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A Real Options Approach to Nuclear Waste Disposal in Sweden

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Abstract

This report is concerned with an investigation of how the real options approach can be useful for managerial decisions regarding the phase-out of nuclear power generation in Sweden. The problem of interest is the optimal time-schedule for phase-out activities, where the optimal time-schedule is defined in purely economical terms. The approach taken is actual construction and application of three real options models, which capture different aspects of managerial decisions. The first model concerns when investments in deep disposal facilities should optimally be made. Although the model is a rough simplification of reality, the result is clear. It is economically advantageous to postpone deep disposal forever. The second model focuses on how the uncertainty of future costs relates to managerial investment decisions. Construction of this model required some creativity, as the nuclear phase-out turns out to be quite a special project. The result from the second model is that there can be a value associated with deferral of investments due to the uncertainty of future costs, but the result is less clear-cut compared to the first model. In the third model, we extend an approach suggested by Loubergé, Villeneuve and Chesney (2001). The risk of a nuclear accident is introduced through this model and we develop its application to investigate the Swedish phase-out in particular, which implies that waste continuously disposed. In the third model, focus is shifted from investment timing to implementation timing. The results from the third model are merely qualitative, as it is considered beyond the scope of this work to quantitatively determine all relevant inputs.

It is concluded that the phase-out of nuclear power generation in Sweden is not just another area of application for standard real options techniques. A main reason is that although there are a lot of uncertain issues regarding the phase-out, those uncertainties do not leave a lot of room for managerial flexibility if analyzed in compliance with the Swedish framework. Still, we argue that the real options approach can really be useful as a complement to other calculation techniques as indicated by our models. Hopefully, this work may inspire to future investigations of this interesting but highly unexplored area of application for real options.

Acknowledgements

First and foremost, we would like to thank our supervisor, Professor Göran Bergendahl, for his help and for the interesting discussions we have had during the work with this report. We are also grateful for the enthusiastic support from Senior Lecturer Peter Rosén.

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1 Introduction

This chapter introduces the problem to be analyzed. The problem is described and it is determined what efforts have to be made to solve the problem. The chapter also states the purpose of the work and clarifies the role of the particular work, in relation to others'. Finally, the method and document outline of the work is presented.

1.1 Background

Sweden has radioactive waste originating mainly from nuclear power generation. The toxic waste represents a significant environmental threat, and it is considered to be Sweden's common responsibility to deal with this waste. Hence, it has been decided not pass it on to future generations, but to manage and dispose of it today (at least in the best possible sense). Since 1985, there have been facilities in operation to deal with the waste. However, the most important one remains to be built: a deep repository for final disposal of the spent nuclear fuel. The work of finding a site for the deep repository is currently under way. By approximately 2015, SKB[1], representing the nuclear power companies, anticipates that Sweden will be in a position to place the first canister containing spent nuclear fuel in the deep repository. (www.skb.se, 2003-12-18)

Every year, SKB calculates the total costs of the phase-out of nuclear power generation in Sweden. SKI[2], representing the government, reviews the calculations from SKB and then suggests an appropriate fee that the nuclear power plants should pay for waste management. The Swedish government finally determines the fee. Today the nuclear power plants pay SEK 0.005 per kilowatt-hour for waste management. The Nuclear Waste Fund administers these funds, which currently total about SEK 30 billion, to finance waste handling. (SKB: Plan 2003)

"Viewed as a social phenomenon, the deep repository involves people, responsibility, public opinion, and politics. Considerable uncertainty still exists and its nature fluctuates, which makes it important to keep the door open, to discuss, to listen, and to respect". (www.skb.se, 2003-12-18). This uncertainty must be taken into account when calculating the costs and deciding the financing form, for phasing out the nuclear power generation in Sweden. A valuation technique that is helpful when the level of uncertainty and flexibility is high is provided by the real options approach. This approach is the extension of financial option theory, to options on real assets. When the outcome of a project to a large extent depends upon uncertain factors, it is preferable if

[1] Svensk Kärnbränslehantering AB, Swedish Nuclear Fuel and Waste Management Company

[2] Statens Kärnkraftinspektion, Swedens Nuclear Power Inspectorate

investment decisions are flexible. Real Options Analysis is a method to capture the value that such flexibility creates. A major advantage of the technique is that it can be used to eliminate the "now-or-never thinking", inherent in traditional discounted cash flow analysis (NPV), and instead provide a more dynamic view of capital allocation. This is one of the advantages that make Copeland and Antikarov (2001) express their opinion that *"in ten years, real options will replace NPV as the central paradigm for investment decisions"*.

Because of the uncertainties involved, it seems that managerial decisions regarding the phase-out of nuclear power generation in Sweden, is an area of application where the real options approach could be valuable. Within each area of application, the real options approach has to be adapted and it will become clear that the nuclear phase-out in Sweden contains subtleties that call for special consideration and prevent the usage of the most general and common real options methods.

1.2 Problem Description and Problem Analysis

The problem treated in this thesis can be summarized in the following question:

How can the real options technique be used for managerial decisions regarding the optimal time-schedule for the phase-out of nuclear power generation in Sweden?

The *optimal-time schedule* is in this work defined as the time-schedule for the implementation of the phase-out for nuclear power generation that minimizes the present value of total costs. As discussed in the background, the nuclear waste should be disposed of; the question is *when*. It is still not finally determined when the nuclear power plants should be shut down, or when the first canister of waste should be placed in the primary rock. There are several types of nuclear waste such as the fuel, reactor waste and less active waste. We are only concerned with the different types of waste to the extent that the form of disposal is affected.

The problem is treated from a view similar to that of SKB, i.e. focus is on the costs of dealing with nuclear waste and not on the specific financing system. In accordance with our definition of the optimal time-schedule, we will focus on the economical part and not on the political and ethical issues that are always intertwined with this subject. Thus, in this work, the managerial decisions are equivalent to the decisions available for the management of SKB.

To answer the question stated above, the following will be required:

1. A systematization of the relevant uncertainties and flexibilities. Such systematization forms the basis for any application of real options theory.
2. Construction and application of suitable real options models, consistent with those uncertainties and flexibilities.
3. An assessment of the real options approach as a tool for managerial decisions regarding the phase-out.

We are not aware of any work with an approach to the managerial decisions, regarding the phase-out of nuclear power generation in Sweden, similar to the approach taken in this work. Furthermore, the Swedish program for nuclear waste disposal is a project with huge complexity. Nowhere in the world has such a project yet been undertaken (SKI: Perspektiv på kärnkraft, 2003). Under these circumstances, it is believed that the most difficult and critical part will be the actual construction of suitable real options models. Hence, creativity should be a key aspect.

Managerial decisions regarding the phase-out are implicitly considered to be important to most people in Sweden, since at the end of the day, it is the electricity consumers who pay for the disposal and management of nuclear waste. The managerial decisions taken in Sweden may also prove to be decisions that can be considered in other countries, as Sweden is a forerunner in this issue. The real options approach to this particular problem also deserves academic attention, since the problem of interest has some particular characteristics and since real options is a relatively new and not fully developed technique. The question of nuclear power waste disposal in general is also a question that engages a lot of individuals for other reasons, such as where the repository site should be. In total, this is a subject that affects many people and has many implications on every-day life.

1.3 Purpose

The purpose of this work is to investigate the usefulness of real options techniques in the specific context of nuclear waste disposal in Sweden, focusing on the time-schedule, by actual application of such techniques.

In more detail the purpose is broken down to:

1. Specify the flexibilities and uncertainties inherent in the problem.
2. Clarify the decision alternatives (options).
3. Ascertain what sort of real options techniques that can possibly be used in the context of dealing with nuclear waste.
4. Evaluate the usefulness of those techniques from a qualitative point of view.

Our purpose is not to construct a full calculation model that can replace the method used by SKB today. Conversely, we aim to show how the real options approach may serve as a useful complement. We desire to show that the real options technique can prove useful for managerial decisions regarding certain aspects of the phase-out of nuclear power in Sweden, and in countries with a similar approach to waste handling.

1.4 Method

In order to fulfill the purpose of this work, we intend to devise and actually apply real option models to the problem on nuclear waste disposal. By being creative in the modeling, we seek to provide new insights and to that extent create new knowledge. We suggest that our results can mainly be validated by letting people with relevant competences evaluate our models. If experts are convinced by our argumentation, then it is fair to say that new knowledge has been created. It is however considered beyond the scope of this work to include other's evaluation in this report. For simplicity, and since we are not experts on nuclear waste handling, we aim for qualitative results and general principles, rather than quantitative outcomes.

When it comes to the field of real options in conjunction with nuclear waste management, one could expect that there is very little coverage even in scientific publications. Indeed, not much work is available related to the work that is conducted in this report. Only one article (a working paper) has been identified, dealing with a real options approach to nuclear waste disposal (Loubergé et al., 2001). This article is very academic in its approach and targets an audience well versed in mathematics. A textbook (Chapman and Ward, 2002) that discusses investment decision regarding the phase-out of nuclear power generation in UK is also available. The authors recognize that there are managerial options present in this context that could possibly be evaluated using a real options technique. However, they do not persist to address the question of how this can actually be done.

Our work builds upon and extends the work described in these two texts with a stress on the article. However, these texts are not sufficient as the article is too narrow and academic and the book is much too basic and vague for our purpose. Hence our method has to include real options research from other areas. Information regarding option theory is mainly derived from published scientific articles. This is the case since this subject is quite fresh, and relatively few books are published in the field. Especially books discussing more advanced real options theory are rare.

As our area of interest is the Swedish model of nuclear waste disposal, we have to investigate how this model works and determine the flexibility and uncertainty involved. This is conducted by requesting information from the organizations in charge of planning the phase-out of Swedish nuclear power generation, SKB and SKI. This predominately means published reports from both institutions, but we have also had personal contact with SKB to clarify certain issues. One should observe the fact that SKB is a private institute, owned by the nuclear power companies. SKB may therefore have an incentive to present a biased view. They are however monitored by SKI, which may reduce such risks. In any case, such biasing would not significantly affect the work performed in this report, as we are mainly concerned with the general aspects of the phase-out.

Since this work is based on modeling, it is important to keep in mind that a model is just a model. Reality can only be modeled to a certain point, and major simplifications are made in this work because of the complexity of the problem. This point is important to acknowledge when the models are used for drawing conclusions.

1.5 Limitations of Scope

The work is limited to consider radioactive waste that is produced from nuclear power generation in Sweden only. It is also limited by the strong restriction of only considering decision alternatives within the framework of the Swedish model. The Swedish model referred to is the model currently considered by SKB. Hence we regard the problem from a point of view similar to that of the nuclear companies, and not the point of view of politicians or the Swedish public. Thus, this implies that some decision alternatives apparent to others, but not found viable by SKB, are disregarded from.

The real options models to be constructed, require that major simplifications of the full problem have to be made, which is a limitation per se. This fact adds to our desire to limit ourselves to qualitative conclusions, as is discussed in the previous section.

We will consider the target audience to be familiar with basics of real option theory and economical issues in general. Some insights in financial modeling are also beneficial, as the mathematical explanation is limited to a certain level.

1.6 Document Outline

This report basically follows the traditional format for academic reports. Table 1.1 provides an overview of the report.

Table 1.1: The disposition of the report.

Chapter	Content
1	Introduction
2	The Swedish Program for Disposal of Nuclear Waste
3	Option Theory
4	Real Options and Nuclear Waste Management
5	Modeling and Application
6	Conclusions
7	References
8	Appendices

Chapter 2 provides the theoretical background of how nuclear waste management is treated in Sweden. Chapter 3 describes real options analysis with focus on specific theory needed for this work. Chapter 2 and 3 are hence partly summarizing theoretical chapters, that need not be studied in detail if this knowledge is already familiar. However, the two chapters do constitute the basis for the remaining part of the report. In Chapter 4, the theory of nuclear waste management is connected to the theory of real options. The chapter is important because it discusses the uncertainties and flexibilities and their treatment in the real options framework, i.e. it provides the starting point for modeling and application in the following chapter. Chapter 5 is the culmination of our work. This is the where creativity comes into play and the actual real options modeling is performed. Results are commented and analyzed successively in this chapter. Chapter 6 contains the conclusions including suggestions for future work.

2 The Swedish Program for Disposal of Nuclear Waste

This chapter provides a description of how the phase-out of nuclear power generation in Sweden is currently treated. An understanding of this issue is necessary for understanding the models constructed in Chapter 5. It will also constitute the basis for a systematization of uncertainties and flexibilities in Chapter 4. Since a full description of the program would contain a vast amount of information, this chapter is very summarizing.

2.1 Swedish Politics and Model for the Nuclear Phase-Out

To provide some perspective for the uncertainties and flexibilities to be presented, the chapter begins with a short description of the Swedish nuclear history. Thereafter the core of the Swedish model for nuclear phase-out is presented. The chapter basically follows material from SKI (Perspektiv på kärnkraft, 2003).

The Swedish nuclear history begun in essence in the 1950's, when a Swedish nuclear weapon was discussed. During the 60's this idea was abandoned and in 1964 the first reactor for nuclear power generation was put into operation. In the beginning of the 70's all political parties supported a commitment to nuclear power, but a few years later a public opinion against it had grown strong. The opinion led to a referendum about the future role of nuclear power generation in Sweden, which took place in March 1980. The result caused the Parliament to decide on a program with twelve reactors that should be phased out no later than 2010.

The Tjernobyl-disaster in 1986 initiated a new political nuclear debate, which led to the Social Democrats' promise of a "premature" phase-out of two reactors. Only five years later, it was however decided to postpone this premature phase-out. In 1997 new guidelines were presented, in which the final date for nuclear power generation, 2010, was abandoned. It was instead prescribed that the final date should be based upon the rate at which phase-out could be performed taken into account the power supply and the possibility to use environmentally friendly generated power. Today, there are eleven reactors in operation in Sweden localized to Barsebäck, Ringhals, Oskarshamn, and Forsmark. The Swedish government has the right to demand that a nuclear reactor is closed down at a date decided by the Parliament. We suggest that the historical swings in nuclear politics are kept in mind when the future phase-out is discussed. If the phase-out is performed as planned, the current date is somewhere in the middle of what will be the total history of nuclear power activities in Sweden.

The Swedish model for nuclear phase-out consists of interim storage of waste for about 40 years after which it is deep disposed in the Swedish primary rock for all foreseeable future. Initially, the radioactive fuel is stored in special basins within the nuclear plants. It cools off there for about a year as the radioactivity decreases. The fuel is then transported on a specially designed ship to the interim storage named CLAB (*"centralt lager för använt kärnbränsle"*) outside Oskarshamn. During interim storage the fuel is placed in basins, until it has cooled off enough for deep disposal. This first period, although short, is most critical since the radioactivity decreases exponentially. Finally, the fuel is put in canisters that are deep disposed in the primary rock, about 500 meters below ground. The tunnels are filled up and after about 100.000 years, the fuel is not more hazardous than the uranium ore from which it was originally manufactured and occurs naturally in the Earth's crust. It is not decided where and how, in detail, the waste should be deep disposed. The Parliament has however decided that the deep disposal is to be located in Sweden.

Nowhere in the world does a final deep disposal for nuclear fuel yet exist. As in Sweden, the direction in most nuclear countries is towards geological final storage. Alternative methods are however examined in parallel, in several countries. However, since the real options models to be developed in this work should be limited by the framework of the Swedish model, we do not consider any alternatives to deep disposal than in primary rock.

2.2 *Financing and Planning*

It is the companies owning the nuclear power plants in Sweden that are responsible for taking the actions that are necessary for the phase-out. There is a Swedish law (Finansieringslagen 1992:1537) coupled to this responsibility, which prescribes that the reactor owners must calculate and present the future costs for the phase-out. The nuclear power companies have together tasked to SKB to ensure that this responsibility is fulfilled. Every year, SKB calculates the total costs of the phase-out. As described in Section 1.1, these calculations are used as a basis for the funding of means to cover the phase-out. The Nuclear Waste Fund is mainly invested in securities with a real rate of return. The reactor owners then have the right to get compensation from the fund needed for the phase-out activities.

In principle, the fund should at any time cover the planned future costs for the phase-out. A successive build up to this level is however allowed during the first 25 years of operation for each nuclear reactor. If a reactor is prematurely closed down, the owners are still responsible for the costs. The fact that SKB calculates the expected costs, imply that they also have a plan for the phase-out and a time-schedule for its implementation. Their planning is summarized under the designation *reference scenario*, which describes a specific solution for the phase-out (SKB: Plan 2003). This scenario is based on that the nuclear reactors operate for forty years before they are phased out. The reference scenario is used as a basis for their cost calculations. SKB however point out that the reference scenario should not be considered a final standpoint from their side. In any case, it is natural to let the reference scenario constitute the basis for the real options models to be constructed and discussed in this work.

2.3 SKB's Calculation of Costs

The costs according to the reference scenario are calculated by SKB using a traditional calculation method, where the conditions are predetermined and assumed constant. However, they also employ a probabilistic method that takes into account the variations and uncertainties embedded in the phase-out. The probabilistic method starts from a calculation principle named *the successive principle*. Every cost item or variation is then viewed as a stochastic variable. The total cost takes the form of a distribution function, which indicates with what probability a certain cost will be realized. From this function, it is possible to deduce what factors that have most impact on the result and to review and break down these factors to reduce uncertainty. The calculations can then be repeated resulting in less inaccuracy. The successive principle deserves its name due to this successive convergence towards a, at least in theory, more certain prognosis. In this work we will make use of the fact that SKB already have identified and ranked the major uncertainties.

Table 2.1 presents a summary of future costs (2004 and forward) for the reference scenario as calculated by SKB (SKB: Plan 2003). The costs are undiscounted and presented in January 2003 prices. These costs will be taken as input in the real option models.

Table 2.1: Future costs for the reference scenario presented in January 2003 prices and undiscounted. The asterisks denote costs relating to activities and systems that are already in operation.

Type of cost	MSEK	Percentage of total costs
SKB*	4860	9,8 %
Transportation*	2230	4,5 %
Demolition of power plants	13130	26,5 %
Interim storage (CLAB)*	4610	9,3 %
Encapsulation	7920	16,0 %
Deep disposal (external facilities)	250	0,5 %
Deep disposal (localization)	1040	2,1 %
Deep disposal (above ground)	5420	11,0 %
Deep disposal (below ground, fuel)	8150	16,4 %
Final storage (less active waste)	580	1,2 %
Final storage (reactor waste)*	420	0,8 %
Final storage (demolition waste)	960	1,9 %
Total	49570	100 %

It is clear from Table 2.1 that the demolition of the nuclear power plants and the actual deep disposal are very cost intensive and that those are costs yet to be taken. A more detailed partition of costs is presented in Appendix 1.

2.4 SKB's Overall Time-Schedule

It is the time-schedule for the nuclear phase-out that is of interest in this work and it is considered appropriate to start from the overall time-schedule that SKB use. The time-schedule is subject to uncertainty, so it is described as a probable case together with a low-cost alternative and a high-cost alternative. (SKB:Plan 2003, Underlag för kostnadsberäkningar)

The probable case is based on that the deep disposal is performed in two stages. The first stage starts in 2015 by disposal of 400 canisters. During the first stage and until the second stage, the deep disposal is evaluated. The second stage encompasses all the remaining waste. The second stage in initiated in 2023 with the disposal of 100 canisters and then 160 canisters per year are disposed. The rate of disposal is basically determined by the restriction that the waste has to be in interim storage for at least 25 years. The second stage will go on until the middle of 2040 and thereafter the remaining phase-out follows. The full phase-out is planned to be completed in 2052.

The low-cost alternative involves a considerable time between the first and second stage. The second stage starts in 2046 and is finished in 2052, which implies that the encapsulation capacity must be increased. *The high-cost alternative* implies that basically no staging is performed. In this scenario the disposal is completed in 2036 and 80-200 canisters are disposed each year. SKB recognizes that the probability for the high cost alternative has become more probable is recent years, since they do not believe that a considerable time between the two stages will be needed.

Figure 2.1 summarizes SKB's time-schedule for the disposal of nuclear waste in Sweden. Already at this stage, the designations of the alternatives suggest that lower costs are achieved when investments are postponed. The rationale for this is that the rate of return from the Nuclear Waste Fund is expected to exceed cost increases.

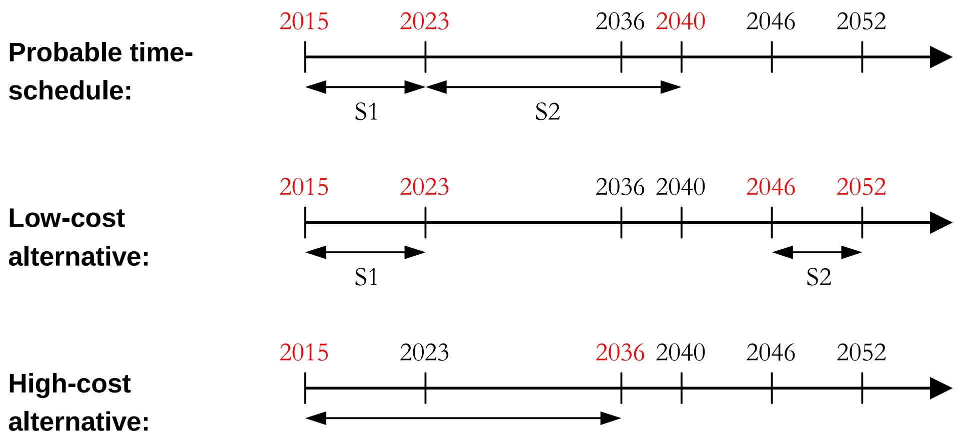

Figure 2.1: Probable time-schedule for the Swedish phase-out together with the low-cost alternative and high-cost alternative.

The consequences resulting from each of the two alternatives can be broken down in economical details, but in this work the alternatives are simply used to provide an illustration of the flexibility that is currently taken into account in the planning.

2.5 Uncertainties

SKB use a vast list of uncertainty descriptions that they take into account in the probabilistic calculations. They have also created a list of conditions that are considered to be fixed, and are hence not included in the calculations. In this work, we take the same conditions to be fixed and thereby reduce the possible amount of uncertainty and flexibility to a reasonable level. The list of conditions is presented in Appendix 2, since it provides a good view of the level at which uncertainties and flexibility are considered. As described in Section 2.3, the probabilistic method used by SKB enables a sensitivity analysis that reveal the relative importance of the uncertainties they take into account in the calculations. SKB stress that four uncertainties deserve special attention (SKB: Plan 2003, Supplement and SKB: Plan 2003, Underlag för kostnadsberäkningar). The four uncertainties, together with one additional uncertainty of interest, are summarized below.

Overall strategy for the demolition of nuclear power plants is in the most probable case described by that the demolitions take place as soon as possible when the operations in the plants have been terminated. A low-cost alternative constitutes of postponing the demolitions. In this scenario the demolitions are however to be finished no later than about 2054. Consequences of this alternative are basically that costs will increase due additional service time for the reactors and the need for additional competence. The additional costs are however eliminated due to that the waste from the reactors will be less radioactive at disposal.

Delays in the start-up imply a low-cost alternative. In this alternative the starting date for deep disposal, 2015, is postponed 10 years. A reason for such a delay could be that permission for disposal at the preferred location is not granted. The consequences would be increased encapsulation capacity and maintenance costs. The alternative is however still considered to be low-cost.

Cost development for established operations is not known today. In the probable case, the cost development is assumed to follow CPI. SKB also consider a low-cost alternative in which the cost development fall short of CPI by 1% and a high-cost alternative in which the cost development exceed CPI by 2%.

Retrieval of canisters before regular operation would imply additional costs. If this uncertainty is realized it would in the probable case mean that the deep disposal is postponed 25 years, i.e. starts in 2040. A new location for the deep disposal would have to be found at the same costs as the first one. The consequences for the retrieval are that several operations have to be brought to an end and later reinitiated. SKB also consider a low-cost alternative and a high-cost alternative dependent on the reason for retrieval.

A final uncertainty, recognized by SKB, which is of particular interest for this work is the *operating time of the nuclear power plants*. This is the major determinant for when the demolition of the plants should take place, but it is also of more general interest. In the probable scenario, SKB recognize that all reactors currently in use are operated for 40 years. In a low-cost alternative all reactors are closed down after 60 years of operation, which implies that the demolition of the plants is postponed 20 years. In a high-cost alternative all reactors are closed down after 30 years or operation, and the demolition of the plants takes place 10 years earlier than in the probable scenario. In any case, the demolition cannot start earlier than 2011, since it requires certain facilities to be in place.

2.6 Flexibility

The above description of the overall time-schedule and the uncertainties may suggest some level of timing flexibility for phase-out activities that SKB considers to be reasonable. The well-defined high-cost and low-cost alternatives may furthermore cause the flexibility to appear quite clear. This is however not a correct interpretation. How the timing of activities for the phase-out turns out, depends on political decisions yet to be taken. How long the nuclear power plants should be operating is a critical issue for the time-schedule of the phase-out and there is a controversy between Swedish politicians on this issue.

The overall impression from our research is that the time-schedule may not be as clear-cut as it appears at a first glance. The phase-out of nuclear power generation in Sweden is yet at the stage of planning and although the final date for the phase-out is 2052 in the reference scenario we do not hold it unlikely that this could be delayed to 2060 or even 2070. The task of SKB is however still to make as good cost calculations as possible, which requires strict definitions of uncertainties as described above. Although the date of termination of nuclear power generation is not known, this does not have any major impact on when the first canister of waste can be deep disposed. The deep disposal will be constructed so that it can be expanded, in accordance with the development of the phase-out, although some of the waste is already disposed (www.skb.se, 2003-12-18).

How the uncertainties and flexibilities can be analyzed in a real options framework is addressed in Chapter 4. Chapter 3 will however first provide the tools necessary, namely option theory.

3 Option Theory

This chapter provides a short introduction to option theory relevant for this particular work, beginning with financial options and moving on to real options. Different classes of real options are discussed as a basis for Chapter 4 and 5. Furthermore, the specific mathematics behind option valuation required for this work is presented.

3.1 Financial Options

A financial option is a financial instrument that gives the holder a possibility to choose whether to take an action or not. This section gives a short introduction to option theory and the nomenclature often encountered when studying this area of interest.

Options are generally divided into two types: *call options* and *put options*. A call option implies the right to buy a particular asset for an agreed amount at a specified time in the future. Such an option would be used (or *exercised*) if the price of the underlying asset is above the cost of exercising the option. The underlying asset can e.g. be common stock, foreign currencies or future contracts. The payoff of a call option can be expressed as

$$V = Max(S - E, 0),$$

if S is the price of the underlying asset and E is the exercise price (or *strike price*). Conversely, a put option gives holder the right to sell a particular asset for an agreed amount at a specified time in the future. In the case of a put option, the holder wants the price of the underlying asset to drop, which renders the following payoff:

$$V = Max(E - S, 0).$$

The payoff functions can be diagrammed as in Figure 3.1a and 3.1b, where the shaded area represents the region where the option will be taken advantage of.

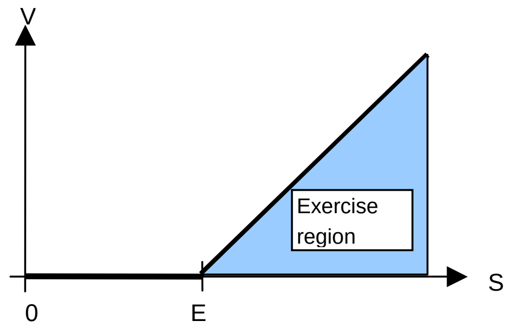

Figure 3.1a: The payoff from a call option.

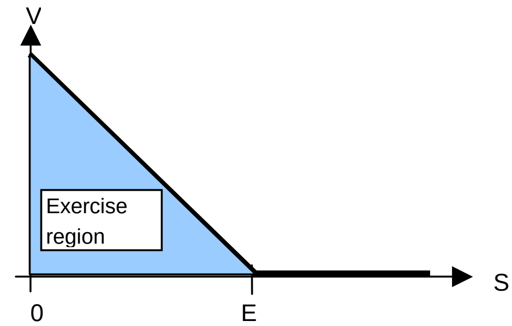

Figure 3.1b: The payoff from a put option.

Options can also be divided into categories depending on when they can be exercised. Some, referred to as *European options*, can only be exercised at a given expiry date. *American options* on the other hand can be exercised at any time before the expiry date. Thus, American options give the holder more flexibility and are therefore more valuable than their European counterparts.

Options are associated with two main value drivers (Grinblatt and Titman, 2002): *volatili*ty *of the underlying asset* and *time to expiration*[3]. Option value is positively correlated with both – the higher volatility and the longer before expiration, the more valuable is the option. The current value of an option can be derived by using the principle of no arbitrage and a tracking portfolio, ending up in either the discrete binomial model or in the continuous-time Black-Scholes formula. This value can be used for pricing options on the market. For the issuer (or *writer*) of an option there are no positive future cash flows from the option. Thus, to compensate for this, the buyer of the option pays a sum, the option price, to the writer for acquiring the option. The question of option pricing has been addressed in numerous articles and textbooks and we refer to them for further study (see e.g. Bodie and Merton, 2000 for a basic discussion).

The simple calls and puts are the most common options and are hence often referred to as *plain vanilla* options. However, a vast amount of other options not as common do exist. Consequently, these are referred to as *exotic* options. Two types of exotic options are used in this work, *barrier options* and *spread options*. Those two types are therefore discussed below.

[3] In more detail, there are six value drivers for financial options: volatility of the underlying asset, time to expiration, price of the underlying asset, strike price, interest rate and cash dividends (Bodie and Merton, 2000)

3.1.1 Barrier Options

A barrier option is very similar to a plain vanilla option, with one exception; the presence of a barrier. This barrier is a set price of the underlying asset that works as a trigger. If the trigger price is reached before the expiry date of the option there are two possibilities. If the option is a *knock-out option*, it ceases to exist with the first crossing of the barrier. Conversely, if it is a *knock-in option* it comes into existence. Hence, the difference between a plain vanilla option and a barrier option is that the value of the barrier option is dependent on what path the underlying assets follow until the maturity date. Therefore barrier options are sometimes referred to as *path-dependent options*.

There exist both *single barrier options* and *double barrier options*. A single barrier option has only one trigger price, whereas a double option has two trigger prices resembling a corridor. Since there is a risk of hitting the barrier and thereby get knocked either in or out, a barrier option is cheaper than its vanilla counterpart. How much cheaper depends on at what price the barrier is located.

Barrier options have been studied extensively since a pioneering study by Merton (1973). This work consisted of an analysis of knock-out options where the barrier is below the current stock price, hence called down-and-out options. Research has very much been focused on the pricing of barrier options, see e.g. Goldman, Sosin and Gatto (1979) and Sandmann and Reimer (1995). We consider knock-out barrier options in Section 5.3, when dealing with the uncertainty of future costs.

3.1.2 Spread Options

According to Wilmott (2000), spread options can be seen as vanilla options with a maximum pay-off. In the case when there is an assumption that the market will rise one can reasonably choose between investing in a vanilla call option or in *a bull spread* (a bull is a rising market). An ordinary call option would have the best upside potential as it follows the underlying asset linearly beyond the exercise price. However, if the expected rise of the market is not as forceful, a bull spread may be the best choice. The rationale for this is that a spread option is less flexible than a vanilla option, and thus less expensive. The payoff function for a general bull spread, made up of calls with strike prices E_1 and E_2 is given by:

$$V = \frac{1}{E_2 - E_1}\left(Max(S - E_1, 0) - Max(S - E_2, 0)\right)$$

This is illustrated with an example adopted from Wilmott (2000). Suppose one call option with a strike price of 100 is bought and another one with a strike price of 120 is issued. Suppose also that they have the same expiry date. Then the resulting portfolio has a payoff as shown in Figure 3.2a. This payoff is zero below 100, 20 above 120 and linear in between.

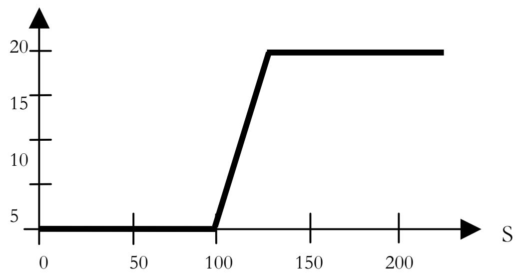

Figure 3.2a: The payoff from a bull spread.

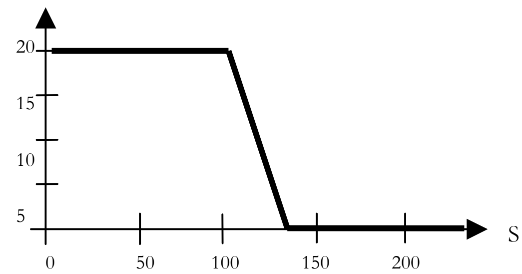

Figure 3.2b: The payoff from a bear spread.

If the tables are turned and instead a put option is issued with a strike price of 100, and another put option bought with a strike price of 120, the payoff is as shown in Figure 3.2b. This resulting option is called *a bear spread*, benefiting from a bear, i.e. a falling market.

An overview of spread options and other exotic options can be found in Zhang (1995). As spread options most commonly are used in credit risk management, research has also focused on that area of application. Finnerty and Grenville (2002) give an introduction to the usage of spread options in this regard, and Bhansali (1999) provides a more in-depth discussion and analysis. However, we use spread options in a slightly different setting, in Section 5.4.

3.2 Option Mathematics

As is obvious from the discussion above, options valuation is very much concerned with mathematics. Since the option value is dependent on the price development of the underlying asset, it is necessary to find a way to model the asset price and how it evolves over time. A very common solution is to model the asset price as a stochastic process, with a variance and a drift. One such process is the Brownian motion. It is extensively used in this work and is therefore described below.

3.2.1 Brownian Motion

In 1828, botanist Brown described the motion of a pollen particle in liquid as strangely irregular. It became one of Einstein's famous achievements to explain this phenomenon. He concluded that this motion, or random walk, was due to collisions between the particle and molecules in the liquid. In 1931, Wiener provided mathematical foundation for this motion through the description of a stochastic process, the Wiener process. However, already in 1900, Louis Bachelier first proposed that financial markets follow a random walk that can be modeled by standard probability calculus. (Sun, 1995)

The random walk model is widely used for modeling financial markets. Work by Samuelson (1965) and Fama (1970) have showed that changes in stock prices must be unforecastable if they are properly anticipated, i.e., if they fully incorporate the expectations and information of all market participants. The existence of an efficient market is debated though and some, such as Lo and MacKinlay (1999), have recently disputed the random walk theory. However, the assumption of an efficient market is a key ingredient in the option pricing formula by Black and Scholes (1973), which is very much used by the financial community for option valuation. We share the view of Black and Scholes to the extent that random walk theory applies.

To apply the random walk theory to asset prices in the market, certain assumptions have to be made. The random walk is subject to a drift, which is the trend of the asset price. The variation around this trend is called the volatility, which is suitably expressed through the standard deviation. The parameter μ denotes the drift rate and σ denotes the standard deviation of that drift throughout this work. The randomness of the asset price (S) can be modeled by using an iterative process where the asset price in the former time step is used as an input for computing the asset price in the next time step.

$$S_{i+1} = S_i(1 + \mu\,\delta t + \sigma\,\varepsilon\,\delta t^{1/2}) \qquad (3.1)$$

Following the presentation in Wilmott (2000), the time step is denoted by δt in this process. The last term in expression (3.1) is the part providing the randomness with ε being a standard-normal random variable (i.e. normally distributed with zero mean and unit variance). Note that the random term needs to be proportional to the square root of the time interval in order to assure that in the limit, $\delta t \rightarrow 0$, the process still contains uncertainty and that the variance does not explode. When the time step is taken to the limit, the discrete world is left in favor of continuous time. Expression (3.1) then becomes a stochastic differential equation (SDE):

$$dS = \mu\,dt + \sigma\,dX\,, \qquad (3.2)$$

where dX is referred to as the standard Wiener increment, which can be seen as a random variable with $\mathbf{E}\{dX\} = 0$ and $\mathbf{E}\{dX^2\} = dt$.

Expression (3.2) is known as a *standard Brownian motion*. Since this version of Brownian motion can take on negative values, it is not very well suited for directly modeling stock prices, as Wilmott (2000) recognizes. Instead, a non-negative version of Brownian motion called *geometric Brownian motion* is commonly used, that enables the study of fractional changes in the stock price S. The geometric Brownian motion is expressed as the stochastic differential equation:

$$dS = \mu S dt + \sigma S dX$$

In this work, it is necessary to solve such stochastic differential equations. However one has to use another approach compared to when solving deterministic differential equations. The procedure of solving the former type was developed by Itô, and his important lemma is described in the following section.

3.2.2 Itô's Lemma

Stochastic variables behave differently from their deterministic counterparts, i.e. they do not obey the ordinary rules of calculus. Conversely, they follow a theory known as Itô's lemma, which is usually expressed as (Wilmott, 2000):

$$dF = \frac{dF}{dX} dX + \frac{1}{2} \frac{d^2 F}{dX^2} dt$$

The same expression can also be written in an integral form as:

$$F(X(t)) - F(X(0)) = \int_0^t \frac{dF}{dX}(X(\tau)) dX(\tau) + \frac{1}{2} \int_0^t \frac{d^2 F}{dX^2}(X(\tau)) d\tau$$

Itô's lemma is subsequently used for finding a solution to the geometric Brownian motion. However, standard Brownian motion is also used in this work and its solution is therefore presented first.

3.2.3 Standard Brownian Motion

For a standard Brownian motion, *dS* is given by

$$dS = \mu dt + \sigma dX \ .$$

This can be explicitly solved by writing it in its equivalent integral form

$$S(t) - S(0) = \int_0^t \mu \, dt + \int_0^t \sigma \, dX = \mu t + \sigma(X(t) - X(0)),$$

which holds true if μ and σ are assumed to be time-independent. If X(0) is furthermore assumed to be zero, the solution becomes:

$$S(t) = S(0) + \mu t + \sigma X(t).$$

3.2.4 Geometric Brownian Motion

For a geometric Brownian motion, dS is given by

$$dS = \mu S dt + \sigma S dX \ , \tag{3.3}$$

This can be solved explicitly by letting F=log(S) and using Itô's lemma. We get

$$\left.\begin{aligned} \frac{dF}{dS} &= \frac{1}{S} \\ \frac{d^2F}{dS^2} &= -\frac{1}{S^2} \end{aligned}\right\} dF = (\frac{1}{S})dS + \frac{1}{2}\sigma^2 S^2(-\frac{1}{S^2})dt = (\mu - \frac{1}{2}\sigma^2)dt + \sigma dX \ ,$$

when dS is substituted for (3.3). In integral form this is equivalent to

$$\log S(t) - \log S(0) = \int_0^t (\mu - \frac{1}{2}\sigma^2)dt + \int_0^t \sigma dX = (\mu - \frac{1}{2}\sigma^2)t + \sigma(X(t) - X(0)),$$

if μ and σ are assumed to be time-independent. Hence the solution to the stochastic differential equation can be written as

$$S(t) = S(0)\exp\left[(\mu - \frac{1}{2}\sigma^2)t + \sigma(X(t) - X(0))\right].$$

3.3 Real Options

Real options analysis (ROA) has emerged as a relatively new way of thinking about corporate investment decisions. The technique is based on the notion that any corporate decision to invest or divest real assets can be seen as an option. In this context, the option gives its holder the right but not the obligation to make an investment or divestment. Thus, the decision-maker has some flexibility that should be taken into account when valuing real assets. (Park and Herath, 2000)

According to Miller and Park (2002), the real options approach provides a method for such considerations. As such, the real options technique can be uses to remedy some of the shortcomings of conventional discounted cash flow (DCF) valuation. The main drawbacks of DCF valuation are namely, according to Herath, Jahera and Park (2001), perceived to be: (1) the selection of an appropriate discount rate, (2) the ignorance of flexibility, and (3) the now-or-never approach for investment decisions.

One of the breakthroughs in real options analysis was when Cox and Ross (1976) recognized that the payoff for a real option can be replicated by an equivalent portfolio of traded securities. This enables so-called risk-neutral valuation which facilitates the actual computations of real options value, because it is then possible to discount cash flows at the risk-free interest rate with true probabilities replaced by risk-neutral ones. Both Kasanen and Trigeorgis (1993) and Mason and Merton (1985) have extended this idea, and argue that real options may be treated and valued as financial option regardless if the underlying commodity is traded or not. The one thing that matters, is that there exists a security on a complete market that shares the risk characteristics of the real asset. However, in some situations the financial option pricing theory may have to be a bit stretched to fit a real options approach, as noted by Miller and Chan (2002).

An important characteristic of the real options approach is that it enables managers to view investment decisions as "now-or-later" instead of "now-or-never", and thus provide a more dynamic view of capital allocation. In ROA, the underlying asset is the cash flow from a project and the expiry date is when a critical decision has to be made.

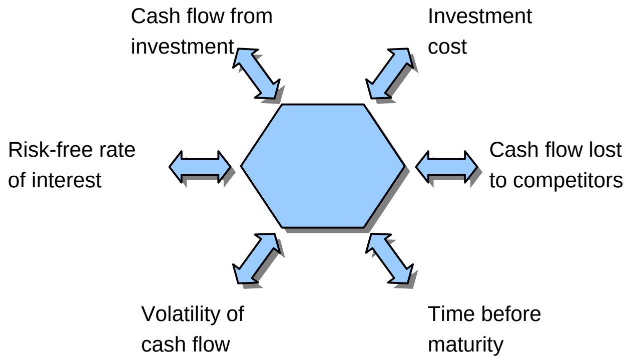

Figure 3.3: Value drivers for real options.

Copeland, Koller, and Murrin (2000) have identified six variables (see Figure 3.3) that determine the value of a real option (by fitting the value drivers for financial options, presented in Section 3.1, into the real options framework):

- *Expected cash flows from the investment:* As the expected cash flows are increased, so is the NPV. Hence the option value also increases.
- *Investment cost*: If the investment cost (or exercise price) increases, the option loses some of its value.
- *Cash flow lost to competitors:* When cash flows are lost to competitors, the option value decreases. This can be compared to dividends for financial options.
- *Time before maturity of the option:* A longer time to maturity enables increased knowledge and reduced uncertainty. Hence, the option value increases together with a longer time before expiry.
- *Volatility of the present value:* With managerial flexibility the option value increases as the volatility increases.
- *The risk-free rate of interest:* A higher risk-free rate of interest increases the effect of deferring the investment cost. Thus, the option value is increased.

A project's value as determined via the ROA approach can be substantially different from the value determined via an ordinary DCF valuation. The ROA approach always results in a higher or equal value, compared to that resulting from a DCF approach. As Copeland, Koller, and Murrin (2000) point out, the difference should be small when the NPV is so high or so low that flexibility is unlikely to be used. The greatest difference is realized when the NPV is close to zero, and there is a close call whether to go ahead with the project or not. How the value of flexibility is influenced by uncertainty (likelihood of receiving new information) and managerial flexibility (ability to respond) is depicted in Figure 3.4.

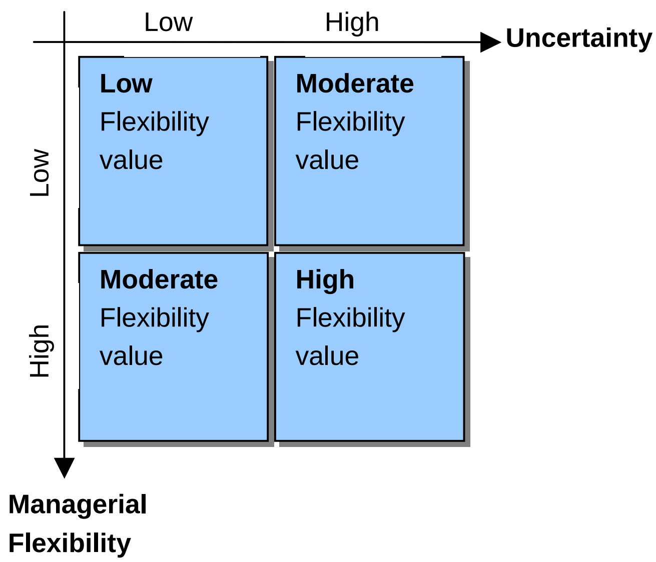

Figure 3.4: The value of flexibility in relation to the ability to respond and the likelihood of receiving new information. (Copeland, Koller, and Murrin, 2000)

For further studies of real options, we suggest a review of the research performed in this area by Park and Herath (2000).

3.3.1 Real Options Taxonomy

As Trigeorgis (1993) points out, several real options occur naturally, whereas others can be added into a project at a cost. Examples of the former are options to defer, shutdown or abandon, while options to expand or to grow may be examples of the latter. Based on material in Trigeorgis, the six most common categories of real options are summarized.

Option to defer: The possibility to defer an investment decision until conditions are satisfactory is an option to defer. Exploiting valuable land or resources can for example be deferred until market prices have reached a profitable level.

Abandonment option: If market conditions decline, there may be a possibility to abandon a project and liquidize all assets in second-hand markets.

Option to expand/contract/shutdown and restart: If market conditions decline temporarily, production can possibly be momentarily contracted or even halted and then restarted when better times arrive. Conversely, if the market shows better performance than anticipated, an option to expand may be exercised.

Time to build option: Certain investments can be staged, with a series of outlays and with the possibility to abandoning the project prematurely. Each stage can be seen as an option on the value of subsequent stages and hence this option should be valued as a compound option.

Switch option: This option conveys the probability of using alternative technologies depending on input and output. If the demand or prices change, the output mix may be adjusted. Similarly, different inputs may be used for producing the same output.

Growth option: This option lets the management take advantage of and calculate the value of future interrelated opportunities. An early investment can be a prerequisite that opens up new growth possibilities for the future.

Chapter 4 discusses the usefulness of these options classes for the approach taken in this work and how real options and nuclear waste management can be combined.

4 Real Options and Nuclear Waste Management

This chapter provides the systematization of uncertainties and flexibilities, which in turn enables a clarification of the decision alternatives. The decision alternatives are then fitted into the real options framework, and suitable classes of real options are identified. Models for these real options are constructed in Chapter 5.

4.1 Systematization of Uncertainties and Flexibilities

The purpose of systemizing uncertainties and flexibilities is to clarify the decision alternatives for which real-option models can be created (concerning the optimal time-schedule for the nuclear phase-out). As stated in Section 1.2, the optimal-time schedule is in this work defined as the time-schedule that minimizes the present value of total costs. In Chapter 2 the overall time-schedule for implementation of the phase-out by SKB was presented. This time-schedule is in itself uncertain but it was presented together with five additional uncertainties that have considerate impact on total costs:

1. Overall strategy for the demolition of nuclear power plants
2. Delays in the start-up
3. Cost development for established operations
4. Retrieval of canisters before regular operation
5. Operating time of the nuclear power plants

All those uncertainties must have an influence on the optimal time schedule, since they have an influence on costs. The systematization of uncertainties, as a ranking of the most important ones for total costs, performed by SKB does not immediately fit our purpose. It is considered suitable to group the uncertainties, and the flexibility related to those uncertainties, into three different types based on how they fit into the real options framework and how they influence the optimal time-schedule.

The first type of uncertainty is the uncertainty inherent in the overall time-schedule itself. This uncertainty regards when the actual stages of deep disposal of spent fuel should be implemented. This is the major activity in the phase-out and a major determinant of when other activities should be implemented. The more flexibility that exists on this fundamental level, the more room does there exist to create an optimal time-schedule that yields minimum costs. If it is "allowed" to change the time-schedule for implementation, then it should also be allowed to change the timing of the related investments. Different timings for investments imply different present values of costs. It is in this sense that flexibility in the overall time-schedule can be a creator of value. The obvious question at this stage is thus how the uncertainty in the overall-time schedule is related to managerial flexibility. This is not a trivial question. There seems to be managerial flexibility regarding how the stages of deep disposal should be carried out, because it is clear that the opinions of SKB (considered to be the "managers") are important. However, this flexibility is likely to depend on political decisions, public opinion etc. In any case, the approach taken in this work assumes the existence of an optimal time-schedule that minimizes costs. We therefore have to assume that there exists flexibility regarding timing for the implementation of the deep disposal and hence flexibility regarding its investment timing. Exactly how much managerial flexibility that really exists, influences the importance and applicability of our results as they are put in a bigger picture, rather than the construction of our models.

The second type of uncertainty includes *operating time of the nuclear power plants*, *overall strategy for the demolition of nuclear power plants* and *cost development for established operations*. Those uncertainties can be taken into account in a real options approach if they are connected to managerial flexibility. Again, we will assume that they are. The real options approach is particularly useful for capturing the value of managerial ability to respond to uncertain cost development. SKB's identification of uncertainty in cost development for established operations can therefore suitably be extended to uncertainty regarding all future costs.

The third type of uncertainty concerns uncertainties arising from unexpected problems, i.e. *delays in the start-up* and *retrieval of canisters before regular operation*. If these uncertainties are realized, they will have a direct impact on the implementation on the time-schedule for most activities. As those uncertainties are formulated by SKB, it is however clear that they are not meant to be associated with managerial flexibility. If retrieval is necessary, this does not mean that managerial decisions, such as abandoning the project or choosing an alternative method, can be taken. Contradictory, it means that the part of the project must be repeated, although maybe with some new insights. Similarly, as delays in the start-up is defined, this should not be considered something that management should endeavor although it may imply lower costs. Since these two uncertainties are not related to managerial flexibility, they are not to be considered in the real options framework.

Apart from the uncertainties presented by SKB, the occurrence of a future nuclear accident should probably affect the implementation of the time-schedule. This uncertainty should therefore be taken into account when designing the optimal time-schedule. It is reasonable to believe that the real options approach should be useful for this consideration.

4.2 Application of Real Options Theory

Based on the discussion in the previous section it seems reasonable that real option models can be constructed, in which managerial decision alternatives are mainly related to investment timing. It is also clear that although the analysis was restricted to the most important uncertainties only, the outcome of those uncertainties can heavily influence each other. This implies that one single and complete real options model has to include interactions between different options. Indeed, it is possible to implement such models and some convincing work by e.g. Brennan and Schwartz (1985) and Trigeorgis (1991) has been performed in this area. However, as Trigeorgis (1993) point out it may be difficult to find analytical solutions to such models or even to write down the partial differential equations of the underlying stochastic process, for a real-life problem. As mentioned in Section 1.4 it is not the purpose of this work to construct a complete model of the nuclear phase-out, but rather to show that a real options approach may be useful. It is also our intent to make models simple and ensure that their interpretations are not obscured by complicated mathematics. Therefore, we make simplifications and let different aspects of the phase-out be captured by different real options models. In Chapter 4, the most common classes of real options were presented:

- Option to defer
- Abandonment option
- Option to expand/contract/shutdown and restart
- Time-to-build option
- Switch option
- Growth option

Obviously the option to defer is relevant in this work, since there are decision alternatives related to investment timing. Correspondingly, options for premature investments (in relation to what is planned for by SKB) can be considered. The abandonment option is clearly inappropriate to consider for most or possibly all activities in the context of this work. Similarly, the option to expand/contract/shutdown and restart are better suited for other projects than the nuclear phase-out in Sweden. The time-to-build option, implies the possibility of staged investments. It is clear from Section 2.4 that the deep disposal will be performed in two stages, but there is not managerial flexibility to respond to the outcome of the first stage (at least not in an ordinary sense). Regardless of the outcome, subsequent activities will have to be performed according to the overall plan. Hence, the time-to build option is not further considered. The switch option could be useful if alternative methods to geological deep disposal, are considered. This seems to be quite a clear-cut example of how a real options approach could be valuable, but it will not be considered since it does not fit into the framework of the Swedish model. The switch option will however be used, but with a different interpretation. The option to carry out the deep disposal at a particular time can namely be viewed as an option to switch from interim storage to deep storage. Finally, the growth option is not considered, because we would take on a very positivistic view if we say that the disposal of nuclear waste would give significant future interrelated opportunities of value.

With some knowledge about how real options normally are applied to value projects, it should be quite clear from the discussion so far, that the project of phasing out nuclear power generation is not an ordinary one. Although uncertainty is high, it does not come with that much flexibility. There is however one other characteristic that makes this area of application particularly interesting. Ordinarily, the real options approach is implemented using risk neutral valuation. The risk-free rate is hence used as the discount rate. This technique is justified only if there is the possibility of replicating the underlying variables with a tracking portfolio. In the context of nuclear waste disposal, Loubergé, Villeneuve and Chesney (2001) argue that such a portfolio does not exist. The reason is two-fold. First, the financial markets do not span the stochastic fluctuations of their underlying assets. This statement of course depends on which the underlying assets are and need not be true regarding e.g. investment decisions (but this is not what they consider in their work). Secondly, there are no financial instruments with a duration comparable to the decay of the radioactive waste. This is certainly true, but only some of the modeling presented in this work take radioactive decay into consideration. However, ordinary financial instruments still have too short durations for our purposes. In any case, it is considered very difficult (and for some aspects impossible) to find a tracking portfolio for the underlying variables in the context of nuclear waste disposal. We therefore follow the suggestions by Loubergé et al. (2001), that the discount rate should be exogenously specified. SKI suggests such a discount rate, which is the real rate of return from the Nuclear Waste Fund (obviously the relevant alternative cost for investments). Their real discount rate (suggested for calculating fees for 2004) is 3,25% until and including 2020 and 2,5% thereafter (SKI: Antagande om real avkastning, 2003).

It is worth mentioning that Loubergé et al. (2001) acknowledge that the problem of defining the appropriate discount rate for long-term public investments in safety is heavily debated and is one of the most compelling issues in economics today. Chapman and Ward (2002) also provide a fruitful discussion of the ethical aspects of the discount rate, used for investments regarding permanent disposal of nuclear waste.

Based on the considerations in this chapter, three different models are constructed in Chapter 5. The first two models regard investment timing and the related timing options. The third model focuses on implementation timing and the simile of switch options.

5 Modeling and Application

This chapter is the culmination of our work. The theory and insights presented in previous chapters are combined into real options models for the phase-out of nuclear power generation in Sweden. The ways of exploiting real options identified in Chapter 4 are analyzed in three different models.

5.1 Introduction

Suggestions for how real options can be used for investment decisions regarding the phase-out of nuclear power generation in Sweden is presented in three successive models. The three models capture different aspects of the phase out, with increasing degree of mathematical complexity. The first model shows how the value of flexibility regarding investment timing for the deep disposal facilities can be captured as the value of a timing option. The second model suggests how real options can be used for investment decisions relating to the uncertainty of future costs, taking into account that a lot of funding has already been performed in Sweden. The third model is focused on the timing of deep disposal implementation, rather than investment timing. As such, it shows how the time for optimal deep disposal can be obtained as the tradeoff between costs associated with interim storage and costs of a future accident. Each model is first developed and motivated, and then applied to the actual problem. Finally the results are analyzed and discussed. In all models we regard 2004 as the base year.

5.2 First Model

As a starting point for the first model, we study the case when the waste is disposed of in a way consistent with the reference scenario of SKB. The problem of concern is then to determine the optimal time for taking the investment for the deep disposal facilities, in relation to the investment timing in the reference scenario. For simplicity, all costs are assumed to be deterministic and known in the first and basic model.

5.2.1 Model Development

For the reference scenario we consider the most likely case for the nuclear phase-out as described by SKB (see Section 2.4). In this scenario, the deep disposal should be ready to be adopted in 2015 for some of the nuclear waste. The interim storage will however continue until 2040, since the waste must cool off somewhat before final storage. We assume that all investment costs arising from the construction of the interim storage (I_1) are already taken, since the interim storage is already in operation. However, we will assume that this type of storage inflicts a cost Q_1 each year, originating from for example personnel and maintenance costs. When all waste is deep disposed, it is probable that this type of costs is negligible. The investment cost for construction of the deep disposal facilities is denoted I_2, and is for the reference scenario assumed to coincide with the adoption of the deep disposal (in 2015).

During interim storage of nuclear waste, risks arise from e.g. threats of terrorists or accidents. This type of risks may also occur when the power plants are demolished and after the waste has been deep disposed. The risks can be thought of as "costs" and should hence be accounted for when calculating the cost of keeping the nuclear waste in interim storage. In the first model we will disregard from these costs, again to keep things simple. Figure 5.1 depicts the cash flows associated with the reference scenario, as used in the first model.

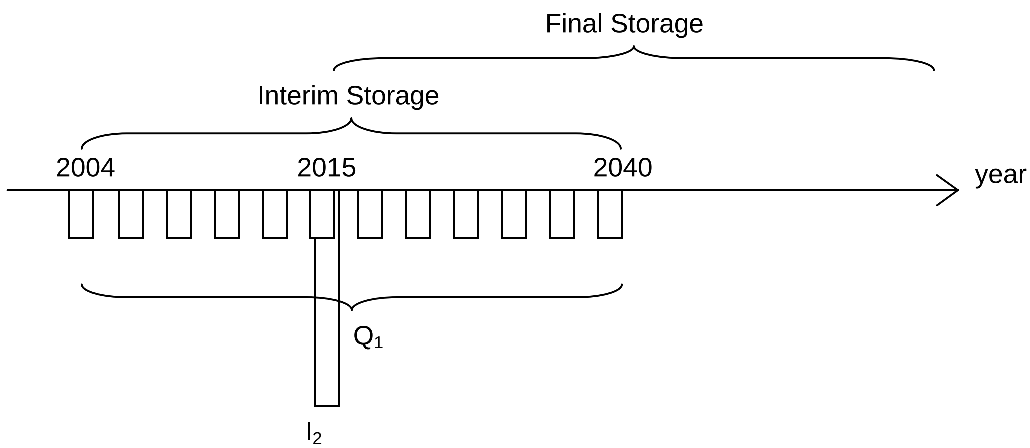

Figure 5.1: Cash flows associated with the reference scenario by SKB, as used in the first model. Q_1 is the annual cost of interim storage and I_2 is the investment cost for the deep disposal.

By using a standard present value computation, the cost today can be expressed as

$$C_1 = \sum_{t=2004}^{2040} \frac{Q_1}{(1+r)^{t-2004}} + \frac{I_2}{(1+r)^{2015-2004}},$$

where r is the discount rate.

To calculate the optimal investment timing for the deep disposal, some flexibility for this scenario is assumed. Due to technical reasons the nuclear waste must be in interim storage no less than 25 years before submerged into the bedrock. This requirement combined with that radioactive reactor parts must also be disposed of, implies that interim storage must be present at least until 2036. (SKB: Underlag för kostnadsberäkningar, 2003) The maximum time however is more subjected to political decisions than technology, as discussed in Chapter 4. Without limiting this maximum time, Figure 5.2 displays how the flexibility manifests itself in cash flows.

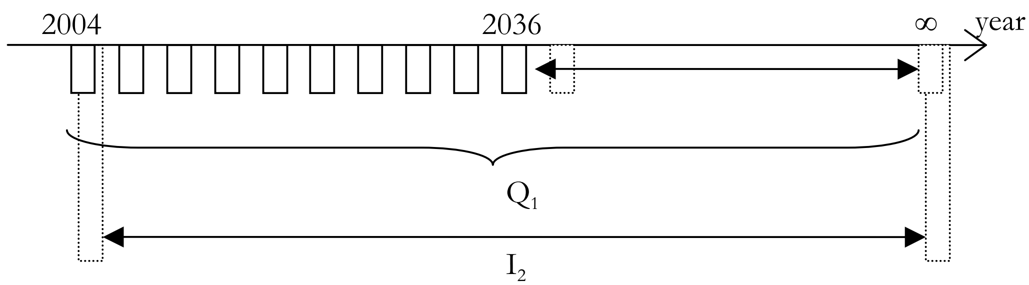

Figure 5.2: Cash flows associated with the assumed flexible scenario, as used in the first model. Q_1 is the annual cost of interim storage and I_2 is the investment cost for the deep disposal, as previously.

Now, we seek the optimal time for making the deep disposal investment (I_2). This date could be in the interval between 2004 and infinity. Denoting this time by τ, the cost of the project including flexibility is found by the following expression:

$$C_2(\tau) = \sum_{t=2004}^{Max(\tau,\,2036)} \frac{Q_1}{(1+r)^{t-2004}} + \frac{I_2}{(1+r)^{\tau-2004}}, \forall \tau \geq 2004$$

The *Max* function is required because the interim storage must be present at least until 2036 even if the deep disposal is built prior to this date. To calculate the value of the assumed flexibility, C_2 is subtracted from C_1. The difference, C_1-C_2 thus has a positive value when the cost including flexibility is less than the cost associated with the reference scenario. The value of flexibility as function of τ, is expressed as

$$V(\tau) = C_1 - C_2 = \begin{bmatrix} \sum_{t=2004}^{2040} \frac{Q_1}{(1+r)^{t-2004}} + \frac{I_2}{(1+r)^{2015-2004}} \\ - \sum_{t=2004}^{\max(\tau,\,2036)} \frac{Q_1}{(1+r)^{t-2004}} - \frac{I_2}{(1+r)^{\tau-2004}} \end{bmatrix}, \forall \tau \geq 2004 \qquad (5.1)$$

Maximizing this function with respect to τ is clearly equivalent to finding the time that minimizes the costs of deep disposal. It is apparent that this possibility of finding an optimal date for deep disposal arises from the choice of when the investments should be conducted. This choice, or timing option, is hence associated with a value!

5.2.2 Application of the First Model

The discount rate to be used in this model should be the alternative cost for investments, which is the real rate of return from the Nuclear Waste Fund. The real discount rate is thus 3.25% up to and including year 2020, and is then 2.5% in eternity, in accordance with Section 4.2. In Appendix 1, we estimate the cost for interim storage to 90 MSEK per year and the investment needed for the deep disposal to 14 860 MSEK (as mentioned in Section 1.2 we are only concerned with different types of fuel to the extent that the form of disposal is affected). These costs are in January 2003 prices and undiscounted. This implies that as long as these costs develop at par with inflation, they can be distributed in time without needing to change their absolute values. With these figures, expression (5.1) can be plotted against τ as in Figure 5.3, for τ being varied between 2004 and 2100.

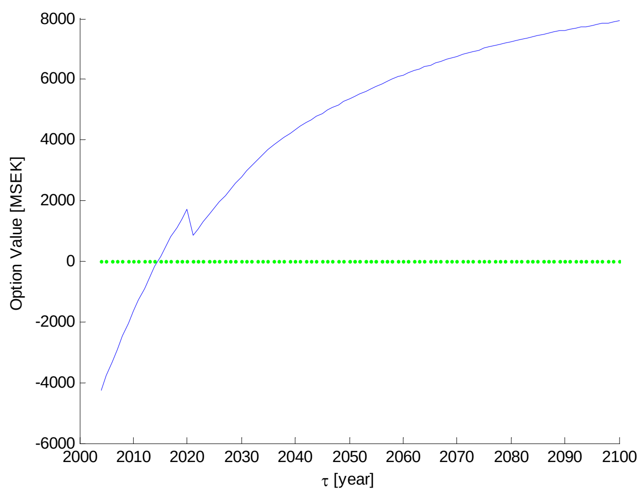

Figure 5.3: The value, V(τ), of flexible investment timing regarding the deep disposal facilities. The "discontinuity" of the curve is caused by the change of discount rates.

Figure 5.3 shows that the value of the timing option is negative if the investment is taken earlier than planned, and positive if the investment is postponed. As suggested by the figure, the value of the option approaches a limiting value in infinity. It is therefore optimal to wait forever before investing in the deep disposal. As the slope of the option value ultimately tends to zero, the value of the option will not grow much in the latter years. Figure 5.4 shows that this conclusion is true, also for most other discount rates.

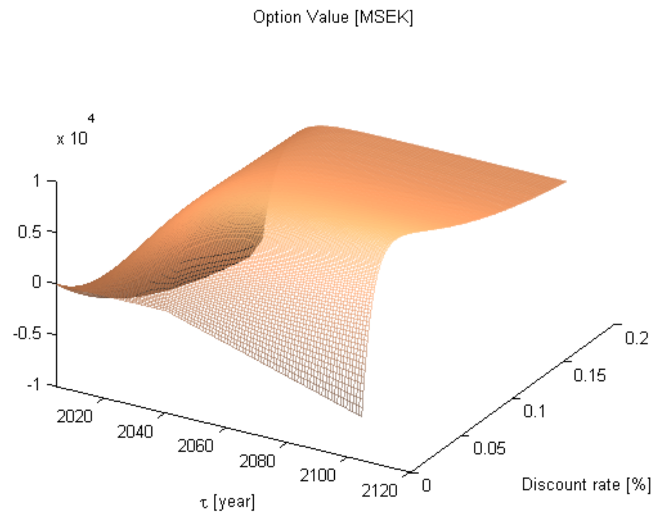

Figure 5.4: The value of deferring the deep disposal of nuclear waste in Sweden, as a function of the discount rate and the timing of investment in deep disposal facilities.

5.2.3 Analysis

It is evident from the calculations performed in this section that there exists a value associated with the deferral of the deep disposal investment. Indeed, it proved advantageous to postpone the investment forever. This is mainly due to the fact that the investment needed for the deep disposal facilities are so much greater than the costs for interim storage. The discount rate is then high enough, to make infinite postponement advantageous. It is thus the combination of cost relationships and the time value of money that lead to this result. This first model could also be used to consider when other costs should be incurred, such as the investments regarding demolition for nuclear power plants. It is then immediately clear that if these costs are quite independent of other phase-out activities, those investments should be postponed, due to the time value of money. In a more ordinary project, there are usually not only costs but also some related income. In these cases the time value of money may play a more interesting role, since it implies that it is desirable to postpone costs but to realize gains as soon as possible. The lack of an income-side in the nuclear phase-out project is thereby a major reason for postponement being so advantageous.

The estimation of the investment cost for the deep disposal used in this first model may seem a bit rough. We assumed that this cost was taken instantaneously as a lump sum. However, this should not be regarded as a loss of generality as the cost very well may be seen as a series of costs spread out in time, but with the same present value as our one-time cost. This approach, to change the timing of cash flows but with an unchanged present value is used also by SKB in their calculations (SKB: Underlag för kostnadsberäkningar, 2003) and called *stretching*.

The result from the first model is very clear. However, at least two important factors were not considered in this model, the uncertainty of future costs and costs related to risks for accidents or other threats. These to issues are examined in the two following models.

5.3 *Second Model*

It became clear from the first model that as long as the investment costs follow inflation, the development of CPI, it is advantageous to postpone investments. In this model the future costs were assumed deterministically known. In this second model future costs are instead considered uncertain, which is the case in reality. Again, the problem of concern is to determine optimal investment timing for phase-out activities; in this case more generally than for the deep disposal facilities specifically.

5.3.1 Model Development

SKB has recognized that the cost development for established operations is not known today, as described in Section 2.5. SKB take this uncertainty, and almost every other possible uncertainty, into account in their probabilistic calculations. Those calculations are used to determine how much money that should be funded to cover the phase-out. Most of the planned funding has already been performed today. In other words, the funded money already takes the relevant uncertainties into account. However, it is clear that uncertainty of costs at a future date will still exist until the day that date is reached. To set up a real options model that connects this uncertainty and already performed funding, we define the uncertainty of future costs in relation to the funded amount to cover that cost. For example, an unexpectedly high cost is unexpectedly high in relation the funded amount that is expected to cover that particular cost. The costs covered by the funding are thus considered as “state zero”, from which deviations will be observed in the future. It is these cost deviations that are studied in this chapter. We let the “funding scenario” denote the scenario in which all investments are incurred as planned and in which all future costs are exactly covered by the Nuclear Waste Fund. Figure 5.5 illustrates our definition of uncertain costs, as uncertain in relation to the funding scenario. For simplicity, we have set the costs of the funding scenario to zero, since it is only cost deviations that will be studied anyway. Today is at time zero, where costs are certain.

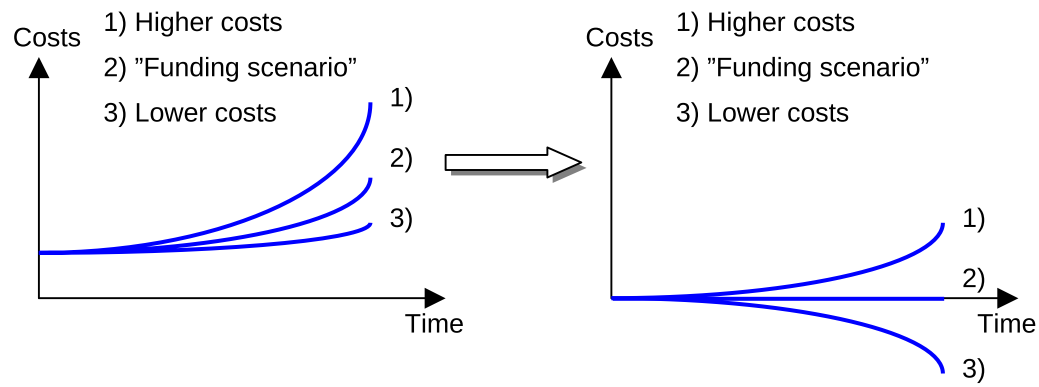

Figure 5.5: The "funding scenario" is used as a state zero and cost deviations from this scenario are then studied. For simplicity, the costs in the funding scenario are considered as zero costs.

The second model is focused on how the uncertainty of future costs relates to optimal investment timing. In accordance with the discussion above, an investment then means that money are taken from the fund and invested in real disposal activities. We assume that there exists flexibility to deviate from the investment timing inherent in the "funding scenario", to take into account more recent information. It should be noted that, in this model unexpectedly high costs could be considered the equivalent of either actual unexpected cost increases or unexpectedly low real rate of return from the fund. Either of the two, should have the same impact on investment decisions. However, cost increases due to increased inflation should not be considered primarily, since the fund is constructed to automatically respond to those changes (being invested in securities with a real rate of return, see Section 2.2).

As described in Section 3.2, uncertainty in option-pricing theory is modeled as a stochastic process and it is suitable to use Brownian motion to model the uncertainty of cost development. We consider it appropriate to use standard Brownian motion, rather than geometric Brownian motion in this model. The reason is that it is development of cost deviations *in relation to* the funding scenario, rater than ordinary cost development that we study. Hence negative cost deviations must be allowed in our model, which is quite the opposite case from what geometric Brownian motion was constructed for (see Section 3.2.1). Denoting cost deviations by S(t), the drift by α and the standard deviation by σ, the stochastic differential equation and its solution are (according to Section 3.2.3):

$$dS(t) = \alpha dt + \sigma dX \quad \text{and} \quad S(t) = S(0) + \alpha t + \sigma\big(X(t) - X(0)\big)$$

S(0) and α are taken to be zero, i.e. cost deviations are studied around zero costs and there is no drift, in accordance with our approach as illustrated in Figure 5.5. The standard deviation is taken to be 10%, merely for the purpose of illustration. To identify the optimal time to invest, a direct Monte Carlo method is used[4]. A time span [0,T] divided into N equal intervals is created and the dynamics of the cost deviations is simulated by generating K Brownian paths of {S(t)}. The optimal exercise time for the i:th simulated path is calculated as the time corresponding to the minimum cost for that path. The simulations are repeated many times and every simulation produces an optimal investment time, corresponding to the minimum cost for that simulated path. The minimum costs and their corresponding times are illustrated in Figure 5.6 for a thousand paths. The figure also contains the maximum costs for the paths and their corresponding times, to show that the result is as symmetric as suggested in the right part of Figure 5.5.

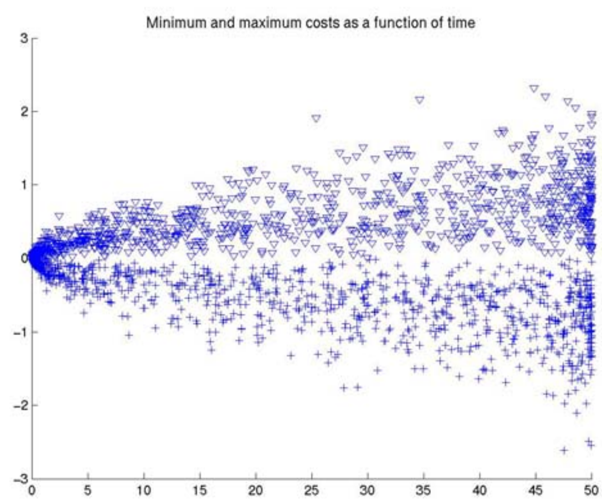

Figure 5.6: The minimum (+) and maximum (∇) costs calculated for a thousand simulation paths. The x-axis represents the time scale (50 years) and the y-axis represents the cost deviations from the funding scenario.

From Figure 5.6 it seems that the minimum costs for the Brownian paths are more concentrated to the beginning and the end of the time interval (the +'es are more frequent around t=0 and t=50 than in between). Indeed, this is the case. In Figure 5.6, the costs were not discounted, and if this is done the minimum costs will be even more concentrated towards t=0. Thus, the result implies that along each Brownian path the minimum cost is most likely to be found near t=0. It may therefore seem advantageous to invest as soon as

[4] Every numerical technique in which random numbers play an essential role can be called a "Monte Carlo" method after the famous Mediterranean casino town (Thijssen, 1999).

possible. This conclusion would however be wrong for two important reasons. First, we have not considered the amount saved and it is clear from Figure 5.6 that the minimum costs found near t=0 correspond to quite a small cost save. Secondly, there is symmetry between minimum and maximum costs in Figure 5.6. Hence, a large probability of facing the minimum investment cost also implies a large probability of facing the maximum investment cost (the ∇'es are also frequent near t=0 in Figure 5.6).

Still, it seems reasonable that some flexibility for postponing investments can really be associated with a value. In general it is clear if this flexibility of deferral exists, its value can indeed be captured as the value of a standard deferral option. Two aspects make the case of nuclear disposal differ significantly from those general situations in which standard deferral option techniques are usually applied, as discussed in Chapter 4. The first problem is that risk neutral probabilities cannot be used, which is a requirement for such valuation techniques. The second and more severe problem is that, if costs rise instead of becoming lower, there does not exist an option to take corresponding action, such as abandoning the project. To be able to capture the value of investment timing, these problems must be solved in a way agreeing with the structure of the problem of nuclear waste disposal according to the Swedish model.

The first problem is solved by using an exogenously determined discount rate as in the first model, and by using simulations. We suggest that the second problem can reasonably be solved by introducing a barrier, above which costs are not accepted to increase. The advantage of making this assumption is that it makes the probability distribution of the minimum and maximum cost deviations asymmetric. In other words, the maximum cost increase is pre-determined, but the maximum cost decrease can become arbitrarily large (dependent on when the option to invest is exercised). It should be clear from Chapter 3 that asymmetry of the payoff distribution is really the key behind the creation of value captured by option theory. In more standard applications of real option theory, this asymmetry is usually embedded in the structure of the application problem, e.g. through the possibility of abandonment. In the case of nuclear waste disposal within the framework of the Swedish model, we suggest that the asymmetry has to be more creatively created, in this case through the explicit assumption of a limiting cost barrier.

Based on the assumption of a barrier, above which costs are not allowed to increase, the value of flexibility in investment timing can be estimated through simulations. At date zero the investment costs are known for certain and the cost deviation from the expected costs is thus zero. Cost deviations are then simulated to develop along a Brownian path, as discussed above, until the date of expiration of the option to defer investment. If the barrier is hit before the date of expiration, the option automatically expires at zero value. The investment then has to be taken at the expected cost plus the cost deviation for which the barrier was defined. If the Brownian path reaches the expiration date, the investment is then taken for the expected cost reduced or increased with the cost deviation at the date of expiration. Comparison with Section 3.1.2 makes it clear that we are indeed considering a *barrier knock-out option*. The simulation approach described above has also been used by others to simulate just barrier knock-out options (cf. Glasserman and Staum, 2001). Figure 5.7 illustrates two Brownian paths of which only survives until the date of expiration.

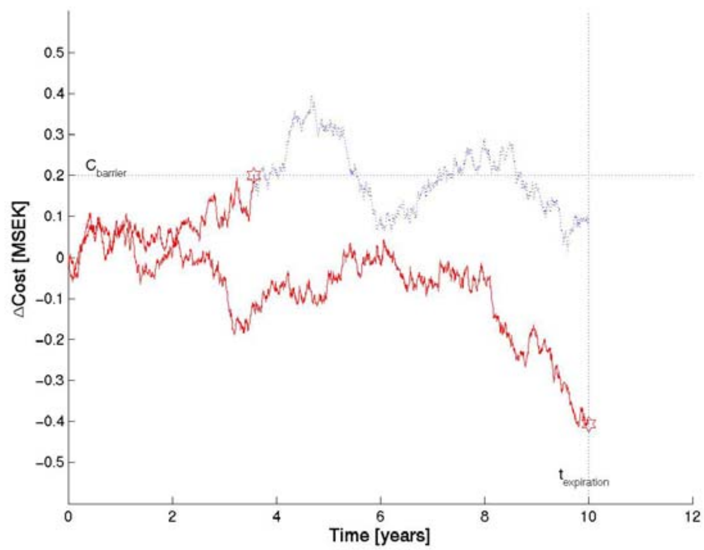

Figure 5.7: The development of cost deviations simulated by two Brownian paths of which only the lower survives until the time of expiration. The limiting cost barrier is set at a cost increase of 0.2 MSEK.

In Figure 5.7, the barrier is defined for a cost increase of 0.2 MSEK and the time to expiration is taken to be 10 years. Again, those values are only chosen for the purpose of illustration. The value of the option to defer investment can be captured by running the simulation for thousands of Brownian paths. The cost deviation resulting from each path (either that of the barrier or that at the time of expiration) are then discounted. Finally the payoff resulting from the option is calculated by averaging the cost deviations resulting from each Brownian path.

5.3.2 Application of the Second Model

In accordance with the model development described above, the second model is applied to the nuclear phase-out in a very general way. We apply it for cost development in general, and the parameter values are chosen merely to illustrate the model. The purpose is to make a qualitative point, rather than to obtain quantitative results. In Figure 5.8 the payoff is illustrated for times to expiration in the range of zero to 20 years (solid curve). The standard deviation of the cost deviations was taken to be 10% and the level of the barrier is 0.02 MSEK. It is clear from this figure that the flexibility results in a positive payoff (a negative cost deviation). Figure 5.8 also illustrates the influence of the discount rate.

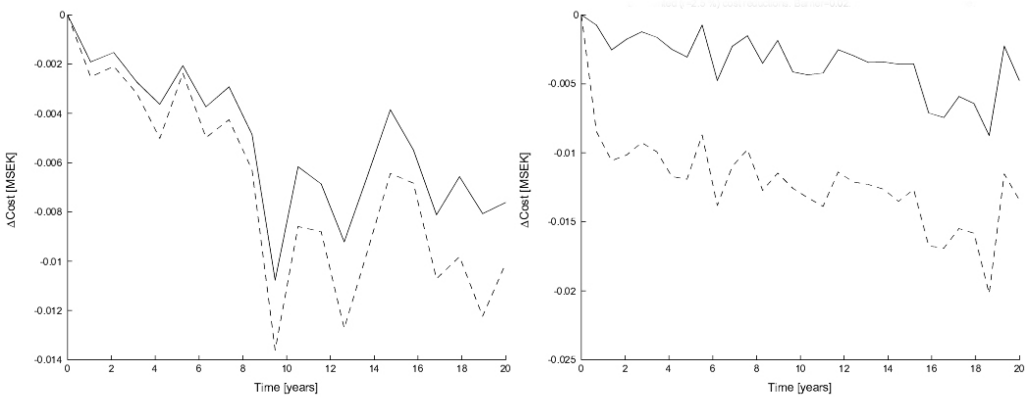

Figure 5.8: Left: Payoff resulting from the investment deferral option based on undiscounted cost deviations. Right: As the left figure but based on a discount rate of 2.5%.

The dashed curve in Figure 5.8 represents simulations performed as just described. The deferral option should in this case be viewed as a European option, since it can only be exercised at the date of expiration (except for in the undesired case when is automatically expires at the barrier). The solid curve represents an alternative approach. In this case, for Brownian paths that survive until the expiration date, the cost deviation is determined as the minimum cost along the path (rather than the cost deviation at the time of expiration). In this approach the deferral option is hence like an American option, since it can be exercised at any time before the expiration date. As expected, the American option approach gives a higher payoff due to this extra flexibility. The European approach is however considered more reasonable, since optimal exercise is hard to accomplish in reality due to the uncertain future. However, the American approach does provide some additional insight.

It is clear from Figure 5.8 that there can be a positive payoff resulting from flexibility of investment deferral. It is also clear that this payoff increases with the time to expiration, which is a classical result from option theory (see Section 3.1). The results presented in Figure 5.8 should however not be immediately extrapolated for other times to expiration, other standard deviations and other barriers. We argue that those variables have a non-trivial impact on the payoff. For example, lowering the barrier implies a lower loss when the barrier is hit (increased payoff), but it also increases the probability of hitting the barrier before the date of expiration (decreased payoff). We suggest that additional simulations is the safe way to examine situations in which parameters should be chosen differently, than in our example.

5.3.3 Analysis

The approach taken in the second model shows that it can be rationale to defer investment decisions due to the possibility of lower future investment costs than expected. The necessary condition for this conclusion is that the payoff function is asymmetric and biased towards lower costs. In our second model, this condition was quite artificially fulfilled by assuming a barrier above which costs are not allowed to increase. The application of the second model was very general and just an example of how the method could be used. We also pointed out, that the results should not immediately be generalized. This model should therefore mainly be viewed as a source of inspiration, for how a real options approach may be useful for considering uncertain costs. However, the actual development of the model, to which most of the chapter was dedicated, should be useful in itself. We stressed the difficulties specific for the problem of nuclear phase-out within the framework of the Swedish model that are not quite compatible with an ordinary real options approach. Mainly, it is the lack of managerial flexibility to appropriately respond to the cost development that makes the nuclear phase-out differ from more common areas of application for real options theory.

In the second model, one of the simplifications from the first model was resolved; that costs were assumed deterministically known rather than uncertain. However, the costs related to risks of accidents have still been omitted. This is the focus of the final model, in which the uncertainty of future costs is kept as an important consideration. In the third model, focus is also shifted from the timing of deep disposal investments to the timing of deep disposal implementation.

5.4 *Third Model*

In the first model we argued that there are risks associated with the nuclear waste management both before and after deep disposal. However, costs associated with these risks were ignored to keep the first model simple. Yet, it is clear that the risk of accidents could play a central part for determining the optimal time-schedule. For example, the identification of a post-disposal nuclear accident implies an incentive to defer the deep disposal. A longer time before disposal may imply a more efficient waste processing before disposal, and hence the severity of a post-disposal accident should decrease. Furthermore the longer the pre-disposal time, the less radioactive will the waste be, due to natural decay, at the time of disposal. If a cost of post-disposal nuclear accident is defined, this cost can be compared with the additional interim storage cost, resulting from postponing the deep disposal. The problem of finding the optimal time of deep disposal under these constraints is addressed in the third and final model (costs relating to the possible risk of accidents during the actual demolition of the power plants and during transportation to the deep disposal are ignored).

5.4.1 Model Development

When this, the third model, is developed we do not consider the investment costs for the deep disposal facilities. In other words, we assume that the Nuclear Waste Fund will cover any cost increases over time. This is clearly a slight simplification, as the cost increases should be more than covered by the real rate of return from the fund (see Section 4.2). It is desirable to provide an estimation of how the cost of interim storage cost and a post-disposal accident cost vary in time. For this purpose, geometric Brownian motion is suitable, as is normal for modeling fluctuating financial assets. Indeed, Loubergé, Villeneuve and Chesney (2001) have presented a model for nuclear waste disposal that is based on such premises. They also introduce a third cost, a processing cost that is incurred at the deep disposal date and is assumed time-independent. We follow the work by Loubergé et al. (2001), but extend their analysis to study the Swedish nuclear phase-out in particular.

We denote the cost of a post-disposal nuclear accident by S_t and the cost of interim storage by Q_t. Denoting the time of the deep disposal by τ, the equations of geometric Brownian motion for cost of interim storage and accidents can be written (Loubergé et al., 2001):

$$\frac{dS_t}{S_t} = -\mu_1 dt + \sigma_1 dW_t^1 \qquad t \le \tau$$

$$\frac{dS_t}{S_t} = -\alpha dt + \Sigma d\left(W_t^1 - W_\tau^1\right) \qquad t \ge \tau$$

$$\frac{dQ_t}{Q_t} = \mu_2 dt + \sigma_2 dW_t^2$$

In these equations μ_1, α, and μ_2 denote the drift of the stochastic processes, and σ_1, Σ, and σ_2 represent the standard deviation of each Brownian motion. Note that the cost of accidents is composed by two geometric Brownian processes. The cost development is modeled by one process before deep disposal, and by another process once deep disposal has occurred. In the first case the cost of accidents has a negative drift, i.e. μ_1 is positive, which implies that waste processing should become more efficient as time passes. In other words, μ_1 represents a positive drift in technical efficiency. Since S_t is modeled as a geometric Brownian motion, random and temporary regressions in technical efficiency are however still accepted. When deep disposal has occurred, the severity of a nuclear accident (and hence S_t) cannot be reduced by improved technical efficiency. Instead the severity of a nuclear accident should decline as the radioactivity of the waste is reduced. The drift in this case is the natural rate of decay, α, which is a positive number. Finally note that the drift (μ_2) for Q_t should generally be thought of as positive, representing cost increases over time. However, for the model to be realistic, Q_t should not only include costs of investments and maintenance cost but also costs of for example accidents during interim storage, which motivates that μ_2 does not only represent the rate of inflation. If μ_2 was only the rate of inflation, then μ_2 should be set to zero when applying the model to nuclear phase-out in Sweden, since the interest rate of the nuclear fund adjusts to cancel the effect of inflation (actually over-compensates as discussed above). For simplicity, μ_2=0, is used and thus a possible drift in pre-disposal accident costs is ignored. For the sake of generality, μ_2 is however kept in the formulae. Having defined the equations of cost developments, Itô's lemma (see Section 3.2.2) implies the following expression for the costs:

$$S_t = S_0 \exp\left(-\mu_1 t + \sigma_1 W_t^1 - \frac{1}{2}\sigma_1^2 t\right) \qquad t \le \tau$$

$$S_t = S_\tau \exp\left(-\alpha(t-\tau) + \Sigma\left(W_t^1 - W_\tau^1\right) - \frac{1}{2}\Sigma^2(t-\tau)\right) \qquad t \ge \tau$$

$$Q_t = Q_0 \exp\left(\mu_2 t + \sigma_2 W_t^2 - \frac{1}{2}\sigma_2^2 t\right)$$

To give a conceptual view of this result, Figure 5.9 graphically shows an example of the cost developments in time (for times less than τ), where the initial values of S_0 and Q_0 are set to 20 and 2, respectively.

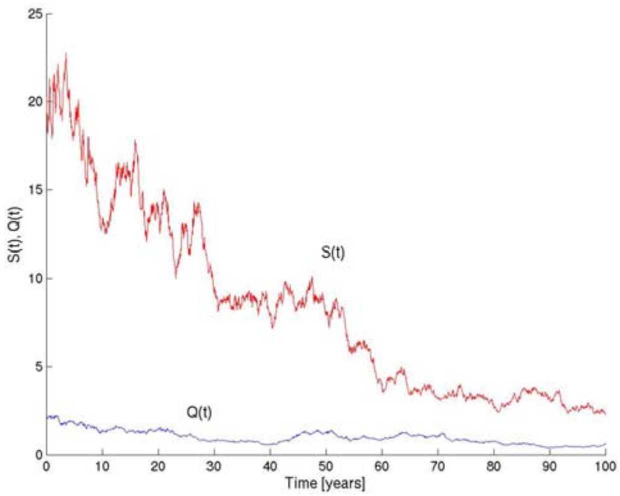

Figure 5.9. An illustration of how S_t and Q_t may develop in time according to the presented formulae (for times less than τ).

The processing cost that is realized when the nuclear waste is readied for deep disposal, is denoted by C and is (merely for simplicity) assumed to be time-independent. Based on the cost of interim storage, the cost of a post-disposal nuclear accident and the processing cost, a complete cost function $G(Q_0, S_0)$ can be defined. The problem of concern, to find the optimal time for deep disposal, is then equivalent to finding the time τ that minimizes the cost function $G(Q_0, S_0)$. Loubergé et al. (2001) show that the minimum cost function can be expressed as:

$$G(Q_0, S_0) = \inf_{\tau \in [0,+\infty]} \mathbf{E}\left[\int_0^{\tau} e^{-\rho s} Q_s \, ds + e^{-\rho \tau}\left(C + \frac{\lambda}{\lambda + \alpha + \rho}\right) S_{\tau}\right] \tag{5.2}$$

In other words, the optimal time for deep disposal (τ) is found by minimizing the expectancy value of the expression inside the brackets of expression (5.2). Here, λ is a parameter relating to the probability of a nuclear accident. The parameter is shortly explained in Appendix 3, and for a more thorough discussion, see Loubergé et al. (2001). The minimum cost function obviously depends on the tradeoff between a current random interim storage cost and the cost associated with the possibility of a future accidental radiation release. This can be interpreted as a switch option where the cost for taking the action is C. Hence, C is the strike price of the option. Loubergé et al. (2001) develop this recognition, which enables the cost function to be calculated using an analytic option valuation formula for American spread options. However in this work, we choose to use a numerical valuation method (evaluated in

MATLAB®[5]) instead of following their lead in this aspect. The foremost reason for this approach is to ensure that the methodology is not obscured by complicated mathematics. The result will be the same with both methods, though.

5.4.2 Application of the Third Model

As stated in the previous section, μ_2 is set to zero as the model is applied to the Swedish nuclear phase-out. The discount rate ϱ is set to 2.5 % to reflect the long-term real rate of return from the Nuclear Waste Fund. The remaining parameters are set according to the Table 5.1:

Table 5.1: Parameter values and descriptions, as used in this work.

Parameter	Description	Value
α	Drift for costs associated with accidents after deep disposal due to rate of radioactive decay post-disposal.	0.00005
λ	Parameter for determining the probability of accidents.	0.5
μ_1	Drift for costs associated with accidents after deep disposal due to technical development pre-disposal.	0.01
ϱ	Discount rate.	0.025
μ_2	Drift for costs associated with price development and accidents before disposal.	0
σ_1	Standard deviation for costs associated with accidents after deep disposal due to technical development pre-disposal.	0.1
σ_2	Standard deviation for costs associated with price development and accidents before disposal.	0.1

By setting the parameters to these values, we are basically following Loubergé et al. (2001). This may not be the very best choice of values, but they do not seem unreasonable, and it is considered beyond the scope of this work to explore this issue further. As with the second model, the purpose is namely to make a qualitative point, rather than to obtain quantitative results.

The parameter values are inserted into expression (5.2), and the minimum cost function is calculated for a selected range of values for S_0 and Q_0. The left part of Figure 5.10 shows

[5] MATLAB® is a registered trademark of The MathWorks Inc.

how the minimum cost function depends on S_0 and Q_0 (for C=0). The flat part of the surface represents a situation for which immediate deep disposal is optimal. For mathematical proof that this is really so, see Loubergé et al. (2001). The costs yielding the remaining part of the surface correspond to a situation where it is preferable to postpone the investment. The general shape of the surface is quite intuitive. If the (initial) cost of a post-disposal accident is zero (S_0=0), it is always preferable to carry out the deep disposal immediately since postponing it will only imply increased interim storage costs. As the cost of accidents increases (S_0 increases), it becomes likely that deep disposal should be postponed (if the interim storage costs are small enough; small Q_0).

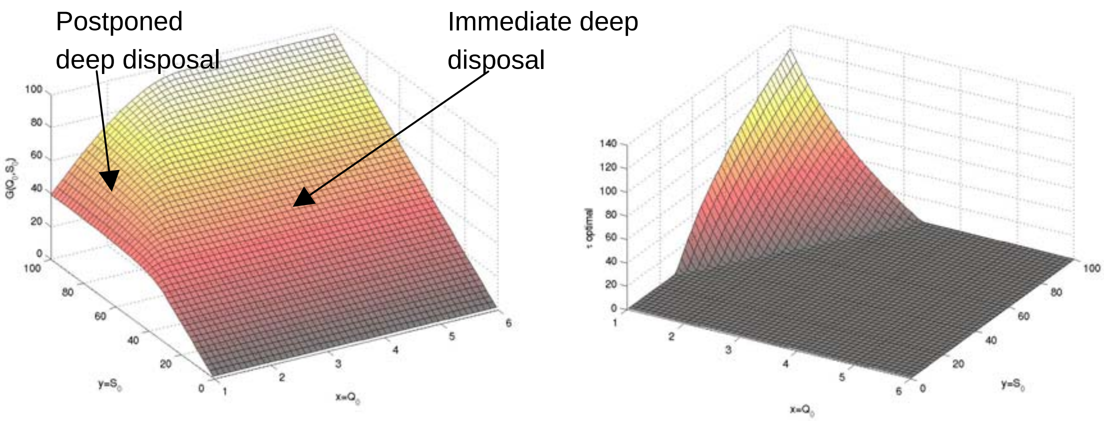

Figure 5.10: Left: G(x,y) for C=0. Right: Optimal disposal time for C=0.

In other words, the left part of Figure 5.10 suggests if deep disposal should be postponed, but not for how long. The optimal time for deep disposal is presented in the complementary figure to the right. Note that this figure is rotated with respect to the left one, to provide a more informative view. When comparing the two figures, it becomes evident that the flat part of the surface in the left figure really corresponds to immediate disposal ($\tau_{optimal}$=0).

In Figure 5.10 the processing cost, C, was taken to be zero. If this cost is increased, optimal exercise should be postponed, ceteris paribus. In this case, the date of optimal disposal is not reached before the decrease in the present value of the post-disposal accident costs does not only cover the increase in present value of the interim storage cost, but also cover the exercise price of the option. This situation is illustrated in Figure 5.11 for C=100.

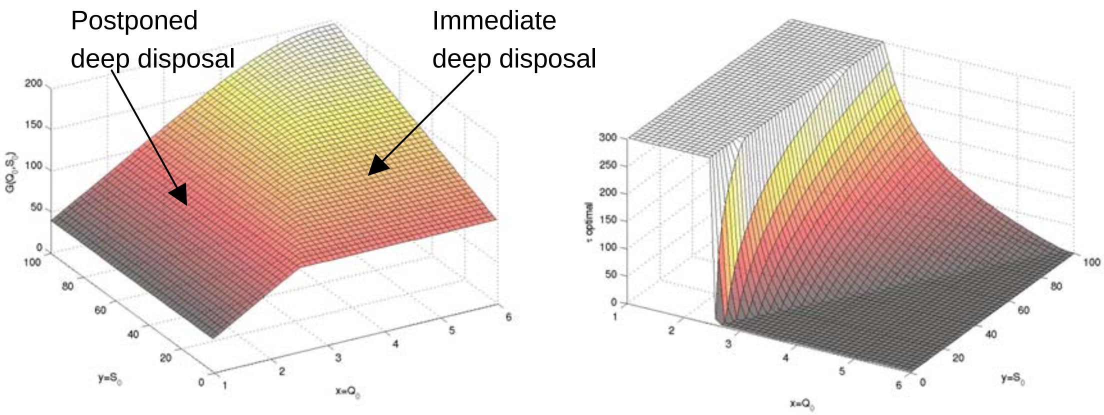

Figure 5.11: Left: G(x,y) for C=100. Right: Optimal disposal time for C=100.

Note that the horizontal part of the surface to the right in Figure 5.11 (for low Q_0) should be disregarded, since it does not represent optimal times for deep disposal times. Those are simply too high to fit in the figure ($\tau_{optimal}$>300 years).

So far, we have followed Loubergé et al. (2001) in the sense that we have assumed that all waste is disposed at the same time. However, the deep disposal in Sweden is to be constructed so that waste can continuously be added to the deep disposal. We now consider how the model can be useful for this more realistic situation. In the case of zero processing cost, the optimal stopping time is simply determined by the ratio S_0/Q_0 if the other parameters are held constant. In the case of a non-zero processing cost, the value of the processing cost is also important for the outcome. Figure 5.12 shows the optimal time for deep disposal as a function of S_0/Q_0. To the left, the processing cost is zero and to the right it is taken to be 15 (simply to illustrate the difference between zero and non-zero processing costs).

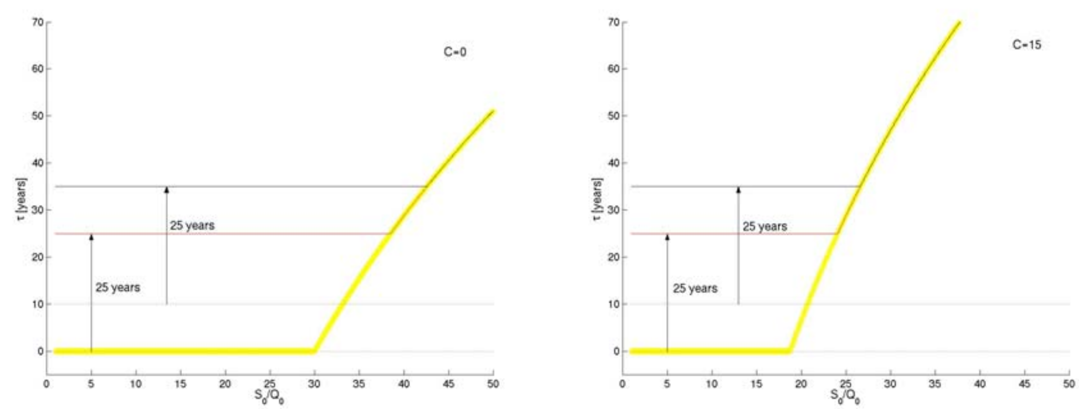

Figure 5.12: Left: The optimal time for deep disposal as a function of the ratio S_0/Q_0 for C=0. Right: As the left figure but for C=15.

In Sweden, it has been determined that nuclear waste must be in interim storage for a minimum of 25 years (see Section 5.2.1). For a given value of S_0/Q_0 the optimal time for deep disposal for waste that has already been in interim storage for at least 25 years is illustrated by the broad curve in Figure 5.12. The optimal time for deep disposal of waste that is produced today is given by the curve starting at 25 years and that for waste produced in 10 years is given by the curve starting at 35 years. The point is that those curves join the broad curve for high enough S_0/Q_0-ratios.

The implication of this is illustrated in an example. Consider the case when the reasonable S_0/Q_0-ratio is determined to be about 35 and C=0. Waste that has already been in interim storage for 25 years should not be disposed of before in slightly more than 10 years (see broad curve in Figure 5.12 left). Waste that is produced today should however optimally be disposed immediately after the compulsory interim storage time of 25 years. The reason for this result is that when we calculate the costs for waste produced in the future, we let the development of its costs join the development of costs for earlier produced waste. We feel that this is the most realistic and reasonable approach.

Another way of approaching the problem of optimal deep disposal timing would be to calculate the probability of disposing the nuclear waste optimally (i.e. at minimum costs) within a given time frame. This is again an approach that is used by Loubergé et al. (2001). The probability can be computed by letting the Brownian processes evolve over time and determine the optimal time using expression (5.2), without taking the expectancy value. By repeating this procedure, and determining how many times the optimal time turns out to be within the given time frame (out of the total number of runs), the probability is found. This is illustrated in Figure 5.13, which shows the probability for a horizon of 60 years, as a function of the discount rate. It follows from the above discussion that the relation between S_0 and Q_0 should be crucial for the result. In Figure 5.13 the simulation is performed for $S_0=10Q_0$ (left) and $S_0=20Q_0$ (right).

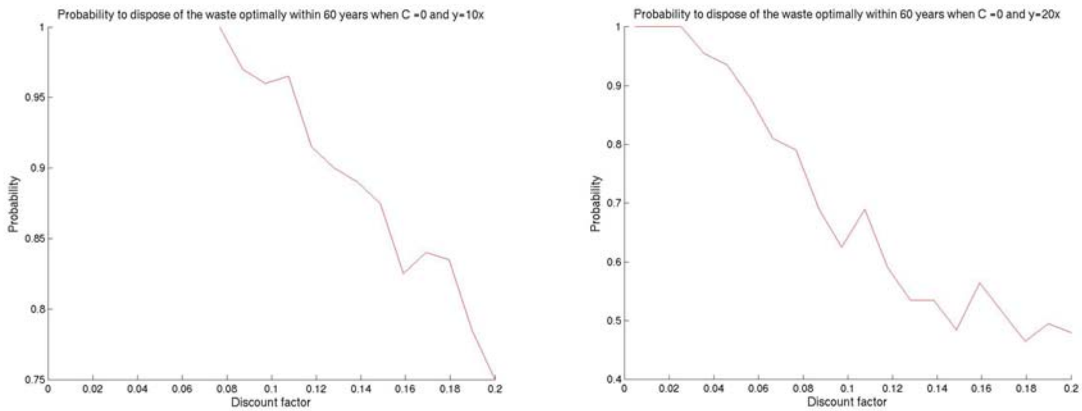

Figure 5.13: Left: Probability of optimal deep disposal within 60 years for $S_0=10Q_0$. Right: As the left figure but for $S_0=20Q_0$.

From Figure 5.13 left, it is clear that optimal deep disposal is very likely within the next 60 years, for $S_0=10Q_0$. For a discount rate below 8% the probability is unity, i.e. the nuclear waste should definitely be disposed of within 60 years. From Figure 5.13 right, it is clear that the probability is reduced as the relative cost of a post-disposal accident is increased (as should be expected).

5.4.3 Analysis

With this third model we shifted focus from the problem of finding an optimal time to invest (as investigated in the first two models) to the problem of finding an optimal time for when the actual waste disposal should be conducted. We kept the uncertainty of future costs from the second model, although geometric (rather than standard) Brownian motion was used in this third model. Most importantly, the role of accidents was introduced. Within the framework developed by Loubergé et al. (2001), it is possible to compute the optimal time of disposal by minimizing a cost function. It is evident from our investigation that a main determinant for the optimal time for deep disposal is the initial ratio between interim storage costs and costs from accidents subsequent to disposal. The determination of what these initial costs should be, for quantitative use of the model to the phase-out in Sweden, is considered beyond the scope of this work. This is the main reason, why we have not been able to conclude weather or not deep disposal should be deferred, using this third model. It is reasonable to believe, that those initial costs are not so easily determined, but we are convinced that the model is still very illustrative and qualitatively important.

In this third model, the analysis by Loubergé et al. (2001) was extended, mainly by showing what would happen if there were a continuous flow of waste to the interim storage and to the deep disposal. We regard this to be an important and interesting consideration, since waste is planned to be continuously disposed and since it is yet not clear when the reactors will be taken out of operation in Sweden. The model accommodates the continuous flow of waste by considering future costs, developed as the Brownian processes. The optimal time for disposing the waste produced later will be identical to the time for disposing the earlier produced waste (after the compulsory interim storage of 25 years). However, if the ratio S_0/Q_0 is low enough, the already produced waste should be stored earlier than the additional waste. Thus, the point is that additional running years for the reactors may result in different optimal times for waste disposal, depending on when the waste was produced. This result is considered to be non-trivial, although it was easily found using the model. A final methodological point that can be taken from the third model is that it may be instructive to calculate the probability of optimal disposal within a given time frame, rather than to calculate the optimal time itself.

6 Conclusions

Based on the work presented in this report, we argue that the nuclear-phase out in Sweden is certainly not just another area of application for which standard real options models can be used. Nevertheless, a real options approach can be useful as indicated by our modeling. Since most work in this report concerns modeling and the specific structure of our problem, so do the conclusions.

6.1 Usefulness and Appropriateness of the Real Options Approach

The Swedish nuclear phase-out has a number of characteristics that make this project differ significantly from the kind of projects in which real options techniques are often applied. The most important such characteristics that have been discussed in this work, are the lack of an income-side, the argument that risk-neutral valuation cannot be used, and the seemingly weak managerial flexibility.

The lack of an income-side, simply makes it advantageous to postpone activities due to the time-value of money, which makes application of standard real options techniques less interesting than for many other projects. The argument that risk-neutral valuation cannot be used (at least not easily), makes calculations more difficult and the standard calculation techniques built on the premise of a tracking portfolio cannot be used. Finally, lacking managerial flexibility makes the real options approach less useful in a most fundamental way. This last characteristic is given specific attention in the following paragraph.

A partial purpose of this work was to clarify the decision alternatives (basically to systemize the uncertainties and flexibilities), as this is the basis for any real options model. To systemize the uncertainties, work already performed by SKB proved to be very helpful. However, we have argued that those uncertainties are not meant to be associated with a lot of managerial flexibility. A major and often cited advantage of the real options approach is that it can be used to eliminate "now-or-never thinking" in favor of "now-of-later thinking", concerning capital allocation. However, the framework of the Swedish model for nuclear phase-out does not allow anything than "now-or-later thinking" in the first place. The nuclear waste is to be deep disposed in the primary rock in Sweden and not passed on to future generations in any other form, and that is it! This makes the managerial flexibility very limited in comparison with more ordinary projects, where possibilities such as abandoning the project, change technique or expanding or contracting the project may exist. In Section 3.3 it was stated that the real options approach is most useful when uncertainty is high in the sense that there is a likelihood of receiving new information and when managerial flexibility is high in the sense that there is room for managers to respond appropriately to this new information. Thus, large flexibility and uncertainty in general terms may not be enough to make the real options approach particularly useful. In chapter four, we argued that uncertainties such as *delays in the start-up* and *retrieval of canisters before regular operation* are very important for total costs (and are very important in the calculation techniques by SKB) but that those uncertainties are not well suited for consideration in a real options approach. On the other hand, we considered uncertainties such as *uncertain cost development* as highly suitable for a real options approach. Our argument, that managerial flexibility is not that large, depends on the view we have taken, letting the framework of the Swedish model limit the decision alternatives. We strongly believe that this is the most reasonable view to take, given our problem of concern. If the real options approach would be applied to nuclear-phase out in countries where planning have not come as far as in Sweden, the real options approach would probably be useful in a broader sense. In any case, we have only been concerned with the time-schedule of the nuclear phase out and we have assumed that there is at least some managerial flexibility regarding investment and implementation timing. How large that flexibility really is influences the importance of the results as they are put in a bigger picture, rather than our modeling. Our point is not at all that the real options approach is useless, but we believe that there is not as much room for this approach as it may initially appear, due to the restrictions inherent in the Swedish model.

Another fundamental issue that deserves a comment is our definition of the problem. We aim for an optimal time schedule, in the sense that it minimizes the present value of total costs, i.e. we take a purely economical approach. Since aspects such as politics and ethics are so important for the nuclear phase-out, one could argue that our approach is less useful in this context than it would be for other projects in which economical issues are the main decision determinants. Indeed, this controversy between our approach and the strong ethical incentives for waste disposal, has made the application of real options more difficult as it requires the problem to be restructured to fit our purposes. However, we argue that this controversy does not make our results less useful, as it is only our purpose to focus on the economical aspects of the phase-out. Some of the ethic questions are nonetheless captured in the third model when costs associated with accidents and other threats are introduced.

Because the phase-out of nuclear power generation is a very special project as just argued, because not much work in our area of interest has been performed earlier and because we chose actual application as the method in this work, some creativity was definitely needed to construct the real options models. In the second model, we discussed the difficulty arising from the fact that the funding of means for covering the phase-out takes place regardless of when investments in real disposal activities are carried out. The problem of waste disposal has, by this and other intricacies, had to be transformed into a form that suits the real options approach and the real options theory may have had to be slightly stretched to fit the problem. A particular way in which the problem has been transformed is through the division of costs, since the models are built upon some tradeoff between different costs. There is a risk that this cost division becomes quite artificial. In the work by Loubergé, Villeneuve and Chesney (2001) a particular processing cost gets very special attention and it is later recognized that this cost corresponds to the strike price of an American spread option. The cost division that singles out this particular cost would probably not be the same under another calculation approach. This construction of views, transformation of the problem and stretching of the theory may cause the models to appear less appropriate. However, we believe that this creativity certainly is needed and that it even brings new insights. As long as the conditions and simplifications are clearly defined, which we mean that they are, the models can be useful. However, the modeling has forced us to make significant simplifications of reality, since we have been far from able to capture the full flexibility of the problem. We have considered one or two uncertainties at the time while there may exist hundreds. It is thus important to remember that the models are nothing but models and that the results should not be over-interpreted.

Having constructed three real options models that capture different aspects of the phase-out, the conclusions from these should be stressed. From the first model, it is concluded that deferral of investments is economically advantageous since there is only a cost-side and no income-side in the project, and since there is a positive alternative cost for investment (the real rate of return from the nuclear fund). Furthermore, since the investment cost of the deep disposal facilities is much larger than the annual cost of interim storage the discounting procedure makes infinite interim storage economically advantageous. From the second model, it is concluded that there may at least be an incentive to defer investments due to the uncertainty of future costs, although the result is not as clear-cut as from the first model. We believe that the second model is mainly useful for providing a structuring of the problem and for providing qualitative insights. In the third model, we extended the analysis of a model by Loubergé et al. (2001), to examine how the optimal time for carrying out the deep disposal may vary for waste is produced at different times. We consider this to be an important extension of their analysis, since all waste will not be deep disposed at the same time in Sweden (which contradicts their basic assumption). Indeed, it is not even known when the nuclear reactors will be taken out of operation. The conclusions from the third model are again qualitative, but that is in accordance with the purpose of this work. Overall, we have shown that the real options approach provides insight for decisions regarding as well investment timing as implementation timing regarding the nuclear phase-out in Sweden.

Our conclusions, as presented above, depend on our approach to the problem. The overall purpose of this work was to investigate the usefulness of real options techniques, by actual application of such techniques. We feel that the method of actual application is highly advantageous, since it really requires an understanding of the underlying problem and since it does not leave too much room for vagueness. However, due to this approach we have mainly focused our attention on the mathematical aspects of the real options approach to nuclear waste disposal in Sweden. It can certainly be useful to speak more loosely about the possible application of the general knowledge provided by this work. The real options approach is a lot more than a mathematical toolbox. In fact, Bodie and Merton (2000), argue that two main reasons for taking on a real options approach to an investment project is that it helps structuring the project and that the role of uncertainty is clarified. Although, a lot of our work concerns structuring the problem, it is reasonable to believe that some "real options thinking" can be useful for managerial decisions regarding the nuclear phase-out, in an even broader sense than explored in this report.

The concluding argument is that there are more clear-cut areas of application to which the real options approach is easily generalized, than the phase-out of nuclear power generation in Sweden (when decision alternatives are restricted by the framework of the Swedish model). Still, it is our hope that the modeling presented in this report, convincingly shows that the real options approach can be useful for managerial decisions in this context.

6.2 Suggestions for Further Work

As discussed in the previous section, we believe that a less mathematical approach to evaluate the usefulness of the real options framework may be one interesting digression. In this work, we have only been concerned with the optimal time-schedule for the nuclear phase-out, found by minimizing costs. There are other issues, such as location of the deep disposal and cost saves resulting from e.g. research and development that we believe can be studied in a similar real options framework. Furthermore, we limited the decision alternatives by the framework of the Swedish model. It would really be interesting to consider the real options approach for nuclear phase-out in countries, in which e.g. various techniques for final disposal are still considered. Probably, other categories of real options than used in this work may then be applicable. We believe that the aspect of determining the economically preferable technique could be a relatively straightforward application of the real options framework.

Our work can also be further developed by taking the same approach we did. New and improved models real options models can of course be constructed. Our modeling contains significant simplifications of reality, which can certainly be relaxed in more advances models. Finally, a lot of our results were qualitative. An obvious extension of our work is therefore to run the simulations with parameters as realistic as possible; to explore which quantitative results that can also be obtained.

Hopefully, the issues discussed when constructing real options models for the nuclear phase-out in this work may serve as a source of inspiration for future work in this weakly explored field of real options application.

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Appendices

Appendix 1: Estimated Costs of the Nuclear Phase-out

The following table shows the estimated future costs (2004 and forward) for the phase-out of nuclear power generation in Sweden according to the reference scenario. The costs are in January 2003 prices and undiscounted. (SKB: Plan 2003)

Type of cost	MSEK	Percentage of total costs
SKB adm of FUD	4860	9,8 %
Transportation	2230	4,5 %
(Investment)	(1160)	
(Maintenance)	(1070)	
Demolition of power plants	13130	26,5 %
(Maintenance)	(2300)	
(Demolition)	(10830)	
Interim storage (CLAB)	4610	9,3 %
(Investment)	(990)	
(Maintenance)	(3220)	
(Demolition)	(400)	
Encapsulation	7920	16,0 %
(Investment)	(2150)	
(Maintenance)	(5600)	
(Demolition)	(170)	
Deep disposal (external facilities)	250	0,5 %
(Maintenance)	(250)	
Deep disposal (localization)	1040	2,1 %
Deep disposal (above ground)	5420	11,0 %
(Investment)	(1870)	
(Maintenance)	(3440)	
(Demolition)	(110)	
Deep disposal (below ground, fuel)	8150	16,4 %
(Investment)	(4580)	
(Maintenance)	(1170)	
(Demolition)	(2400)	
Final storage (less active waste)	580	1,2 %
(Investment)	(360)	
(Maintenance)	(120)	
(Demolition)	(100)	
Final storage (reactor waste)	420	0,8 %
(Investment)	-	

(Maintenance)	(420)	
(Demolition)	-	
Final storage (demolition waste)	960	1,9 %
(Investment)	(70)	
(Maintenance)	(700)	
(Demolition)	(190)	
Total	49570	100 %

To estimate the investment costs for the deep disposal facilities, used in Section 5.2.2, we sum up all costs for the deep disposal (250+1040+5420+8150 MSEK), arriving at 14 860 MSEK. Although this value contains maintenance costs and demolition costs, we consider this value to be appropriate, as this really is the cost that is realized if deep disposal is implemented. To estimate the annual cost of interim storage, we simply divide the future maintenance cost for interim storage (3220 MSEK) with the number of years deep disposal is planned to be used, according to the reference scenario (2040-2004=36 years), arriving at approximately 90 MSEK per year.

Appendix 2: Fixed Conditions

The following table shows the fixed conditions used by SKB to limit the uncertainties that are considered in their cost calculations (SKB: Underlag för kostnadsberäkningar 2003). The same conditions are considered as fixed when developing the real options models in our work. The table is freely translated from Swedish to English.

Description	Motive/Discussion
The democratic system, with its financial institutions and its political/social structure remains during the calculation period. War and other major international crises are assumed to not significantly disturb the system.	
The system is built upon dealing with used fuel that currently exists in Sweden and fragments that will be added are for facilities within Sweden.	The amount of fuel includes the MOX-fuel that with specific permission has been taken here, in exchange for Swedish fuel transported to reprocessing.
The used fuel is taken to final disposal without being reprocessed.	
The disposal of fuel shall, as far as possible, relieve the responsibility of future generations to take care of the fuel and other waste.	This "ethical" condition excludes the possibility of a significantly longer interim storage, while awaiting the possibility of alternative future solutions or for other reasons.
It shall be possible to retrieve the canisters after final disposal.	This condition provides future generations with the possibility to, at their own cost, make use of the fuel or change the method of final disposal.
A supervised period with access to the final disposal in not included. After final disposal, the deep disposal is to be sealed and remaining facilities are demolished.	This does not exclude a supervised period for some reason (for example due to an expected retrieval), but it will not be financed within the framework of the financing law.
The type of fuel used today is kept during the time of operation, which is the time period underlying the calculation.	
Fuel produced in the future is assumed to be burnt out to the degree of 45MWd/kgU for BWR and 50 MWd/kgU for PWR.	The reason for this being a fixed condition is that the impact of future changes would be negligible for the calculation. This is for two reasons. (1) only a small part of the dimensioned amount is "future" and (2) changes can only be realized in the long term in this context (5 years or more).
Degree of usage regarding the reactor operation during the future calculation period remains.	For the same reason as above, variations on this issue influences costs insignificantly. (However, the assumption of different degrees of future usage, can significantly change the appraisal of the fees that are

	needed to cover the costs. This does not affect the calculation, but it does affect the following process.)
The calculation should not include costs for special treatment of fuel or other waste, caused by a major reactor accident.	This is covered by insurance.
The used fuel should be managed in accordance with the KBS-3 method, which implies that the fuel elements are encapsulated in copper-coated canisters, surrounded by a bentonit buffer and placed in a drilled hole at a certain dept in the primary rock.	The news is that the KBS-3 method is now lied down. This implies that the financing should not cover alternative methods that imply a more expensive waste handling. This does not exclude principles providing lower costs. Neither does it exclude that a long development period or handling period, implies increased cost coverage by the rate of return from funded means.
Each fuel element must be in interim storage in CLAB for no less than 25 years before encapsulation.	This is a condition for the calculation. In reality an even shorter storage time may occur for certain fuel elements.
The deep disposal should be carried out in two stages, an initial stage with a limited number of canisters and then a stage of regular operation.	This condition does not say anything about the time period between the stages or anything about the amount canisters in the first stage. These could be varied.
Retrieval, as a cost included in the calculation, is limited to consider retrieval no later than the starting date of the second stage. It also includes only one retrieval. The retrieval is followed by establishment of a new final disposal, according to the KBS-3 method.	No limitations regarding the reason for this type of retrieval are considered, except for that it is not due to the KBS-3 method itself.
The calculation should be performed in today's prices.	The future cost development depends on inflation, and on the productivity development. Together, those items imply that the probable cost development can be assumed to follow CPI. This is the starting point for defining the real rate of return of funded means. Uncertainties regarding this issue should however be considered in the calculations.
The discounting procedure is based on a decided interest rate.	The question regarding real rate of return from funded means and the decided discount rate, has such a significant impact on the results, that it is included in the fixed conditions. Separate calculations are then performed for different discount rates.

Appendix 3: Probability of a Nuclear Accident

As mentioned in Section 5.4.1, λ is a parameter relating to the probability of a nuclear accident. Assume that a post-disposal nuclear accident occurs at time τ+T, where τ is the time of the deep disposal. The probability distribution of T is then given by the exponential law of the parameter λ:

$$\mathbf{P}(T\langle t) = \int_0^t \lambda e^{-\lambda s} ds = 1 - e^{-\lambda t}$$

The parameter λ can thereby be adjusted to reflect the likelihood of the accident. A lower λ means that a post-disposal nuclear accident is less probable in the next few centuries. These definitions follow Loubergé et al. (2001) and we refer to their work for a more thorough discussion.