel needed and the consumables used to run the facility. Low fuel costs have from the outset given nuclear energy an advantage compared with coal and gas-fired plants [112]. In addition, Uranium is abundant and widely available in politically stable countries. The enrichment and fabrication processes account for about half of the total fuel cost.

In the DCF model, fuel, O&M and fixed (overhead) costs are all assumed to be random walk processes. The formula is the same as Equation 4.3, and the dynamic behavior is similar to that shown in Figure 4-5.

4.4.7 Decommissioning costs

A good rule of thumb is to assume that decommissioning costs are about one third of total construction costs [113]. Increased accuracy is not really necessary because if decommissioning happens far in the future (which is usually the case) its discounted value becomes only a few percent of the investment cost. For example, in the United States decommissioning costs account for 0.1-0.2 $cent/kWh$, which is no more than 5% of the cost of the electricity produced [114]. The DCF model adds a cost item equal to one third of total construction cost to account for decommissioning. The cash outflow happens in the year following the end of operations.

4.4.8 Transportation costs

A marine nuclear power plant is entirely built in a shipyard and then towed to the site. Thus, transportation costs must be taken into account for siting, decommissioning and major interim maintenance. There are two main transportation modes: wet tow (the unit floats on own keel and tugs pull it to the final location) and dry tow (the unit is loaded on the deck of a transport ship and transported to the site). There are dozens of companies which can do a wet tow as there are hundreds of suitable tugs. However, there are only few companies (less than a dozen) that can do a dry tow of medium size, and currently only one which can deal with very large size structures [100]. An excellent candidate for transporting these structures is the BOKA Vanguard ship (previously Dockwise-Vanguard), which is shown in Figure 4-11 [115]. Transportation cost is rather uncertain because it depends on route, time (dry tow is faster), flexibility (dry tow is less flexible) and ship availability. For example, in October 2013 Costa Crociere announced a $ 30,000,000 option with Royal Boskalis Westminster to use BOKA Vanguard to transport Costa Concordia to China (however Costa Concordia was instead refloated and towed to Genoa in July 2014) [116]. In the DCF model, transportation costs are considered not only for siting, but also for decommissioning and every time the rig is transported to the shipyard for exceptional circumstances or maintenance. If these operations happen far in the future, their discounted value becomes very small.

The skeleton of the marine plant in consideration is built in a shipyard somewhere in Asia. In this phase the cost is roughly between 4.5 and 6.5 $ per kg of steel erected and transported to the Canadian shore. Then, construction is finalized in a Canadian shipyard, such as the Irving shipyard or the Davie Shipyard (this phase is called outfitting). In the DCF model one variable is used for transportation costs from location x in Asia to the Canadian shipyard. Another variable

Figure 4-11: BOKA Vanguard transporting the ENI Goliat oil rig to its site in the Barens Sea.

is used for transportation costs from the Canadian shipyard to site. They are both assumed to be normally distributed with mean and standard deviation selected by the modeler. The distributions are truncated below 0%.

4.4.9 Extraordinary repairs

The model distinguishes between regular maintenance and extraordinary repairs. The former takes three months to complete (i.e. one fourth of the yearly revenues are subtracted), and it happens offshore (no need of towing) every x years, set by the modeler. The latter is assumed to be a rare unpredicted event requiring the rig to be towed back to the shipyard. The modeler selects the yearly probability of this extraordinary circumstances happening.

If the platform needs extraordinary repairs in any given year, the following costs are applied: loss of revenues, transportation costs, and cost of extraordinary repair (e.g. material, labor, shipyard). Loss of revenues is calculated on the basis of the outage duration, which is drawn from a normal distribution with $\mu = 6$ months and $\sigma = 0.5$ months. Cost of extraordinary repairs is also drawn from a normal distribution with $\mu = 100$ \$ millions and $\sigma = 10$ \$ millions. These values are based on experts judgement. It is assumed that if extraordinary repairs are needed in the last 10 years of the plant lifetime, the plant is permanently shut down instead.

4.4.10 Discount rate

The discount rate is at the heart of any discounted cash flow model. Unfortunately, it is hard to estimate. The discount rate can be considered almost as the rate of return required by the investor which includes costs, risks and lost opportunities. Discount rates vary across industries and even between projects. Moreover, they are time-dependent and they are not necessarily the same in different countries. The discount rate captures the firm's cost of capital: the firm should be able to raise funds at the discount rate and should be able to invest these funds so that the return on these investments equals the discount rate [104]. As a practical matter most system designers have to use the discount rate set by higher authority [104]. In most companies, the discount rate is decided from above and employees use that value "blindly" to all projects. While a reasonable range of discount rates is typically known within an industry, in practice often designers do not have a choice about the discount rate.

A large project such as a nuclear power plant is financed through a mix of debt and equity. Debt financing comes from banks and investors who, in return for lending the money, receive a promise that the principal and interest on the debt will be repaid on a regular schedule. With equity financing, the capital comes from the owners of the project. The owners are more vulnerable to the risk of default because debtors have preferential access to liquidation proceeds in the case of bankruptcy. Thus, the cost of the owners‘ equity, that is, their return expectations, is higher than the cost of debt, which is the interest on loans [104]. In short, the discount rate depends on the financing scheme.

The Weighted Average Cost of Capital (WACC) is the average after-tax cost of capital in which each category of capital is proportionately weighted. The DCF model uses the WACC as a reasonable estimate for the disocunt rate:

$$WACC = \frac{E}{E+D} \cdot C_e + \frac{D}{E+D} \cdot C_d \cdot (1-T) \tag{4.5}$$

Where E and D are the market values of firm's equity and debt, C_e and C_d are the costs of equity and debt, and T is the tax rate. The NPV of a project depends on discount rate in a rather complex way. For some projects the smallest disocunt rate possible is the best choice. For other projects the NPV initially increases with the discount rate up to a tipping point when the NPV starts to decrease. At a fundamental level, these different behaviors depend on: project duration, cash flows size, when these cash flows happen throughout the project (soon vs. far in the future). In general, nuclear constructions belong to the first type of projects (i.e. the smaller the discount rate, the better).

4.5 Real options analysis

The DCF model implicitly assumes that the management team holds the assets passively throughout the project's lifetime. As stated in the context of the SD model, instead of simply sitting back and watching the future unfolding, managers monitor the project dynamically, they react to changes and take corrective actions in response to deviations from the plan. If things go well, the project may be expanded; if they go badly, the project may be cut back or abandoned altogether. Projects that can be modified in these ways are more valuable than those that do not provide such flexibility [105]. Building flexibility into the design comes at a cost. However, the more uncertain the outlook, the more valuable this flexibility becomes.

In technical terms, *real options* are a right but not an obligation to make a business decision. Practically, they are options to modify the project. Some examples are:

- Real option to delay/defer: delay investment without losing the opportunity (e.g. submitting a patent);
- Real option to switch/redeploy: switch the use of assets should market conditions change;
- Real option to expand/contract: adjust the scale of an investment depending on the market conditions;
- Real option to abandon: cease a project or an asset to realize its salvage value.

An successful example of real option theory application is the decision to plan for vertical phasing [3] of the Health Care Service Corporation (HCSC) headquarters building. The corporation wanted a single building downtown in Chicago that could host its entire staff. However, it did not want to commit in the 1990s to what it might need in the 2010s and beyond. HCSC thus designed the building with the flexibility to expand when needed. 30 stories above ground (plus 3 below ground) were built during the first phase in 1997. A decade after the company exercised the option to expand and 24 more stores were built (Figure 4-12). Planning for flexibility was initially more expensive, but in this case it paid off.

Often sensitivity analyses and Monte Carlo simulations do not recognize the possibility to modify projects. Conversely, our DCF model uses some variables to introduce the possibility of

---

[3] Vertical phasing occurs when a building is originally constructed to a certain height, but includes the intentional capacity for it to expand vertically in the future [117]

Figure 4-12: Health Care Service Corporation (HCSC) headquarters in the center of image before and after vertical phasing (adapted from [117]).

uncertain events happening, and it allows users to exercise different real options. The DCF model allows to evaluate explicitly the following real options:

- The nuclear power plant can be designed so that its capacity can be doubled (e.g. it can host an additional reactor module) in case of favorable market conditions.
- The floating structure can be designed so that it can be relocated in case a local public utility commission decides to withdraw support for the project, or in case of anticipated forced shutdown due to mining operations cessation.

These real options are decisions made in the future in response to uncertain events. Building flexible designs costs more and requires more effort, so the question is: when does it make sense? Our DCF model can provide an answer.

The theory of real options originates from financial options valuation. It values financial options that give a holder the right to defer unfavourable payoffs. Groundwork for financial option pricing was laid by Black, Scholes and Merton. Their efforts brought about the famous Black–Scholes–Merton formula, which provides a closed-form solution to value European call options. *Design* options are not different from *financial* options: they both provide the right but not the obligation to a future action [118]. However, although financial options pricing is a conceptually appealing theory, it is typically not suited for a valuation of options in the kind of technology projects dealt with in this work. This is because critical assumptions behind financial options pricing generally do not apply to engineering systems and technological projects [104].

4.6 Example: use the DCF model as stand-alone application

This Section illustrates the benefits of using the DCF model to:

- Evaluate stochastically the value of a nuclear project;
- Prioritize investments and direct research efforts;
- Perform a real options analysis to drive the power plant design.

On the base of the probabilistic model described in the previous section, we evaluate the performance of a project based on a generic marine small modular reactor serving mining operations in the North of Canada. We call this "baseline" project. The plant's nominal net capacity is $60MW_e$. The assumptions regarding price of electricity, construction cost, construction time, interests during construction, disocunt rate, fuel, O&M, transportation, decommissioning, and fixed costs, are those presented in Section 4.4. In particular, in this example the overnight cost is drawn from a lognormal distribution with $\mu = 5,000\$/kW_e$, $\sigma = 1,575$, truncation limits $= 2,000$ and $12,000$ $\$/kW_e$. Construction time is also drawn from a lognormal distribution with $\mu = 5$ years, and truncation limits = 3 and 9 years. The Monte Carlo method is used to propagate uncertainties. The sample size of the Monte Carlo simulation is equal to 5,000 runs. Figure shows the NPV cumulative distribution function from the simulation. Table 4.1 is a summary of average, standard deviation, minimum and maximum results, values of 5^{th} and 95^{th} percentiles, P_5 and P_{95}, as well as the probability of negative NPV.

Secondly, the DCF model can be used to understand what are the variables contributing the most to project success, and ultimately drive investment decisions. An example will illustrate the concept. Suppose the consortium developing the nuclear power plant is looking to determine what is the best investment among:

- Increasing by 10% the capacity factor in the first 3 years of operations [4], or

---

[4] Recall that the capacity factor in the first few years of operations is rather low according to the model developed by Du and Parsons [108] and discussed in Section 4.4.2.

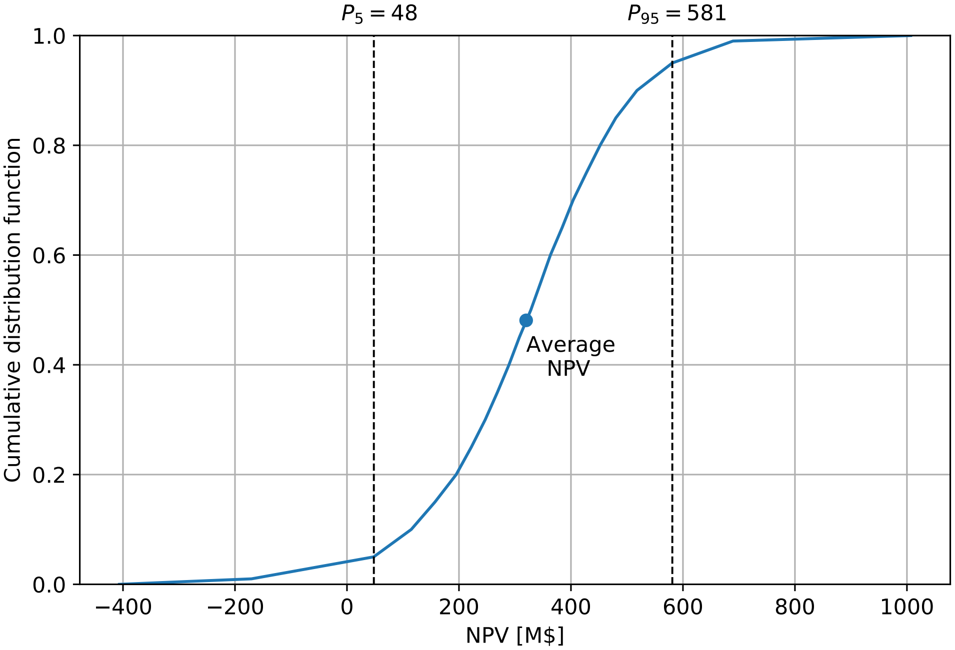


Figure 4-13: NPV cumulative distribution function from the Monte Carlo simulation of a nuclear project.

- Supporting lobbying/negotiation activities aimed at increasing the price of electricity by a mere 1 $cent/kW_e$ (an increase of about 6.7% of the baseline).

Where would you put the resources? The DCF model helps answering this question. Figure 4-14 and Table 4.2 compare the results for (1) the baseline project presented above, (2) the project with improved capacity factors and (3) the project with higher price of electricity. Based on these results, increasing the price of electricity (even by such a little amount) is a better choice because the average NPV is about 1.1 times higher than that of the project with enhanced capacity factor. In addition, the financial risk (i.e. probability of negative NPV) is reduced from 2.6 to 2.4%. In

	Value	Units
Average NPV	319	M$
Standard deviation	163	M$
P_5	47	M$
P_{95}	570	M$
Minimum	-543	M$
Maximum	893	M$
Probability NPV<0	3.1	%

Table 4.1: Simulation results for NPV of the baseline project.

	Baseline project	Improved CF	Higher electr. price	Units
Average NPV	319	341	371	M$
Standard deviation	163	163	172	M$
P5	47	68	86	M$
P95	570	595	629	M$
Minimum	-543	-491	-423	M$
Maximum	893	895	984	M$
Probability NPV<0	3.1	2.6	2.4	%

Table 4.2: Comparison of simulation results for NPV of (1) baseline project, (2) project with improved capacity factor, and (3) project with higher price of electricity.

general the whole CDF curve is shifted to the right (which is good).

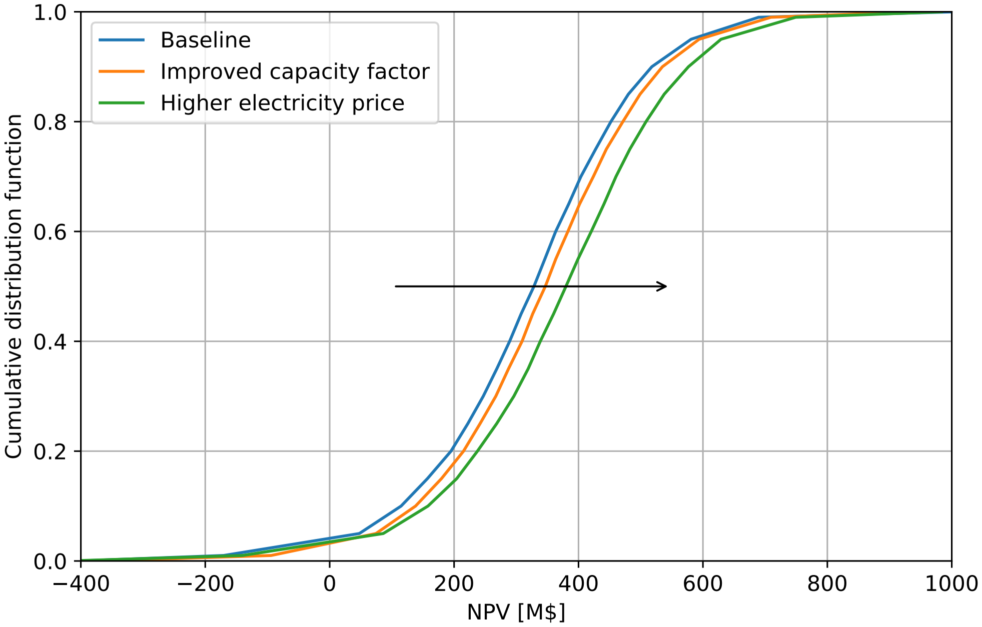


Figure 4-14: Comparison of NPV cumulative distribution functions for (1) baseline project, (2) project with improved capacity factor, and (3) project with higher price of electricity.

Finally, the DCF model allows users to exercise different "options", a decision made in response to an (uncertain) event. As discussed in Section 4.5, this is called real options analysis. Again, we show the concept with an example. Does it makes sense to build a nuclear power plant whose capacity can be expanded in the future? Would the larger investment be justified? In the DCF model if the plant is built with the option to expand, every year there is a chance that it is doubled to $120 MW_e$. `Yearly Probability That Power Output Is Doubled` is set to 0% if the plant is *not* designed with the option to expand and 5% otherwise. If plant capacity is doubled `Power Output` is set to $120MW_e$, all other cost items expressed in $[\$/kW_e]$ are also doubled (e.g. fuel, O&M costs), and the cost of a reactor module is added to the cash flow analysis. The cost of adding a module includes reactor equipment, turbine upgrade (or replacement) and installation costs. This is about 15-20% of the capital cost (Figure 1-4 in Section 1.3.2). Note that if the expansion happens far in the future the effect on the present value is small. Reasonably, overnight cost and construction time for such plant would be larger. Here we assume that the mean overnight cost for a power plant with the option to expand is $500\$/kW_e$ and that the mean construction time increases by one year. Figure 4-15 compare the NPV cumulative distribution functions for the baseline project and the project with the option to expand. While the curves are almost equivalent for negative values of the NPV (financial risk), the upside of having the option to expand is quite impressive (right hand side of the plot). The average NPV is about 1.6 times higher than the baseline project. The standard deviation is larger, which means that the NPV result is more uncertain. However, the average range of outcomes is shifted to higher values. Based upon these results, the decision makers should opt for building a power plant with the option to expand. A sensitivity analysis to test these assumptions ($500\$/kW_e$ increase in overnight cost, 1 more year to build, 5% probability per year to upgrade capacity) could be carried out but it is not important in the context of this example, which shows versatility and power of the DCF model.

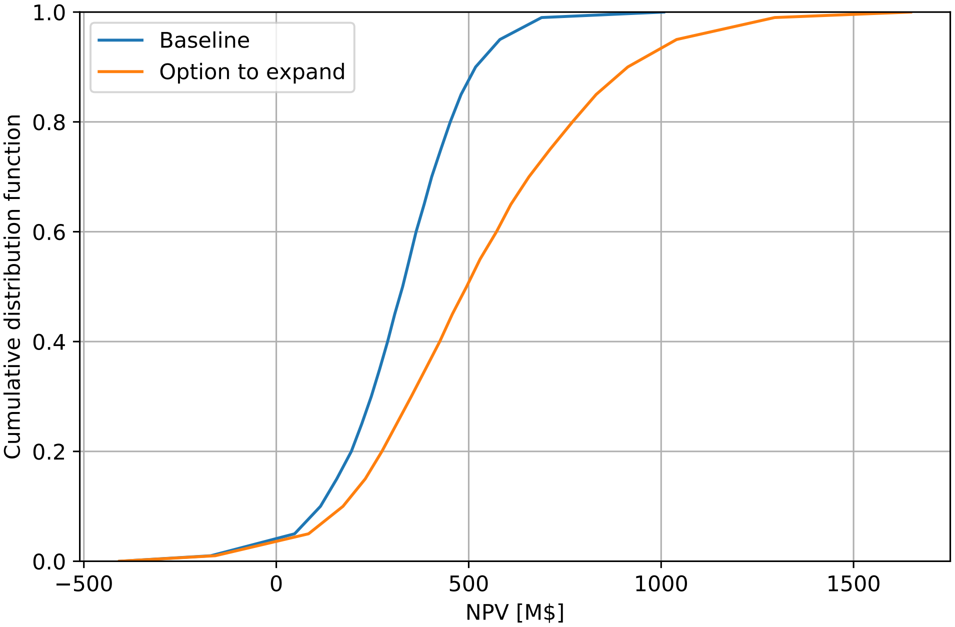


Figure 4-15: Comparison of NPV cumulative distribution functions for (1) baseline project, (2) project with option to expand.

Chapter 5

Decision Management Framework

5.1 Decision management

5.1.1 Need for a solid decision management process

Many systems engineering decisions are difficult because they include numerous stakeholders, multiple competing objectives, substantial uncertainty, and significant consequences [119]. Framing a decision problem is complicated, especially in the context of highly complex, dynamic, interconnected systems such as nuclear projects (Section 2.2). As Keeney puts it: “Most important decisions involve multiple objectives, and usually with multiple-objective decisions, you can’t have it all. You will have to accept less achievement in terms of some objectives in order to achieve more on other objectives. But how much less would you accept to achieve how much more?” [120]. In these cases, good decision making requires a formal decision management process.

This is particularly important in the initial stage of a project: making a poor decision at this point will have significant cost and schedule ramifications as changes become more difficult or even impossible to make later in the process. Unfortunately, this is also the phase when the level of knowledge upon which we base our decisions is minimum (Figure 5-1). The decision space must be carefully selected in order to mitigate the risk of later costly changes, and maximize the system’s probability of success. Intentional or unintentional premature reduction of the choice space may reduce the value of the project [121].

According to Parnell et al. [122] the decision process is (1) collaborative, (2) iterative, (3) it explicitly considers the environment and (4) it emphasizes value creation. The decision management method most commonly employed by systems engineers is the trade space analysis.

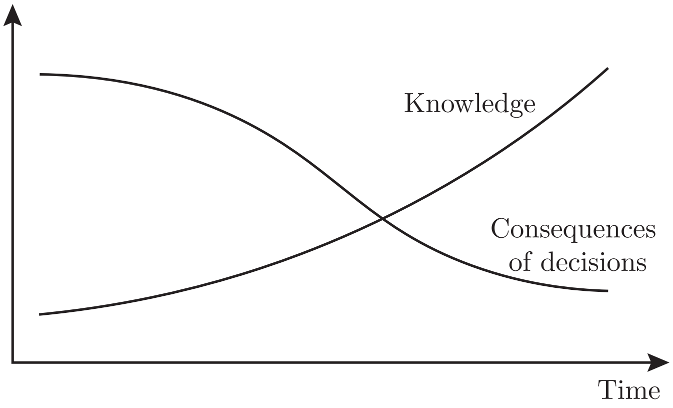


Figure 5-1: Extent of knowledge about the system and decision consequences as a function of time.

5.1.2 Trade spaces and Pareto frontier

Projects must perform well over several criteria. Each project has advantages and disadvantages, and trade-offs between multiple dimensions of choice are always necessary. Multi-objective decision making is necessary because real-world problems have multiple, possibly conflicting, objectives. In multi-objective decision making, policies are mapped to vectors rather than scalars:

$$V : \Pi \mapsto \mathbb{R}^{\mathrm{n}} \tag{5.1}$$

Where V is the value function and Π is the policies space. But why not just scalarize? Scalarization functions project multi-objective values to a scalar:

$$\mathbf{V}^{\pi}_{\mathbf{w}} = f(\mathbf{V}^{\pi}, \mathbf{w}) \tag{5.2}$$

Where $\mathbf{w}$ is the vector of weights. For example, in the linear case:

$$\mathbf{V}^{\pi}_{\mathbf{w}} = \sum_{i=1}^{n} w_i V^{\pi}_i = \mathbf{w} \cdot \mathbf{V}^{\pi} \tag{5.3}$$

The problem is that this is equivalent to an a priori prioritization of the objectives. A priori scalarization is sometimes impossible, infeasible or undesirable [123]. It is therefore not possible to define an objective function suitable for overall optimization. Consequently, it is not possible to determine preferred designs or policies through a purely mathematical procedure that ranks projects unambiguously [104]. In addition, such approach directs the focus to a restricted part of the trade space, leaving the decision makers with an incomplete knowledge of the bigger picture.

Trade space analysis is preferred in multidimensional choice problems. In general, a trade space is a representation of a set of options in a space defined by two or more metrics [124]. Historically most trade space analyses focused on design and architectural decisions. The axes of an architecture trade space are typically utility and cost (or similar measures). For example Figure 5-2 illustrates a trade space for different steam turbines, where net electric power $[kW]$ and total installed cost $[\$/kW]$ are used as metrics [1]. Each point represents a unique system design or architecture. Trade space plots include numerous architectures, represented at lower fidelity and evaluated with a few simple key metrics. Decomposing a trade decision and condensing all information about complex designs down to a few metrics allows decision makers to work within human cognitive limits without oversimplifying the problem. In this work the trade space concepts are applied not only to architectural decisions but also to managment decisions. So each point represents a combination of design choices *and* management choices such as how much should different project phases overlap.

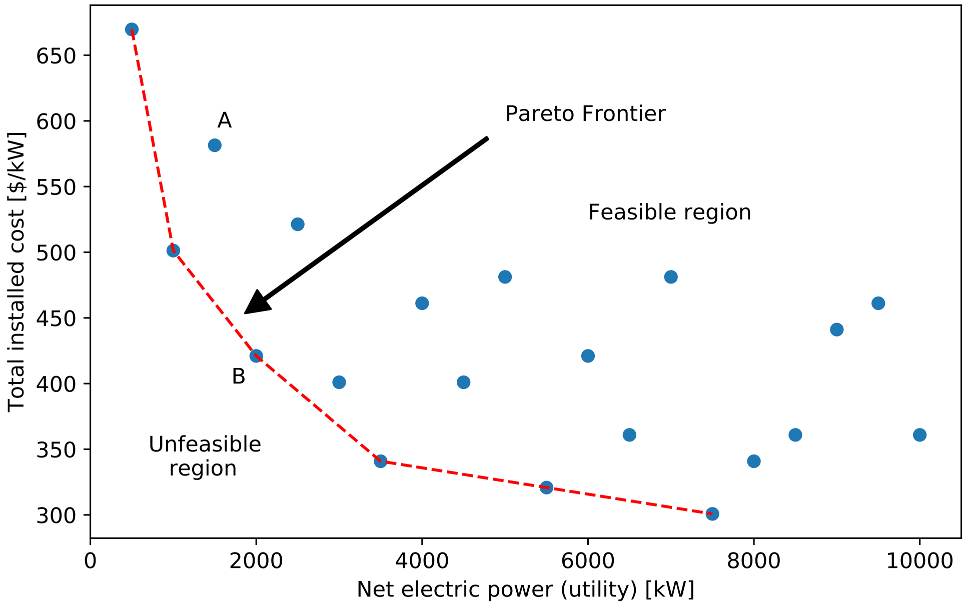


Figure 5-2: Steam turbines trade space, using net electric power and total installed cost as metrics.

Because we have two or more metrics represented in a trade space, it is unlikely that any single choice is uniquely the best [124]. However, looking at Figure 5-2, it is possible to distinguish between dominated and non-dominated options. An option A is dominated by option B if all of A's

---

[1] These are not actual data.

objective values are worse than the corresponding objective values of B. For example, in Figure 5-2, option A costs more than option B and it generates less power. On the contrary, it is not possible to improve non-dominated alternatives in any single dimension without giving up performance in some other. The set of non-dominated solution is called *Pareto frontier* (Figure 5-2). These solutions are “equally good”. When stakeholders make a decision, they - implicitly or explicitly - assign a weight to each objective and the trade space effectively collapses to a single point. Note that complete exploration of the trade space considers dominated solutions as well as the Pareto frontier. Dominated solutions are not necessarily poor choices as they might actually outperform dominant solutions on the basis of other metrics. For example, the concept of fuzzy Pareto frontier was introduced to capture a narrow swath of choices near the frontier. The fuzzy frontier can be an explicit acknowledgement of performance uncertainty, ambiguity in measurement, errors in the model, or like [124].

5.1.3 Developing objectives and measures

A project is successful when it achieves a sufficiently large number of stakeholder’s objectives. The values of the stakeholder’s satisfaction vector are not binary: objectives can be satisfied only up to a certain extent and with different levels of quality. There are different degrees of success. However, there exists a threshold below which the project can be considered a failure. Sometimes a project is a success for some stakeholders and a failure for others.

The first step to measure the degree of success is to develop objectives and measures. Usually stakeholders value competing objectives of performance, development schedule, unit cost, support costs, and growth potential. For corporate decisions, shareholder value would also be added to this list [119]. A functional decomposition can help generate a thorough set of potential objectives. Each objective should be essential and controllable and the set of objectives should be complete, non-redundant, concise, specific, and understandable [125]. Figure 5-3 shows an example of objectives valued by stakeholders in a nuclear project. The terminal values are the objectives. Each stakeholders value these objectives differently: for example, in a nuclear project the regulator values more the Core Damage Frequency (CDF), while the nuclear power plant owner focuses on maximizing the NPV.

Each objective is monitored through a specific measure, so that alternative options (e.g. projects) can be compared subjectively. A measure (attribute, criterion, and metric) must be unambiguous, comprehensive, direct,operational, and understandable [126]. Choosing the right measure is eas-

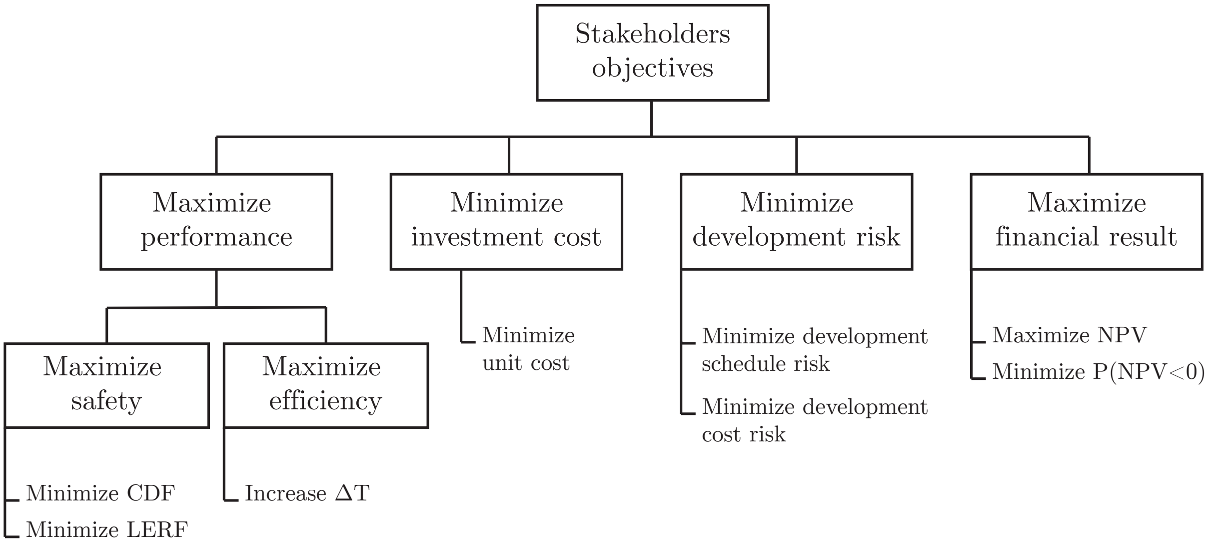


Figure 5-3: Example of objectives valued by stakeholders in a nuclear project.

ier for some objectives than others. For example, the NPV is appropriate to evaluate the degree to which "maximize NPV" is satisfied; but what is a good indicator for "minimize development schedule risk"? It is crucial that decision makers agree upon these metrics.

A defining feature of multi-objective decision analysis is the transformation from measure space to value space [119]. This transformation is performed by a function which takes a measure x_i and returns a value $v_i(x_i)$ on a scale between 0 and 100 (or 0 and 1). There is a point on the x axis in Figure 5-4 where regardless of how well an alternative performs in other measures, the decision maker will walk away from the alternative. This is called *walk-away* point and it must be mapped to a 0 value on the y axis. An example is a nuclear plant with a CDF not complying with the regulations. That plant might have a low overnight cost but it will never be built, no matter what. Conversely, there is an x_i beyond which no additional value is achieved. This is called *stretch goal* and it must be mapped to a 100 (or 1) value on the y-axis. Using a same example of the CDF, there is a point where adding safety systems does not make sense anymore. The relationship between measure and mapped value can be of any type. This transformation is necessary because the relationship is not necessarily linear, as shown in Figure 5-4.

Assuming that "maximize performance" in Figure 5-3 is the same across all combinations of design/projects, then the comparison of nuclear projects in this work should focus on "minimizing investment cost", "minimizing development risk", "maximizing financial result". For each objective, a measure is derived from the SD and DCF models illustrated in Chapters 3 and 4. Thus, SD

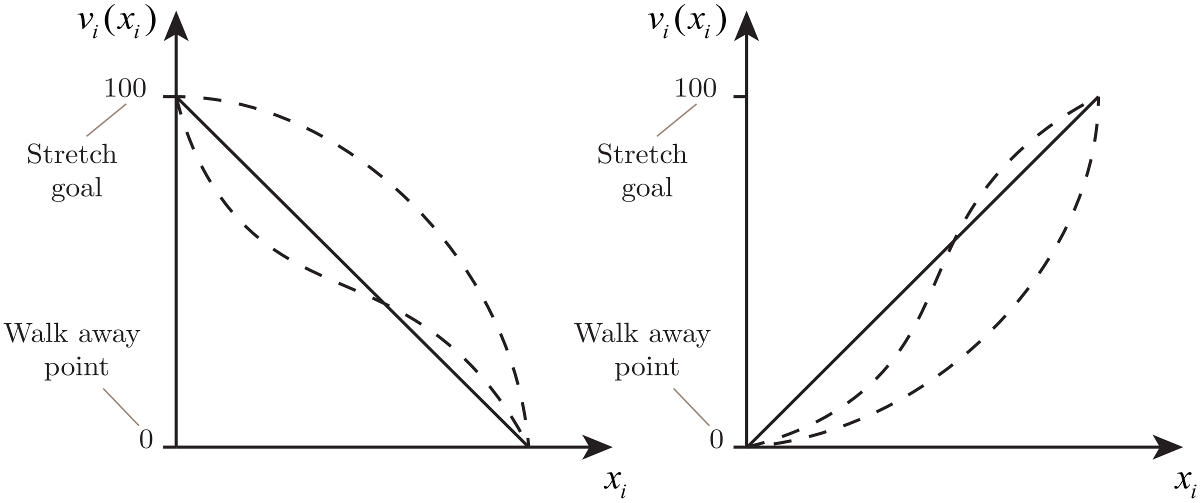


Figure 5-4: Examples of functions mapping from measure space to value space.

and DCF models provide a rational mean for measuring some pre-defined objectives. Once the stakeholders accept the structure and the assumptions behind these models, they can rely on them not only for managing projects but also for comparing alternative policies and designs. Table 5.1 lists the stakeholders' objectives and their relative measures. Finally, these objectives can be plotted in trade spaces and the projects compared. When possible, weights can be assigned to each objective using any method (for example, the swing weights matrix method [127]).

Objective	**Measure**	**Model**
Minimize unit cost	Base Case Cost [person-month]	SD model
Minimize development schedule risk	Build Finish Realized - Build Finish planned [months]	SD model
Minimize development cost risk	Cost Relative to Base Case [-]	SD model
Maximize NPV	Average NPV [M$]	NPV model
Minimize P(NPV<0)	P(NPV<0) [-]	NPV model

Table 5.1: Stakeholders' objectives and measures. The measure variables are named as in the relative models.

Chapter 6

The Marine Small Modular Nuclear Power Plant

6.1 Case study: marine small modular nuclear plant

6.1.1 Project background and motivation

The future of Canadian mining lies in the North. Northern mines are economic drivers. They are foundational to Canada's economy, employing the most Aboriginal Canadians of any private sector, and responsible for up to 68% of GDP in Northern Canada. The region possesses an untapped potential in minerals and Heavy Rare Earth Elements (HREE).

With challenges such as difficult terrain, harsh weather conditions, high costs of diesel fuel, and lack of access to carbon-free, reliable energy sources, successful Northern mining means expert operational execution at the intersection of economic, environmental and social benefit. Replacing diesel fuel with lower-cost, carbon-free, baseload nuclear energy is an unprecedented opportunity for remote mining operations to maximize financial returns while satisfying environmental and social requirements. This is also a great opportunity for offshore small modular reactor designs specifically developed for operations in remote areas.

To guarantee safe, reliable and clean energy supply for Northern Canada mining operations, novel development scenarios are currently under development. In this case study, we investigate in detail three designs: a gravity based platform, a floating barge platform and a spar-type platform. In the following analysis we examine the example of integrating one or two integral small modular reactor modules (60 MW_e each) into these three power plants and compare their performance in terms of design, construction and deployment life-cycle. All designs seek to minimize complexity thus containing development and construction costs, while ensuring high safety standards through passive safety systems and easy access to a virtually infinite heat sink (e.g. the ocean).

The three options differ with respect to geometry, overnight cost, required development effort, flexibility (relocatable vs. not-relocatable), mobility (self-moving vs. transportable), operating conditions (fixed vs. floating), ability to withstand severe events such as earthquakes and tsunamis (fixed vs. floating), safety performance in general, construction methods and shipyard requirements, maintenance requirements, refuelling method.

To achieve a significant construction cost reduction, this analysis assumes that the plant is built in a shipyard. However, it's important to realize that the shipyard approach is rewarding only if the design of the plant is completed before construction begins (which is not the case in traditional nuclear power plants). In other words, the shipyard construction model has a great potential only if things are done right the first time.

6.1.2 The gravity-based plant

The gravity-based platform is fixed to the seabed thorough a set of piles (Figure 6-1). The structure is about $80\,m$ wide, $85\,m$ long and $43\,m$ tall (excluding piles), and it's ideal for near-shore, shallow water, or dredged channel deployment. Pile mounting allows for rapid and low cost permanent or semi-permanent placement. Pile mounting also reduces civil works requirements. The weight of the platform acting on the piles is reduced by the structure buoyancy. The first plant hosts only 1 integral small modular reactor module ($60\,MW_e$). However, it is designed to accommodate an additional module for two reasons: (1) in case of increase in demand, the power output can be doubled rapidly in the face of a relatively small investment; (2) should more plants of the same type be built for operations in sites with larger load requirements, this design would guarantee more flexibility. The reactor modules are protected by multiple steel and water barriers, and they are located below the water line during operations, which ensure passive and indefinite heat rejection to the ocean. The design is such that refueling and maintenance operations can be performed on the deck level to facilitate access and logistics. Steel structure and layer of water provide enough protection from external hazards such as airplane crashes, missiles and fires. In case oil is spilled in the ocean and set to fire, it would stay above the water surface, separated from the steel structure. The simple prismatic structure reduces fabrication costs, and its dimension are such that it can be built in many shipyards around the world. The estimated overall plant weight with 2 modules is about $35,000\,ton$. Among all three designs, the gravity-based platform is the one that deviates the least from a terrestrial plant as it is attached to the seabed. Development costs are thus reduced. The plant is connected to the onshore switchyard via AC cables whose investment cost is lower than DC cables for distances below $80 - 100\,km$ [128]. Helipad and living quarters are located on the upper deck.

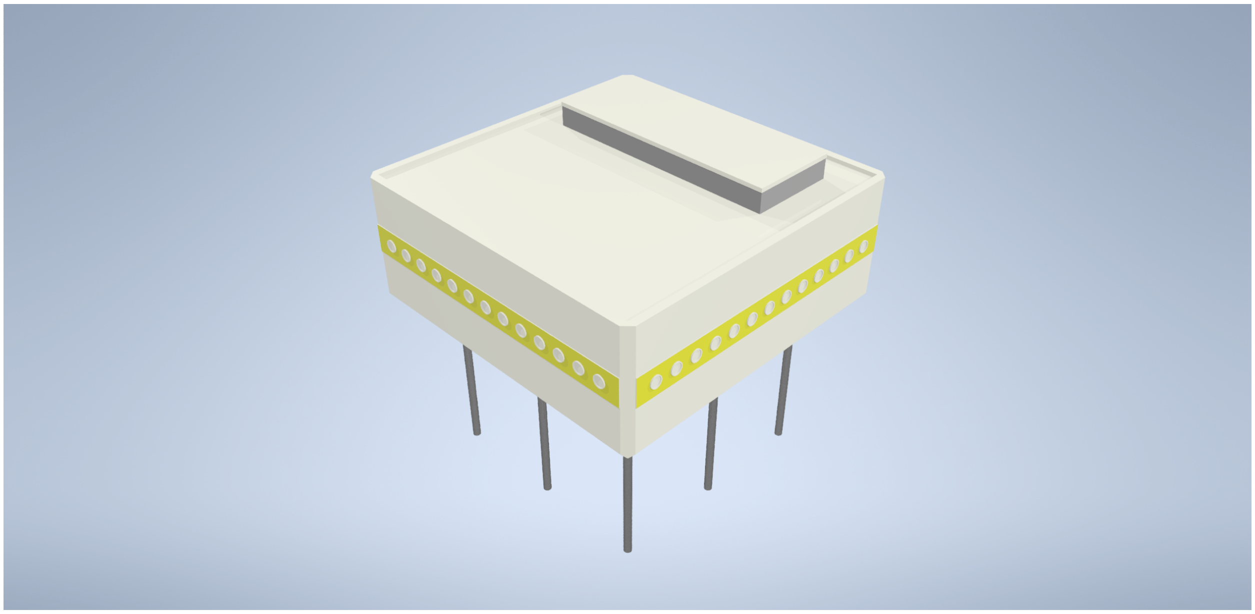


Figure 6-1: Conceptual representation of the gravity-based plant design.

6.1.3 The floating barge plant

The concept of a floating nuclear power plant capable of providing energy to far flung and difficult locations was first considered 40 years ago. Westinghouse has been pursuing the idea of a floating plant as far back as the 1970s [129]. Most recently, both China and Russia have been actively pursuing the idea of a nuclear power plant hosted by a floating barge. The plant considered in this analysis is conceptually similar to the Russian and Chinese designs. The Akademic Lomonosov, owned by Rosatom, is a non-self-propelled powership with a net capacity of 38 MW_e, and it's the first Russian floating nuclear power station. Construction started on April 14^{th} 2007 and the first criticality was reached on November 1^{st} 2018. The total estimated cost is about 336 million USD, but this number is highly uncertain [130]. Two Chinese companies are also developing offshore reactors. Details of China's floating nuclear power plants are not fully known due to secrecy around the designs. Both, however, are small pressurised water reactors based on previous onshore designs and will be incorporated into ships or barges. The first has been developed by the Nuclear Power Institute of China (NPIC), a subsidiary of the China National Nuclear Corporation (CNNC), and it has a net capacity of about 100 MW_e. The second floating power plant is being developed by China General Nuclear Power Group (CGN) and it has a net capacity of about 60 MW_e [131]. These massive research and industrial efforts undertaken by global leading economies reinforce the idea that there are several benefits of floating nuclear power plants.

As for the gravity-based platform, also the floating barge is intended to house two generic small reactor modules, but the initial plan is to install only one. The barge is thought for near-shore, shallow water applications, where the risk of sinking is null. The flat bottom with enforced stern and bow make it easy to transport, and the overall prismatic structure is designed to reduce fabrication costs. Plant geometry and layout are similar to those of common ships, which makes most shipyards around the world potentially capable of building the structure. The estimated overall plant weight with 2 modules is about $30,000\,ton$. The plant is expected to be about 180 m long, 40 m large and 40 m tall (from the bottom to the upper deck). The floating barge is towed to deployment site (e.g. it's not self-powered) and moored in place during operations. Compared to a generic standard terrestrial design, some changes to the equipment layout are likely necessary to fit the new geometry. The plant is connected to the onshore switchyard via AC cables whose investment cost is lower than DC cables for distances below $80 - 100\,km$. Helipad and living quarters are located on the upper deck.

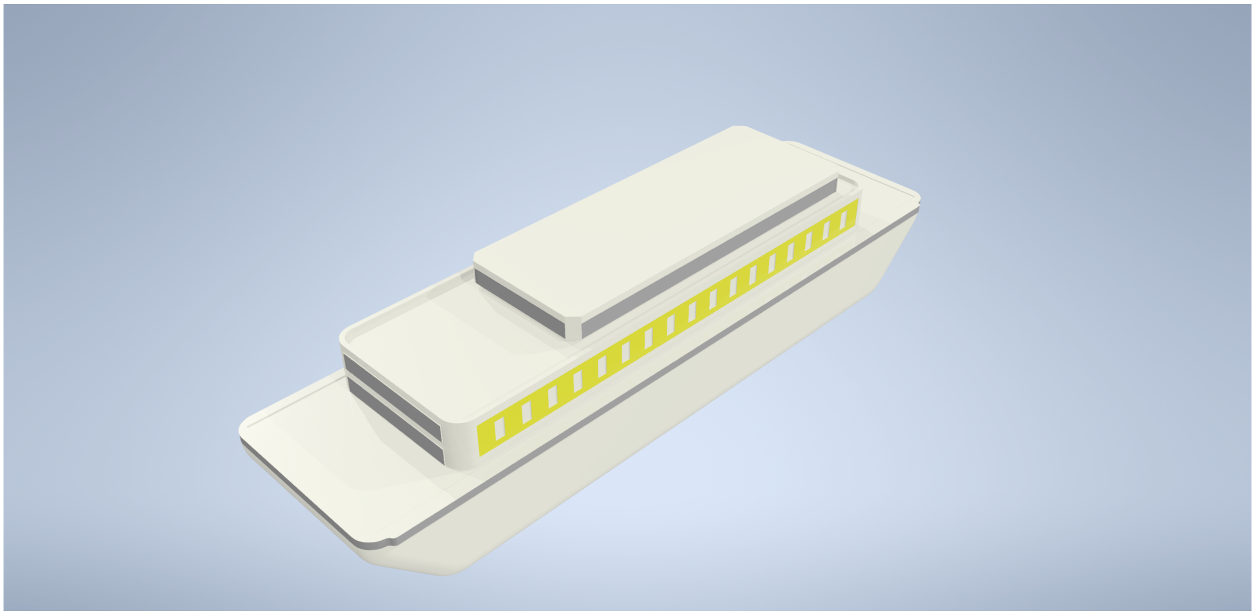


Figure 6-2: Conceptual representation of the floating barge plant design.

6.1.4 The spar-type plant

The third option (Figure 6-3) is a spar-type platform with similar to those extensively employed in the oil & gas offshore industry. The conceptual design is similar to the MIT Offshore Floating Nuclear Plant (OFNP) [132]. A spar is a simple cylindrical, partially-submerged, floating rig, with a low center of gravity for added stability. The cylindrical structure offers the best compromise between cost and dynamic stability with respect to waves, wind and blast. As for the gravity-based platform and the floating barge, also the spar-type platform design drastically reduce the transmission of seismic loads from the ocean floor. Assuming the integration of a generic integral small modular reactor into a spar, we estimated a draft of about 45 m and a top-section diameter of about 65 m, a bottom-section diameter of about 50 m, and the main deck is about 30 m above the water level. The power plant geometry may require deeper waters compared to the other two design options. The plant is designed so that the natural heave frequency of the plant is higher than the frequency of tsunami waves; therefore, the plant rides a tsunami wave with no risk of flooding. The spar-type plant is considered to host up to two generic integral small modular reactors. During normal operations, the reactors are located below the sea level and they have access to the ocean heat sink. In case of emergency, the ocean acts as a passive heat sink with virtually infinite capacity. Refuelling operations are performed within the platform. The structure's weight and size are well within the capabilities of modern shipyards in the U.S. and worldwide. For example, Thunder Horse PDQ, which is the largest oil/gas floating platform in the world ($140,000\,ton$ displacement, 136 m length, 30 m draft), was built by Daewoo Shipbuilding and Marine Engineering (DSME) in 24 months. The Technip yard in Finland routinely completes construction of large spar-type platforms (with diameters larger than 40 and drafts above $100m$) within 20 months. Newport News Shipbuilding recently completed the Gerald Ford, an aircraft carrier of $100,000\,ton$ displacement, 340 m length, 41 m deck elevation, 12 m draft, with 2 nuclear reactors aboard, in only 36 months [128]. These spectacularly short construction times for such large and complex structures are a result of the streamlining and efficiencies achievable in today's shipyards. The plant is connected to the onshore switchyard via AC cables whose investment cost is lower than DC cables for distances below $80 - 100\,km$. Helipad and living quarters are located on the upper deck.

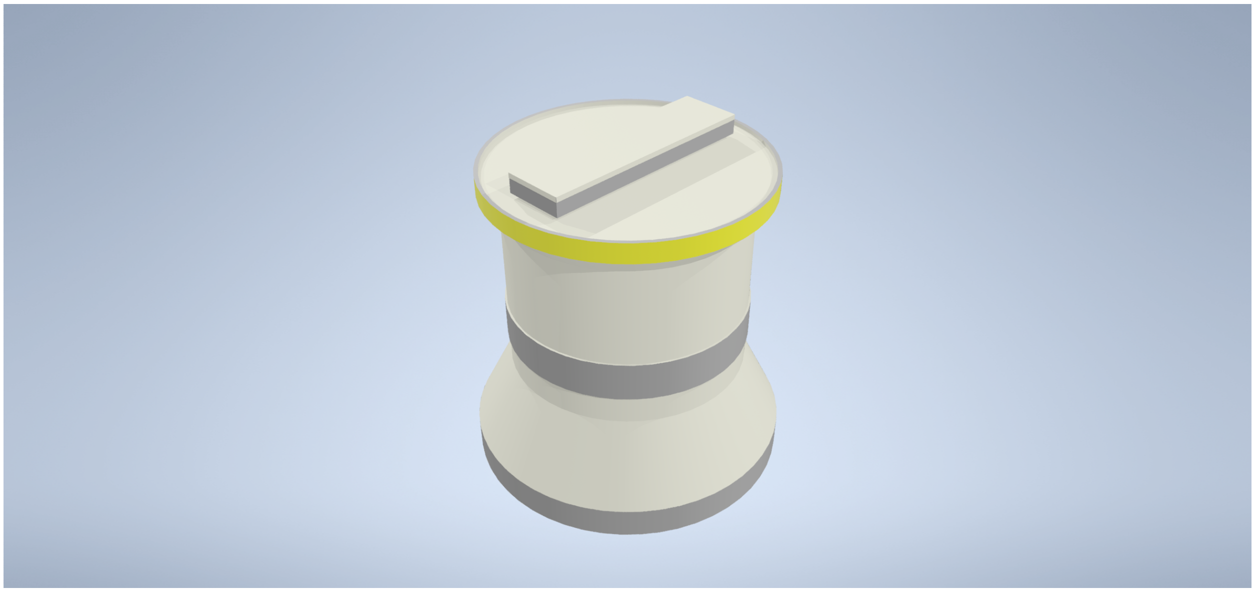


Figure 6-3: Conceptual representation of the spar-type plant design.

6.1.5 Table of decision options

Success probability of a project depends on the decisions made during its execution. The architecture of a system (e.g. a nuclear power plant) and the way it is delivered are essentially the product of these interconnected choices. Building a complex system entails making millions of decisions but the first ten (roughly) are the most important and tend to determine the majority of the performance and cost [124]. Ten choices alone theoretically generate $2^{10} = 1024$ project options if only two alternatives per decision are possible, $3^{10} = 59,049$ possible combinations if three alternatives are possible, and so on. These are early stage decisions. Making a poor decision at this point will have significant cost and schedule ramifications as changes become more difficult or even impossible to make later in the process (Section 5.1). A set of six decisions are selected in this case study. These include both design and project choices. The motivation behind this selection is presented here, while Section 6.1.6 illustrates how these decisions are represented in the SD and DCF models.

The first decision pertains the overall *deployment concept*. In this work, we evaluated three deployment concepts in parallel: a gravity-based plant, a floating barge and a spar-type plant. Selecting one from another will involve a trade-off between simplicity, cost and safety. Understanding how each concept performs with respect to the stakeholders' objectives will help collecting critical insights before converging to one choice and focusing the resources there.

The second decision concerns the plant's *capacity* necessary to power off-grid communities and industrial facilities such as remote mines requiring about 60 MW_e. Nevertheless, the nuclear power plant could be designed with extra space and predisposition for an additional reactor module in the future (if needed). A power upgrade would be necessary, for example, in case of expansion of industrial operations, addition of desalination units, power supplied to local communities, etc. Fundamentally, it is a real options valuation (option to expand). A larger initial investment would buy the owners the right but not the obligation to expand operations in the future at a lower cost.

The third decision is about the plant's *flexibility.* Financing a nuclear power plant is a risky investment, especially if the plant is sited in a remote area and it serves only one customer. In this context flexibility refers to the predisposition of the power plant to be relocated to a different site. If for example a remotely located mineral smelter or a mine site terminates operations before the end of the power plant's planned lifetime, a relocatable structure can potentially protect from a financial disaster and avoid decommissioning. It is another real options valuation (option to relocate). Again, a larger initial investment would buy the owners the right but not the obligation to relocate the plant if needed.

Decisions about deployment concept, capacity and flexibility are *design* decisions. These are highlighted in yellow in Table 6.1. On the other hand *project* decisions are highlighted in orange. These are about how the nuclear project is managed. Often problems in nuclear construction projects derive from a combination of the following factors:

1. Schedule disruptions caused by plan changes, scope growth, strikes, problems with suppliers, weather, etc.;
2. Rework getting out of control either because too much of it is generated or because rework tasks are not discovered quickly enough;
3. Insufficient or inadequate management staff, especially in case of emergencies (e.g. when rework peaks or when changes must be accommodated).

The benefits of using the SD model to manage schedule disruptions is discussed in Section 3.4. Rework gets out of control for many reasons (Section 3.4.6). Among them, excessive overlap between work phases and insufficient level of FEED effort can be directly controlled by managment decisions. Size and availability of management and technical leadership can also be controlled. Table 6.1 lists the six decisions the relative alternatives. There are 324 combinations of designs/projects in total. In practice, not all combinations are possible. For example it is assumed that the gravity-based plant is fixed and cannot be relocated. Consequently, the total number of combinations is reduced to 270. Analyzing these alternative decisions, we intend to answer the following questions:

Decision	**Options**
Capacity	- 60 MW - 60 (+60) MW
Deployment concept	- Gravity-based - Floating barge - Spar-type
Flexibility	- Non-relocatable - Relocatable
Overlap design/build	- Large - Medium - Small
Effort spent on FEED	- Current level - 1.5 x current - 2.0 x current
Management/technical leadership team	- Fixed without buffer - Fixed buffer - Dynamic hiring

Table 6.1: Table of decision options. Design decisions are indicated in yellow and project management decisions in orange.

- How do different levels of overlap between design and construction affect the measures of project success?
- How do different levels of FEED effort affect the measures of project success?
- How do different management hiring policies affect the measures of project success?

6.1.6 Translating decisions into SD and DCF simulations

This section illustrates how the six decisions are represented in both the SD and the DCF models. Representing project decisions (overlap, level of FEED, management/technical team) in the SD model is rather simple. This is explained below and summarized in Table 6.3.

Overlap between design and construction

Overlap between phases A and B is defined here as the fraction of tasks reported to be complete in the upstream phase that triggers the start of the downstream phase. For example, if overlap between *D&P* and *B&C* is 0.5, it means that *B&C* starts when 50% of *D&P* work has been reported to be completed[1]. A well known technique for earlier completion of construction projects is to overlap

---

[1] Actual degree of completion will be less because of undiscovered rework.

the project activities or phases that normally would be performed in sequence. Overlapping is inherently risky because it increases uncertainties and can result in more changes and rework [133].

The structure of overlap and interconnections between phases is presented in Section 3.3.8. Here only overlap between *D&P* and *B&C* is considered. Overlap between *F&L* and *D&P* is fixed because (1) *F&L* and *D&P* are intrinsically iterative and often overlap cannot be directly controlled by management; (2) in any case *F&L* effort is much smaller compared to the other work phases (and so is potential rework). The degree of overlap between *D&P* and *B&C* is controlled by `Build Fraction Design Complete to Start Build Rampup`. In general, as overlap decreases (i.e. as `Build Fraction Design Complete to Start Build Rampup` increases) also cost and construction time decrease because rework generation is smaller. Conversely, total project duration increases because *B&C* starts later, when more *D&P* tasks have already been completed. This is shown in Figure 6-4, where cost (effort), project schedule and construction time are plotted against the overlap between *D&P* and *B&C*. The slope change of effort between 0.5 and 0.7 overlap is a result of the nonlinear behavior of the model, which cannot be predicted by the human brain alone. For the project in Figure 6-4, the first option is selected for all decisions in Table 6.1 (e.g. $60MW_e$, pile-mounted, non-relocatable, etc.).

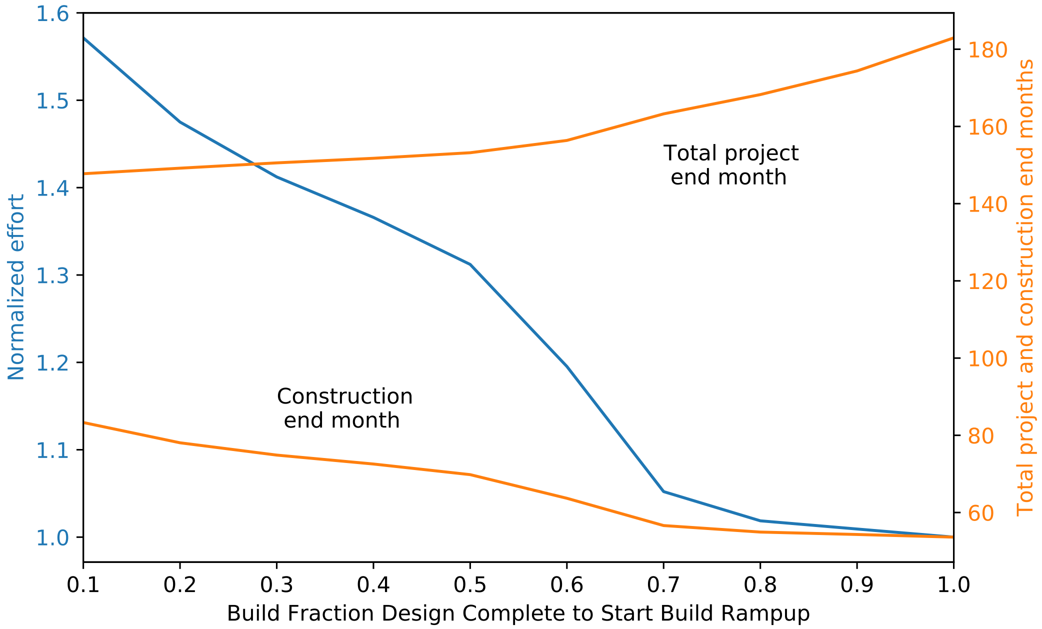


Figure 6-4: Cost (effort), project schedule and construction time as a function of overlap in a project where “Alternative 1” is selected for all decisions in Table 6.1.

For simplicity, only three levels of overlap are considered: large, medium, small (Table 6.1). `Build Fraction Design Complete to Start Build Rampup` is 0.08 for large overlap projects. This is the same as in traditional nuclear projects (Section 3.4, Figure 3-29). In small overlap scenarios, `Build Fraction Design Complete to Start Build Rampup` is 0.5 because some components have long lead times and it seems unreasonable to go beyond that. In medium overlap scenarios, a value in the middle is chosen (0.3).

Level of FEED effort

The structure of level of FEED effort is presented in Section 3.3.7. Three levels of FEED effort are considered (Table 6.1). It is assumed that in historical nuclear projects the level of effort spent on FEED was about 50% with respect to a theoretical optimum. The theoretical optimum is the point where there are no negative effects on `Fraction of Work Correct` and `Productivity`. The level of FEED effort is controlled setting `FEED Planned Effort Multiple of Optimal` equal to 0.5. This structure is adopted for easy policy testing as it allows easy changes in *F&L* scope relative to optimal. In the other two scenarios `FEED Planned Effort Multiple of Optimal` is equal to 0.75 and 1.00 respectively. The interpretation is that in "medium FEED projects" FEED effort is 1.5 times more than in standard projects, while in "large FEED projects" it is 2 times more. `FEED Planned Effort Multiple of Optimal` only controls *F&L* scope. Reasonably, increased FEED effort is achieved through a combination of increased scope *and* staff. It is assumed that peak staff increases as the square root of effort (because effort is proportional to the area under the staff curve). Thus, in the medium and large FEED scenarios `FEED Normal Staff` is multiplied by $\sqrt{1.5}$ and $\sqrt{2.0}$ respectively (Figure 6-5).

Size and availability of management/technical staff

Size and availability of management and technical team is discussed in Section 3.3.9. As shown in Table 6.1, three project options are considered: fixed management team with no buffer, management team with a fixed buffer in case of emergencies, management team with possibility to hire new managers dynamically (with a hiring delay). In the first option the managment team is strictly sufficient to meet the planned requirements. When emergencies arise (e.g. changes, excessive rework, schedule disruptions) the project must wait while managers complete newly added tasks before proceeding. In the second case a fixed buffer of managers/technical leaders is available. The buffer size is decided a priori as stakeholders anticipate that problems can arise during the project.

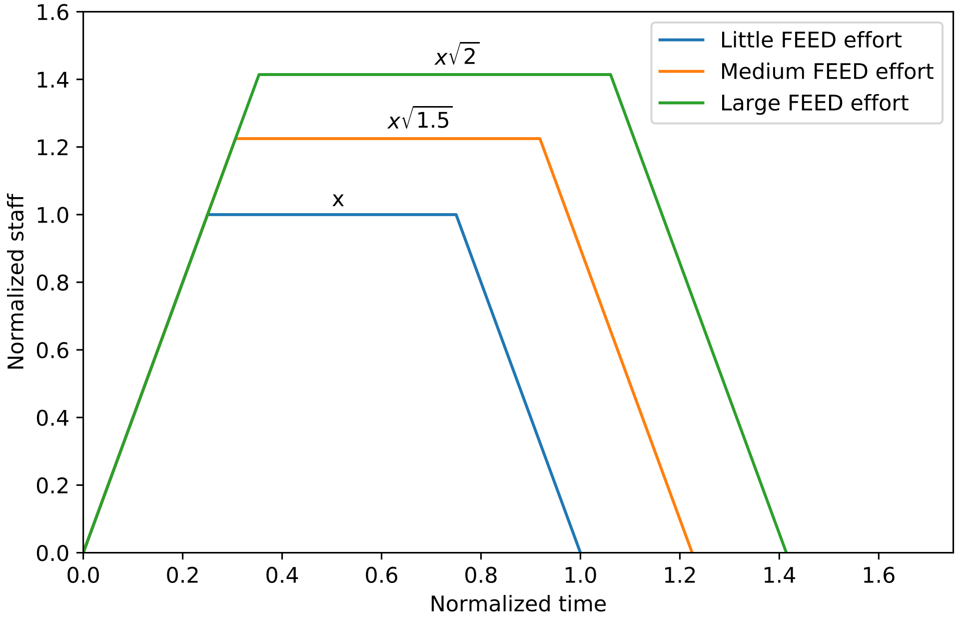


Figure 6-5: Schematic representation of different levels of effort spent on *F&L*.

The model assumes that buffer staff remains idle until needed (in a real project, buffer staff would be assigned to low priority tasks instead of remaining idle). The third scenario assumes a dynamic hiring policy: managers are hired as emergencies arise. A hiring delay is set a priori and it should be of the order of a few months. Size of the management team is defined in the SD model as a fraction of the total project planned staff. Buffer size is defined as a fraction of the management team size. For example, if project staff is 50 people (on average), `Program Technical Leadership Fraction of Program Planned Staff` is 0.1, and `Program Technical Leadership Normal Buffer` is 0.2, then management staff is $50 \cdot 0.1 = 5$ people, buffer staff is $5 \cdot 0.2 = 1$ person and total management staff is $5 \cdot 1.2 = 6$ people. In the first scenario `Program Technical Leadership Fraction of Program Planned Staff` is 0.025, which is consistent with the IAEA manpower guidelines [82], and `Program Technical Leadership Normal Buffer` is 0 because there is no buffer. In the second scenario `Program Technical Leadership Normal Buffer` is arbitrarily set to 0.5. As the buffer size increases, effort (cost) reaches a minimum as shown in Figure 6-6. Then it starts rising again when the disadvantages exceed the benefits of having extra staff on the project. As expected, the project duration decreases with buffer size, reaching an asymptotic value when adding extra staff stops being valuable. In the third case, setting `Program Tech Leadership Change Switch` to 1 activates dynamic hiring. 3 months seems a reasonable value for `Program Tech Leadership`

`Change Delay`. It appears that hiring delay does not play a major role: going from 3 to 12 months, the total project effort increases by 4%. Finally, `Program Tech Leadership Allocation Max` sets the maximum allowed fractional increase in temporary management/technical staff (currently 2).

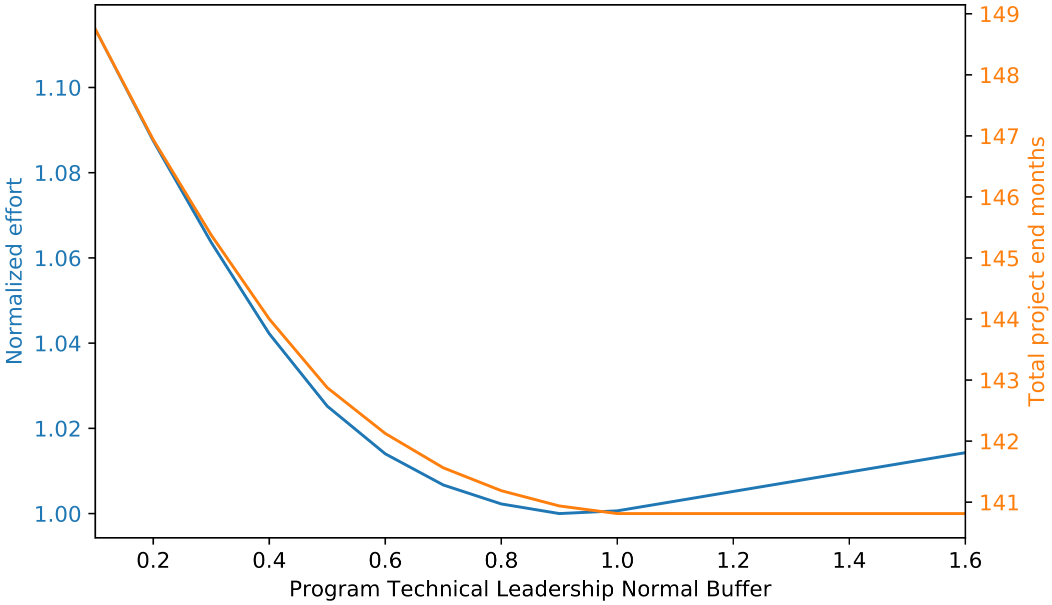


Figure 6-6: Cost (effort) and project schedule as a function of management buffer size in a project where "Alternative 1" is selected for all decisions in Table 6.1.

Capacity

The authors of the IAEA manpower guide [82] specify that "*...the power rating of the plant has practically no effect on the manpower requirements of supporting activities and most project-related activities such as pre-project activities, project management and engineering, quality assurance and control, commissioning, operation and maintenance. It has only an effect on the requirements for manufacturing and construction. Thus, the overall ranges given in this Guidebook can be considered as applicable to any size of nuclear power plant between 600 and 1300* MW_e" [82]. In this case study we investigate the integration of one or two reactor modules of $60MW_e$ each, thus the SD model input scope must be reduced. It is assumed that scope reduction (area under staff curve) is achieved through a combination of (1) shorter project duration and (2) smaller procurement, manufacturing and construction planned staff (as in Figure 6-5). The average nuclear plant's net power output is about 900 MW_e, that is 15 and 7.5 times larger than the designs that we consider here. *F&L* scope, duration and staff are kept the same for all capacities (as suggested by IAEA). *D&P* and *B&C* scopes of the $60 MW_e$ and $60(+60) MW_e$ projects are set to 10% and 15% with respect to a standard nuclear power plant (100%). This choice gives results that are consistent with the schedule *target* set by this case study (around 3 years to build the power plant and start commercial operations in 5 to 6 years) and it gives reasonable cost results (4,000 to 7,000 $\$/kW_e$). Scope does not scale perfectly linearly because *F&L* scope is fixed (as per IAEA guidelines). Staff levels and project duration scale approximately as the square root of scope (as in Figure 6-5). All input files for scopes below 100% include two changes (besides the reduction in scope): (1) the curves of required vs. needed suppliers work are adapted to the new scope level; (2) timing and duration of task growth step changes are scaled accordingly (otherwise these changes would affect the project at different relative project progresses and make the comparison unfair).

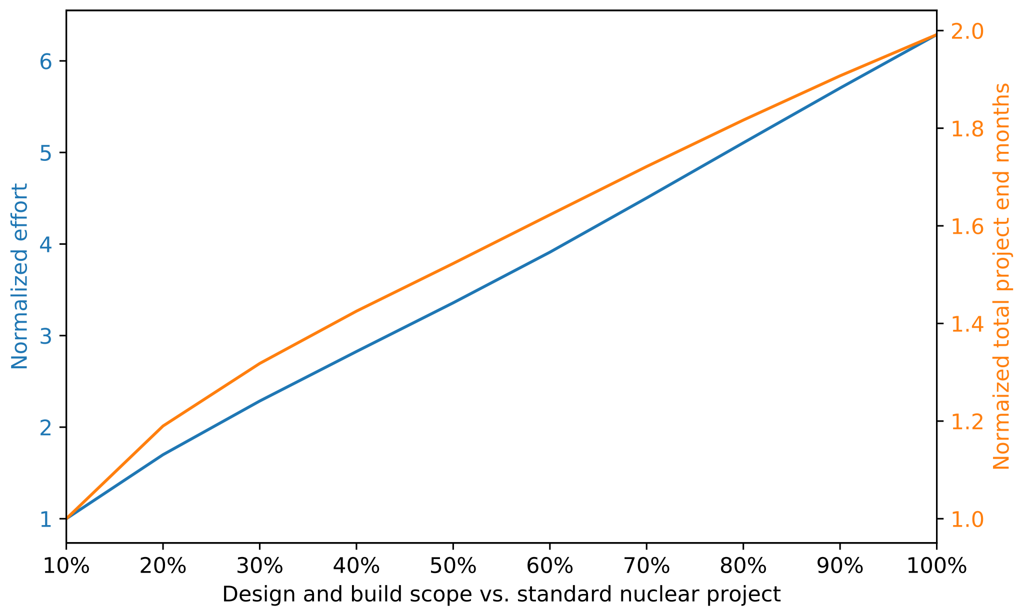


Figure 6-7: Cost (effort) and project schedule as a function of project *D&P* and *B&C* scope.

Note that in reality small power plants (i.e. small projects) might benefit from easier coordination, fewer and simpler components, fewer errors, increased productivity, etc. (this has not been demonstrated yet). For simplicity, it is assumed that plant's capacity affects only scope, staff and duration of the project. If deemed necessary, other benefits derived from smaller size (if any) can be accounted for by (1) directly reducing the relevant negative effects on `Productivity` and `Fraction of Work Correct`; (2) "artificially" selecting a smaller scope (for example, 9% instead of 10%).

Deployment concept

As shown in Table 6.1 three design options are considered: the gravity-based plant, the floating barge, and the spar-type platform. The first plant is fixed to the seabed with a set of pillars. The design strategy for this first option is to adapt a terrestrial SMR power plant layout for marine deployment, with minimal changes to the layout. This is the cheapest option because development effort is minimized. The second design is similar to the offshore nuclear power plants recently developed in Russia and China [130], [131]. It is a "regular" barge hosting a nuclear reactor. Additional analyses will be necessary to prove that the floating structure meets the safety standards, thus the project is likely to last longer. Requirements are in general more uncertain and the degree of novelty is greater compared to the gravity-based design. The third plant is also a floating concept. Spar platforms are rather common in the oil and gas industry. However, no nuclear plant has ever been coupled with a spar-type structure. Additional development effort will be needed with respect to both the fixed plant and the barge designs. In addition, not all shipyards are capable of building large spars. These factors make the spar design even more uncertain and novel than the barge. In the first and second designs a refueling barge docks on the power plant, receives the reactor module, and performs the refueling operations. *If* multiple units are built, the cost of the refueling barge is shared among them. In the third design refueling happens within the platform as in traditional nuclear plants. So in projects (1) and (2) additional scope is necessary to build the refueling barge, while in project (3) additional scope is necessary to build the refueling equipment within each plant. It is assumed that these effects balance off so that different refueling strategies do not affect the decision about deployment concept significantly. In summary, the main differences between the three deployment concepts (in terms of design and construction project) lay within project scope, uncertainty of requirements and novelty. Table 6.2 ranks qualitatively the three concepts on the basis of these criteria from 1 (smallest) to 3 (greatest). The pile mounted plant design is the reference case (e.g. no changes with respect to the standard project except for reduced scope). It is assumed that each step in Table 6.2 corresponds to a 5% increase in scope, a 10% increase in `Effect of Uncertain Requirements on Fraction Correct`, and a 10% increase in `Magnitude of Effect of Novelty on Fraction Correct`. To give an idea, in a project with 10% scope, everything else being the same, increasing the effect of uncertain requirements and novelty by 30% delays the project by about 6 months and increases the total project effort by about 7.5%. The negative effect of uncertain requirements is greater in projects with larger scope. For example, in a project with 20% scope, increasing the effect of uncertain requirements and novelty by 30% delays the project by about 7.5 months and increases the total project effort by about 19.5%.

	Gravity-based	**Floating barge**	**Spar-type**
Project scope	1	2	3
Uncertainty of requirements	1	2	2
Novelty	1	2	3

Table 6.2: Deployment strategies ranking on the basis of project scope, requirements uncertainty and concept novelty.

Flexibility

As shown in Table 6.1, two options are considered: (1) the structure cannot be relocated (as any traditional nuclear power plant); (2) the structure can be relocated in case of exceptional circumstances (e.g. loss of political support, interruption of mining operations). The second plant requires an architecture suitable for a broader range of sites and conditions. Requirements are more uncertain. Extra development effort is required in all work phases. In summary, it is assumed that a relocatable power plant requires about 5% more effort in all phases. In addition, the `Effect of Uncertain Requirements on Fraction Correct` is increased by 10%

Connection between SD and DCF model

Representing the decisions in Table 6.1 in the DCF model is more complicated because the only traces of what happens before operations (different design choices, management strategies, construction performance, etc.) are in the overnight cost and construction time. Thus, it is necessary to find a way to make the transition from the SD (which contains these traces) to the DCF models, ensuring mutual consistency. A script is written to (1) generate the input files for the SD model; (2) run all 270 combinations of design/project decisions in Vensim®; (3) store the results in separate files. For each simulation, `Project Cumulative Effort` [person-month] is converted to overnight cost and used as an *input* for the DCF model. Then, interests during construction (IDC) are added to calculate capital cost. The conversion from effort to overnight cost is shown in Equation 6.1. This approximation is acceptable compared to the overall model uncertainty (at least it ranks the combinations).

Decision	**Options**	**Model implications**
Capacity	60 MW	10 % scope *
	60 (+60) MW	15 % scope *
Deployment concept	Gravity-based	Reference case
	Floating barge	Scope + 5% **
	Spar-type	Scope + 10% **
Flexibility	Non-relocatable	Reference case
	Relocatable	Scope + 5% **
		Uncertain requirements + 10%
Overlap design/build	Large	Build Fraction Design Complete to Start Build Rampup = 0.08
	Medium	Build Fraction Design Complete to Start Build Rampup = 0.3
	Small	Build Fraction Design Complete to Start Build Rampup = 0.5
Effort spent on FEED	Current level	FEED Planned Effort Multiple of Optimal = 0.5
		FEED Normal Staff = 30
	1.5 x current	FEED Planned Effort Multiple of Optimal = 0.75
		FEED Normal Staff = $\sqrt{1.5} \cdot 30$
	2.0 x current	FEED Planned Effort Multiple of Optimal = 1.0
		FEED Normal Staff = $\sqrt{2.0} \cdot 30$
Management/technical leadership team	Fixed without buffer	Program Technical Leadership Normal Buffer = 0
	Fixed buffer	Program Technical Leadership Normal Buffer = 0.5
	Dynamic hiring	Program Technical Leadership Change Switch = 1

Table 6.3: Representation of decisions in SD model. (*) = with respect to standard size nuclear power plant. (**) = with respect to the reference case.

$$OCC\ [\$/kW_e] = \left(\frac{E\ [person \cdot month] \cdot W\ [\$/hr] \cdot H\ [hr/(person \cdot month)]}{P\ [kW_e] \cdot f} \right) \tag{6.1}$$

E is the `Project Cumulative Effort`, which is an output of the SD model. W is the cost of labor. According to the Bureau of Labor Occupational Employment Statistics Survey the median pay for construction laborers and helpers in 2018 was $16.74\,\$/hr$ [134]. That has to be adjusted to account for taxes and overhead, which vary across projects. Here it is assumed that the average cost of labor (W) is $25\,\$/hr$. H is the number of hours each person works per month, which is on average $130\,hrs/(person \cdot month)$ according to the Bureau of Labor [134]. P is the net electrical output. $90,000kW_e$ is used rather than $120,000kW_e$ for the $60(+60)MW_e$ design because the option to expand is not necessarily exercised and so an intermediate value is assumed for simplicity. f is the fraction of overnight capital cost attributable to `Project Cumulative Effort`. f is about 82.5% (all costs except for nuclear island and turbine equipment in Figure 1-4, Section 1.3.2). IDC stands for “interests during construction” (also known as “accumulated funds during construction”, AFDC). It is a multiplier for overnight cost and it represents the cost carrying the loan prior to plants operations [2]. The formula for IDC is presented in Section 4.4.5. Figure 6-8 shows the IDC as a function of construction time for interests rates of 6%, 7% and 8%.

N is derived from the SD simulation output `Build Actual Schedule Duration`. The same variable is also used as the input mean of the construction time skewed lognormal distribution (as presented in Section 4). In summary, different project decisions in Table 6.1 result in different overnight costs and construction times, which are derived from the SD model and appear in the DCF model. This is the point of connection between the two models.

Design decisions are relatively easy to represent in the DCF model. `Power Output` is the net power plant electricity output in MW_e. This is initially set to $60MW_e$ for all combinations of designs/projects. If the plant is built with the option to expand, every year there is a chance that it is upgraded to $120MW_e$. `Yearly Probability That Power Output Is Doubled` is set to 0% if the plant is *not* designed with the option to expand and 5% otherwise. If plant capacity is doubled `Power Output` is set to $120MW_e$, all other cost items expressed in $[\$/kW_e]$ are also doubled (e.g. fuel, O&M costs), and the cost of a reactor module is added to the cash flow analysis. The cost of adding a module includes reactor equipment, turbine upgrade (or replacement) and installation costs. This is about 15-20% of the capital cost (Figure 1-4 in Section 1.3.2). Note that if the expansion happens far in the future the effect on the present value is small. The DCF model allows

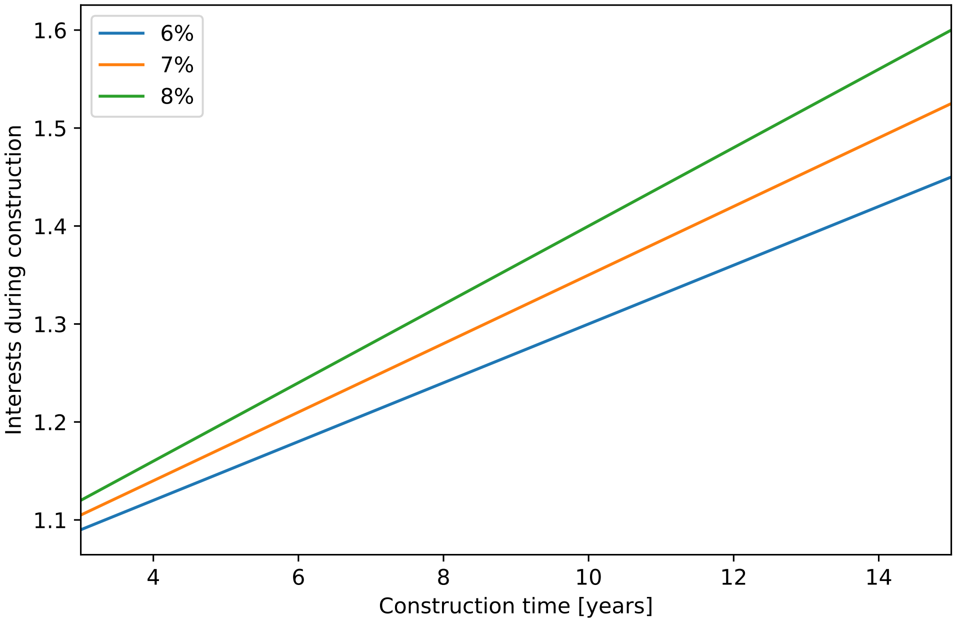


Figure 6-8: Interests during construction (as a multiplier of overnight cost) as a function of construction time for interests rates of 6%, 7% and 8%.

the user to set whether a plant is relocatable or not. In each year of the project, the model performs the following steps:

- Step1: determines whether the project loses political support (probability = 2%);
- Step 2: if so and the plant cannot be relocated, the project proceeds to decommissioning.
- Step 3: if political support is lost, but the plant can be relocated, the model adds cost of towing to new site as well as additional relocation costs (switchyard, new contracts, licenses, etc...). Then operations are re-started in the next year.

6.2 Management insights and policy results

Section 6.1 illustrates how design and project decisions can be modeled using system dynamics and the DCF model. This section shows the results, i.e. how all combinations of projects/designs defined in Table 6.1 perform with respect to the success measures. All quantitative models are imperfect. All outcomes are therefore, to some degree, uncertain. Nuclear projects are complex and dynamic systems, and their outcomes have high stakes in the real world. In these projects the difference between good predictions and not-so-good predictions has major consequences, typically hundreds of millions or billions of dollars in value. This makes understanding uncertainty a matter of considerable importance [135]. The DCF model lends itself well to incorporating uncertainties and propagating them using the Monte Carlo method. On the other hand, neither standard regression modeling nor standard Monte Carlo are appropriate for quantifying confidence intervals in outcomes of typical SD models. The problem with regression formulas is that they rest on assumptions nearly always impossible to satisfy in a megaproject modeling setting: complete data, perfectly accurate data, no lagged independent variables as dependent variables, linear relationships. The problem with Monte Carlo is that at least some variables in the SD model are used to calibrate it to real data. Randomly selected (even small) parameter variations around the original value may produce model behavior inconsistent with known real behavior[2]. To overcome this problem Graham et al. have adopted fit-constrained Monte Carlo trials as a practically useful and analytically sound method of quantifying confidence intervals in constrained outcomes [135]. Unfortunately, this analysis requires considerable effort and computer time, as well as moderate amounts of analyst time to set up, monitor, gather, analyze, distill, and communicate results from the tests.

Scenario analysis is an alternative approach to model and analyze projects with significant uncertainty in their network structure and/or duration of some activities. Here the 270 design/project combinations are used to frame a large-scale scenarios analysis. Scenario analysis can be thought of as performing multiple sensitivity analyses at the same time. Scenario analysis is often preferred over sensitivity analysis because it allows to look at different *but consistent* combinations of variables. In fact, decision makers generally prefer to give an estimate of revenues, costs or schedule under a particular scenario than to give some absolute optimistic or pessimistic value [105].

The scope of this section is limited to treating three questions: (1) how do different levels of overlap between design and construction affect project success? (2) how do different levels of FEED affect project success? (3) How do different management hiring policies affect the measures of project success? Besides answering these questions, the goal of this analysis is:

- To provide a framework to compare different combinations of projects/designs on the basis of the success criteria;
- To evaluate the "average" behavior of the 270 projects with respect to the success criteria.

---

[2] In some SD analyses a probability distribution function is chosen for a few relevant variables and then a Monte Carlo simulation is performed. However, in this model it seems complicated to select these variables.

How does overlap affect project success?

Figure 6-9 shows a trade space for the 270 project combinations. The two axes are total project time and cumulative effort. Total project time includes all three phases from the outset of pre-project activities to commissioning. Project cumulative effort is directly proportional to overnight cost (Section 4.4.5). Each cross on the trade space represents a different project (e.g. a different combination of decisions in Table 6.1). Projects with large, medium and little degrees of overlap between *D&P* and *B&C* are shown respectively in blue, orange and green.

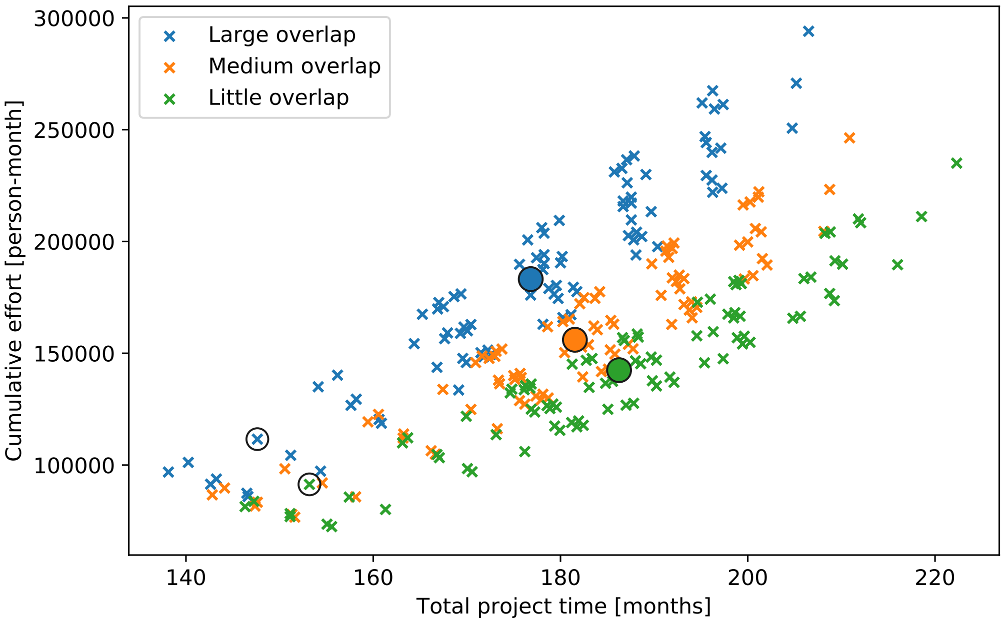


Figure 6-9: Total project time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of overlap). The three circles at the center are the centroids of each cluster. The two projects circled in black are identical except for the degree of overlap.

First, are these results realistic? Total project time ranges between 138.1 and 222.3 months (11.5 and 18.5 years). Considering that (1) total project time includes not only construction time but also *F&L* and *D&P*, and (2) these results already incorporate a certain degree of delays, this range seems absolutely reasonable. Overnight cost (derived from project cumulative effort on the y-axis) ranges between 3,045 and 12,356 $\$/kW_e$, which shows very good agreement with the statistics in Figure 4-8.

The Pareto frontier is located at the bottom-left of the plot. It is the "edge of the envelope" formed by the set of non-dominated solutions. The projects on the Pareto frontier perform equally well with respect to cumulative effort and total project time.

Figure 6-9 suggests that choosing between different levels of overlap involves a trade-off between cost and time. On the one hand, reducing overlap increases total project duration because construction starts later, when more design tasks have been completed. On the other hand, little overlap reduces cumulative effort (e.g. cost) because fewer errors are made and productivity is enhanced during construction. Resolving this trade-off requires that stakeholders rank each metric. If it is possible to assign different weights to total project time and cumulative effort, then the decision collapses to a single point on the plot. Resolving the trade-off also depends on the specific projects that are being compared. Let us consider, for example, the two projects circled in black at the bottom-left of the plot. These are identical projects except for the degree of overlap. Large overlap allows one to save about 5.5 months over the total duration of the project but it requires an additional 20,231 persons-month to complete (corresponding to 1,063 $\$/kW_e$).

The three circles at the center of Figure 6-9 are the centroids of each cluster. Given a set of points $(x_1, y_1), (x_2, y_2), (x_3, y_3) \cdots, (x_n, y_n)$, the centroid is the arithmetic mean positions of all the points:

$$\left(\frac{x_1 + x_2 + x_3 + \cdots + x_n}{n}, \frac{y_1 + y_2 + y_3 + \cdots + y_n}{n}\right) \tag{6.2}$$

In this context the centroid provides an indication of the "average" behavior of all projects clustered according to different levels of overlap. It is the "average" behavior of a large-scale scenario analysis consisting of 270 projects. Table 6.4 shows total project time and cumulative effort (converted to overnight cost) ratios and differences between maximum and minimum centroids. In this case, the centroids with the largest and smallest project duration (x-axis) are respectively the green and blue ones (little and large overlap). The little overlap centroid takes 5.3% more to complete or about 9.4 months. Conversely, the centroids having the largest and smallest overnight costs are respectively the blue and green ones. The blue centroid is 28.6% larger than the green one and the difference between the two is about 1,712 $\$/kW_e$. The gain in terms of overnight cost is rather impressive compared with the relatively small increase in total project duration! This holds even if one assumes that Interests During Constructions (IDC) are paid over all that additional 9 months time (which is not necessarily the case). Assuming a 7% interests rate and using the formula for IDC presented in Section 4.4.5, the same overnight cost would increase by a factor $1 + (N \cdot x)/2 = 1 + ((9.4/12) \cdot 0.07)/2 \approx 1.03$.

	Ratio max/min centroid	Difference max/min centroid
Overnight cost	1.286	1,711 [$/kW_e$]
Total project duration	1.053	9.4 [months]
Build time	1.283	1.8 [years]
Median NPV	1.286	665.1 [M$]
Prob (NPV<0)	2.946	11.8%

Table 6.4: Effort (converted to overnight cost), total project time, build time, median NPV, project financial risk. Ratios and differences between maximum and minimum centroids in the overlap trade space.

Figure 6-10 shows a different trade space. The y-axis is still project cumulative effort, while the x-axis is build time. As before the crosses on the trade space represent different projects and the large circles are the centroids of each cluster. Are these results realistic? The range of cumulative effort is the same as in Figure 6-9. Build time ranges between 54.6 and 131.1 months (4.6 and 10.9 years), which shows very good agreement with the statistics in Figure 6-11.

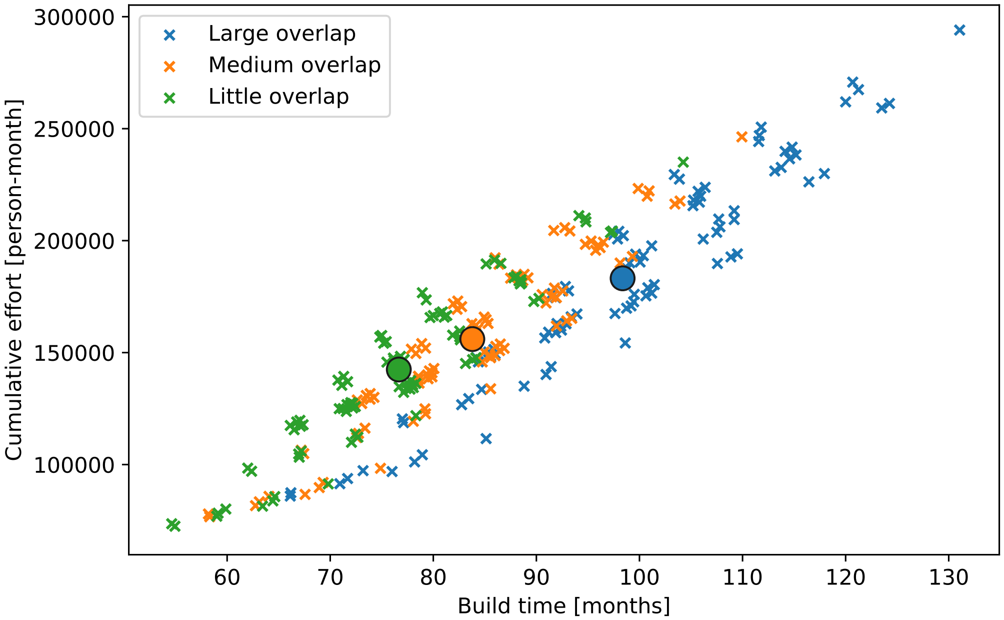


Figure 6-10: Build time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of overlap). The three circles at the center are the centroids of each cluster. Reducing the degree of overlap not only reduces cost (y-axis) but it also tends to correlate with shorter construction times (x-axis).

Figure 6-10 suggests that reducing the degree of overlap between *D&P* and *B&C* not only reduces cost (y-axis) but it also tends to correlate with shorter construction times (x-axis). The

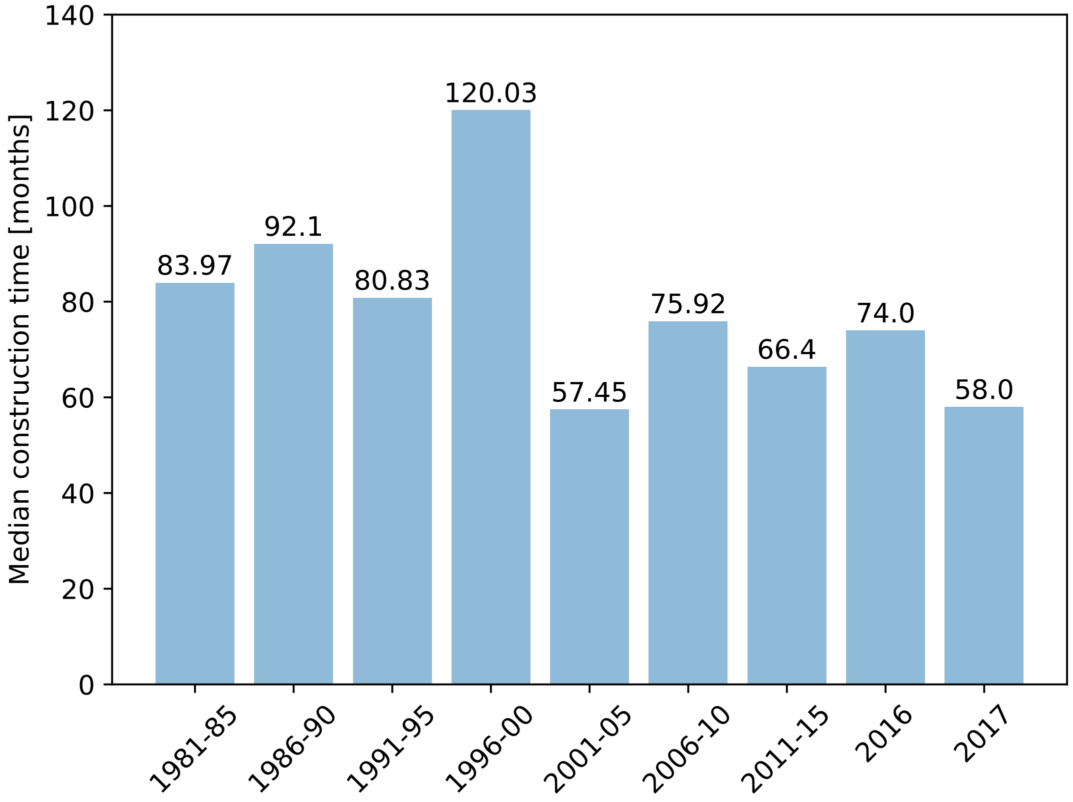


Figure 6-11: Median construction time required for nuclear reactors worldwide from 1981 to 2017 in months (adapted from [136] and [13]).

Pareto frontier is almost reduced to a point. The centroids show the average behavior of all projects: reducing overlap between design and construction appears to be clear winner. Table 6.4 shows build time and cumulative effort (converted to overnight cost) ratios and differences between maximum and minimum centroids. Moving from large to little overlap projects, the overnight cost is reduced on average by 1,712 $\$/kW_e$ and construction takes about 1.8 years less to complete! Besides performing worse with respect to build time and cumulative effort, large overlap projects (blue cluster) seem to be more sparse, suggesting a more uncertain outcome. To help visualizing this, the box plots corresponding to different levels of overlap for build time were generated (Figure 6-12 to the right). The same color code is adopted. The dotted line connecting the median build time of each cluster highlights the decreasing trend. Figure 6-12 also shows the same information for cumulative effort and total project duration (at the left and the center), thus condensing all insights discussed above. In summary, reducing overlap causes the *total* project to last longer because construction starts later. However, fewer errors are made because of the higher degree of design completion prior to construction start. In turn, construction time and cumulative effort (cost) are reduced.

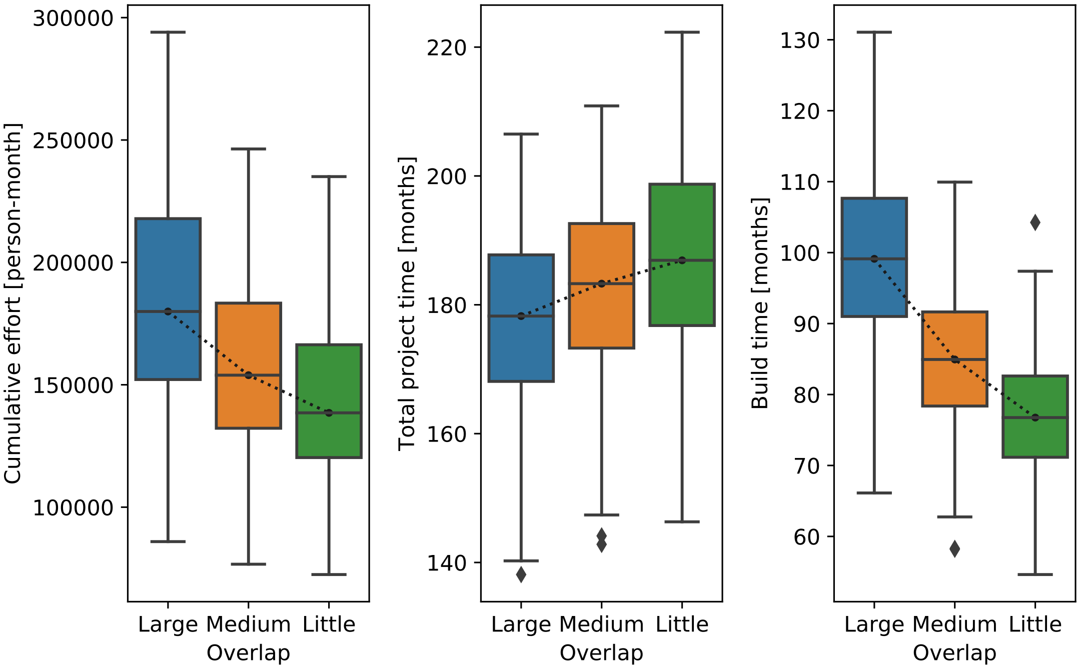


Figure 6-12: Comparison of box plots for different levels of overlap for cumulative effort (left), total project time (middle) and construction time (right). The dotted lines connect the median values of each overlap cluster, highlighting a decreasing/increasing trend.

Moving to the financial results, Figure 6-13 shows the median NPV[3] - build time trade space for the 270 combinations of projects/designs. Compared to the previous figures, two separate clusters are presented. The $60MW_e$ projects form the bottom-left group, while the projects with the option to expand capacity form the upper-right group. The two black stars indicate the centroids of these clusters, while the three circles in the middle indicate the centroids of all projects together. As expected, projects with the option to expand take more time to build on average, but they also tend to have significantly larger median NPVs (compare the stars). Independently from the power plant capacity, projects with little overlap between design and construction perform better both in terms of median NPV and construction time. The vertical line at $x = 0$ shows that only large overlap projects have a negative median NPV. Minimum and maximum median NPV values are $ -82.4 and 582.8 million. Table 6.4 shows median NPV and build time ratios and differences between maximum and minimum centroids.

---

[3] Median is chosen over the mean because the distributions are sometimes skewed.

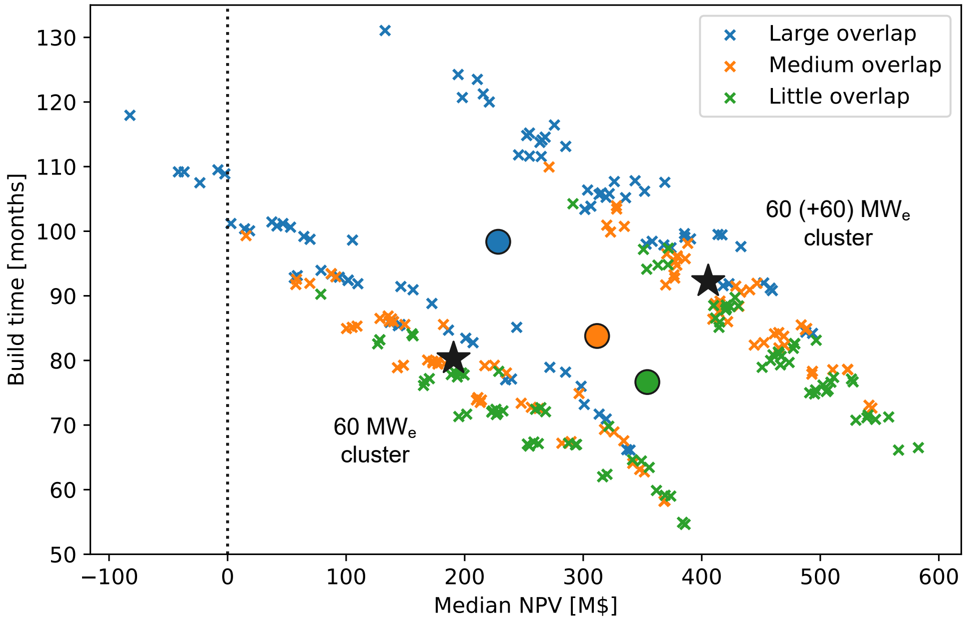


Figure 6-13: Median NPV - build time trade space for the 270 combinations of projects/designs (divided by level of overlap). The two black stars indicate the centroids of the 60 and 60(+60) MW_e clusters, while the three circles at the center are the centroids of each overlap cluster.

Figure 6-14 is the trade space of project financial risk (x-axis) and cumulative effort (y-axis). For each project, the DCF model provides a distribution of NPVs. Project financial risk is measured as the probability of negative NPV, which is obviously always positive. Moving from large to little overlap projects, both cumulative effort and financial risk decrease (Table 6.4). As before, there are two distinct clusters for the $60MW_e$ and the $60(+60)MW_e$ projects, respectively at the bottom and the top of the plot. As expected, a power plant with the option to expand capacity costs more as it requires additional analyses, development time, additional uncertainty, etc. However, it potentially reduces the financial risk rather significantly, as shown by the black stars in Figure 6-14.

How does FEED level affect project success?

Figure 6-15 shows the total project time - cumulative effort trade space for the 270 projects. The plot is the same as Figure 6-9 but here the projects are grouped by level of effort spent of FEED (little, medium and large). As before there seems to be, on average, a trade-off between total project duration and cumulative effort. Since the three clusters overlap more, their centroids are closer. Table 6.5 shows that going from "optimal" FEED to half of the optimal amount, the overnight cost

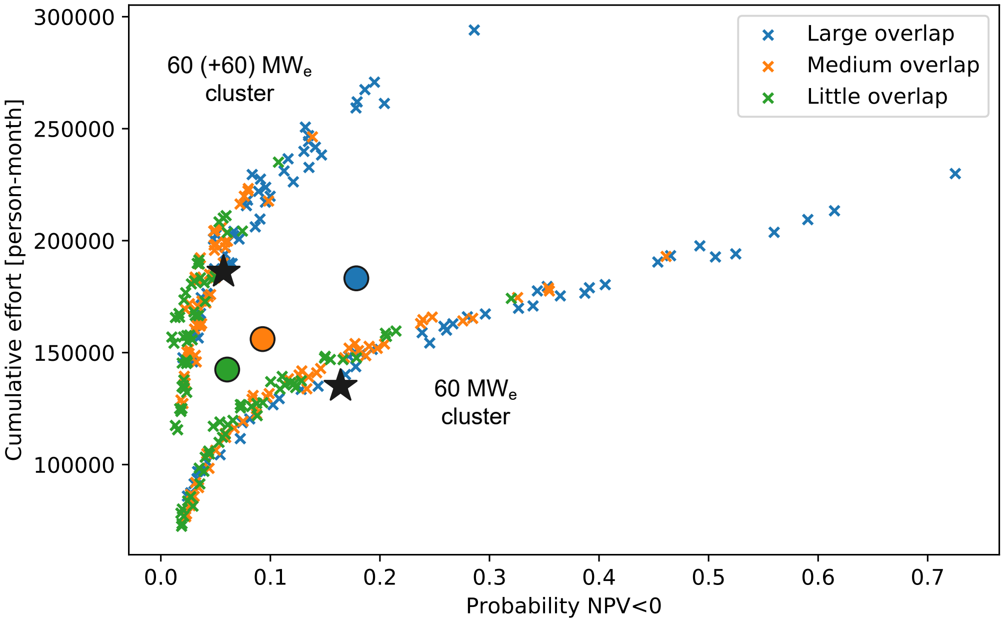


Figure 6-14: Probability of negative NPV - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of overlap). Stars: centroids of 60 and 60(+60) MW_e clusters. Circles: centroids of each overlap cluster.

increases by 16%. This is consistent with the analysis performed by Honour: Figure 3-14a shows that going from 15% (optimal) to 7.5% of equivalent Systems Engineering (SE) effort, actual cost increases by about 20%. Since (1) FEED is a subset of SE and (2) overnight cost does not include interests, our results seem realistic. In absolute terms, spending more effort on FEED potentially reduces the overnight cost by 1,006 $\$/kW_e$ in the face of a total project duration increase of only 3.1 months.

The reader may notice that Figure 6-9 is a topologically stratified space. Strata are a rather common feature in trade spaces, denoting step changes caused by some characteristics of the system.

	Ratio max/min centroid	Difference max/min centroid
Overnight cost	1.161	1,006 [$\$/kW_e$]
Total project duration	1.017	3.1 [months]
Build time	1.171	1.1 [years]
Median NPV	1.286	74.4 [M$]
Prob (NPV<0)	1.896	7%

Table 6.5: Effort (converted to overnight cost), total project time, build time, median NPV, project financial risk. Ratios and differences between maximum and minimum centroids in the FEED trade space.

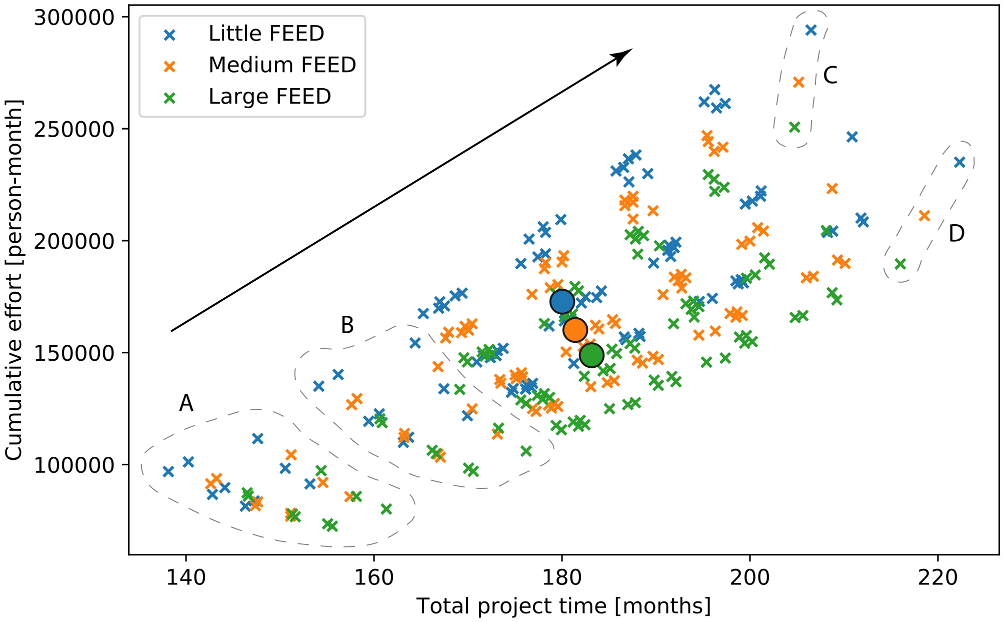


Figure 6-15: Total project time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of FEED effort). Circles: centroids of each cluster. A and B indicate projects based on the gravity-based design without and with the option to expand. C and D indicate triplets where the tipping point is reached, e.g. larger FEED is better both in terms of cumulative effort and total project time.

The arrow indicates the direction of increasing project complexity, intended as combination of scope, novelty and uncertainty of requirements. In other words, the arrow indicates the progression from gravity-based plants to floating barge plants to spar-type plants, from basic plants to those with the option to expand capacity and be relocated. For example, A and B indicate projects based on the gravity-based design without and with the option to expand. Interestingly, the slope of strata decreases moving from bottom-left to the top-right of the plot. As project complexity increases, devoting more effort to *F&L* activities becomes increasingly beneficial. This is consistent with our experience: simpler projects require less FEED. For sufficiently large levels of complexity, there exists a tipping point beyond which larger FEED effort not only costs less but it also results in a shorter total project time. The tipping points are found around the triplet indicated with the letter C. Triplet D is beyond the tipping point, and larger FEED is better both in terms of cumulative effort and total project time.

Figure 6-16 shows that spending more effort on FEED reduces construction time and total project effort. On average, little FEED plants take about 1.1 years more to build and have an overnight cost 1,006 $\$/kW_e$ larger (Table 6.5). As shown in Figure 6-17, as FEED effort increases total project time increases (on average) because more *F&L* tasks must be completed before starting with the downstream phases. However, spending more resources on pre-project activities, requirements engineering, stakeholder analysis and all other FEED activities reduces the number of mistakes made throughout the project and increases overall productivity, therefore reducing construction time and overnight cost. As suggested by Honour's work [87] and explained in Section 3.3.7, we would expect to see an "optimal" level of FEED effort beyond which fraction correct and productivity start decreasing (at some point doing more FEED work adds hours of work with little or no improvement in downstream work quality, and leads to bureaucratic increases in procedures and documentation, etc.). We do not observe this in Figure 6-17 because in the simulations the large FEED case corresponds to the theoretical FEED optimum.

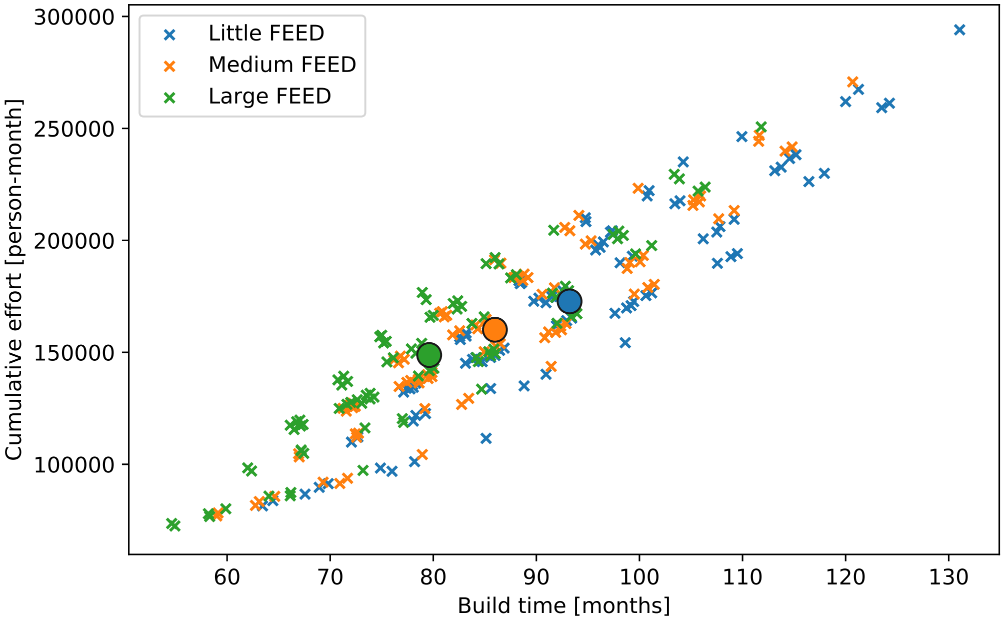


Figure 6-16: Total project time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of FEED effort). Circles: centroids of each cluster.

Figures 6-18 and 6-19 are conceptually similar to the overlap case. Allocating more resources to FEED correlates with larger median NPV and smaller financial risk. There are no large FEED projects with a negative median NPV. Table 6.5 shows that large FEED projects have a median NPV 28.6% larger (corresponding to 74.4 $M\$$) and that financial risk is reduced by 7%. Buying the option to expand in case of favorable market conditions increases the median NPV by about

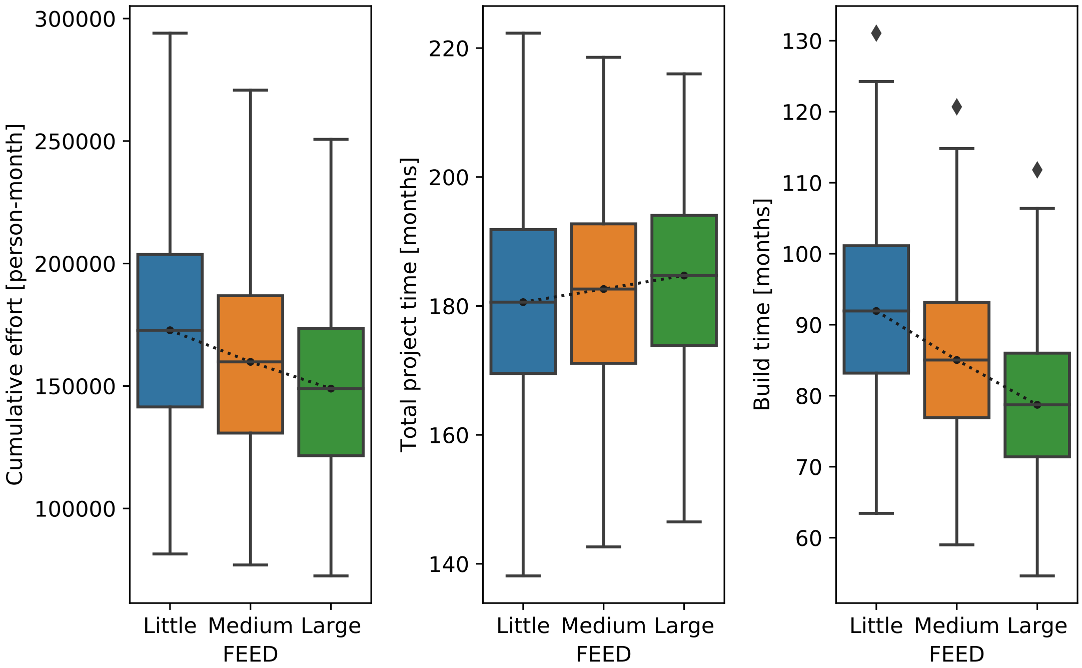


Figure 6-17: Comparison of box plots for different levels of FEED for cumulative effort (left), total project time (middle) and construction time (right). The dotted lines connect the median values of each overlap cluster, highlighting a decreasing/increasing trend.

200 $M\$$ and causes financial risk to reduce approximately from 16% to 6%, as shown by the black stars in Figures 6-18 and 6-19.

How do different management team hiring policies affect project success?

As explained in Section 6.1.6 three different policies regarding size and availability of leadership team (both management and technical leaders) are evaluated. In the first policy the number of leaders is fixed and there is no buffer. The team is sized based on the initial requirements and if emergencies arise leaders must put in stand-by some tasks and solve them first. In the second policy the project can rely on a buffer team that intervenes in case of problems (rework, scope growth, etc.). In the third policy managers and technical leaders can be hired dynamically as needed (with an adjustable hiring delay). Fixed buffer (orange) and dynamic hiring (green) perform very similarly across all trade spaces and metrics (Figures 6-20 to 6-24). Dynamic hiring seems to perform slightly better but there is no substantial difference. For example, increasing hiring delay might make the fixed buffer option slightly preferable. Compared to the cases of overlap and FEED, there are never trade-offs here (not even in Figure 6-24. Projects without leadership team buffer (blue points) are

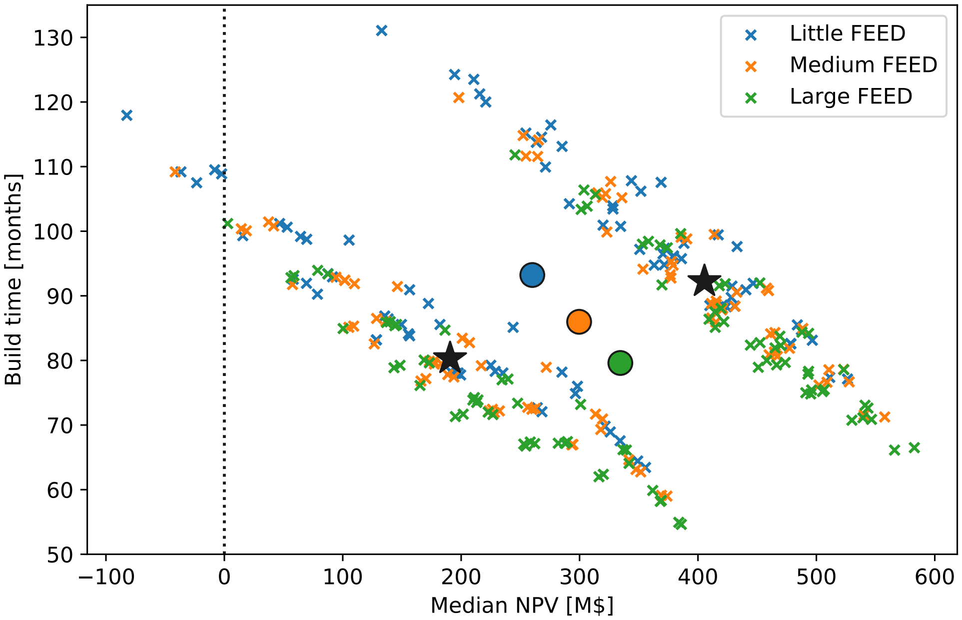


Figure 6-18: Median NPV - build time trade space for the 270 combinations of projects/designs (divided by level of FEED effort). Stars: centroids of 60 and 60(+60) MW_e clusters. Circles: centroids of each FEED level cluster.

systematically worse in all metrics. Table 6.6 summarizes ratios and differences between maximum and minimum centroids in all trade spaces.

	Ratio max/min centroid	Difference max/min centroid
Overnight cost	1.108	702 [$/$kW_e$]
Total project duration	1.043	7.7 [months]
Build time	1.085	7.1 [months]
Median NPV	1.181	48.5 [M$]
Prob (NPV<0)	1.513	4.8%

Table 6.6: Effort (converted to overnight cost), total project time, build time, median NPV, project financial risk. Ratios and differences between maximum and minimum centroids in the management and technical leadership trade space.

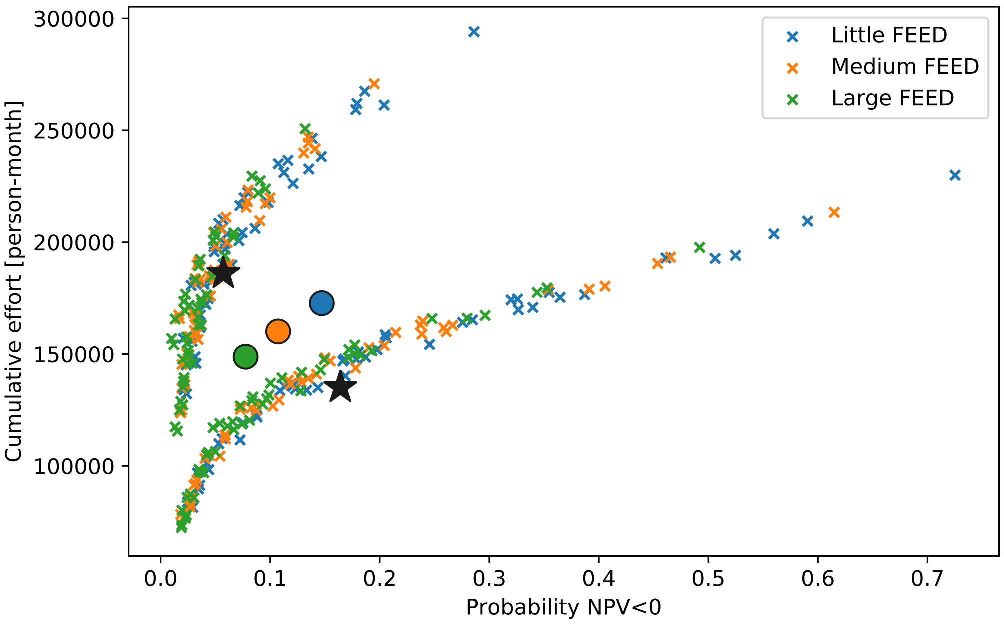


Figure 6-19: Probability of negative NPV - project cumulative effort trade space for the 270 combinations of projects/designs (divided by level of FEED effort). Stars: centroids of 60 and 60(+60) MW_e clusters. Circles: centroids of each FEED level cluster.

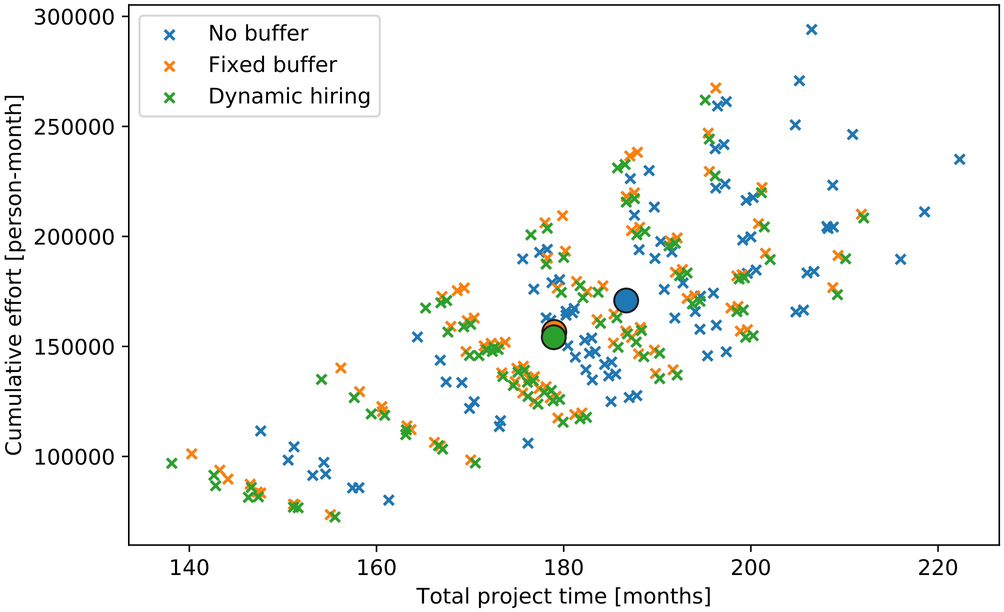


Figure 6-20: Total project time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by management team hiring policy). Circles: centroids of each cluster.

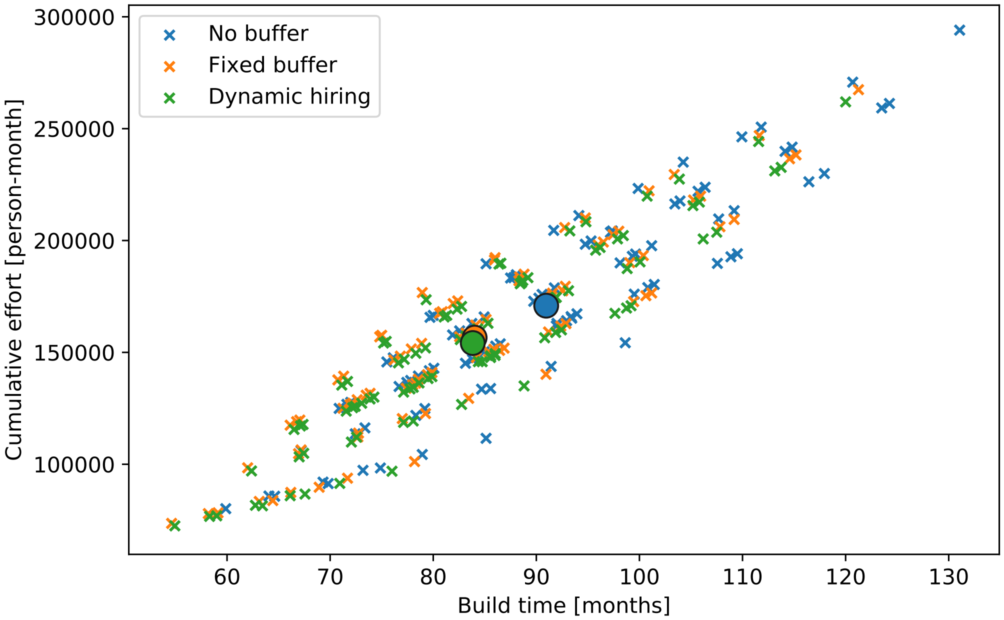


Figure 6-21: Total project time - project cumulative effort trade space for the 270 combinations of projects/designs (divided by management team hiring policy). The three circles at the center are the centroids of each cluster.

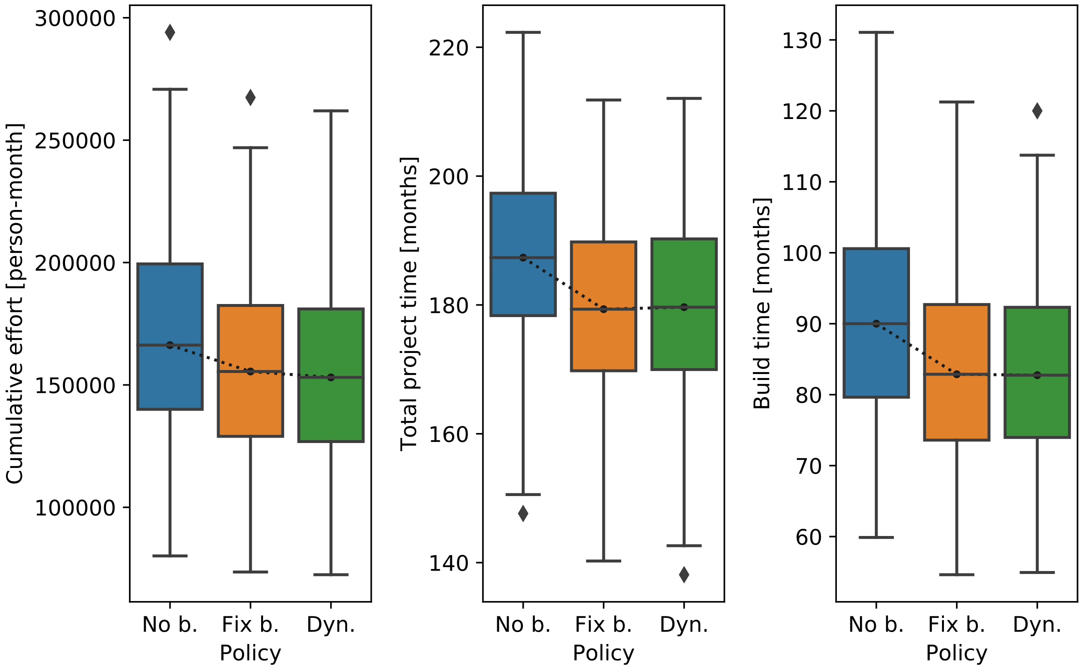


Figure 6-22: Comparison of box plots for different levels of FEED for cumulative effort (left), total project time (middle) and construction time (right). The dotted lines connect the median values of each overlap cluster, highlighting a decreasing/increasing trend.

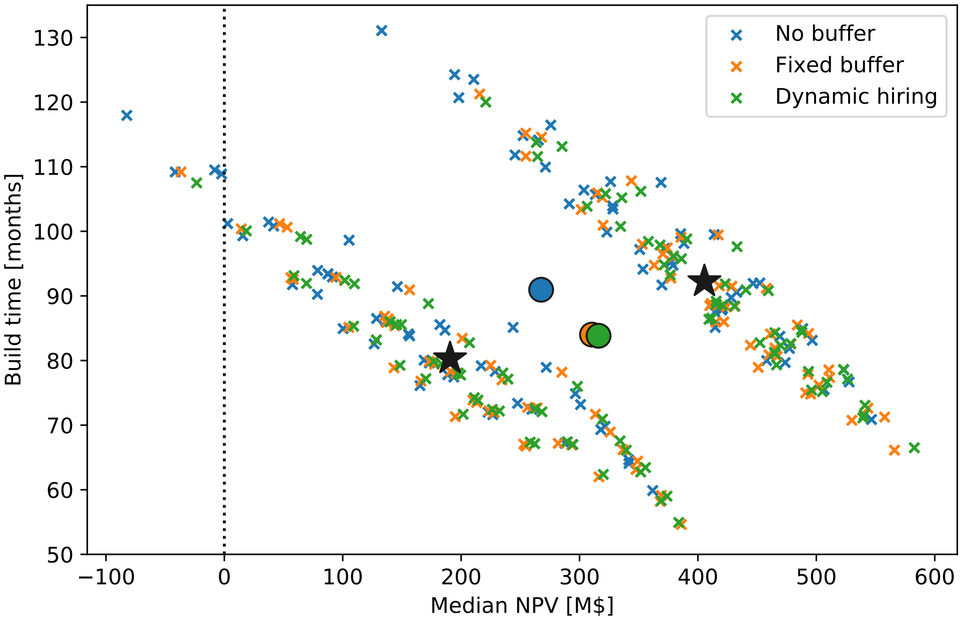


Figure 6-23: Median NPV - build time trade space for the 270 combinations of projects/designs (divided by management team hiring policy). Stars: centroids of 60 and 60(+60) MW_e clusters. Circles: centroids of each hiring policy cluster.

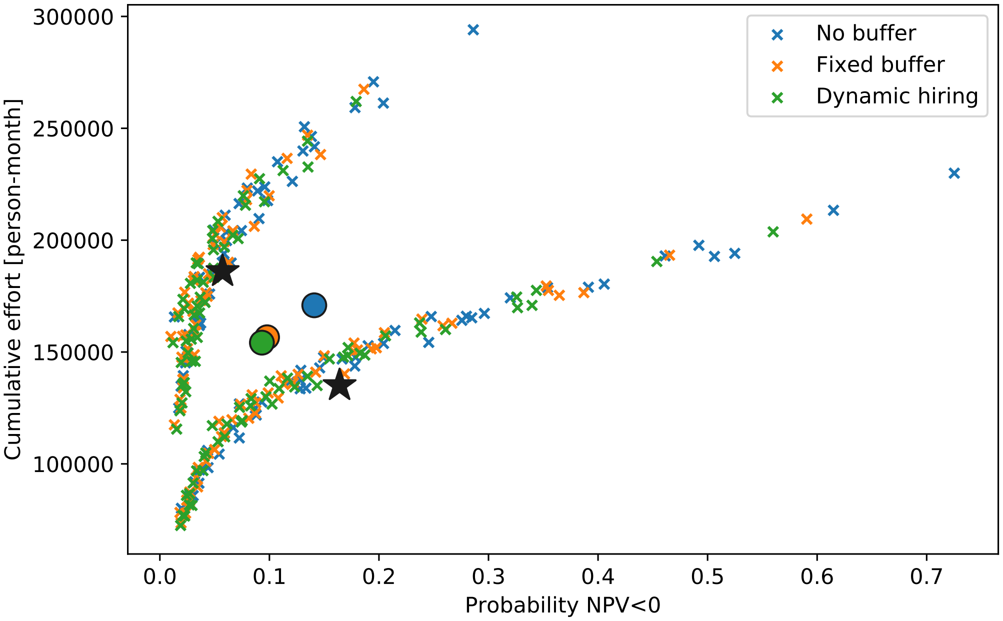


Figure 6-24: Probability of negative NPV - project cumulative effort trade space for the 270 combinations of projects/designs (divided by management team hiring policy). Stars: centroids of 60 and 60(+60) MW_e clusters. Circles: centroids of each hiring policy cluster.

Chapter 7

Conclusions

7.0.1 Summary

Increasing electricity demand and the need of moving away from carbon-emitting technologies suggest that nuclear energy will play an increasingly important role in the future worldwide. Currently, nuclear energy faces four major challenges: safety, radioactive wastes, proliferation of nuclear weapons and cost. Technical and political solutions exist for the first three[1]. On the contrary, the problem of cost is still fundamentally unresolved. Nuclear power plants are expensive to design and build but relatively cheap to operate. Thus, the cost of nuclear energy largely depends on capital cost. The capital cost of nuclear power plants is literally dominated by factors other than those of physical equipment, such as project preparation, site preparation, engineering, planning, installation, and management. Interestingly, project planning, monitoring, execution and management is where too often the nuclear industry has failed in the past. As of 2014, the average time and cost overrun for nuclear projects worldwide are 64% and 117.3%, respectively. Hence, the need to focus on improving *the way power plants are built and delivered.* Nuclear projects are failure-prone financially because they are long, complex enterprises with multiple stakeholders who often have conflicting goals. Despite this advanced management methods have not penetrated sufficiently to ensure success. This work focuses on project management but we acknowledge that there exists an alternative approach which turns nuclear projects into ”normal” projects, in terms of scope, complexity and capital at risk. For example, the nuclear industry is pursuing the development of micro-reactors, a type of plug-and-play nuclear batteries that would be two orders of magnitude smaller in physical size, wholly manufactured and fueled in a factory, and transported to the site

---

[1] In reality, the discussion is not this simple, but it goes beyond the scope of this report.

within standard-size freight containers, requiring minimal site excavation and preparation.

In this work we develop an improved framework for (1) managing megaprojects, (2) estimating their value and (3) making project/design decisions involving numerous stakeholders, multiple competing objectives, and substantial uncertainty. The framework is built on two pillars: a System Dynamics (SD) model and a Discounted Cash Flow (DCF) model. The SD model is based on the "Lyneis" model [70] adjusted for a nuclear project. It is a virtual "lab" that allows one to simulate the design and construction of a single unit turnkey power plant. The model has three work phases (FEED & licensing, design & procurement, build & commissioning), each comprising a rework cycle and the feedback loops affecting productivity and error generation. The three phases are nearly identical in structure, the only differences being those necessary to represent interactions between the phases, and any parametric differences. The DCF model is used to estimate the probability distribution function of the present value of the nuclear project as an investment based on its future cash flows. "Traditional" and "non-standard" uncertainties are taken into account explicitly and the Monte Carlo method is used to propagate them. Architecture, assumptions, validation and calibration of the two models are discussed. Two examples are provided to illustrate the use of SD and DCF as stand-alone applications. In the first example, we show the benefits of using the SD model to control project changes, adapt to a new set of constraints and drive management responses. In the second example, we show the benefits of using the DCF model to (1) evaluate stochastically the value of a nuclear project, (2) prioritize investments and direct research efforts and (3) perform a real options analysis to drive the power plant design. Then, the two models are combined into a consistent framework covering the entire lifetime of a nuclear project. A case study is used to demonstrate that the framework is not only valuable but also feasible. The case study is an actual, ongoing project in North America based on a marine nuclear power plant entirely built in a shipyard and towed to the site upon completion. We frame a multi-objective decision making problem to illustrate the importance of a solid decision management process in megaprojects. We derive 270 different projects from the combination of six high-level design/project choices: capacity, deployment concept, flexibility, overlap between design and construction, level of effort spent on FEED, size and availability of management team. We simulate them using our modeling framework, we represent them using trade spaces, and evaluate them against project success objectives to derive general policy insights.

7.0.2 Contributions and policy insights

This framework represents a synthesis of management methods that was not practically available before. This work documents the development of the models, it shows why they should be used, it applies them to an actual case study hence providing a real-world application, and it makes the method credible, publicly available and convenient to adopt. The method takes into account feedbacks, delays, interrelationships between variables, non-linearities and uncertainty. In addition, it covers the entire lifetime of the nuclear power plant. The outcome of this method is a set of practical and project-specific recommendations that should minimize the likelihood of project delays and cost overruns. In particular, the main contributions of this work are:

- A System Dynamics (SD) model of a nuclear project is proposed. This model allows planners to simulate the design and construction of a nuclear power plant (up to commissioning). The model is calibrated using historical data and experts' surveys. One of the major benefits of the SD model is that it allows one to handle project changes (that will always occur), providing the decision makers with a tool to respond with flexibility. The model addresses the three recommendations provided by Lyneis and Ford [63] to increase SD application in project management: (1) it adds a success story to the literature; (2) it makes the SD model available to everyone, i.e. easier and less expensive to develop; (3) it explicitly integrates the SD model with another traditional project management tool (DCF).
- A probabilistic Discounted Cash Flow (DCF) model that focuses on operational profitability (from commissioning to decommissioning) is proposed and the uncertainties of the main variables are characterized. The DCF model allows one to simulate not only traditional uncertainties in nuclear projects evaluations (fluctuating price of electricity, fuel and O&M costs, capacity factor, discount rate, etc.) but also non-standard ones such as the possibility of forced shutdown due to loss of stakeholders' support or mining operations cessation.
- Successful applications are presented to show that the use of SD (and in general the proposed framework) provides managers and planners with a valuable insurance against project catastrophes. A rough cost-benefit analysis is performed to illustrate the potential huge upside gains deriving from the use of project dynamics modeling, in face of a cost that is insignificant relatively to the capital cost of a standard nuclear power plant. Historically, for every dollar invested in project dynamics in proactive applications about $ 400 are saved. The benefits of

using project dynamics in legal disputes can be even greater. Assuming an *initial* estimated capital cost of \$ 6 to \$ 9 billions to build a new reactor, and conservatively assuming that in 2019 hiring a consulting company to support the project costs \$ 1 million per year for 10 years, the total modeling cost would be only about 0.01% of the capital cost.

- A comprehensive framework based on the SD and DCF models is developed. The proposed framework is a powerful addition to the current nuclear design, construction and management standard because it covers the entire lifetime of the nuclear power plant, from the initial conceptual idea to decommissioning. So the scope of the project is broader than is usually defined. The proposed framework is applied to support the design of an actual marine nuclear power plant in North America, and reduce the project's cost with successful results.
- A process to evaluate and compare many combinations of design choices and management policies is illustrated. The following insights are derived:
    1. Reducing overlap causes the *total* project to last longer because construction starts later. However fewer errors are made because of the higher degree of design completion prior to construction start. In turn, construction time and cumulative effort (cost) are reduced. On average, projects with little overlap have larger median NPVs and smaller financial risk (probability of negative NPV).
    2. Comparing projects with different levels of effort spent on FEED, there exist on average a trade-off between total project duration and cumulative effort. However, there exist a tipping point beyond which larger FEED effort not only costs less but it also results in a shorter total project time. Spending more time on FEED also correlates with reduced construction time, larger NPVs and smaller financial risk.
    3. Fixed buffer and dynamic hiring policies perform very similarly across all trade spaces and metrics. Projects without leadership team buffer (fixed or dynamic) are systematically worse in all metrics.
    4. Projects with the option to expand take more time to build on average, but they also tend to have significantly larger median NPVs and lower financial risk.

7.0.3 Future directions

While the framework developed in this work is ready for use and it has proven to be very valuable, future improvements should seek to address the following points:

- **Metrics of success**. Appropriate metrics should be developed to measure the benefits of using the proposed framework. Communicating the SD and DCF models is often difficult and time consuming. Conversely, the time to convince decision makers is usually limited, and simple messages can be more effective.

- **SD model (1)**. The SD model can be viewed as an encyclopedia of nuclear projects, containing all variables driving progress and performance as well as their causal links. As any other source of information, it should be updated as new information (experience) is gained, which is why it was made available to the public.

- **SD model (2)**. Transitioning from a SD project to another can be cumbersome and it often requires the mediation of expert system dynamicists. For example, Fluor Corporation has been training hundreds of project managers and planners in the ongoing internal use of their model [75]. Adaptation/reuse should be simplified through, for example, (1) enhanced modularity features, (2) collection of reusable models with curated documentation.

- **DCF model**. The way uncertainty is modeled is rather refined for most variables. Nevertheless, improvements are possible in some areas, for example the probabilistic representation of rare events, and the representation of dynamic processes and feedbacks in electricity price modeling.

- **Policy insights**. Three questions about (1) overlap, (2) level of FEED and (3) management team were addressed in this work. Since the framework has intentionally a very broad scope, it can be used to analyze virtually any aspect of a nuclear project.

Bibliography

[1] D. Hess. *Reducing the costs of nuclear energy in three steps.* 2018. URL: `https://energypost.eu/putting-nuclear-energy-on-the-critical-path/` (visited on 07/05/2019).

[2] Massacusetts Institute of Technology. *The Future of Nuclear Energy in a Carbon-Constrained World.* Report. 2018.

[3] World Nuclear Association. *Nuclear Power in the World Today.* 2019. URL: `http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx` (visited on 07/03/2019).

[4] B.K. Sovacool. *Contesting the Future of Nuclear Power: A Critical Global Assessment of Atomic Energy.* World Scientific, 2011.

[5] B.K. Sovacool and Valentine S.V. *The National Politics of Nuclear Power Economics, Security, and Governance.* Routledge, 2012.

[6] R. Niehoff. "Organization and Administration of the United States Atomic Energy Commission". In: *Public Administration Review* 8 (1948).

[7] US Department of Energy (DoE). *The History of Nuclear Power.* Report. 1994.

[8] World Nuclear Association. *History of Nuclear Energy.* 2019. URL: `http://www.world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx` (visited on 07/03/2019).

[9] Library of Congress Prints and Photographs Division. *Shippingport Atomic Power Station, On Ohio River, 25 miles Northwest of Pittsburgh, Shippingport, Beaver County, PA.* 1963.

[10] S. dalquist. *Timeline - A Chronology of Public Opinion on Nuclear Power in the United States and United Kingdom.* report. 2004.

[11] International Monetary Fund. *Interest Rates, Discount Rate for United States [INTDSRUSM193N].* 2019. URL: `https://fred.stlouisfed.org/series/INTDSRUSM193N` (visited on 09/04/2019).

[12] C.D. Smith. *Palestine and the Arab-Israeli Conflict.* Bedford/St. Martin's, 2004.

[13] International Atomic Energy Agency (IAEA). *Power Reactor Information System (PRIS) Database.* 2019. URL: `https://pris.iaea.org/PRIS/home.aspx`.

[14] Carbon Brief. *Mapped: The world's nuclear power plants.* 2016. URL: `https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants` (visited on 07/05/2019).

[15] J.R. Lovering, A. Tip, and T. Norhaus. "Historical construction costs of global nuclear power reactors". In: *Energy Policy* 91 (2016).

[16] A. Grubler. "The cost of the french nuclear scale-up: A case of negative learning by doing". In: *Energy Policy* 38 (2010).

[17] Cour de Comptes. *Les couts de lafiliere electronucleaire (The costs of the nuclear power sector of France).* Report. 2012.

[18] L.E. Rangel and F. Leveque. "Revisiting the Cost Escalation Curse of Nuclear Power: New Lessons from the French Experience". In: *Economics of Energy and Environmnetal Policy* 4 (2015).

[19] M.S. Kim. *How greed and corruption blew up South Korea's nuclear industry.* Published by the MIT Technology Rewiew. 2019. URL: `https://www.technologyreview.com/s/613325/how-greed-and-corruption-blew-up-south-koreas-nuclear-industry/` (visited on 07/06/2019).

[20] World Nuclear News. *Toshiba sells Westinghouse related assets in USA.* 2018. URL: `http://www.world-nuclear-news.org/C-Toshiba-sells-Westinghouse-related-assets-in-USA-0604185.html` (visited on 07/05/2019).

[21] World Nuclear News. *Increased productivity at Vogtle construction site.* 2019. URL: `http://world-nuclear-news.org/Articles/Increased-productivity-at-Vogtle-construction-site` (visited on 07/04/2019).

[22] R. Pavey. *Price of Vogtle expansion could increase $900 million.* Published by The Augusta Chronicle. 2012. URL: `https://www.ucsusa.org/nuclear-power/cost-nuclear-power` (visited on 07/04/2019).

[23] Georgia Power Company. *Seventeenth Semi-Annual Construction Monitoring Report for Plant Vogtle Units 3 and 4.* Report. Submitted to the Georgia Public Service Commission. 2016.

[24] R. Walton. *Vogtle Cost Upgrade Causes Rethinking of $25B Nuclear Plant's Future*. Published by Power Engineering magazine. 2018. URL: `https://www.power-eng.com/articles/2018/08/vogtle-cost-upgrade-causes-rethinking-of-nuclear-plant-s-future.html` (visited on 07/04/2019).

[25] South Carolina Electric & Gas Company. *Quarterly Report to the South Carolina Office of Regulatory Staff*. Report. 2015.

[26] World Nuclear News. *Landmark module installation at VC Summer*. 2015. URL: `http://www.world-nuclear-news.org/NN-Landmark-module-installation-at-VC-Summer-2407157.html` (visited on 07/04/2019).

[27] Wikipedia. *Nuclear Power Debate*. 2019. URL: `https://en.wikipedia.org/wiki/Nuclear_power_debate#Accidents_and_safety` (visited on 07/03/2019).

[28] D.J. Ball, L.E.J. Roberts, and A.C.D. Simpson. *Research Report 20*. Report. 1994.

[29] S. Hirschberg, G. Spiekerman, and Dones R. *Severe Accidents in the Energy Sector*. Report. 1998.

[30] Wikipedia. *Energy Accidents*. 2019. URL: `https://en.wikipedia.org/wiki/Energy_accidents` (visited on 07/03/2019).

[31] C. Corkhill and N. Hyatt. *Nuclear Waste Management*. IOP Publishing, 2014.

[32] A. White et al. *Nuclear Energy: Science, Systems and Society*. 2018.

[33] The Union of Concerned Scientists. *Nuclear Power Cost. Nuclear Power is an Increasingly Expensive Source of Energy*. 2019. URL: `https://www.ucsusa.org/nuclear-power/cost-nuclear-power` (visited on 07/04/2019).

[34] Forbes Magazine. *Nuclear Follies*. 1985.

[35] Black & Veatch. *Cost and Performance Data for Power Generation Technologies*. Report. 2012.

[36] F. Ganda et al. "Reactor Capital Costs Breakdown and Statistical Analysis of Historical U.S. Construction Costs". In: (2016). Paper presented at the International Congress on Advances in Nuclear Power Plants (ICAPP 2016), San Francisco, USA.

[37] J.M. Nicholas. *Managing Business and Engineering Projects: Concepts and Implementation*. Prentice-Hall, 1990.

[38] A. Sharon, O.L. De Weck, and D. Dori. "Project Management vs Systems Engineering Management: A Practitioners View on Integrating the Project and Product Domains". In: *Systems Engineering* (2010).

[39] Project Management Institute. *A guide to the project management body of knowledge (PMBOK guide)*. project Management Institute, Inc., 2017.

[40] US Department of Defence (DoD). *Department of Defence Standard: Work breakdown Structures (WBS) for Defense Materiel Items (MIL-HDBK-881)*. Report. 2011.

[41] O.L. De Weck and J.M. Lyneis. *MIT ESD.36 System Project Management course assignments*. 2008.

[42] H.M. Sapolsky. *The Polaris System Development. Bureaucratic and Programmatic Success in Government*. Cambridge, Massachusetts: Harvard University Press, 1972.

[43] S.D. Eppinger and T.R. Browning. *Design Structure Matrix Methods and Applications*. Cambridge, Massachusetts: The MIT Press, 2017.

[44] E. August, C. Eckert, and P. Clarkson. "Using design structure matrices in visualising design processes." In: *Studies in Multidisciplinarity* 2 (2005), pp. 305–317.

[45] R. Marshall. "The Contribution of Earned Value Management to Project Success of Contracted Efforts". In: *Journal of Contract Management* (2007), pp. 21–331.

[46] Wikipedia. *Earned Value Management*. 2019. URL: `https://en.wikipedia.org/wiki/Earned_value_management` (visited on 05/03/2019).

[47] Q.W. Fleming and J.M. Koppelman. *Earned Value Project Management*. 4th ed. Project Management Institute, Inc., 2010.

[48] B. Flyvbjerg. *The Oxford Handbook of Megaproject Management*. Oxford Handbooks, 2017.

[49] B. Flyvbjerg. "What You Should Know about Megaprojects and Why: An Overview". In: *Project Management Journal* 45 (2014), pp. 6–19.

[50] B. Flyvbjerg. "From Nobel Prize to Project Management: Getting Risks Right". In: *Project Management Journal* 37 (2006), pp. 5–15.

[51] K. Aaltonen and J. Kujala. "A Project Lifecycle Perspective on Stakeholder Influence Strategies in Global Projects". In: *Scandinavian Journal of Management* 26 (2010), pp. 381–397.

[52] C. Cantarelli et al. “Lock-in and Its Influence on the Project Performance of Large-Scale Transportation Infrastructure Projects: Investigating the Way in Which Lock-in Can Emerge and Affect Cost Overruns”. In: *Environment and Planning B: Planning and Design* 37 (2010), pp. 792–807.

[53] J. Ross and B.M. Staw. “Organizational Escalation and Exit: Lessons from the Shoreham Nuclear Power Plant”. In: *The Academy of Management Journal* 36 (1993), pp. 701–732.

[54] H. Drummond. *Is Escalation Always Irrational? Organisation Studies.* Report. 1998.

[55] K.M. Eisenhardt. “Agency Theory: An Assessment and Review”. In: *Academy of Management Review* 14 (1989), pp. 57–74.

[56] J. Stiglitz. *The New Palgrave: Allocation, Information and Markets - Principal and Agent.* New York: W. W. Norton, 1989.

[57] B. Flyvbjerg, B. Garbuio, and D. Lovallo. “Delusion and Deception in Large Infrastructure Projects: Two Models for Explaining and Preventing Executive Disaster”. In: *California Management Review* 51 (2009), pp. 170–193.

[58] N.N. Taleb. *The Black Swan: The Impact of the Highly Improbable, Second Edition.* London and New York: Penguin, 2010.

[59] P.W.G. Morris and G.H. Hough. *The anatomy of major projects: a study of the reality of project management.* John Wiley and Sons, 1987.

[60] A.G. Rodrigues. “SYDPIM integration of SD and PERT/CPM tools: Assessing Fagan Analysis in a large-scale software project”. In: *Systems Engineering* (1999).

[61] D.H. Meadows et al. *The Limits to Growth: A Report to The Club of Rome.* Report. 1972.

[62] Wikipedia. *System Dynamics.* 2019. URL: `https://en.wikipedia.org/wiki/System_dynamics` (visited on 05/03/2019).

[63] J.M. Lyneis and D.N. Ford. “System dynamics applied to project management: a survey, assessment, and directions for future research”. In: *System Dynamics Review* 23 (2007), pp. 157–189.

[64] F.H.A Rahim, N.N. Hawari, and N.Z. Abidin. “Supply and demand of rice in Malaysia: A system dynamics approach”. In: *International Journal of Supply Chain and Management* 6 (2017), pp. 234–240.

[65] System Dynamics Society. *What is system dynamics*. 2019. URL: `https://www.systemdynamics.org/what-is-sd` (visited on 05/05/2019).

[66] J.M. Forrester. *Industrial Dynamics*. Cambridge, Massachusetts: The MIT Press, 1961.

[67] A. De Marco. "Modeling project behavior: dynamic tools for early estimates in construction project management". In: (2006). Paper presented at PMI Research Conference: New Directions in Project Management, Montreal, Quebec, Canada.

[68] L.A. Martin. *An introduction to feedback*. Report. Prepared for the MIT System Dynamics in Education Project Under the Supervision of Prof. Jay W. Forrester. 1997.

[69] C.W. Kirkwood. *System Dynamics Methods: A Quick Introduction*. Report. Course material, Arizona State University. 1998.

[70] J.M. Lyneis. *Project Dynamics*. Unpublished material. 2019.

[71] B. Oezbas, O. Ozgun, and Barlas Y. "Modeling and Simulation of the Endogenous Dynamics of Housing Market Cycles". In: *Journal of Artificial Societies and Social Simulation* 17 (2014).

[72] Inc. Ventana Systems. *Vensim*. https://vensim.com/.

[73] J.M. Lyneis, K.G. Coopera, and S.A. Elsa. "Strategic management of complex projects: a case study using system dynamics". In: *System Dynamics Review* 17 (2001), pp. 237–260.

[74] Wikipedia. *Fluor Corporation*. 2019. URL: `https://en.wikipedia.org/wiki/Fluor_Corporation` (visited on 09/04/2019).

[75] K. Cooper and G. Lee. *Managing the Dynamics of Projects and Changes at Fluor*. report. 2009.

[76] K.G. Cooper. "Naval Ship Production: A Claim Settled and a Framework Built". In: *Informs Journal of Applied Analytics* 10 (1980), pp. 20–36.

[77] System Dynamics Society. *Litton Case Study*. 2019. URL: `https://www.systemdynamics.org/litton` (visited on 09/04/2019).

[78] Wikipedia. *Computational Fluid Dynamics*. 2019. URL: `https://en.wikipedia.org/wiki/Computational_fluid_dynamics` (visited on 09/05/2019).

[79] Crisp Ideas. *The failure of system dynamics to become part of the management consulting profession's standard toolbox.* 2016. URL: `https://crispideas.wordpress.com/2016/12/10/the-failure-of-system-dynamics-to-become-part-of-the-standard-toolbox/` (visited on 09/04/2019).

[80] D. Rumeser and M. Emsley. "Key Challenges of System Dynamics Implementation in Project Management". In: *Procedia - Social and Behavioral Sciences* 230 (2016), pp. 22–30.

[81] H. Rahmandad and K. Hu. "Modeling the rework cycle: capturing multiple defects per task". In: *System Dynamics Review* 26 (2010), pp. 291–315.

[82] International Atomic Energy Agency (IAEA). *Manpower Development for Nuclear Power, a Guidebook.* Report. 1980.

[83] International Atomic Energy Agency (IAEA). *Project Management in Nuclear Power Plant Construction.* Report. 2012.

[84] W. Ibbs, M. Berry, and X. Sun. "Visualizing Skipped and Out-of-Sequence Work". In: *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction* 9 (2017).

[85] I.S. Abotaleb and I.H. El-Adaway. "First Attempt Toward a Holistic Understanding of the Interdependent Rippled Impacts Associated with Out-of-Sequence Work in Construction Projects: System Dynamics Modeling Approach". In: *Journal of Construction Engineering and Management* 144 (2018).

[86] International Council on System Engineering (INCOSE). *What is System Engineering?* 2019. URL: `https://www.incose.org/about-systems-engineering` (visited on 08/05/2019).

[87] E.C. Honour. "System Engineering Return on Investment". PhD thesis. University of South Australia, 2013.

[88] Energy Information Administration (EIA) - U.S. Department of Energy (DoE). *An Analysis of Nuclear Power Plant Construction Costs.* Report. 1986.

[89] J. Wang. *Encyclopedia of Business Analytics and Optimization.* Business Science Reference (an inprint of IGI Global), 2014.

[90] Y. Barlas. "Formal aspects of model validity and validation in system dynamics". In: *System Dynamics Review* 12 (1996).

[91] A. McLucas, M.J. Ryan, and K. Chan. "On the Validation of System Dynamics Models". In: *Conference paper* (2012). presented at Systems Engineering and Test and Evaluation Conference.

[92] G.E.P. Box and N.R. Draper. *Empirical model-building and response surfaces*. Wiley & Sons, 1987.

[93] J.D. Sterman. *Business Dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill, 2000.

[94] H. Ullah. "On the Validation of System Dynamics Type Simulation Models". In: *telecommunication Systems* 51 (2012).

[95] M.M. Hossen, S. Kang, and J. Kim. "Construction Schedule Delay Risk Assessment by Using Combined AHP-RII Methodology for an International NPP Project". In: *Nuclear Engineering and Technology* 47 (2014).

[96] B.K. Sovacool, A. Gilbert, and D. Nugent. "An international comparative assessment of construction cost overruns for electricity infrastructure". In: *Energy Research & Social Science* 3 (2014).

[97] K.S. Reichelt and J.M. Lyneis. "The Dynamics of Project Performance: Benchmarking the Drivers of Cost and Schedule Overrun". In: *European Management Journal* 17 (1999), pp. 135–150.

[98] K.G Cooper. "The rework cycle: how it really works and reworks". In: *PMNETwork* 7 (1993), pp. 25–28.

[99] I.J. Martinez Moyano. "Documentation for model transparency". In: *System Dynamics Review* 28 (2012), pp. 199–208.

[100] P. Minelli et al. "Comparison of Net Present value for Construction Projects of Two Offshore Floating Nuclear Power Plant Designs, Using a Monte Carlo Method for Evaluation of Project Uncertainties". In: *Conference paper* (2018). presented at the International Congress on Advances in Nuclear Power Plants.

[101] Energy Information Administration (EIA) - Office of Integrated and International Energy Analysis. *Annual Energy Outlook 2015 with Projections to 2040*. Report. 2015.

[102] J. E. Parsons and A. S. Mello. "Lecture Notes on Advanced Corporate Financial Risk Management". 2017.

[103] R.G. Richardson. *Money and Banking Interactive Notes*. Report. Interactive Series Book 3, Kindle Edition. 2019.

[104] R. DeNeufville and S. Scholtes. *Flexibility in Engineering Design*. The MIT Press, 2011.

[105] R.A. Brealey, S.C. Myers, and F. Allen. *Principles of Corporate Finance*. 12th ed. McGraw-Hill, 2014.

[106] F. Steiger. "The Validity of Company Valuation Using Discounted Cash Flow Methods". In: (2010). Seminar paper.

[107] A. Bihani. "A New Approach to Monte Carlo Simulation of Operations". In: *International Journal of Engineering Trends and Technology (IJETT)* 8 (2014), pp. 218–222.

[108] Parsons J.E. Du Y. *Capacity Factor Risk at Nuclear Power Plants*. Report. MIT Center for Energy and Environmental Policy Research, 2012.

[109] Wikipedia. *Power Purchase Agreement*. 2019. URL: `https://en.wikipedia.org/wiki/Power_purchase_agreement` (visited on 07/15/2019).

[110] J. Portugal-Pereira et al. "Better Late Than Never, But Never Late Is Better: Risk Assessment Of Nuclear Power Construction Projects". In: *Energy Policy* 120 (2018), pp. 158–166.

[111] J.G. Zack and P.V. Badala. *Pricing Constructor Delay Costs. A research Perspective Issued by The Navigant Construction Forum*. Report. 2016.

[112] World Nuclear Association. *Economics of Nuclear Power*. 2019. URL: `https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx` (visited on 09/02/2019).

[113] E. bertel and T. Lazo. "Decommissioning policies, strategies and costs: an international overview". In: *NEA News* 35 (2003), pp. 8–11.

[114] Inc. IBP. *Russia Nuclear Industry Business Opportunities Handbook, Volume 1 (Strategic Information, Developments, Contacts)*. International Business Publications, 2017.

[115] Wikipedia. *BOKA Vanguard*. 2019. URL: `https://en.wikipedia.org/wiki/BOKA_Vanguard` (visited on 04/20/2019).

[116] BBC News. *Huge salvage vessel may help lift Costa Concordia wreck*. 2013. URL: `https://www.bbc.com/news/world-europe-24483469` (visited on 04/19/2019).

[117] J.R. Pearson and K.S. Wittels. *Real Options in Action: Vertical Phasing in Commercial Real Estate Development*. 2008.

[118] A. Borison. "Real Options Analysis: Where Are the Emperor's Clothes?" In: *Journal of Applied Corporate Finance* 17-2 (2005), pp. 17–31.

[119] BKCASE Editorial Board. *"Decision Management" in The Guide to the Systems Engineering Body of Knowledge (SEBoK) v. 2.0*. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Computer Society. 2019. URL: `https://sebokwiki.org/wiki/Decision_Management` (visited on 07/18/2019).

[120] G.S. Parnell. *Trade-off Analytics: Creating and Exploring the System Tradespace*. John Wiley & Sons, 2016.

[121] A.M. Ross and D.E. Hastings. "The Tradespace Exploration Paradigm". In: 2005.

[122] G.S. Parnell, P.J. Driscoll, and D.L. Henderson. *Decision Making in Systems Engineering and Management*. 2nd ed. John Wiley & Sons, 2011.

[123] D.M. Roijers and S. Whiteson. *Multi-Objective Decision Making, Synthesis Lectures on Artificial Intelligence and Machine Learning*. Morgan & Claypool, 2017.

[124] E. Crawley, B. Cameron, and D. Selva. *System Architecture - Strategy and Product Development for Complex Systems*. Pearsons, 2016.

[125] W. Edwards, R.F. Miles, and D. Von Winterfeldt. *Advances In Decision Analysis: From Foundations to Applications*. Cambridge University Press, 2007.

[126] R.L. Keeney and R.S. Gregory. "Selecting Attributes to Measure the Achievement of Objectives". In: *Operations Research* 53 (2005), pp. 1–11.

[127] G.S. Parnell and T.E. Trainor. "Using the Swing Weight Matrix to Weight Multiple Objectives". In: *Incose International Symposium* (2009).

[128] Minelli P. *Offshore Floating Nuclear Power Plant: Balance of Plant Design for Maximum Efficiency and Compactness*. Report. MIT Department of Nuclear Science and Engineering, 2014.

[129] J. A. Ashworth. "Atlantic Generating Station". In: *Nuclear Technology* 22(2) (1974), pp. 170–183.

[130] Wikipedia. *Akademik Lomonosov*. 2019. URL: `https://en.wikipedia.org/wiki/Akademik_Lomonosov` (visited on 04/19/2019).

[131] Power Technology. *Floating nuclear power: will China pave the way?* 2018. URL: `https://www.power-technology.com/uncategorised/floating-nuclear-power-will-china-pave-way/` (visited on 04/19/2019).

[132] J. Buongiorno et al. "The Offshore Floating Nuclear Plant Concept". In: *Nuclear Technology* 194:1 (2016), pp. 1–14.

[133] R. Dehghan and J.Y. Ruwanpura. "The Mechanism of Design Activity Overlapping in Construction Projects and the Time-Cost Tradeoff Function". In: *Procedia Engineering* 14 (2011), pp. 1959–1965.

[134] U.S. Department of Labor. *Bureau of Labor Statistics - Occupational Outlook Handbook*. 2019. URL: `https://www.bls.gov/ooh/construction-and-extraction/construction-laborers-and-helpers.htm` (visited on 07/22/2019).

[135] *Using Fit-Constrained Monte Carlo Trials to Quantify Confidence in Simulation Model Outcomes*. Proceedings of the 35th Annual Hawaii International Conference on System Sciences. IEEE, 2002.

[136] World Nuclear Association. *World Nuclear Performance Report*. Report. 2018.

Appendix A

Our SD model considers error propagation, OOS work, coordination, uncertainty requirements, novelty, level of FEED effort, overlap between project phases, availability and size of management/technical leadership team, suppliers problems, task growth. The scenario that includes all these factors is discussed in Section 3.4.3. In this Appendix we summarize the content of the "changes" files (the .cin files that are loaded in addition to the model) that specify the parameter changes to represent these effects.

Error propagation

The main variables[2] used to introduce the effect of error propagation are (see Section 3.3.2):

- FEED Normal Sensitivity of Fraction Correct to Undiscovered Rework = 0.5
- Design Normal Sensitivity of Fraction Correct to Undiscovered Rework = 0.5
- Design Maximum Sensitivity of Fraction Correct to FEED Undiscovered Rework = 0.8
- Design Minimum Sensitivity of Fraction Correct to FEED Undiscovered Rework = 0
- Design Table for Effect of Progress on FEED Sensitivity[3] ((0,1), (0.1,1), (0.2,1), (0.3,0.9), (0.4,0.75), (0.5,0.5), (0.6,0.25), (0.7,0.1), (0.8,0), (0.9,0), (1,0))
- Build Normal Sensitivity of Fraction Correct to Undiscovered Rework = 0.4
- Build Maximum Sensitivity of Fraction Correct to Design Undiscovered Rework = 0.4

Precedence and OOS work

The main variables used to introduce the effect of OOS work are (see Section 3.3.3):

- FEED Switch for Effect of Precedence on Productivity = 1
- FEED Sensitivity of Fraction Correct to Precedence Effects = 0.8
- FEED Fraction of Work OOS to Hit Zero PDY = 1
- FEED Normal Hardness of Precedence Constraint = 0.25

---

[2] The first word of each variable indicates the work phase to which the variable belongs.

[3] Lookup variables are expressed here as sets of points.

- FEED Ability to Accelerate Task Sequence = 1.3
- FEED Fractional Increase in Planned Work Rate With Scope Growth = 0
- Design Switch for Effect of Precedence on Productivity = 1
- Design Sensitivity of Fraction Correct to Internal Precedence Effects = 0.8
- Design Fraction of Work OOS to Hit Zero PDY = 1
- Design Normal Hardness of Precedence Constraint = 0.25
- Design Ability to Accelerate Task Sequence = 1.3
- Design Fractional Increase in Planned Work Rate With Scope Growth = 0
- Build Switch for Effect of Precedence on Productivity = 1
- Build Sensitivity of Fraction Correct to Internal Precedence Effects = 0.8
- Build Fraction of Work OOS to Hit Zero PDY = 1
- Build Normal Hardness of Precedence Constraint = 0.25
- Build Ability to Accelerate Task Sequence = 1.3
- Build Fractional Increase in Planned Work Rate With Scope Growth = 0

Coordination

The main variables used to introduce the effect of coordination are (see Section 3.3.4):

- FEED Switch for Coordination Effect = 1
- FEED Switch to Phase out Coordination Effect = 1
- FEED Sensitivity of Fraction Correct to Coordination = 1
- FEED Normal Relative Effort Required for Rework = 0.5
- FEED Relative Effort Required for Rework Coordination = 0.15
- FEED Priority to Coordination = 0.75

- FEED Switch to Phase out Coordination Priority = 1
- Design Switch for Coordination Effect = 1
- Design Switch to Phase out Coordination Effect = 1
- Design Sensitivity of Fraction Correct to Coordination = 1
- Design Normal Relative Effort Required for Rework = 0.5
- Design Relative Effort Required for Rework Coordination = 0.2
- Design Priority to Coordination = 0.75
- Design Switch to Phase out Coordination Priority = 1
- Build Switch for Coordination Effect = 1
- Build Switch to Phase out Coordination Effect = 1
- Build Sensitivity of Fraction Correct to Coordination = 1
- Build Normal Relative Effort Required for Rework = 0.5
- Build Relative Effort Required for Rework Coordination = 0.15
- Build Priority to Coordination = 0.65
- Build Switch to Phase out Coordination Priority = 1

Uncertain requirements

The main variables used to introduce the effect of uncertain requirements are (see Section 3.3.5):

- FEED Magnitude of Effect of Uncertain Requirements on Fraction Correct = 0.21
- FEED Timing of Effect of Uncertain Requirements ((0,1), (0.025,1), (0.05,1), (0.075,1), (0.1,1), (0.125,1), (0.15,1), (0.175,1), (0.2,1), (0.225,1), (0.25,1), (0.75,0), (1,0), (1,0))
- Design Magnitude of Effect of Uncertain Requirements on Fraction Correct = 0.08
- Design Timing of Effect of Uncertain Requirements ((0,1), (0.025,1), (0.05,1), (0.075,1), (0.1,1), (0.125,1), (0.15,1), (0.175,1), (0.2,1), (0.225,1), (0.25,1), (0.75,0), (1,0), (1,0))

Novelty

The main variables used to introduce the effect of novelty are (see Section 3.3.6):

- FEED Magnitude of Effect of Novelty on Fraction Correct = 0.1
- FEED Timing of Effect of Novelty ((0,0), (0.025,0), (0.05,1), (0.075,1), (0.1,1), (0.125,1), (0.15,1), (0.175,1), (0.2,1), (0.225,1), (0.25,1), (0.275,1), (0.3,1), (0.325,1), (0.35,1), (0.375,1), (0.4,1), (0.425,1), (0.45,1), (0.475,1), (0.5,1), (0.75,0), (1,0))
- Design Magnitude of Effect of Novelty on Fraction Correct = 0.095
- Design Timing of Effect of Novelty ((0,0), (0.025,0), (0.05,1), (0.075,1), (0.1,1), (0.125,1), (0.15,1), (0.175,1), (0.2,1), (0.225,1), (0.25,1), (0.275,1), (0.3,1), (0.325,1), (0.35,1), (0.375,1), (0.4,1), (0.425,1), (0.45,1), (0.475,1), (0.5,1), (0.75,0), (1,0))
- FEED Switch for Progress Growth[4] = 1
- Design Switch for Progress Growth = 1
- Build Switch for Progress Growth = 1
- FEED Fraction Scope Growth = 0.05
- FEED Fraction Scope Growth Discoverable by Design = 0.5
- FEED Table for Fraction Remaining Scope Growth Design ((0,0), (0.05,0), (0.1,0), (0.15,0), (0.2,0.1), (0.25,0.3), (0.3,0.5), (0.35,0.7), (0.4,0.9), (0.45,1), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))
- FEED Table for Fraction Remaining Scope Growth Build ((0,0), (0.05,0), (0.1,0), (0.15,0), (0.2,0.1), (0.25,0.3), (0.3,0.5), (0.35,0.7), (0.4,0.9), (0.45,1), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))
- Design Fraction Scope Growth = 0.05
- Design Fraction Scope Growth Discoverable by Design = 0.5

---

[4] The next variables pertain scope growth due to novelty (e.g. “scope growth from progress”.

- Design Table for Fraction Remaining Scope Growth Design ((0,0), (0.05,0), (0.1,0), (0.15,0), (0.2,0.1), (0.25,0.3), (0.3,0.5), (0.35,0.7), (0.4,0.9), (0.45,1), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))
- Design Table for Fraction Remaining Scope Growth Build ((0,0), (0.05,0), (0.1,0), (0.15,0), (0.2,0.1), (0.25,0.3), (0.3,0.5), (0.35,0.7), (0.4,0.9), (0.45,1), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))
- Build Fraction Scope Growth = 0.05
- Build Table for Fraction Remaining Scope Growth ((0,0), (0.05,0), (0.1,0), (0.15,0), (0.2,0.1), (0.25,0.3), (0.3,0.5), (0.35,0.7), (0.4,0.9), (0.45,1), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))

Level of FEED effort

The main variables used to introduce the effect of level of FEED effort are (see Section 3.3.7):

- FEED Optimal Scope = 1860
- FEED Planned Effort Multiple of Optimal = 0.5
- FEED Sensitivity of Fraction Correct to Level of Effort = 0.25
- Design Table for Effect of FEED Effort on Productivity ((0,0.05), (0.1,0.1), (0.2,0.2), (0.3,0.3), (0.4,0.4), (0.5,0.5), (0.6,0.6), (0.7,0.7), (0.8,0.8), (0.9,0.9), (1,1), (1.1,1), (1.2,1), (1.3,1), (1.4,0.9), (1.5,0.8))
- Design Maximum Sensitivity of FEED Effort on Productivity = 0.15
- Design Minimum Sensitivity of FEED Effort on Productivity = 0.05
- Design Table for Effect of FEED Effort on Fraction Correct ((0,0.05), (0.1,0.1), (0.2,0.2), (0.3,0.3), (0.4,0.4), (0.5,0.5), (0.6,0.6), (0.7,0.7), (0.8,0.8), (0.9,0.9), (1,1), (1.1,1), (1.2,1), (1.3,1), (1.4,1), (1.5,1))
- Design Maximum Sensitivity of FEED Effort on Fraction Correct= 0.25
- Design Minimum Sensitivity of FEED Effort on Fraction Correct= 0.1

- Build Table for Effect of FEED Effort on Productivity ((0,0.05), (0.1,0.1), (0.2,0.2), (0.3,0.3), (0.4,0.4), (0.5,0.5), (0.6,0.6), (0.7,0.7), (0.8,0.8), (0.9,0.9), (1,1), (1.1,1), (1.2,1), (1.3,1), (1.4,0.9), (1.5,0.8))
- Build Maximum Sensitivity of FEED Effort on Productivity = 0.2
- Build Minimum Sensitivity of FEED Effort on Productivity = 0.15
- Build Maximum Sensitivity of FEED Effort on Fraction Correct= 0.3
- Build Minimum Sensitivity of FEED Effort on Fraction Correct= 0.1

Overlap between *F&L* and *D&P*

The main variables used to introduce the effect of overlap between *F&L* and *D&P* are (see Section 3.3.8):

- Design Switch for Linear FEED Required = 1
- Design Required FEED Progress at Design Start = 0.9
- Design Fraction Complete to Require FEED 100% = 0.3
- Design Switch If Shortfall Must Lead to Zero PDY = 0
- Design FEED Shortfall to Hit Zero Productivity = 0.25
- Design Managerial Willingness to Charge Ahead of FEED = 0.5
- Design Table for Effect of FEED Shortfall on Productivity ((0,1), (0.2,0.9), (0.4,0.775), (0.6,0.6), (0.8,0.35), (1,0), (5,0))
- Design Sensitivity of Fraction Correct to FEED Shortfall = 0.75

Overlap between *D&P* and *B&C*

The main variables used to introduce the effect of overlap between *D&P* and *B&C* are (see Section 3.3.8):

- Build Switch for Linear Design Required = 1
- Build Required Design Progress at Build Start = 0.3

- Build Fraction Complete to Require Design 100% = 0.99
- Build Fraction Complete to Start Transition = 0.8
- Build Fraction Complete to End Transition = 0.95
- Build Switch If Shortfall Must Lead to Zero PDY = 0
- Build Normal Design Shortfall to Hit Zero Productivity = 0.25
- Build Design Shortfall to Hit Zero Productivity at End of Phase = 0.025
- Build Managerial Willingness to Charge Ahead of Design = 0.6
- Build Table for Effect of Design Shortfall on Productivity ((0,1), (0.2,0.9), (0.4,0.775), (0.6,0.6), (0.8,0.35), (1,0), (5,0))
- Build Sensitivity of Fraction Correct to Design Shortfall = 0.03

Availability and size of management/technical leadership team

The main variables used to introduce the effect of the availability and size of management/technical leadership team are (see Section 3.3.9):

- Program Technical Leadership Fraction of Program Planned Staff = 0.025
- Program Technical Leadership Normal Buffer = 0
- Program Sensitivity of Productivity to Technical Leadership = 0.235
- Program Sensitivity of Fraction Correct to Technical Leadership = 0.235
- Program Multiplier for Rework Tasks = 0.6
- Program Weight on FEED Rework = 0.9
- Program Weight on Design Rework = 0.1
- Program Weight on Build Rework = 0.1
- Program Multiplier for Scope Growth Tasks = 1

- Table for Implementation Effort Fraction of Design Effort ((0,0.05), (0.1,0.05), (0.2,0.05), (0.3,0.05), (0.4,0.05), (0.5,0.05), (0.6,0.05), (0.7,0.05), (0.8,0.05), (0.9,0.05), (1,0.05))
- Design Implementation Tuner = 0.1
- Table for Implementation Effort Fraction of Build Effort ((0,0), (0.1,0), (0.2,0), (0.3,0), (0.4,0), (0.5,0.1), (0.6,0.2), (0.7,0.25), (0.8,0.25), (0.9,0.25), (1,0.25))
- Build Implementation Tuner = 0.1

Suppliers

The main variables used to introduce the effect of suppliers are (see Section 3.3.10):

- Supplier Fraction Design Complete When First Work Released = 0.05
- Supplier Fraction Design Complete When All Work Released = 0.7
- Sensitivity of Supplier Work Rate to Design Undiscovered Rework = 1
- Supplier Exogenous Effect on Work Rate = 0.55
- Supplier Fraction Complete When Design Work First Delivered = 0.05
- Supplier Fraction Complete When Final Design Work Delivered = 0.56
- Design Fraction Complete When First Supplier Work Needed = 0.1
- Design Fraction Complete When All Supplier Work Needed = 0.8
- Design Maximum Effect of Supplier Shortfall = 0.4
- Design Switch to Activate Supplier Impacts = 1
- Design Switch to Increase Hardness With Progress = 0
- Supplier Fraction Complete When Build Work First Delivered = 0.12
- Supplier Fraction Complete When Final Build Work Delivered = 0.72
- Build Fraction Complete When First Supplier Work Needed = 0.025
- Build Fraction Complete When All Supplier Work Needed = 0.9

- Build Maximum Effect of Supplier Shortfall = 0.6
- Build Switch to Activate Supplier Impacts = 1
- Build Switch to Increase Hardness With Progress = 0
- Design Normal Effect of Supplier Coordination on Productivity = 0.03
- Build Normal Effect of Supplier Coordination on Productivity = 0.03

Task growth

The main variables used to introduce the effect of task growth are (see Section 3.3.11):

- FEED Magnitude of Task Growth = 0.57
- FEED Time of Task Growth = 5
- FEED Duration of Task Growth = 36
- Design Magnitude of Task Growth = 0.025
- Design Time of Task Growth = 70
- Design Duration of Task Growth = 6
- Build Magnitude of Task Growth = 0.025
- Build Time of Task Growth = 120
- Build Duration of Task Growth = 5
- FEED Magnitude of Change = 0.2
- FEED Time of Change = 10
- FEED Duration of Change = 6
- Design Magnitude of Change = 0.025
- Design Time of Change = 100
- Design Duration of Change = 12

- Build Magnitude of Change = 0.025
- Build Time of Change = 130
- Build Duration of Change = 36