Assessing the Added Value of Phased Renovation in Residential Buildings with Real Option Analysis

An Application to the Dutch Social Housing Sector

Master Thesis

Matthijs J. Joon

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Abstract

Dutch social housing corporations must phase out the worst-performing energy labels (E, F, G) by 2028 and deliver a CO_2-neutral stock by 2050, while minimising costs in in a construction market with ever changing construction costs. Nearly all social housing corporations are therefore renovating their portfolios. The standard valuation tool in the sector used for making renovation decisions, Discounted Cash Flow (DCF) analysis, does not account for the potential value of flexibility when applying a phased renovation strategy. Consequently, the integral-versus-phased renovation choice is made without an explicit valuation of timing flexibility.

This thesis develops and applies a Real Options Analysis (ROA) framework and model that quantify the financial value of flexibility under construction cost uncertainty, in order to support the renovation timing decisions of Dutch social housing corporations. The phased programme is framed as a portfolio of nine American put options on construction cost. Component-level volatility is calibrated from the BDB renovation cost index. A multi-group, Cox-Ross-Rubinstein (CRR) Binomial Lattice Model is created in Microsoft Excel and combined with two discounted cash flow scenarios that compare integral and phased execution.

The framework is applied to a fictional case and to an existing renovation in Rijswijk. In the fictional case, the value of flexibility is positive but modest, in the order of one per cent of total budget. One- and two-way sensitivity analyses identify construction cost volatility (σ) and the gap between WACC and renovation cost inflation (μ) as the principal drivers of the comparison. However, the probability of the options landing in-the-money remain below 5% for all component groups, meaning that the flexibility advantage is realised in only a small share of cost-paths.

The contribution of this thesis lies in extending Real Options Analysis to mandatory-investment problems with timing flexibility within a finite horizon: a transparent and applicable framework that supports renovation decision-making in the Dutch social housing sector.

Keywords: Real Option Analysis, Phased Renovation, Integral Renovation, Social Housing, Renovation Cost Volatility, Binomial Option Pricing Model.

Preface

This thesis was, from beginning to end, an exercise in working out something that did not yet have a settled shape. Applying real options analysis to social housing renovation meant bringing together financial theory, construction economics, and the Dutch social housing sector and translating their overlap into something that a corporation could actually use to inform a decision. The process was demanding and, above all, a matter of constant reshaping. Many versions of the report and the model at the centre of this thesis were drafted, tested, set aside, and rebuilt before they found their place in the final product. There were many stretches where the model resisted, stretches where the literature did, and stretches where the only move was to start a part over from scratch. What kept the work worthwhile, through all of that rebuilding, was the chance to think seriously about a question that truly matters for the housing sector.

I owe my greatest thanks to my supervisors, Prof. dr. ir. Vincent H. Gruis and Dr. ir. Ad Straub. Their guidance was clear and patient: reassuring at the start when the scope of the problem was overwhelming, and critical when I had been satisfied too easily during the process. The quality of this thesis owes much to their willingness to engage enthusiastically with the topic.

I am also grateful to the professionals at Dutch housing corporations and consultants who agreed to be interviewed during this study. Their time and willingness to share their knowledge shaped the research in ways that pure literary research never could have. Several conversations effectively redirected the research, and I am thankful for that openness.

A specific word of thanks goes to BDB Bouwkostendata and to OnderhoudNL for granting access to the BDB-cost index data for this research. Without that data, the development of the model would not have been possible. I have tried to handle that material with the care it deserves.

To my friends and family, thank you for the patience and the steady belief that this would all eventually come together. And to Marlou, thank you for the encouragement and the support through every stretch of this thesis. It would not have been possible without you.

Matthijs Joon
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Nomenclature

Abbreviations

ATM / ITM / OTM	At-The-Money / In-The-Money / Out-of-The-Money
BDB	Company providing the renovation cost-index
BKT	Bathroom, Kitchen and Toilet
BOPM	Binomial Option Pricing Model
CAGR	Compound Annual Growth Rate
CRR	Cox–Ross–Rubinstein (binomial lattice framework)
DCF	Discounted Cash Flow
E-NPV	Expanded Net Present Value
NPV	Net Present Value
OV	Option Value
ROA	Real Options Analysis
WACC	Weighted Average Cost of Capital
WSW	*Waarborgfonds Sociale Woningbouw*
WWS	*Woningwaarderingsstelsel*

Main model symbols

Δt	Time step in the binomial lattice
μ	Renovation cost inflation rate
σ	Annualised volatility of construction costs
σ_g	Group-level, cost-weighted volatility
d	Down-factor in the binomial lattice
D_i	Budgeted cost of component i across the complex
K	Strike price; in this model, the initial estimated renovation cost
$K_g(0)$	Initial total renovation cost of group g
OV_g	Root-node option value of group g
OV_{Total}	Sum of group-level option values across the nine lattices
p	Risk-neutral probability of an up-move
q_{ITM}, q_{ATM}, q_{OTM}	Risk-neutral probabilities of being In-, At- or Out-of-The-Money at the terminal node
r	Continuously compounded risk-free interest rate
R	Risk-free growth factor
u	Up-factor in the binomial lattice
w_i	Labour cost share of component i

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Introduction

1

Under the Dutch Climate Act (2019), the Netherlands must be climate neutral by 2050, with intermediary targets by 2030, when greenhouse gas emissions should be reduced by 55%. Highlighted within this strategy is the need for more energy efficient buildings and the objective of renovating underperforming dwellings. Approximately 2.4 million of the dwellings in the Netherlands are owned by Social Housing Associations (Van Der Bent et al., 2021), which accounts for one-third of the total housing stock in the country. A vast part of this stock was built during the post-war building boom from 1945 - 1975, as described by Boelhouwer & Priemus (2014). These buildings typically have poor energy performance. Therefore, housing associations bear a substantial responsibility in the national effort to decarbonise the built environment. At present, the pace of new construction, acquisition, demolition, and disposal is insufficient to keep environmental and residential quality up to date (Lambrechts et al., 2021). Consequently, the existing stock must be renovated, and at scale.

The pressure and urgency of renovation is further intensified by the threat of new regulations. Housing corporations with dwellings holding energy labels D or lower faced the prospect of rent freezes (*huurbevriezing*) last year (Rijksoverheid, 2025b), creating a strong financial incentive to improve the energy performance of their least efficient buildings. Currently, regulations on rent freezes have been put on hold by the government, but National Performance Agreements (*Nationale Prestatieafspraken*) have been made between Aedes, the Ministry of Housing and Spatial Planning, and others, which state that social housing will phase out dwellings with label E, F, and G by 2028 (RVO, 2024). As a result, most corporations are actively addressing their worst performing assets. In a study conducted by Straub & Meijer (2025), most retrofits were aimed at achieving an average energy label B in order to achieve the same target as all other housing corporations: a CO_2-neutral housing stock in 2050.

However, the path towards this sustainable future is characterised by uncertainty. Construction costs in the Dutch building sector have shown volatility in recent years, driven by fluctuating material prices, labour market tightness, and supply chain disruptions (Baarsma & Scholten, 2025); often due to geo-political events. In addition, government policies and subsidies are inconsistent (Lambrechts et al., 2021), and technological innovations continue to change the cost-effectiveness of various renovation measures, as can be observed in price reports on technologies such as PV-panels (IRENA, 2021). In this context of persistent uncertainty, housing corporations face a strategic question: should they undertake complete and comprehensive renovations immediately, capitalising on economies of scale and current pricing conditions, or should they adopt a more cautious, phased approach that preserves flexibility to respond to future cost developments?

This thesis investigates this question through the lens of Real Options Analysis (ROA), a financial valuation methodology that explicitly accounts for the value of flexibility under uncertainty. Through the application of ROA to a case study of social housing renovation under the uncertainty of renovation costs, this research aims to provide housing associations with a more sophisticated framework for decision-making: one that improves the traditional Net Present Value (NPV) calculations to capture the strategic value of flexibility.

1.1 Problem Statement

As mentioned in the opening, buildings constructed in the Netherlands before 1975 have a particularly poor energy performance, since Dutch regulations concerning thermal insulation values in buildings were introduced after 1975 (Loussos et al., 2015). With over 50% of residential buildings being built before 1971 during the post-war building boom, the share of buildings to be improved is large. These buildings typically exhibit poor energy efficiency, with energy labels in the D to G range, and require major intervention to meet current standards. The renovation measures necessary to achieve energy performance improvements, such as added insulation, efficient heating systems, mechanical ventilation with heat recovery, and renewable energy generation, require significant investment from the owner.

These investment decisions are typically approached by semi-public owners, such as housing corporations, using financial appraisal methods such as the NPV analysis. The NPV calculation is the most notable analysis method for financial appraisal and calculates the present value of expected future cash flows, discounted at an appropriate rate, and recommends making investments where this value exceeds the initial investment (Geltner et al., 2013). While the NPV analysis is a solid framework for evaluating investments under certainty, its application to make renovation decisions under uncertainty has limitations. It treats investment decisions as immediate: either the investment is made now or rejected. This method fails to account for the possibility that deferring an investment, or undertaking it in phases, may in itself be a valuable strategic option.

The concept of Real Options Analysis offers an interesting perspective. The concept was originally developed by Dixit & Pindyck (1994) in the context of financial derivatives and later extended to capital budgeting decisions. The authors show that when investments are characterised by irreversibility and uncertainty in regards to future conditions, the opportunity to wait and gather additional information has a certain quantifiable economic value. This ‘option value’ exists because waiting preserves the ability to make a more informed decision in the future, which could result in potentially avoiding large financial mistakes or taking advantage of favourable developments. Choosing for a phased approach in the context of housing renovation effectively purchases a series of options: the option to proceed with subsequent phases if conditions turn out to be favourable, or to delay, modify, or abandon further investment if the circumstances prove to be unfavourable.

The practical application of real options theory to social housing renovation remains under-researched and underdeveloped. Housing associations continue to predominantly rely on traditional appraisal methods, while potentially undervaluing flexibility. This leads to potential suboptimal investment timing decisions. Therefore, the central problem that is addressed in this thesis consists of two parts: first, to develop a framework for applying ROA to investment decisions on social housing renovations; and second, to empirically assess whether and under what conditions a phased investment approach outperforms a single upfront renovation from a financial and risk perspective.

1.2 Research and Design Questions

The problem statement is formulated into a research question and four sub-questions, which this thesis aims to answer. The central research question guiding this thesis is as follows:

> "*How does a phased investment approach compare to a single upfront renovation financially and in risk terms for Dutch social housing corporations?*"

To address this research question, the following sub-questions structure the research:

1. How can Real Options Analysis be applied to residential renovation investment decisions with renovation costs as the primary variable?
2. How does renovation cost uncertainty influence the value of flexibility in phased renovation strategies?
3. How does a phased renovation strategy compare to an integral renovation strategy in terms of expected returns and risk exposure under renovation cost volatility?
4. Under what conditions does phased renovation financially outperform integral renovation, and vice versa?

1.3 Scope

To ensure feasibility within the constraints of the graduation project, the scope of this research is defined along several aspects.

The first demarcation of the research is geography: the research focuses exclusively on the Netherlands, reflecting the specific regulations, financing structures, and institutional characteristics of the Dutch social housing sector. While the methodological approach may have broader applicability, the analysis and practical recommendations are tailored to the national context.

In terms of asset type, the case study concentrates on a building with an average energy label D, E, F, or G. This asset class has the most urgent need for renovation within the Dutch social housing stock, due to the National Performance Agreements (RVO, 2024). Within this category, the case study examines a representative building typology, specifically, buildings built before 1975. This type of asset is selected for its high occurrence in the Dutch social housing stock.

The analytical perspective that is adopted is primarily financial, assessing renovation strategies from the standpoint of the housing corporation as investor. This perspective uses metrics such as net present value, option value, and moneyness in a valuation model that will assess both the integral and phased strategies. While the research acknowledges the importance of, for instance, tenant welfare and environmental impact, these aspects will be addressed qualitatively rather than being incorporated into the valuation model.

Finally, the research element of this thesis incorporates semi-structured interviews with professionals at Dutch housing corporations. These interviews serve to validate and enrich the theoretical background, under which the identification of key parameters for the valuation model.

1.4 Relevance

This thesis contributes to the growing body of literature on ROA in real estate. While ROA has been applied to development timing decisions (Titman, 1985) and commercial property investment (Geltner et al., 2013), its application to social housing renovations remains scarce. Existing studies on renovation investment appraisal have a tendency to employ traditional life-cycle costing approaches or focus on optimising technical aspects rather than investment timing strategies (Pombo et al., 2016). By developing and applying an ROA framework that is tailored to phased renovation strategies of Dutch social housing associations, this research addresses a gap in the literature.

Dutch housing corporations collectively manage assets worth hundreds of billions of euros (WSW, 2025) and have to decide on major investment decisions. The choice between upfront and phased renovation strategies has implications for financial planning, risk management, and organisational capacity. A quantification of the value of flexibility could offer corporations a more complete basis on which to evaluate phased and integral strategies, complementing instead of replacing the current DCF practice.

This research is socially relevant through the implications that the research has for tenants, communities and the climate. Social housing serves a population that is disproportionately vulnerable to energy poverty (Llera-Sastresa et al., 2017); renovation strategies can directly affect the affordability and quality of the housing available to these households (Croon et al., 2024). Furthermore, the collective renovation decisions of social housing associations influence whether the Dutch climate commitments can be achieved. If standard valuation methods systematically discourage investment by failing to capture the value of flexibility, it may discourage housing corporations to renovate efficiently or to renovate at all, resulting in a delay in the energy transition. Thus, a better understanding of investment timing under renovation cost-uncertainty has implications that extend beyond the financial performance of individual corporations.

1.5 Objective and Motivation

The primary objective of this thesis is to develop and apply an ROA framework and valuation model that enables Dutch social housing corporations to quantify the value of flexibility in phased renovation strategies, thereby improving investment decision-making under renovation cost-uncertainty. This goal consists of several aims:

First, the research tries to establish a theoretical foundation by analysing literature about Real Options theory, real estate finance, the Dutch social housing sector, and housing renovation economics. Second, it aims to identify and characterise the effect of uncertainty affecting renovation investment decisions in the Dutch social housing context, using both literature and practitioner perspectives. Third, the research develops an Excel-based valuation tool that can compare phased and upfront renovation strategies while integrating the option value in staged investment approaches. Finally, the tool is applied to a representative case study and a fictional case study to create insights regarding the conditions under which phased renovation proves financially advantageous.

The motivation for this research has an intellectual and practical side. The application of Real Option Analysis to phased renovation in the Dutch social housing sector is a personal and intellectual challenge. In order to achieve this, new financial knowledge must be acquired and combined with the specific aspects of the social housing sector. Practically, the research responds to the need of housing corporations to make informed decisions on renovation strategies. By combining theory and practice, this thesis aims to make a contribution that is simultaneously academically grounded and professionally useful.

1.6 Research Design

The research uses a mixed-methods design, which combines a qualitative approach with a quantitative approach. This design is applied based on the nature of the research questions: applying ROA to social housing renovation requires theoretical understanding (through literature review), contextual understanding (through practitioner interviews), and quantitative assessment (through financial modelling).

The method consists of 5 sections:

1. A literature review. In the literature review, a theoretical foundation regarding ROA, the Dutch social housing sector, and housing renovation economics is created.
2. Semi-structured interviews. Perspectives from eight relevant professionals from housing associations are gathered on the subjects of uncertainties, decision-making processes, and case study parameters.
3. ROA model. An ROA-valuation model is built that compares the two renovation strategies whilst accounting for embedded flexibility. This model is made in Excel.
4. Case studies. For the case study, the developed ROA model is applied to a renovation project in order to test its practical functioning and to produce realistic results. A second fictional case study is applied in order to perform a sensitivity analysis across the full parameter space of the model.
5. Sensitivity analysis. The model is tested across variations in key parameters. This is done in order to identify conditions that favour each strategy.

The research design integrates deductive reasoning (applying established theory to a new context) with inductive reasoning (deriving insights from observations and practitioner experience).

Literature Review

2

The literature review establishes the theoretical background through engagement with academic and grey literature on Real Options, real estate investment, the Dutch social housing sector, and housing renovation. Academic sources are accessed through Scopus, Google Scholar, and the TU Delft repository; in addition to that, industry reports and policy documents are acquired through various sources such as RVO, WSW, CBS, and Aedes. The literature review is the foundation of the theoretical framework, the methodology, and of the values that will inform the model.

2.1 The Dutch Social Housing Sector

Nowhere else in Europe does social housing occupy such a central place in the housing market as it does in the Netherlands. A report from the Dutch bank ABN Amro (Teixeira, 2025) showed that out of the more than eight million dwellings in the Dutch housing stock in 2024, approximately 60% were owner-occupied and 40% rented. Within the rental segment, around three quarters are operated by housing associations as social housing, which translates into roughly 2.5 million social-rented dwellings. That is close to 30% of the entire national stock. Nearly all of these are owned by social housing corporations: private organisations that operate under a public mandate as defined by the Housing Act, in Dutch: Woningwet (Rijksoverheid, 2025a; Van Der Bent et al., 2021). The Act states that the primary task of a corporation is to provide affordable housing to households with limited financial means, that at least 80% of newly let dwellings must be assigned to qualifying low-income households, and that corporations may engage in only a specified set of activities. Unlike commercial real estate investors, corporations therefore have a dual objective: financial viability is a necessary condition for continuity, but the purpose of the organisation is the procurement of social return.

This dual objective shapes investment behaviour in ways that classical financial theory does not generally anticipate. For instance, renovation expenditure is not undertaken to maximise return on capital through rent-increases, but to fulfil a public service within a constrained budget. The underlying objective of the housing corporation is cost-minimisation under a quality and regulatory floor, rather than profit-maximisation under a market ceiling. This distinction has direct consequences for the way investment uncertainty is interpreted: where a commercial investor would weigh expected revenue against expected cost, the corporation predominantly weighs expected cost against regulatory obligations.

2.1.1 Regulatory Obligations

The regulatory framework within which the corporations operate extends beyond the allocation rules set out above and explicitly defines the required technical condition of the housing stock. The Housing Act (Rijksoverheid, 2025a) requires corporations to maintain their dwellings in a state that preserves residential quality, which in practice enforces replacement of building components at or near the end of their technical lifespan. Renovation, at the level of the individual building components, is therefore not a fully voluntary investment: failing to act eventually puts the corporation in breach of its mandatory maintenance duty.

On top of this baseline maintenance obligation rests a sector-wide sustainability commitment. Under the National Performance Agreements (RVO, 2024), signed in 2022 by Aedes, the Ministry of Housing and Spatial Planning, the Vereniging van Nederlandse Gemeenten, and the Woonbond, the social housing sector has committed to phasing out energy labels E, F, and G by the end of 2028 and to achieving a CO_2-neutral housing stock by 2050. Straub & Meijer (2025) observe, on the basis of a study of seven Dutch corporations, that the EFG phase-out had been integrated into all seven multi-year retrofit programmes examined, with intermediate label-B targets serving as planning anchors towards the 2050 endpoint.

The regulatory pressure intersects with a feature of the existing stock. Dutch regulations about the thermal performance of buildings were introduced only after 1975 (Loussos et al., 2015), and a substantial share of the social housing stock was constructed during the post-war housing boom of 1945-1975, the period during which the social rented sector grew from approximately 12% to 41% of the national housing stock (Boelhouwer & Priemus, 2014). As a result, many corporation-owned dwellings exhibit poor thermal performance, with energy labels concentrated in the D - G range (Filippidou et al., 2017). The combined effect of the mandatory maintenance duty, sector-wide sustainability commitments, and the physical condition of the existing stock means that the question is no longer whether to renovate the worst-performing assets, but how and when (Lambrechts et al., 2021; Straub & Meijer, 2025).

2.1.2 Financing Structures and Cash Flows of Social Housing Renovation

Renovation investment in the sector is primarily financed through internal cash flows generated from rental income and supplemented by long-term loans guaranteed by the Social House-Building Guarantee Fund (WSW), a sector guarantee fund that has been the main channel through which corporations access the capital market (Elsinga & Wassenberg, 2014). Because the WSW is itself backed in last resort by the Dutch State and the municipalities, the guarantee structure carries the highest available credit ratings (S&P Global, 2025) and enables corporations to borrow at favourable rates. However, access to this type of financing is conditional on the corporation's financial position: the WSW and the *Autoriteit woningcorporaties* (Aw) jointly assess each corporation and their financial continuity, which for instance includes the interest-coverage ratio (ICR), the solvency ratio, and the loan-to-value (WSW & Aw, 2024). If a corporation does not meet the thresholds established by the WSW and Aw, access to new guaranteed loans is restricted. Therefore, a corporation is sensitive to both the total volume and the timing of its investments: large simultaneous investments can constrict operating cash flows and affect the ICR, which can limit access to further borrowing;

spreading the same investments over a longer horizon improves liquidity but defers the realisation of the renovation benefits, such as an increase in rental income.

The cash-flow structure of renovation in the corporation context differs in important respects from a commercial renovation. Three features are particularly relevant for the present research.

First, energy savings accrue to the tenant rather than the corporation. Dutch tenants in social housing pay their own energy bills directly to the energy supplier. The corporation, as landlord, is not the beneficiary of reduced energy consumption following an insulation upgrade. Energy price uncertainty therefore shapes the social case for renovation, but it does not enter the corporate cash-flow model as direct revenue. This is a structural feature of the Dutch social housing sector and central in standard energy-retrofit literature, which regularly uses energy savings as the principal pay-off variable (e.g. Copiello et al., 2017; Pombo et al., 2016).

Second, the corporation's ability to recover renovation investments through rent increases is constrained by the Woning Waarderings Stelsel (WWS), a points-based system that caps the maximum permissible rent per dwelling. In 2026, the cap stood at €932.93 per month at 143 WWS points (Volkshuisvesting Nederland, 2026). Renovation measures can improve the WWS score and therefore raise the maximum rent, but the realised income effect depends on the type of measure and on the tenancy status of the occupant. Under the National Performance Agreements, sitting tenants no longer pay a rent increase for insulation-related energy improvements such as façade, roof, and floor insulation or improved glazing (Aedes, 2025). Increases for sitting tenants are still permitted for certain installations (heat pumps, photovoltaic panels), using a methodology developed by Aedes and the Woonbond, and for non-energetic quality improvements, subject to 70% tenant consent and proportionate cost recovery (Rijksoverheid, 2026). The full rent increase up to the WWS cap can therefore only be realised at tenant mutation: the moment when new tenancy occurs.

Third, the annual mutation rate in the social housing sector is on average 5.25%, as indicated by Kattenberg & Hassink (2017). Across an entire building or complex, this implies that the full rent increase from a WWS-improving renovation is only gradually realised over a horizon of one to two decades. Mutation is itself an ongoing process that occurs independently of renovation timing, but the combination of renovation timing and mutation timing determines how quickly the additional rental income from improved WWS scores accumulates. This is in contrast to the commercial sector, where rent increases can be realised more directly upon lease renewal or through market-rate adjustments (Geltner et al., 2013), meaning that the financial return on renovation accrues over a far shorter horizon and is less dependent on natural tenant mutation.

2.2 Traditional Investment Valuation in Housing Renovation

The standard approach to investment valuation in real estate is the Discounted Cash Flow (DCF) method. DCF calculates the NPV of expected future cash flows by discounting each future flow by a rate that reflects the project's risk profile (Geltner et al., 2013). The decision based on the NPV is simple: invest if NPV is positive, reject if NPV is negative, and accept the project with the highest NPV if alternatives compete for the same capital.

DCF analysis is widely used because it is has been grounded in financial theory that has been applied successfully for several decades (Geltner et al., 2013). For projects with relatively stable cash flow profiles and limited managerial discretion over timing or scope, the DCF method produces results that are both defensible and informative. The core of the method lies in the estimation of two cash flows: the initial investment and the following net operating cash flows, and the selection of an appropriate discount rate that captures the project's risk relative to the organisation's cost of capital (Kodukula & Papudesu, 2006).

2.2.1 Limitations under Uncertainty

When the underlying conditions of a project become uncertain and when the decision-maker has the ability to make decisions based on timing and flexibility in the project, the DCF framework exhibits two structural limitations that have been well-documented in the corporate finance and project valuation literature (Trigeorgis & Reuer, 2017; Kodukula & Papudesu, 2006).

The first is deterministic input assumptions. A DCF takes a single estimate for each cash flow and a single discount rate, and produces a single NPV. The result is, by construction, deterministic. Probability distributions of the underlying variables (for instance: material prices, labour costs, subsidy regimes, technological evolution) are reduced to expected values, and the uncertainty that lies within those values is only used indirectly through the risk premium embedded in the discount rate. Sensitivity analyses, in which a single input is varied while the others are held at the same value, and scenario analyses only have a limited effect on this limitation of DCF's: only so many scenarios can be run before the use of more sophisticated tools is needed (Kodukula & Papudesu, 2006).

The second is fixed-path assumption. Kodukula & Papudesu (2006) state that a DCF does not take into consideration the contingent decisions available and the managerial flexibility to act on those decisions and that, for example, the value of the future flexibility to expand, contract, or abandon is not captured by DCF. Furthermore, DCF analysis accounts for only the downside of the risk without considering the rewards. As Kodukula & Papudesu (2006) observe, this inherent bias leads to the rejection of highly promising projects because of their uncertainty.

2.2.2 Limitations in the Renovation Context

The two limitations described above are particularly important for social housing renovation. The underlying conditions are to a significant degree uncertain over the relevant time span: construction costs, available subsidies, technology costs, energy costs, and regulatory demands change and evolve over time. And the decision-maker holds the choice of when and how to act: the corporation can choose to renovate now, defer to a later year within the technical lifespan of the component, or split the scope across multiple phases. Under these three conditions (irreversibility, uncertainty, and managerial flexibility) Dixit & Pindyck (1994) demonstrated that the standard NPV rule does not provide the full picture. The framework that responds to this insight is Real Options Analysis.

2.3 Real Options Analysis

The origin of Real Options Analysis sits in the work of Black and Scholes (1973), who derived a formula which calculates the exact, fair market value of a stock option by measuring its time and risk. Myers (1977) was the first to apply ROA to corporate investment decisions, observing that managerial flexibility in investments resembles, in economic terms, the flexibility that sits in financial options. The term real option was introduced to capture this: a real option is, in the formulation of Kodukula & Papudesu (2006), “a right - not an obligation - to take an action on an underlying non-financial asset, referred to as a real asset”. The action may involve, for example, abandoning, expanding, or contracting a project or even deferring the decision until a later time (Kodukula & Papudesu, 2006). Real options analysis is a tool that helps to quantify the value of an option.

Pindyck (1991) demonstrated that committing to an irreversible investment is costly in itself, because it removes the option to wait for more favourable conditions. Therefore, the act of investing has an opportunity cost that traditional NPV analysis does not have. Dixit & Pindyck (1994) later expanded on this by identifying three conditions that generate option value in investment decisions:

1. Irreversibility (sunk costs cannot be recovered);
2. Uncertainty (future conditions are unknown);
3. Flexibility (decision maker has options regarding timing or scope).

When all three are true, the complete project value is no longer captured by the expected NPV alone but by the expected NPV plus the value of the option to act on future information.

2.3.1 Mandatory Investment

A central methodological difference for this thesis is that the classical real options literature described in the previous paragraphs, including Dixit & Pindyck (1994), assumes that the decision-maker holds the right to invest but also the right never to invest at all. This means that the option can be delayed indefinitely and that the value of it is partially derived from the possibility that the investment may never become attractive.

In the context of Dutch social housing, this assumption does not hold. Corporations are bound to invest in their maintenance works as obliged by the Housing Act (Rijksoverheid, 2025a), by the technical lifespans of their building components, and by the National Performance Agreements (RVO, 2024) - in order to phase out the worst-performing labels by 2028. The option is therefore not whether to invest, but when to invest within a constrained window. The terminal investment is fixed, but the timing within the horizon is flexible.

This institutional reality has two methodological consequences. First, the option must be modelled with a forced exercise at the end of the horizon, instead of a indefinitely delayed option. Second, the value of the option is no longer the value of avoiding the investment, but the value of timing it within the available window. Both consequences motivate the option specification developed in §2.3.2 and §2.3.3 below.

2.3.2 The Option Structure

Two further distinctions are necessary to specify the option structure used in this thesis. The first is regarding the timing of option-exercise. American options can be exercised at any time up to the expiration date, whereas European options can be exercised only on the expiration date itself (Hull, 2022). A corporation does not have to wait until a predetermined date to renovate a component: the renovation can happen at any point within the component's technical lifespan. The American type of option is therefore the relevant one.

The second distinction is regarding the direction of the option. In most applications of real options theory the investment opportunity is modelled as a call option: the holder of the option pays the strike price (the investment cost), and benefits when the value of the asset rises above the strike price (Kodukula & Papudesu, 2006). However, for social housing renovation, the main uncertainty lies on the cost side; not on the revenue side. This is because the corporation's revenues from renovation are heavily constrained by the regulated rent structure whereas its costs can vary through, for example, construction costs. The corporation therefore benefits on a project when costs fall, which in turn corresponds to a put option on construction costs: the option gets its value from the possibility that the costs may fall below their expected level during the option period, which would allow renovation at a more favourable moment.

Combining these two specifications, the phased renovation strategy is most accurately described as an American put option on construction costs with forced exercise at the horizon. The option does not get its value from the possibility of avoiding the investment, but from the ability to time the renovation to a moment where construction costs are relatively favourable.

2.3.3 Basic Real Options

Trigeorgis & Reuer (2017) identify five basic categories of real options that capture the main forms of managerial flexibility in investment. These are summarised in Table 2.1.

Table 2.1. Strategic investment choices as real options (Trigeorgis & Reuer, 2017)

Basic real options	
Type of option	Investment choice/illustration
Defer or stage	Delay or stage market entry when facing demand uncertainty
Grow	Enter new or foreign market
Alter scale (expand/contract)	Expand or contract plant or scale of outsourcing contract
Switch	Switch suppliers or production across foreign subsidiaries
Abandon/exit	Exit market if conditions deteriorate

The category most relevant to the this research is the option to stage, which allows an investor to break a large investment into smaller *sequential* steps. Instead of committing everything upfront, each phase is only undertaken once the previous one is complete, creating a series of decisions rather than a single all-or-nothing commitment. Trigeorgis & Reuer (2017) refer to this series of decisions as compound options: essentially an option on an option (Geske, 1979).

In the model developed in this study (§3), this structure is simplified: each component group is treated as an independent deferral option, the values of which are subsequently summed. This is a deliberate modelling choice that isolates the timing flexibility per component while still maintaining computational manageability. The implications and limitations of this simplification are discussed in the methodology (§3) and the discussion (§5).

2.3.4 Categorising Phased Renovation

Bringing all these elements together, the phased renovation strategy in the Dutch social housing context can be formulated as follows:

A portfolio of several American put options on renovation costs, with one put-option per renovation-component group. Of the component groups, each has:

- A bounded option life equal to the technical lifespan of the component group;
- A forced exercise at the end of its lifespan;
- A strike price equal to the budgeted renovation cost for the component group;
- Its own weighted renovation cost volatility.

The model is further described in §3.

2.4 Real Options Valuation Methods

There are several techniques for valuing real options, each with its own assumptions and trade-offs. Martins et al. (2015) identify five principal methods: the Black-Scholes Option Pricing Model (BSOPM), the Binomial Option Pricing Model (BOPM), Risk-Adjusted Decision Trees (RADT), Monte Carlo Simulation (MCS), and Hybrid Real Options (HRO). Kodukula & Papudesu (2006) group the same techniques into three families: partial differential equations (e.g. Black-Scholes), simulations (e.g. Monte Carlo simulation), and lattices (e.g. binomial tree). All five valuation methods share a common foundation: they each model the value of flexibility by tracking how an uncertain variable, in this study: renovation costs, evolves over time. The choice of method determines how this calculation of the uncertain variable is represented and how the best exercise decision is obtained from it.

The Black-Scholes model produces an option value by putting inputs directly into a single formula (closed-form), making it fast and simple to use. However, it assumes a constant volatility and can only price European-style options exercisable at a single fixed date (Black & Scholes, 1973). Both assumptions do not hold for the renovation context, where volatility is not constant and differs per component and where renovation may occur at any point within the given horizon.

A Monte Carlo Simulation has the ability to generate thousands of possible future paths for the uncertain variable and derives the option value as the average discounted payoff. It handles multiple simultaneous uncertainties well (Hull, 2022), but it struggles with American-style options because it works from the present towards the future, while determining the optimal moment to exercise the renovation requires calculations backwards from the future to the present. Discounting extensions, such as the least-squares method of Longstaff et al. (2001), have been developed in order to address this limitation, but these add considerable computational complexity.

Risk-Adjusted Decision Trees present the investment decision and its outcomes in a transparent and visual format that is easy to communicate to non-expert stakeholders. Their main weakness is that there is no theoretically consistent way to choose the discount rate at each decision point: as the riskiness of the investment changes at each step, a single fixed rate gives inconsistent results.

Hybrid Real Options combines multiple methods (for instance: integrating MCS with decision tree logic) to handle complex problems with several interacting uncertainties. However, this increases the model to a high level of complexity and reduces transparency, making results difficult to interpret for practitioners without a background in finance.

The Binomial Option Pricing Model sits on the middle ground between the compactness of Black-Scholes and the flexibility of simulations. It models the evolution of renovation costs as a tree of possible future values (*see* Figure 2.1): at each time step, the cost can either move up by a factor *u* or down by a factor *d* (following the parameterisation of Cox, Ross, and Rubinstein (CRR) (1979)). Both factors are calculated from the historic volatility of the uncertainty (Kodukula & Papudesu, 2006).

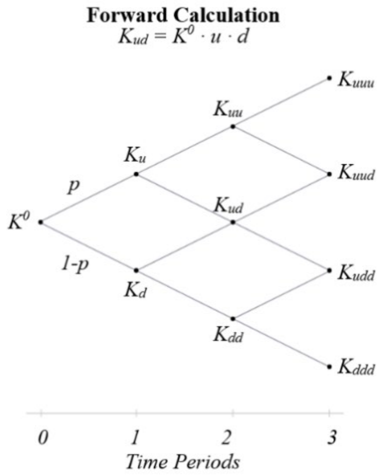


Figure 2.1. Example Forward Binomial Tree Structure (Own illustration)

Then, starting from the terminal nodes of the tree, the model works backwards to determine the option value at each earlier point, comparing the value of immediate exercise against the value of waiting one further period (*see* Figure 2.2). This backward induction discounts throughout at the risk-free rate, which ensures internal consistency (Hull, 2022).

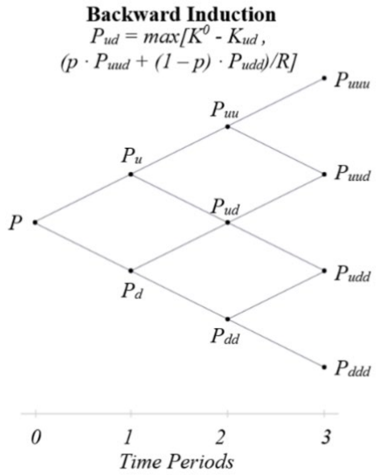


Figure 2.2. Example Backward Binomial Tree Structure (Own illustration)

The BOPM is especially well suited and adopted in this research for the following three reasons. First, the lattice accommodates the American-style exercise, which is essential given that renovation of each component group may occur at any point within the planning horizon. Second, the multi-period structure can handle component groups that are interdependent: if one renovation choice affects a later one, the lattice captures this through the compound-option logic, where the value of a later option depends on whether an earlier one has been exercised (Geske, 1979). When the groups are instead treated as independent options, as is the case in this thesis, the same structure simply becomes a set of separate lattices whose values are added up, which keeps the model straightforward. Lastly, the binomial method is transparent: the tree can be drawn, the up- and down-movements can be inspected, and the backward induction can be traced step by step. Kodukula & Papudesu (2006) explicitly recommend the binomial method as one of the two preferred techniques for practitioner analyses, because the lattice structure makes the results clear to an audience. Therefore, the model can be applied by social housing corporations more easily.

2.5 Real Options in Real Estate and the Built Environment

Titman (1985) was the first in the field of real estate to demonstrate that undeveloped land can be viewed as a call option on developed property: the landowner holds the right, but not the obligation, to transform the land into a productive asset by paying the construction cost (the strike price). The option value can be positive even when the immediate NPV of development is negative, because the landowner can defer development until conditions are more favourable. Williams (1991) extended this to development timing and demonstrated that developers optimally wait for a substantial premium above the NPV break-even point before committing, with the required premium increasing when uncertainty increased. Geltner et al. (2013) name this the *call option model of land value* and establishes that real estate investment exhibits the three Dixit & Pindyck (1994) conditions: construction costs are largely sunk (irreversibility); the development is subject to market risks (uncertainty); and developers have managerial flexibility over the initiation of the project(flexibility).

The literature has since expanded in several directions. Real options have, for instance, been applied to redevelopment and conversion decisions (Williams, 1997) and to mixed-use development sequencing (Rocha et al., 2007). Outside buildings themselves, ROA has also been applied extensively to infrastructure investment under uncertainty (Martins et al., 2015) and to energy-related transformations (Lee et al., 2014; Copiello et al., 2017).

2.5.1 The Identified Gap

Despite the wide scope of the real-options literature in real estate and the built environment, the systematic application of ROA to social housing renovation remains limited. Existing studies focus predominantly on commercial or privately owned buildings, in which the investment logic is different from that of social housing.

Three differences explain the gap. First, the corporate revenue model differs: commercial property generates market-determined rents, while social housing generates regulated rents and has a strong non-financial mandate (§2.1). Second, the investment obligation is different: commercial investors can decline an investment indefinitely, while social housing corporations operate under regulatory (decarbonisation) obligations (§2.1.1). Third, the main source of uncertainty differs: commercial valuation models typically place some type of revenue uncertainty at the centre, whereas the corporate cash-flow structure described in §2.1.2 is impacted more by other types of uncertainty.

The absence of an ROA framework that is made for these institutional features represents the gap that this thesis aims to fill.

2.6 Uncertainty in Housing Renovation

Renovation decisions are influenced by several sources of uncertainty, each of which affects the risk profile of the investment differently. The most commonly discussed are energy prices, government policy and subsidies, the cost of technology, and the cost of renovation. This section examines each of these uncertainties, before explaining why renovation cost volatility is selected as the central variable in this study.

2.6.1 Energy Prices

Energy prices are frequently cited as a key source of uncertainty in renovation investment appraisal (Lee et al., 2014; Copiello et al., 2017). Returns on energy efficiency improvements depend on future energy prices, which have shown historical volatility influenced by for instance geopolitical developments, technological change, and policy interventions (IEA, 2022). In the Netherlands specifically, the transition away from natural gas introduces additional uncertainty into the future price of energy (Mulder & Scholtens, 2013). However, from the perspective of a housing corporation, this uncertainty is largely irrelevant as a direct financial driver for renovation: the financial benefits of reduced energy consumption mainly go to the tenant through lower energy bills, not to the corporation as landlord. This is a characteristic of the Dutch social housing model, in which tenants pay their own energy costs and therefore capture the savings from improved insulation or more efficient heating systems. Energy price uncertainty therefore shapes the social case for renovation, but does not directly enter the corporate cash flow model.

2.6.2 Policy and Subsidies

Financial viability is further affected by policy and subsidy uncertainty. Dutch social housing renovation depends partly on government support through programmes such as the Investeringssubsidie Duurzame Energie en Energiebesparing (ISDE) and the Stimuleringsregeling Aardgasvrije Huurwoningen (SAH). However, these programmes are subject to periodic revision based political priorities and constraints. Lambrechts et al. (2021) characterise Dutch sustainability policy for housing as inconsistent, with subsidy conditions, amounts, and eligibility criteria changing between programme periods. A recent example is the reduction of ISDE subsidy amounts for heat pumps in 2026, which changed the financial prognosis of renovation projects that had been designed around the earlier amounts. The possibility that future subsidies may differ from present subsidies creates a timing dimension that the standard NPV analysis cannot capture.

2.6.3 Technology Costs

A third source of uncertainty relates to the evolving cost-effectiveness of renovation measures. Technological development affects both the cost and the performance of key renovation components. For instance, the Levelised Cost of Energy (LCOE) of utility-scale photovoltaic panels decreased by approximately 85% between 2010 and 2020, with the LCOE of residential PV systems also decreasing by 50 - 82% over the same period (IRENA, 2021). Heat pump technology has also seen efficiency improvements and cost reductions, although at a less extreme pace. However, the speed of future cost reductions remains uncertain. If technology costs continue to fall, there is a potential benefit to deferring investment in order to take advantage of a better cost-performance ratio at a later date.

2.6.4 Renovation Costs

The fourth, and for this study most significant, source of uncertainty is the cost of construction itself. Construction costs in the Dutch building sector have generally risen over time, with periods of sharper increases driven by material prices, the labour-market, and supply-chain conditions (Baarsma & Scholten, 2025). The renovation cost index by BDB Bouwkostendata (2026), from which the renovation cost volatility-parameter in this study is calculated, follows a similar path.

The renovation cost uncertainty is itself correlated with energy-price and technology cost-uncertainty. Energy is an input cost for both materials production and on-site work and the cost of technology is one-to-one incorporated in a renovation budget. However, renovation cost captures the entirety of the cost-side risk relevant to the corporation, of which energy and technology costs are only components.

Therefore, renovation cost is selected as the central stochastic variable in this study. This is further supported by two reasons. First, construction costs enter the corporate cash flow as a ‘first-order’ variable, with no intermediary mechanism that filters or minimised their effect, such as energy prices, where the direct benefits go to the tenants. Second, the variable is quantifiable through a credible external data source (the BDB Bouwkostendata (2026) renovation cost index) which allows the volatility parameter to be calculated from historical index-data using a logarithmic-returns method.

The remaining sources of uncertainty (energy prices, policy and subsidies, and technology costs) are not incorporated as stochastic variables in the model, but are acknowledged as relevant contextual factors.

2.7 A Real Options Framework for Phased Social Housing Renovation

The previous sections have developed the context that shapes investment behaviour in the Dutch social housing sector (§2.1), the limitations of NPV-based valuation under uncertainty (§2.2), the ROA-response to those limitations (§2.3), the available ROA valuation techniques and the rationale for selecting the binomial method (§2.4), the position of real options theory within the broader real-estate literature (§2.5), and the principal sources of uncertainty that affect renovation investment (§2.6). The section brings this together into a conceptual framework that supports the methodology described in the next chapter.

The framework rests on the three conditions under which Dixit & Pindyck (1994) demonstrate that the standard NPV rule understates project value: irreversibility, uncertainty, and flexibility. All three are present in the Dutch social housing renovation context, but two of them take on a specific form in Dutch social housing relative to the classic form.

Irreversibility applies in the conventional sense: renovation investment is sunk once committed, and the works cannot be undone without further investment.

Uncertainty applies on the cost side rather than the revenue side. The corporation’s renovation revenues are regulated by strict rent structures and by the slow realisation of rent-increases through tenant mutation, and are therefore comparatively fixed, whereas the input cost is exposed to many uncertainties. This is the reason the option is specified as a put on construction costs instead of the more-used call-option.

Flexibility remains true, but applies in a bounded way. The corporation cannot defer the investment indefinitely: the maintenance obligation under the Housing Act (Rijksoverheid, 2025a) and the phase-out of the E, F, and G energy labels under the National Performance Agreements (RVO, 2024) together present a deadline within which the renovation must be executed. However, within that deadline the corporation retains flexibility over the timing of each component-group renovation, up to the technical lifespan of the component.

Taken together, these three conditions generate an option value that the standard DCF analysis does not account for, and the phased renovation strategy is the form in which the corporation could exercise this flexibility. The strategy is specified as several American put options on renovation costs, one per component group, each with an option life equal to the technical lifespan of its component group. The valuation of these options by means of a CRR (1979) binomial lattice is developed in the following chapter.

Methodology

3

This chapter presents the methodological foundation of the research. It starts with an overview of the applied methods - following the research design, and concludes with the ethical considerations and data management system.

3.1 Methods

3.1.1 Semi-Structured Interviews

Semi-structured interviews with eight industry experts and housing corporation professionals in various functions, such as asset managers, portfolio strategists, technical managers, validate key parameters and describe current decision-making practices in detail. A purposive sampling strategy ensures relevant expertise and diversity among social housing associations.

The interview protocol addresses five topics: current analysis methods for renovation investment; uncertainty and risk perceptions; experience with phased versus integral approaches; available data and parameters for the quantitative model; and perspectives on Real Options applicability in the sector. The interview protocol, including the topic list and the probing questions, is provided in Appendix II. Interviews are analysed using thematic analysis (Braun & Clarke, 2006) in order to identify and analyse recurring patterns regarding uncertainties, current practices, and case study parameters. In addition to thematic insights, the interviews serve to validate and calibrate specific model inputs, such as mutation rates, relocation cost estimates, return rates, and typical exploitation horizons.

The interviews inform the research on the parametrisation of the quantitative model and the contextual interpretation of the results. For this reason, the relevant findings of the interviews are not reported in a single dedicated section, but are introduced throughout the methodology at the points where they are most relevant and informative. The interviews were most useful for two purposes: grounding the model in current practice with correct assumptions, and clarifying aspects of Dutch housing regulation that the academic literature does not cover in detail, such as the rules on rent increases for sitting tenants and how tenant relocation is handled during integral renovation.

3.1.2 Case Study Development

Two distinct cases are used in the application of the ROA model, each having a different purpose. The first is a fictional case, which is constructed to exercise the full parameter space of the model and used as the basis for the sensitivity analysis (§3.1.4). The second is an existing case, based on the renovation of the Generaal Swartlaan and adjacent streets in Rijswijk by housing corporation Rijswijk Wonen. The case is used to examine what the model produces when applied to a real, publicly documented renovation project. The combination of two cases is consistent with the replication logic for multiple-case designs, in which each case serves a distinct analytical purpose within a shared methodological framework (Yin, 2018).

Both cases concern the same asset class: post-war *portiek*-dwellings with a current energy label between D and G. This typology is selected because it is highly prevalent within the Dutch social housing stock and accounts for a substantial share of the dwellings that fall under the mandatory phase-out of EFG labels established in the National Performance Agreements (RVO, 2024; Van Der Bent et al., 2021).

The fictional case is designed to populate the full operating range of the model. It comprises thirty-two intervention items distributed across the nine component groups, with remaining technical lifespans divided over the planning horizon. This wide span is intentional: each component group reacts differently to changes in volatility, inflation, and the discount rate, depending on its own volatility, remaining lifetime, and weight in the portfolio. A narrower case would mask these differences and limit what the sensitivity analyses can show about the model's behaviour.

The existing case is the Generaal Swartlaan and adjacent Generaal Van Daalenstraat in the Te Werve neighbourhood of Rijswijk, where Rijswijk Wonen renovated 224 *portiek*-dwellings across ten blocks (Buitelaar & Dirks, 2023). An energy step was made from label F to label A, delivered through external facade insulation, replacement of window frames, installation of photovoltaic panels and renewal of the heating system. The programme also includes non-energetic maintenance such as kitchen, bathroom and toilet replacement and renewal of balconies and the inner garden. The case is selected on three grounds. First, it is fully documented in publicly accessible sources, which means the analysis can be reproduced by an external reader and removes the need to obscure figures for confidentiality reasons. Second, it falls within the asset class on which the research focuses, which makes the model's component grouping and lifetime assumptions directly applicable. Third, the integral execution applied by the Rijswijk Wonen provides a clear point of reference: applying the ROA model to the same scope under a phased execution allows the analysis to address what the value of flexibility would have been had the corporation chosen to phase the works rather than commit them in year zero. The financial conclusions drawn from the case are the researcher's own and should not be read as a statement by Rijswijk Wonen about its own renovation programme.

In both cases, the ROA model is applied under the two renovation strategies: an integral strategy in which all works are committed in year zero, and a phased strategy in which each of the nine component groups is treated as a separate American put option on construction costs.

3.1.3 Real Options Model

At the centre of valuing flexibility is a multi-group BOPM, implemented in Microsoft Excel. This section describes the structure and process of the model in full, covering input parameters, binomial tree construction, and two DCF scenarios that form the basis for the comparison between an integral and a phased renovation strategy. The model is constructed from first principles, meaning that it follows mathematical and economical theory without the use of simplified tools or software, and follows the Cox, Ross and Rubinstein (1979) framework. This is the most widely used discrete-time approach (in which the construction costs evolve in monthly/annual steps) for option pricing in real asset applications (Hull, 2022; Martins et al., 2015).

The phased renovation strategy is modelled as a series of American put options (as described in §2.3.2) on construction costs: the housing corporation holds the right, but not the obligation, to defer each renovation component until an optimal moment. The value of this 'deferral flexibility' -

hereafter called the option value - is quantified, discounted, and added to the NPV of the phased strategy, thereby creating an Expanded-NPV (E-NPV) as described by Angelou & Economides (2009). The integral strategy serves as the baseline and has no option value; all investment is committed in year zero. The financial advantage of phased renovation, if any, is expressed as the value of flexibility, defined as the difference between the two NPVs. The value of flexibility therefore consists out of two elements: the deferral effect, which is the time-value of money and arises purely from spending later rather than all at once, and the option value.

The model consists of ten sections contributing to the final renovation strategy comparison. The sections are listed below and explained in this chapter.

1. Renovation input;
2. *Renovation case input;*
3. *Fictional renovation case input;*
4. Renovation costs index (BDB Bouwkostendata);
5. Costs volatility calculation;
6. Binomial trees;
7. DCF - Integral;
8. DCF - Phased;
9. Results;
10. Sensitivity analysis.

Input Data and Component Grouping

The model receives as input a detailed renovation budget comprising up to 41 individual components (O_1 - O_{41}), based on the renovation costs index-groups of the BDB-index (BDB Bouwkostendata). Each component has four key inputs: (i) a budgeted cost D_i for the entire complex; (ii) a remaining technical service life L_i (years), which represents the number of years before replacement is technically necessary; (iii) a labour cost share w_i, which is used to construct a component-specific weighted cost index; and (iv) an additional monthly income per dwelling J_i, representing the possible financial benefit for the corporation after completion of that measure.

The 41 components are aggregated into nine functional groups: (1) Standard works, (2) Ground works, (3) Façade, (4) Roof, (5) Installations, (6) Bathroom, kitchen and toilet (BKT), (7) Finishings, (8) Fire safety, and (9) Other.

Per group, four variables are calculated: the total group costs (K_g), the investment timing under the phased strategy (T_g), the additional monthly income per group (F_g), and the cost weight of each component within its group (n_i).

For investment timing, each group is scheduled for renovation in the year in which its most time-critical component reaches the end of its technical lifespan. This rule ensures that deferred maintenance is not neglected to the point of structural degradation, which is in line with the obligations of housing corporations under the Housing Act (Rijksoverheid, 2025a).

The cost weight of each component within its group, later used in determining a representative group-volatility, is defined as:

$$n_i = \frac{D_i}{K_g} \tag{1}$$

Construction Cost Index and Volatility Calibration

Construction costs are the primary source of financial uncertainty modelled in this study. Renovation costs are volatile and driven by macroeconomic factors such as labour market conditions and materials prices (Copiello et al., 2017).

Volatility is estimated using the DBD-Index for renovation costs ranging from 2021 to 2026 (BDB Bouwkostendata), which provides monthly observations of both labour and materials cost indices per component. For each component i, a weighted composite index of labour and material costs is created:

$$Index_i(t) = w_i \cdot LabourIndex_i(t) + (1 - w_i) \cdot MaterialsIndex_i(t) \tag{2}$$

The monthly log-returns per component are then calculated. This calculates the continuously compounded rate of change between two consecutive months. Natural logarithms are used because log-returns are symmetrical and able to add up to each other over time, whereas regular percentage calculations are not. The series of log-returns serves as the basis for the calculation of the annualised volatility. The formula is as follows:

$$r_i(t) = ln\left(\frac{Index_i(t)}{Index_i(t - 1)}\right) \tag{3}$$

The annualised volatility (σ_i) formula first calculates the standard deviation of all monthly log-returns ($r_i(t)$) for each component i, which gives the monthly volatility. The formula then multiplies by the square root of 12, resulting in the annualised volatility. Annualisation via √12 is the standard approach in options pricing (Hull, 2022) and ensures that the volatility parameter is calculated to the same timescale as the annual steps of the binomial tree. The annualised volatility of component i is defined as:

$$\sigma_i = STDEV\big(r_i(t_1), \ldots, r_i(t_n)\big) \cdot \sqrt{12} \tag{4}$$

The group-level volatility is then computed as a cost-weighted average across all components in the group, using n_i as cost weight from eq. 1:

$$\sigma_g = \Sigma_{i \in g}\, n_i \cdot \sigma_i \tag{5}$$

This ensures that components that have a larger share of the group's budget exert a proportionally greater influence on the uncertainty parameter.

The mean annual drift in construction costs, hereafter referred to as the *construction cost inflation rate* μ, is estimated as the compound annual growth rate (CAGR) over the full index period. The formula for the CAGR is as follows:

$$CAGR = \left[\left(\frac{Ending\ Value}{Beginning\ Value}\right)^{\frac{1}{n}} - 1\right] \tag{6}$$

Where n is the number of years.

Translated to the model:

$$\mu = \left[\left(\frac{Index(t_{end})}{Index(t_{start})} \right) \wedge \left(\frac{1}{(t_{end} - t_{start})/365{,}25} \right) - 1 \right] \tag{7}$$

The inflation rate of construction costs is used to estimate the future costs of components for the phased renovation strategy. If the inflation rate was to be unaccounted for, the discount factor in the DCF would give the phased strategy an unrealistic advantage.

Binomial Lattice Construction and Option Valuation

For each of the nine component groups, a separate binomial lattice is constructed over a horizon of twenty annual time steps. Each binomial lattice consists of two tree structures: a forward tree (cost projections) and a backwards tree (backward induction of cost projections). For an example of a binomial tree structure, please see Figure 3.1.

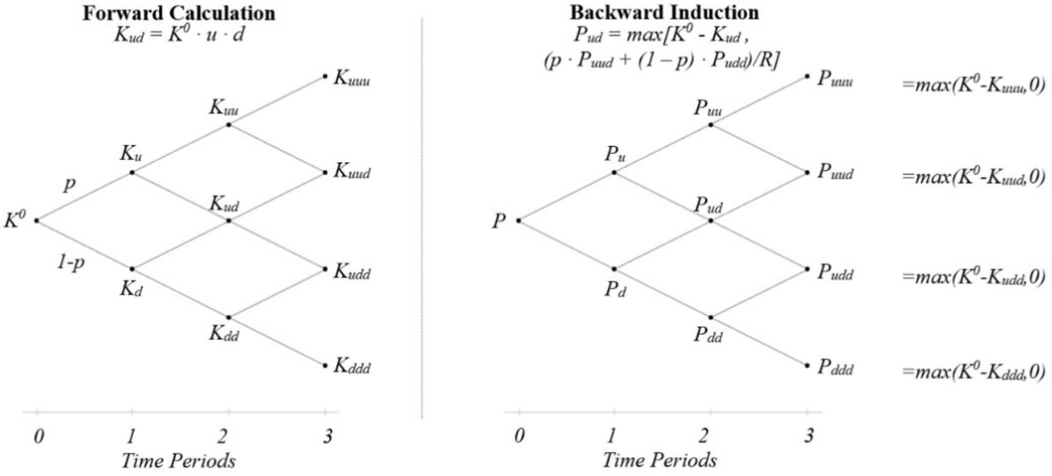


Figure 3.1. Example Binomial Tree Structures (Own illustration)

The trees follow CRR parameterisation (Cox et al., 1979) and have six parameters to calculate the option value: (i) the group's total renovation cost (K_0), (ii) the group-level volatility (σ_g), (iii) an up-factor (u_g), (iv) a down-factor (d_g), (v) a risk-free growth factor (R), and (vi) a risk-neutral probability (p_g).

u_g is a factor by which costs increase in an upward step in the forward tree; d_g is a factor by which costs decrease in a downward step. These are formulated as follows:

$$u_g = \exp\left(\sigma_g \cdot \sqrt{\Delta t}\right) \tag{8}$$

$$d_g = \frac{1}{u_g} \tag{9}$$

The risk-free growth factor R represents the value to which one unit of currency grows over a single time step when invested at the risk-free rate *r*. It is defined as:

$$R = \exp(r \cdot \Delta t) \tag{10}$$

Within the binomial lattice, R serves two related functions. First, it enters the no-arbitrage condition $d < R < u$, which ensures that the risk-free asset does not dominate either the up or down outcome. This is a necessary condition for the model to be internally consistent (Hull, 2022). Second, it is the rate at which the continuation value is discounted at each node during the backward induction: the (probability-weighted) average of the two possible next-period option values is divided by R to express it in present-value terms for the current period.

The final parameter within the CRR framework is the risk neutral probability. It is defined as:

$$p_g = \frac{(R - d_g)}{(u_g - d_g)} \tag{11}$$

Despite the name, p is not an estimate of the likelihood that construction costs will rise in any given period. However, it is the probability that makes the expected value of the binomial tree grow at exactly the risk-free rate R. Therefore, the following holds at every node:

$$p_g \cdot K_g \cdot u_g + (1 - p_g) \cdot K_g \cdot d_g = R \cdot K_g \tag{12}$$

In other words, if the probability p is assigned to an upward move and $(1 - \mathrm{p})$ to a downward move, the expected future cost equals the current cost grown at the risk-free rate.

Forward Tree | Cost Projections

The forward tree projects possible future renovation costs at each node. At time step *t* with *i* upward movements:

$$K_g(t, i) = K_g^0 \cdot u_g^i \cdot d_g^{t-i} \tag{13}$$

This generates a recombining tree with $t + 1$ distinct nodes at each time step. The recombining property of the binomial tree ensures computationally efficient model (Brandão et al., 2005).

In addition, the model reports, for each component, the risk-neutral probability that the cost lattice terminates in-the-money (ITM), at-the-money (ATM) or out-of-the-money (OTM) at the horizon T. For each binomial tree, the risk-neutral probability of reaching each terminal node is computed in Excel through the BINOM.DIST function.

Each terminal node is classified by comparing its terminal cost $S_T(j)$ with the strike K_T: ITM if $S_T(j) < K_T$, ATM if $S_T(j)$ sits at the strike, and OTM if $S_T(j) > K_T$. The total probability of either of the three results is the sum of the per-node probabilities within each classification, so that $q_{\mathrm{ITM}} + q_{\mathrm{ATM}} + q_{\mathrm{OTM}} = 1$.

Together, these probabilities indicate where the terminal cost distribution sits relative to the strike under the risk-neutral measure. A high q_{OTM} implies that, in most paths, the cost ends above the strike and the put expires worthless at T; the option value is then driven mainly by the smaller share of paths that finish ITM or are exercised earlier in the tree. The resulting values per component are reported in Table 4.1b. A visual representation of the distribution of probabilities can be seen in Figure 3.2.

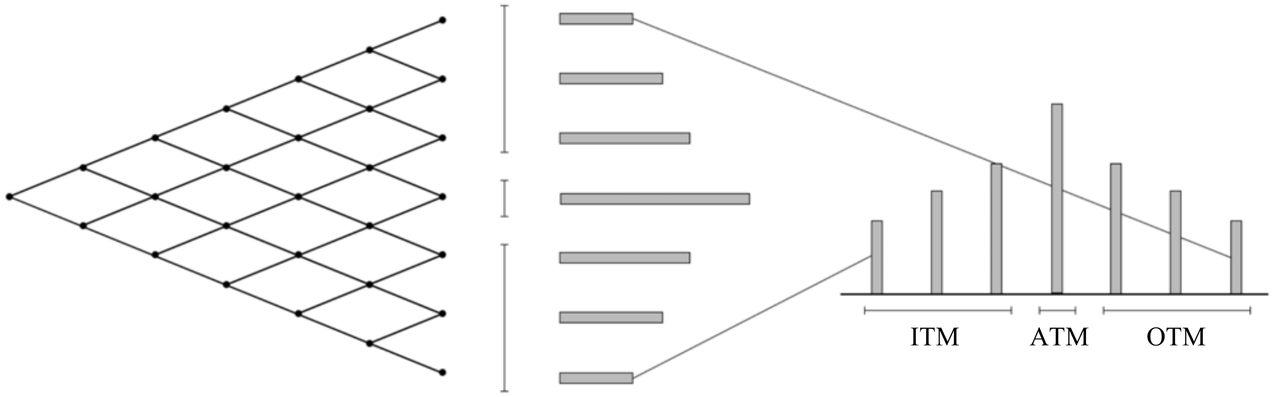


Figure 3.2. Distribution of Probabilities (Own illustration, based on Kodukula & Papudesu (2006))

Backward Tree | Terminal Node

The option is framed as an American put on construction costs. At the terminal nodes ($t = N$), the payoff represents the savings realised if construction costs have fallen below their initial level:

$$V_g(N,i) = max\left(K_g^0 - K_g(N,i), 0\right) \tag{14}$$

A positive payoff arises when realised costs are below the initial estimate, meaning the corporation benefits from having deferred the investment.

Backward Tree | Backward Induction

At each intermediate node ($t < N$), the American option value is determined by comparing immediate exercise against the continuation value:

$$V_g(t,i) = max\left(K_g^0 - K_g(t,i), \frac{\left[p_g \cdot V_g(t+1, i+1) + \left(1 - p_g\right) \cdot V_g(t+1, i)\right]}{R}\right) \tag{15}$$

The formula compares two alternatives at each intermediate node through the *max*-function. The first is the value of exercising the option immediately: the savings achieved by renovating now relative to the original budget ($K_g^0 - K_g(t,i)$). The second is the continuation value: the expected value of holding the option for one more period, which is calculated as the probability-weighted average of the two possible next-period option values, discounted by R.

The option value per group (OV_g) is the root node value:

$$OV_g = V_g(0,0) \tag{16}$$

The total option value across all groups is:

$$OV_{total} = \Sigma_{g=1}^{9} OV_g \tag{17}$$

Because backward induction discounts through each step at the risk-free rate, OV_{total} is already expressed in NPV terms and requires no further discounting when incorporated into the E-NPV summation.

DCF Analysis | Integral Renovation Strategy

Under the integral renovation strategy, all renovation components are executed simultaneously in year zero. Residents are temporarily relocated for the duration of the works, which means the corporation has three categories of cost at the start: the full renovation investment across all component groups, one-off relocation costs per dwelling, and missed rental income for every month the dwellings remain unoccupied during the renovation period.

Once the works are completed, the corporation begins to realise rental income benefits. Because Dutch tenant protection legislation limits the rent increase that can be charged to returning tenants, the achievable rent increase is lower for residents who return to their original dwelling than for new tenants. The weighted average rent increase per dwelling therefore depends on the share of residents who return. As returning tenants gradually vacate over time and are replaced by new tenants at the full post-renovation rate, an additional mutation gain is achieved each year.

All cash flows are discounted to year zero at the Weighted Average Cost of Capital (WACC) in order to calculate the NPV:

$$NPV_{Integral} = \sum_{t=0}^{N} \frac{NetCashFlow_{Integral}(t)}{(1 + WACC)^t} \tag{18}$$

DCF Analysis | Phased Renovation Strategy

Under the phased strategy, each group is renovated at the moment its most time-critical component reaches the end of its technical lifespan (T_g). Due to the smaller size of a single group-renovation it is assumed that residents are able to remain in their dwellings throughout, so there is no rent loss and no relocation expenditure. Because each group is executed at a future point in time, its nominal cost is also adjusted upward for accumulated construction cost inflation at rate μ (eq. 7):

$$I_g(t) = -K_g \cdot (1 + \mu)^t \quad if\ t = T_g, else\ 0 \tag{19}$$

On the income side for the corporation, two effects are modelled. First, each component group generates additional income, for instance through improved WWS points, from the year after its completion. Groups not yet executed contribute nothing; income therefore builds up as more groups are finished over time. Second, rent increases only accrue through natural tenant mutation rather than through a single mass-return moment. Each year, a fraction of tenants vacates and is replaced by new tenants paying the post-renovation rent. The achievable rent increase per mutating tenant is proportional to the share of the total renovation programme that has been completed at that point in time, since new tenants can only be charged for measures that have actually been implemented.

The NPV of the phased cash flows - excluding the option value - is calculated in the same way as for the integral strategy, discounting all net cash flows at the WACC:

$$NPV_{Phased} = \sum_{t=0}^{N} \frac{NetCashFlow_{Phased}(t)}{(1+WACC)^t} \tag{20}$$

Afterwards, the total option value derived from the nine binomial lattices (OV_{Total}) is then added as a year-zero correction, resulting in the E-NPV. No further discounting is applied, since the backward induction procedure has already discounted all option values to t = 0:

$$\text{E\_NPV} = NPV_{Phased} + OV_{Total} \tag{21}$$

The Value of Flexibility

A central output of the model is the *flexibility value*, defined as the difference between the E-NPV and the NPV of the integral strategy:

$$Flexibility\,Value = E\_NPV - NPV_{Integral} \tag{22}$$

A positive value indicates that the phased approach is financially preferable; a negative value favours the integral strategy. To aid interpretation, the flexibility value is decomposed into two additive components. The *deferral effect* captures the pure time-value-of-money impact of spreading investment over time: the benefit of discounting future expenditures against the costs of construction cost inflation, and the delayed rental income. The *option value* captures the additional benefit of being able to respond to future construction cost developments rather than committing everything upfront.

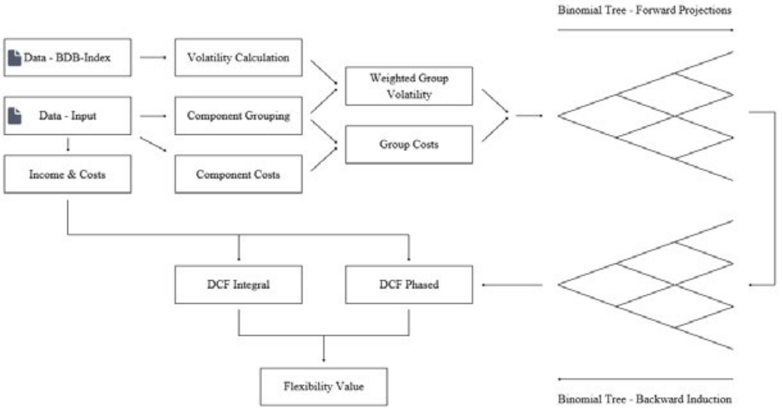


Figure 3.3. Schematic overview of the model's data flow (Own illustration)

3.1.4 Sensitivity Analysis

The model's results depend on a set of input parameters that are either derived from the case study and practitioner interviews or estimated from historical data. A sensitivity analysis is performed in order to assess the robustness of the results and to identify which parameters most strongly influence the comparison between the integral and phased strategies. Sensitivity analysis is standard practice in ROA applications (Dixit & Pindyck, 1994) and is particularly important when models are applied to new contexts, as is the case here.

The sensitivity analysis has three purposes. First, it examines whether the qualitative conclusion of the base case (i.e., whether the phased or integral strategy is preferable) is true across various (plausible) parameter ranges or whether it is sensitive to specific assumptions. Second, it identifies the parameters that most strongly influence the flexibility value. Third, it maps the decision space by showing the combinations of parameter values under which each strategy is financially preferable, which provides practitioners with a tool that goes beyond a single base case result.

The analysis is structured in two phases. In the first phase, a one-way sensitivity analysis is conducted by changing each parameter individually while holding all other parameters at their base values. This isolates the effect of each parameter on the flexibility value and allows for a ranking of parameter importance. In the second phase, two-way sensitivity analyses are conducted for parameter pairs that are expected to interact, in order to identify thresholds and tipping points that determine the best strategy.

The parameters subjected to sensitivity testing are selected based on their theoretical importance within the model and the degree of estimation uncertainty. The following parameters are varied:

Construction cost volatility (σ). Volatility is the central driver of option value in any binomial lattice model: higher volatility increases the spread of possible future cost outcomes, which increases the value of the option to wait for favourable conditions (Hull, 2022). The base volatility is calibrated from the BDB-index data over the period 2021 - 2026. This relatively short calibration window may not be representative of long-run volatility. The sensitivity analysis therefore tests a range of volatility values (for instance ± 10% around the base case) to assess how sensitive the option value is to this parameter. This is expected to be one of the most influential parameters for option value.

Renovation cost inflation rate (μ). The inflation rate determines how quickly future costs are expected to grow. A higher rate increases the cost of future phases, which works against the phased strategy. The base case is derived from the CAGR of the BDB-index, but the rate of renovation cost inflation has been quite variable in recent years. The sensitivity analysis tests the effect of both lower-than-expected and higher-than-expected inflation scenarios.

WACC (discount rate). The WACC is used to discount all cash flows in the DCF analyses and is the primary deterministic variable of the time value of money in the model. A higher WACC increases the discount factor applied to future costs, which would therefore logically benefit the phased strategy (because later costs are worth less in present-value terms), but also reduces the present value of future income from rent increases. The WACC is sensitive to interest rate developments and the specific financial targets of the corporation. Given that interviewees highlighted the interest rate as a key uncertainty affecting investment capacity, the sensitivity of the results to the WACC is particularly relevant.

Risk-free rate (r). The risk-free rate enters the binomial lattice through R (eq. 10), which affects both the risk-neutral probability p (eq. 11) and the discounting of continuation values (eq. 15). A higher risk-free rate reduces the put option value, which is a standard result in option pricing theory (Hull, 2022). This parameter is tested across a range of plausible rates.

Mutation & return rate. The mutation rate represents the annual share of tenants who leave their dwelling and are replaced by new tenants, regardless of renovation. At mutation, the corporation can re-let the dwelling at a rent level reflecting all accumulated WWS points, up to the WWS cap (according to interviewees). This process runs continuously and applies to both strategies. Under the integral strategy, however, an additional parameter plays a role: the return rate. After integral renovation, residents are often temporarily relocated, and a share of them returns to their original dwelling. For returning tenants, only the costs of quality improvements can be passed on as a rent increase. Tenants who do not return are effectively mutated at the moment of renovation, allowing the corporation to charge the higher rent immediately. In subsequent years, regular annual mutation continues, gradually replacing the remaining returning tenants with new tenants at the higher rent level. Under the phased strategy, no relocation takes place, meaning that rent increases are realised solely through the regular annual mutation process. The sensitivity of the results to the mutation rate is tested within the range of 4 - 10%; the return rate is tested within the range of 30 - 70%, which covers the values reported in the interviews.

Relocation costs. Under the integral strategy, residents are temporarily relocated during the renovation works. The relocation cost per dwelling was estimated by interviewees in the range of approximately €7.500 - €20.000 for relocation during the complete integral renovation. Because this cost applies only to the integral strategy, it directly affects the relative advantage of the phased approach. The sensitivity analysis tests the effect of varying relocation cost assumptions.

For the two-way analysis, the interaction between construction cost volatility and the building cost inflation rate (μ) is of particular interest, because these two parameters represent a core-dynamic of the model: volatility increases the option value of the phased strategy, while the renovation cost inflation rate reduces its financial advantage. The flexibility value can be mapped on a two-way sensitivity table (*see* Table 3.1 for an example) across combinations of σ and μ, which allows the identification of a break-even baseline (the set of (σ, μ) combinations at which the two strategies are equally attractive). The interaction between the WACC and the construction cost inflation rate can be tested in the same way, because these two rates determine how the time value of money competes with future cost escalation. The results of the sensitivity analysis are presented in §4.2 and §4.3.

Table 3.1. Example Two-way Sensitivity Analysis Table (Own Work)

Two-way Sensitivity Table					
	α = 0%	α = 5%	α = 10%	α = 15%	α = 20%
σ = 3%	+€12.000	+€4.000	-€5.000	-€14.000	-€21.000
σ = 6%	+€28.000	+€19.000	+€10.000	+€1.000	-€4.000
σ = 9%	+€45.000	+€36.000	+€27.000	+€18.000	+€5.000
σ = 12%	+€61.000	+€52.000	+€43.000	+€34.000	+€13.000
σ = 15%	+€73.000	+€65.000	+€59.000	+€51.000	+€22.000

3.2 Research Ethics

The research involves human participants partaking in semi-structured interviews. Therefore, it is subject to the ethics framework operated by the TU Delft Human Research Ethics Committee (HREC). A research ethics application was submitted before any interview took place, accompanied by an information sheet, a risk-identification and mitigation list, and a template of the written consent form; the application was approved after thorough review by the HREC.

Consent was obtained in writing from each participant after they had received the information sheet and had been given the opportunity to ask questions. The information sheet explained the purpose of the research, the general topics that would be discussed, the way in which the resulting material would be used, the storage arrangements for the data, and the participant's right to withdraw at any moment without giving a reason and without consequence. Withdrawal would have resulted in the exclusion of the interviewee’s material from the analysis. During the duration of this thesis, no participant withdrew.

The participants form part of a relatively small professional community, and the combination of role and organisation can in some cases be identifying even without a name. For this reason the research relies on pseudonymisation rather than full anonymisation: interviewees are referred to in the analysis by a participant code (Interviewee 1, Interviewee 2, etc.), without naming the organisation, without naming the participant, and without naming the function of the participant in the organisation.

At the conclusion of the research, administrative records that have the identities and corresponding interview codes will be deleted in accordance with the retention schedule attached to the data management plan. Pseudonymised transcripts will be retained for the period during which the thesis remains under examination, and afterwards transferred to an archive in line with TU Delft’s research data policy.

No conflicts of interest exist. The researcher has no financial, professional, or personal relationship with any of the housing corporations or interviewees involved in the study.

3.3 Data Management

The research draws on three categories of data, each with its own source and its own storage requirements.

The first is the BDB Bouwkostendata renovation cost index. Access to the index was obtained through a formal academic request to OnderhoudNL and BDB Bouwkostendata and is used under the following conditions: the data may be used for the present research only, the model and the incorporated index cannot be shared, and the index data cannot be presented in the thesis report.

The second is the interview material, which includes the pseudonymised transcripts and the administrative records of the recruitment and consent process. The data is stored safely on a password protected device, a step that is disclosed in the consent form. Only pseudonymised transcripts are circulated within the supervisory team or appended to the thesis if needed.

The third is the case study material. The renovation programme used as the case is documented in publicly accessible sources, and the analysis draws on this material rather than on confidential corporation records. The choice of a publicly documented case was deliberate: it allows the analysis to be reproduced by an external reader without privileged access to internal corporation files, and it removes the need to obscure figures for confidentiality reasons. The financial conclusions drawn from the case are the researcher’s own, and should not be read as a statement by the corporation about its own renovation programme.

Results

4

This chapter presents the quantitative output of the binomial-lattice real options model which was modelled in Microsoft Excel. Two cases are evaluated. A fictional case is constructed to exercise the full parameter space of the model and to enable a comprehensive sensitivity analysis: it contains thirty-two intervention items distributed across the nine component groups and spans the full range of remaining technical lifetimes. An existing case, based on a Dutch social housing renovation project in the city of Rijswijk, is then used to test whether the model can be applied to a real project and to examine what results it produces in that setting. The fictional case is presented first, in §4.1, and forms the basis for the one-way and two-way sensitivity analyses in §4.2 and §4.3. The application to the existing case follows in §4.4.

For clarity, all monetary values are expressed in euros and rounded to zero decimals. Risk-neutral probabilities are denoted q_{ITM}, q_{ATM} and q_{OTM}.

4.1 Base Case Results Fictional Case

4.1.1 Component-Level Option Values

The base case fictional portfolio comprises a total renovation budget of approximately €40.95 million distributed across the nine component groups. Construction cost volatilities, which are calibrated for each component from the labour and material composition of each group using the BDB renovation cost-index (BDB Bouwkostendata, 2026), range from σ ≈ 2.7% (BKT) to σ ≈ 5.9% (Substructure). The resulting component-level option values are reported in Table 4.1a and the risk-neutral probabilities in Table 4.1b.

Table 4.1a. Base case component-level results

	Total Costs K_g	Weigthed σ (annual) σ_i	Option Value OV_g	Option value / component investment OV_g / K_g	Option value / total investment $OV_g / \Sigma K_g$
1 - Standard works	€ 2.235.000	3,2781%	€ 17.448	0,8%	0,04%
2 - Substructure	€ 2.325.000	5,9143%	€ 65.231	2,8%	0,16%
3 - Façade	€ 13.875.000	4,2394%	€ 206.170	1,5%	0,50%
4 - Roof	€ 6.150.000	4,1511%	€ 87.252	1,4%	0,21%
5 - Installations	€ 7.665.000	4,0782%	€ 104.518	1,4%	0,26%
6 - Bathrooms, kitchens and toilets (BKT)	€ 3.750.000	2,7051%	€ 14.996	0,4%	0,04%
7 - Finishes	€ 2.400.000	4,1476%	€ 33.986	1,4%	0,08%
8 - Fire safety	€ 1.800.000	5,3841%	€ 42.866	2,4%	0,10%
9 - Other	€ 750.000	4,0449%	€ 10.039	1,3%	0,02%
Total	**€ 40.950.000**		**€ 582.507**		**1,42%**

Table 4.1b. Base case component-level risk-neutral probabilities

	Risk-neutral probability ITM op T	Risk-neutral probability ATM op T	Risk-neutral probability OTM op T
1 - Standard works	0,06%	0,20%	99,74%
2 - Substructure	4,72%	6,34%	88,94%
3 - Façade	0,80%	1,73%	97,47%
4 - Roof	0,68%	1,53%	97,79%
5 - Installations	0,59%	1,37%	98,04%
6 - Bathrooms, kitchens and toilets (BKT)	0,00%	0,01%	99,99%
7 - Finishes	0,68%	1,52%	97,80%
8 - Fire safety	3,20%	4,84%	91,96%
9 - Other	0,55%	1,30%	98,15%

Three patterns are visible. First, the option value per unit of component investment (OV_g/K_g) correlates positively with the component volatility: Substructure ($\sigma \approx 5.9\%$) and Fire safety ($\sigma \approx 5.4\%$) generate the highest OV_g/K_g, whilst BKT ($\sigma \approx 2.7\%$) and Standard works ($\sigma \approx 3.3\%$) generate the lowest. This is consistent with the central proposition of option pricing theory, namely that the value of an option scales with the spread of feasible outcomes due to higher uncertainty (Hull, 2022). The relationship between volatility and option value is examined in more detail in §4.2.1.

Second, the absolute contribution to total option value is mainly dominated by scale rather than by OV_g/K_g in this case. Façade, with a budget share of approximately 34% of the total programme, contributes the largest absolute option value despite a median volatility, whilst Substructure, with the highest OV_g/K_g, contributes a smaller absolute amount due to its lower budget share. The distinction between relative and absolute contribution is relevant: it indicates that the value of flexibility is not concentrated in a single “key” component group but is, instead, distributed in proportion to the financial footprint of each group.

Third, the risk-neutral probability that the underlying cost path ends below the strike at terminal T (q_{ITM}) is very low for all components. For every group, q_{ITM} is below 5%, and for several groups it is below 1%. As for the “moneyness” of these options: the results can be classified as predominantly Out The Money at T=20. The explanation is straightforward: under the risk-neutral measure, the expected drift is the risk-free rate r, but the calculated component volatilities are small enough that costs at T rarely end below the strike. The option values reported in Table 4.1a therefore arise largely from the American exercise opportunity at the intermediate nodes within the execution window, rather than from terminal-node payoffs.

4.1.2 NPV’s and value of flexibility

The total option value across the nine binomial lattices yields approximately €582,500 (*see* Table 4.2). When this is combined with the discounted cash flows of the phased programme and compared against the integral baseline, the model produces an Expanded NPV for the phased strategy of approximately - €39.82 million, against an integral NPV of approximately - €40.27 million. The resulting value of flexibility is approximately + €443,000 in favour of the phased approach.

Table 4.2. Aggregate financial valuation

		Value (discounted)
Totale option value	€	582.507
Total option value / total investment		1,42%
NPV Integral	-€	40.267.159
NPV Phased	-€	40.406.227
Expanded NPV Phased	-€	39.823.721
Value of Flexibility	€	443.438
Of which option value	€	582.507
Of which deferral effect (time-value)	-€	139.069

Two observations can be made. The value of flexibility is positive but small in relative terms: it represents approximately 1.1% of the total renovation budget. The base case therefore sits close to indifference between the two strategies, and the qualitative conclusion can shift under slight changes to the input parameters. This sensitivity is investigated in §5.2 and §5.3. In absolute terms, however, an advantage of approximately €443,000 across a portfolio of one hundred and fifty dwellings is non-trivial from the perspective of a social housing corporation operating under cost-minimisation rather than profit-maximisation (Van Der Bent et al., 2021).

4.1.3 Option value versus deferral effect

The value of flexibility comprises two additive components. The first is the option value itself (OV_{Total}), namely the gain from being able to respond to construction cost developments rather than committing the full programme upfront. The second is the deferral effect: the net time-value-of-money impact of spreading investments over a twenty-year horizon, which captures the trade-off between discounting future costs against the WACC and inflating them at the renovation cost inflation rate μ, and with the impact of the delayed realisation of rental income.

For the base case, the decomposition yields an option value of approximately + €582,500 and a deferral effect of approximately - €139,000. In other words, pure deferral costs the corporation money under the base-case parameterisation, because inflation on construction costs and the slower path to higher rents exceed the discounting benefit. The combined flexibility value of + €443,000 therefore stems entirely from the option to react.

This decomposition demonstrates that, under the base parameterisation, phasing would not be financially advantageous if it were only a postponement of investment. The advantage emerges only when the option to act on observed cost developments is recognised and valued explicitly. These relative sizes are not fixed, however: they shift with σ, μ, WACC, α and the rental-side parameters. The sensitivity analyses in §4.2 and §4.3 examine these parameters and dependencies systematically.

4.2 One-way sensitivity analysis

The one-way sensitivity analysis varies each parameter of the model individually whilst holding all other parameters at their base values. There are two objectives to this: first, to identify which parameters most strongly influence the value of flexibility; second, to check that the model behaves the way option-pricing theory predicts. Parameters are grouped according to where they enter the model. Parameters that affect the binomial-lattice computation directly (σ and r) alter the option value itself. Parameters that affect only the discounted cash flows (μ, WACC, mutation rate, return rate and relocation costs) do not change the option value but shift the integral and phased NPVs relative to each other. This distinction is reflected in how the tables are laid out.

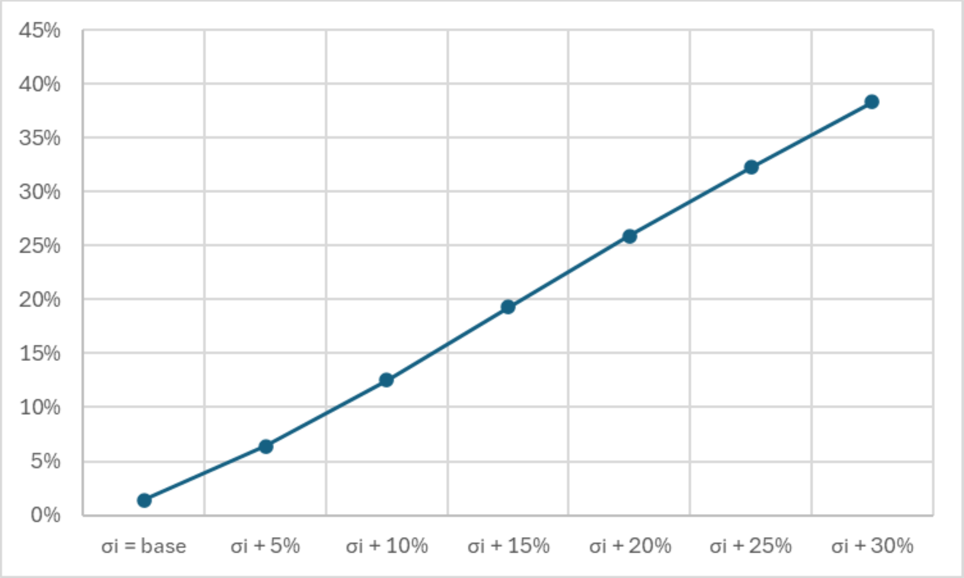
4.2.1 Construction cost volatility (σ)

Volatility is the central driver of option value in any lattice-based pricing model (Cox et al., 1979). The sensitivity is tested by scaling each component-level σ_i by a uniform percentage increment, ranging from the base case to +30%. The results are presented in Table 4.3 and visualised in Figure 4.1.

Table 4.3. Volatility / Option value per component investment

Component Group	**σi = base**	**σi + 5%**	**σi + 10%**	**σi + 15%**	**σi + 20%**	**σi + 25%**	**σi + 30%**
1 - Standard works	0,78%	5,35%	11,40%	18,11%	24,77%	31,19%	37,31%
2 - Substructure	2,81%	8,52%	14,92%	21,65%	28,20%	34,45%	40,41%
3 - Façade	1,49%	6,49%	12,67%	19,40%	26,03%	32,39%	38,45%
4 - Roof	1,42%	6,39%	12,55%	19,29%	25,92%	32,28%	38,35%
5 - Installations	1,36%	6,30%	12,45%	19,19%	25,82%	32,19%	38,26%
6 - Bathrooms, kitchens and toilets	0,40%	4,68%	10,69%	17,34%	24,02%	30,47%	36,62%
7 - Finishes	1,42%	6,38%	12,54%	19,28%	25,91%	32,28%	38,34%
8 - Fire safety	2,38%	7,87%	14,20%	20,94%	27,51%	33,80%	39,79%
9 - Other	1,34%	6,26%	12,41%	19,14%	25,78%	32,15%	38,22%

Figure 4.1. Volatility / Option value per component investment



Two observations stand out. The option value per unit investment increases almost linearly with the volatility shift across the range tested, rising from approximately 1-2% at the base case to approximately 36 - 40% at $\sigma + 30\%$. The increase curves upward at lower volatilities and becomes roughly linear at higher ones. This matches what option-pricing theory predicts: the sensitivity of a put option to volatility stays positive and finite across the relevant range (Hull, 2022).

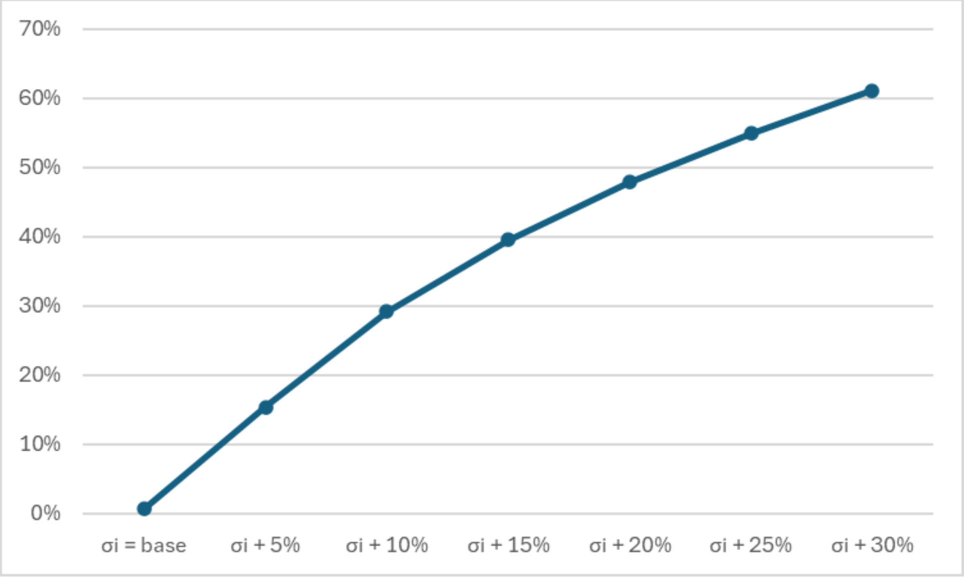
The differences between component groups shrink as volatility rises. At the base case, OV_g/K_g varies from roughly 0.4% to 2.8% across components; at $\sigma + 30\%$, the spread narrows to roughly 36.6% to 40.4%. This shows that, at high volatility, the spread of possible cost outcomes outweighs the baseline differences between components: every component ends up with a similar relative option value because each one produces substantial variation. In practical terms, precise per-component volatility estimates matter less when overall uncertainty in the construction cost environment is high.

The corresponding effect on the risk-neutral ITM probability is shown in Table 4.4 and Figure 4.2. q_{ITM} rises from near zero at the base case to between 59% and 63% at $\sigma + 30\%$. The curve is concave: q_{ITM} rises sharply at first and then levels off.

Table 4.4. Volatility / Risk-neutral probability ITM at T

Component Group	**σi = base**	**σi + 5%**	**σi + 10%**	**σi + 15%**	**σi + 20%**	**σi + 25%**	**σi + 30%**
1 - Standard works	0,06%	12,52%	27,09%	37,92%	46,52%	53,76%	60,07%
2 - Substructure	4,72%	20,75%	33,16%	42,66%	50,47%	57,19%	63,09%
3 - Façade	0,80%	15,66%	29,41%	39,71%	48,00%	55,04%	61,19%
4 - Roof	0,68%	15,38%	29,20%	39,55%	47,86%	54,92%	61,09%
5 - Installations	0,59%	15,14%	29,03%	39,41%	47,75%	54,83%	61,01%
6 - Bathrooms, kitchens and toilets	0,00%	10,60%	25,64%	36,81%	45,61%	52,98%	59,38%
7 - Finishes	0,68%	15,36%	29,19%	39,54%	47,86%	54,92%	61,09%
8 - Fire safety	3,20%	19,20%	32,01%	41,75%	49,70%	56,52%	62,50%
9 - Other	0,55%	15,03%	28,95%	39,35%	47,70%	54,78%	60,97%

Figure 4.2. Volatility / Median Risk-neutral probability ITM at T



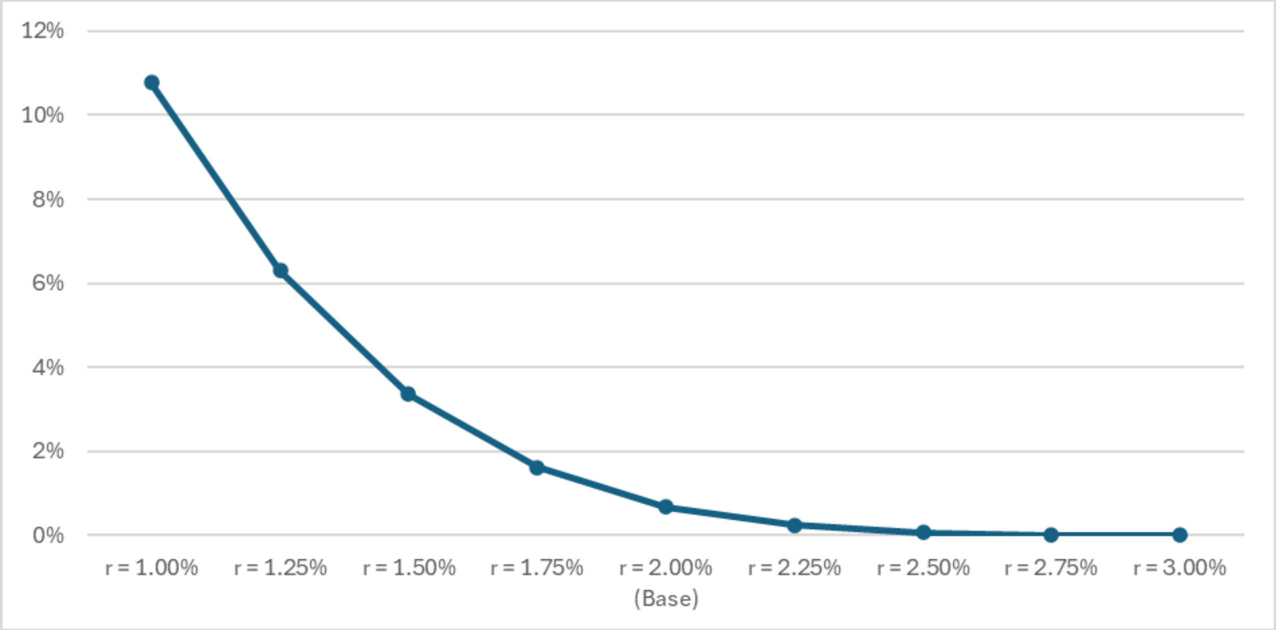
4.2.2 Risk-free rate (r)

For European and American put options, the option value decreases with an increase in the risk-free rate, since a higher r raises the risk-neutral up-probability p = (R – d) / (u – d) and thereby reduces the likelihood of a downward path in the lattice (Hull, 2022). The model reproduces this behaviour clearly. As Table 4.5 and Figure 4.3 show, halving the risk-free rate from 2.00% to 1.00% nearly doubles the option value, whilst raising it from 2.00% to 3.00% reduces the option value by more than half.

Table 4.5. Risk-free rate

Scenario	Option Value	Median Risk-neutral	Median Risk-neutral	Value of Flexibility	Δ base
r = 1.00%	€ 1.138.987	10,76%	78,58%	€ 562.745	€ 556.480
r = 1.25%	€ 923.889	6,30%	86,02%	€ 347.648	€ 341.382
r = 1.50%	€ 784.582	3,37%	91,62%	€ 208.340	€ 202.075
r = 1.75%	€ 676.631	1,61%	95,45%	€ 100.390	€ 94.125
r = 2.00% (Base)	€ 582.507	0,68%	97,80%	€ 6.266	€ -
r = 2.25%	€ 496.936	0,24%	99,08%	-€ 79.305	-€ 85.571
r = 2.50%	€ 417.241	0,07%	99,68%	-€ 159.000	-€ 165.265
r = 2.75%	€ 343.880	-	99,91%	-€ 232.361	-€ 238.627
r = 3.00%	€ 279.107	-	99,98%	-€ 297.134	-€ 303.400

Figure 4.3. Risk-free rate / Median Risk-neutral probability ITM at T



The median q_{ITM} responds even more sharply: it falls from approximately 10.8% at r = 1.00% to effectively zero by r ≥ 2.50%. The chart in Figure 4.3 displays the decrease clearly, with the steepest gradient in the lower-rate range. The numbers under the median risk-neutral probability column in Table 4.5 at r = 2.75% and r = 3.00% reflect the extreme case where *p* approaches 1: nearly all paths in the binomial tree move upward and the put expires worthless at the terminal nodes.

This sensitivity showcases the value of using a risk-free rate rather than a project-specific discount rate for the binomial calculations: the model would behave differently if a higher discount rate were applied within the lattice.

4.2.3 Renovation cost inflation rate (μ)

The renovation cost inflation rate is varied from 2.86% to 6.86%, around a base case of 4.86%. The option value does not change when μ is altered, because, under the risk-neutral measure used in the lattice, the drift of the underlying cost process is fixed at the risk-free rate independently of the real-world inflation rate. Changes in μ therefore only have effect in the model exclusively via the discounted cash flow scenarios, where they enter the cost projections for both strategies.

Table 4.6. Renovation cost inflation rate

Scenario	NPV Integral	NPV Phased	Value of Flexibility	Δ base
μ = 2.86%	-€ 39.590.321	-€ 36.630.342	€ 3.542.485	€ 3.536.220
μ = 3.36%	-€ 39.590.321	-€ 37.472.494	€ 2.700.334	€ 2.694.068
μ = 3.86%	-€ 39.590.321	-€ 38.342.464	€ 1.830.364	€ 1.824.098
μ = 4.36%	-€ 39.590.321	-€ 39.241.199	€ 931.628	€ 925.363
μ = 4.8584% (Base)	-€ 39.590.321	-€ 40.166.562	€ 6.266	€ -
μ = 5.36%	-€ 39.590.321	-€ 41.128.897	-€ 956.069	-€ 962.335
μ = 5.86%	-€ 39.590.321	-€ 42.119.901	-€ 1.947.074	-€ 1.953.339
μ = 6.36%	-€ 39.590.321	-€ 43.143.756	-€ 2.970.929	-€ 2.977.194
μ = 6.86%	-€ 39.590.321	-€ 44.201.562	-€ 4.028.735	-€ 4.035.000

The sensitivity is strong and asymmetric. The NPV of the integral strategy is essentially insensitive to μ, because integral execution occurs at T=0 and there is no time for inflation to accumulate before the cash flow is realised. In contrast, the NPV of the phased strategy is highly sensitive: each successive phase is exposed to additional years of cost inflation, and the cumulative effect compounds over the twenty-year horizon. The result is that the value of flexibility falls almost linearly with μ: it is strongly positive at μ = 2.86% (≈ + €3.5 million) and strongly negative at μ = 6.86% (≈ - €4.0 million). The break-even point, at which the two strategies are financially equivalent, lies just below the base case at approximately μ ≈ 4.9%.

This is the first clear sign that the base-case conclusion is sensitive to the inflation assumption. The base case sits just below the break-even level for μ, so the result is vulnerable to an upward revision of expected inflation. The interaction between μ and WACC is examined more closely in §4.3.2.

4.2.4 WACC

The weighted average cost of capital is varied from 2.22% to 6.22%, around a base case of 4.22%. As with μ, the option value is also invariable to WACC: the lattice uses the risk-free rate as its discount rate and the WACC enters only the discounted cash flow scenarios.

The sensitivity to WACC is approximately the mirror image of the sensitivity to μ. Both NPVs respond to WACC, but the phased NPV responds more strongly because more of its investments occur later in the horizon, where the discounting effect is larger. A high WACC therefore favours the phased strategy by shrinking the present value of later investments. The value of flexibility ranges from approximately - €4.4 million at WACC = 2.22% to approximately + €3.7 million at WACC = 6.22%, with the break-even point again sitting close to the base case at WACC ≈ 4.22%.

The μ and WACC sensitivities show that the model effectively competes one rate against the other: inflation drives future costs upward whilst the discount rate drives their present value downward.

What drives the comparison is therefore the gap between WACC and μ: not the level of either rate on its own.

Table 4.7. WACC

Scenario	NPV Integral	NPV Phased	Value of Flexibility	Δ base
WACC = 2.22%	-€ 38.823.799	-€ 43.786.218	-€ 4.379.913	-€ 4.386.178
WACC = 2.72%	-€ 39.035.414	-€ 42.828.142	-€ 3.210.221	-€ 3.216.486
WACC = 3.22%	-€ 39.232.991	-€ 41.906.517	-€ 2.091.019	-€ 2.097.285
WACC = 3.72%	-€ 39.417.626	-€ 41.019.814	-€ 1.019.681	-€ 1.025.947
WACC = 4.22% (Base)	-€ 39.590.321	-€ 40.166.562	€ 6.266	€ -
WACC = 4.72%	-€ 39.751.991	-€ 39.345.350	€ 989.148	€ 982.883
WACC = 5.22%	-€ 39.903.474	-€ 38.554.822	€ 1.931.159	€ 1.924.893
WACC = 5.72%	-€ 40.045.535	-€ 37.793.679	€ 2.834.363	€ 2.828.097
WACC = 6.22%	-€ 40.178.876	-€ 37.060.675	€ 3.700.707	€ 3.694.442

4.2.5 Relocation costs

The relocation cost per dwelling is varied from €5,000 to €13,000 around a base case of €9,000. Because relocation costs are only incurred under the integral strategy (phased renovation does not require temporary rehousing) the parameter enters the integral NPV directly and leaves the phased NPV unchanged.

Table 4.8. Relocation costs

Scenario	NPV Integral	NPV Phased	Value of Flexibility	Δ base
€ 5,000	-€ 38.990.321	-€ 40.166.562	-€ 593.734	-€ 600.000
€ 6,000	-€ 39.140.321	-€ 40.166.562	-€ 443.734	-€ 450.000
€ 7,000	-€ 39.290.321	-€ 40.166.562	-€ 293.734	-€ 300.000
€ 8,000	-€ 39.440.321	-€ 40.166.562	-€ 143.734	-€ 150.000
€ 9,000 (Base)	-€ 39.590.321	-€ 40.166.562	€ 6.266	€ -
€ 10,000	-€ 39.740.321	-€ 40.166.562	€ 156.266	€ 150.000
€ 11,000	-€ 39.890.321	-€ 40.166.562	€ 306.266	€ 300.000
€ 12,000	-€ 40.040.321	-€ 40.166.562	€ 456.266	€ 450.000
€ 13,000	-€ 40.190.321	-€ 40.166.562	€ 606.266	€ 600.000

The sensitivity is large, linear, and one-sided. Each €1,000 increment in the per-dwelling relocation cost adds €150,000 to the relative advantage of the phased strategy (one hundred and fifty dwellings × €1,000). The value of flexibility moves from approximately - €594,000 at €5,000 to approximately + €606,000 at €13,000. The break-even point sits between €8,000 and €9,000 per dwelling.

This is, after σ, μ and WACC, the strongest single-parameter driver of the result. It also has the cleanest interpretation: relocation cost is, in effect, a one-time penalty on the integral strategy that is wholly avoided under phased execution. From a corporate decision-making perspective, this means that the financial preference between strategies is highly sensitive to assumptions about the difficulty and disruption of temporary rehousing: an assumption that the interviews revealed to be both uncertain and project-specific.

4.2.6 Mutation rate

The annual tenant mutation rate is varied from 2% to 10% around a base case of 6%. Mutation enters the phased NPV, via the rental-side benefits: under the phased strategy, rent uplifts on completed measures can be realised only at the moment of tenant turnover, since sitting tenants cannot be charged the full WWS-based increase for improvements under the National Performance Agreements (RVO, 2024).

Table 4.9. Mutation rate

Scenario	NPV Integral	NPV Phased	Value of Flexibility	Δ base
Mutation = 2%	-€ 39.590.321	-€ 40.541.105	-€ 368.277	-€ 374.543
Mutation = 3%	-€ 39.590.321	-€ 40.429.499	-€ 256.671	-€ 262.937
Mutation = 4%	-€ 39.590.321	-€ 40.330.914	-€ 158.086	-€ 164.352
Mutation = 5%	-€ 39.590.321	-€ 40.243.738	-€ 70.910	-€ 77.176
Mutation = 6% (Base)	-€ 39.590.321	-€ 40.166.562	€ 6.266	€ -
Mutation = 7%	-€ 39.590.321	-€ 40.098.156	€ 74.672	€ 68.407
Mutation = 8%	-€ 39.590.321	-€ 40.037.442	€ 135.386	€ 129.120
Mutation = 9%	-€ 39.590.321	-€ 39.983.480	€ 189.347	€ 183.082
Mutation = 10%	-€ 39.590.321	-€ 39.935.449	€ 237.378	€ 231.113

A higher mutation rate increases post-renovation rents and therefore raises the phased NPV. The value of flexibility moves from approximately - €368,000 at 2% to approximately + €237,000 at 10%, with the break-even point sitting just below the base case at approximately 6%. The sensitivity is of average magnitude: smaller than the cost-side sensitivities but non-negligible. Subsequently, the sensitivity is monotonic and approximately linear.

In practice, mutation may rise during renovation activity (because the disturbance accelerates tenant turnover) or fall (because tenants resist mid-renovation moves). The base-case rate of 6% per year is consistent with the values reported in the interviews, but the sensitivity range laid out in Table 4.9 (2% to 10%) shows that the qualitative conclusion resilient to plausible variation in this assumption.

4.2.7 Return rate

The return rate, which is defined as the part of relocated tenants who choose to return to their renovated dwelling after the integral programme, is varied from 45% to 85% around a base case of 65%. The parameter affects only the integral strategy, since under the phased strategy no relocation occurs.

The mechanism is the following. Tenants who do not return are effectively mutated at the moment of the integral renovation, allowing the corporation to charge the higher post-renovation rent immediately to a new tenant. A higher return rate therefore reduces the financial benefit of the integral strategy, because fewer tenants are replaced by higher-paying new tenants in year one. The value of flexibility consequently rises with the return rate.

However, the scale of the sensitivity is the smallest of all parameters tested in this section: the value of flexibility ranges from approximately + €380,000 at 45% to approximately + €507,000 at 85%, a swing of less than €130,000 across the full range. This response reflects the fact that the return rate operates only on one cash flow component (the difference in early-year rental income between integral and phased), and that the effect of one extra non-returning tenant is limited to the rent difference, instead of scaling with the full renovation budget.

Table 4.10. Return rate

Scenario	NPV Integral	NPV Phased	Value of Flexibility	Δ base
Return = 45%	-€ 40.203.892	-€ 40.406.227	€ 380.171	-€ 63.266
Return = 50%	-€ 40.219.709	-€ 40.406.227	€ 395.988	-€ 47.450
Return = 55%	-€ 40.235.525	-€ 40.406.227	€ 411.805	-€ 31.633
Return = 60%	-€ 40.251.342	-€ 40.406.227	€ 427.621	-€ 15.817
Return = 65% (Base)	-€ 40.267.159	-€ 40.406.227	€ 443.438	€ -
Return = 70%	-€ 40.282.975	-€ 40.406.227	€ 459.255	€ 15.817
Return = 75%	-€ 40.298.792	-€ 40.406.227	€ 475.071	€ 31.633
Return = 80%	-€ 40.314.608	-€ 40.406.227	€ 490.888	€ 47.450
Return = 85%	-€ 40.330.425	-€ 40.406.227	€ 506.704	€ 63.266

4.2.8 Summary of one-way sensitivities

The one-way analysis can be summarised by ranking the parameters according to the magnitude of their effect on the value of flexibility across the tested range. The order is approximately:

Table 4.11. Order of parameters

No.	Parameter	Effect	Description
1.	σ	Dominant	Reshapes the option-value component itself and converges component-level option values at high σ.
2.	μ	Very strong	Flips the qualitative conclusion across the plausible range.
3.	*WACC*	Very strong	Mirror image of μ.
4.	*Relocation cost*	Strong and linear	One-sided effect on the integral strategy.
5.	r	Moderate to strong	The only parameter besides σ that alters the option value itself.
6.	*Mutation rate*	Moderate	Affects only the phased rental-side benefits.
7.	*Return rate*	Weak	Affects only the integral strategy's early-year rental income.

This ranking has two implications for the interpretation of the base-case result. First, the four leading parameters (σ, μ, WACC, relocation cost) are all parameters for which there is some uncertainty in the source data, and small adjustments to any of them may shift the eventual recommendation. Second, the option-value component of flexibility is influenced by only two of the seven parameters (σ and r); the others have effect through the deferral-effect component. This confirms that the binomial lattice and the DCF work as two separate components within the model.

4.3 Two-way sensitivity analysis

Two pairs of parameters are examined in interaction: $\sigma \times \mu$ and WACC $\times\ \mu$. These pairs are chosen because the one-way analyses show that, together, they decide whether the base case lies on the integral or the phased side of break-even. The two-way tables show the line where the two strategies tie financially, mapping which parameter combinations favour each.

4.3.1 Volatility-inflation interaction ($\sigma \times \mu$)

Table 4.12. Value of flexibility: $\sigma \times \mu$

σ \ μ	μ = 2.86%	μ = 3.36%	μ = 3.86%	μ = 4.36%	μ = 4.86%	μ = 5.36%	μ = 5.86%	μ = 6.36%	μ = 6.86%
σi = base	€ 3.979.658	€ 3.137.506	€ 2.267.536	€ 1.368.801	**€ 440.325**	-€ 518.897	-€ 1.509.901	-€ 2.533.756	-€ 3.591.562
σi + 5%	€ 6.009.026	€ 5.166.875	€ 4.296.905	€ 3.398.170	€ 2.469.694	€ 1.510.472	€ 519.467	-€ 504.387	-€ 1.562.193
σi + 10%	€ 8.533.107	€ 7.690.956	€ 6.820.986	€ 5.922.250	€ 4.993.774	€ 4.034.552	€ 3.043.548	€ 2.019.693	€ 961.887
σi + 15%	€ 11.287.504	€ 10.445.352	€ 9.575.382	€ 8.676.647	€ 7.748.171	€ 6.788.949	€ 5.797.945	€ 4.774.090	€ 3.716.284
σi + 20%	€ 14.002.392	€ 13.160.240	€ 12.290.270	€ 11.391.535	€ 10.463.059	€ 9.503.837	€ 8.512.833	€ 7.488.978	€ 6.431.172
σi + 25%	€ 16.609.711	€ 15.767.559	€ 14.897.589	€ 13.998.854	€ 13.070.378	€ 12.111.156	€ 11.120.151	€ 10.096.297	€ 9.038.491
σi + 30%	€ 19.093.213	€ 18.251.062	€ 17.381.092	€ 16.482.357	€ 15.553.881	€ 14.594.659	€ 13.603.654	€ 12.579.800	€ 11.521.994

The $\sigma \times \mu$ table reveals the central trade-off of the model. Along the base-σ row, the value of flexibility falls from approximately + €4.0 million at $\mu = 2.86\%$ to approximately - €3.6 million at $\mu = 6.86\%$, with break-even between $\mu = 4.86\%$ (base-case) and $\mu = 5.36\%$. However, as σ rises, the break-even μ shifts towards the right: at $\sigma + 5\%$ the break-even μ moves to approximately 5.9%, at $\sigma + 10\%$ it shifts beyond the upper end of the tested range, and at $\sigma + 15\%$ and above the value of flexibility remains positive across the entire μ range.

The dominant pattern is therefore the asymmetry between the two parameters: σ tends to win the trade-off at sufficient magnitudes. Once the volatility of the construction cost environment is high enough, the option value component grows large enough to absorb any plausible deferral-effect penalty arising from inflation. This is the direct lattice-model parallel of the central insight of Dixit & Pindyck (1994): when the cost is sufficiently uncertain, the option to wait becomes valuable enough to outweigh the time-cost of waiting.

4.3.2 Discount-inflation gap (WACC $\times\ \mu$)

Table 4.13. Value of flexibility: WACC $\times\ \mu$

WACC \ μ	μ = 2.86%	μ = 3.36%	μ = 3.86%	μ = 4.36%	μ = 4.86%	μ = 5.36%	μ = 5.86%	μ = 6.36%	μ = 6.86%
3,00%	€ 1.768.184	€ 845.606	-€ 107.878	-€ 1.093.326	**-€ 2.111.826**	-€ 3.164.500	-€ 4.252.506	-€ 5.377.036	-€ 6.539.319
3,50%	€ 2.702.496	€ 1.814.004	€ 895.916	-€ 52.777	-€ 1.033.117	-€ 2.046.176	-€ 3.093.060	-€ 4.174.908	-€ 5.292.895
4,00%	€ 3.597.664	€ 2.741.685	€ 1.857.357	€ 943.715	-€ 235	-€ 975.520	-€ 1.983.196	-€ 3.024.352	-€ 4.100.111
4,22%	€ 3.979.658	€ 3.137.506	€ 2.267.536	€ 1.368.801	€ 440.325	-€ 518.897	-€ 1.509.901	-€ 2.533.756	-€ 3.591.562
5,00%	€ 5.278.456	€ 4.483.104	€ 3.661.721	€ 2.813.427	€ 1.937.309	€ 1.032.432	€ 97.827	-€ 867.502	-€ 1.864.580
5,50%	€ 6.067.738	€ 5.300.651	€ 4.508.612	€ 3.690.776	€ 2.846.272	€ 1.974.203	€ 1.073.645	€ 143.643	-€ 816.783

The WACC $\times\ \mu$ table makes the role of the WACC - μ gap explicit. The break-even lines for the value of flexibility run closely along the diagonal where WACC $= \mu$. Above this diagonal (where WACC $> \mu$) the value of flexibility is positive and phasing is preferred. Below it (where $\mu >$ WACC) the value of flexibility is negative and integral execution is preferred. The base case (WACC = 4.22%, $\mu = 4.86\%$) sits just below the diagonal, which fits the small positive flexibility value.

This confirms that the μ and WACC sensitivities in §4.2.3 and §4.2.4 are two sides of the same mechanism. For corporations, what drives the integral-versus-phased comparison is not WACC or μ on its own, but the effective discount rate that emerges from their combination. For social housing corporations specifically: WACC tends to be stable, whilst μ depends on the contractor market and can vary substantially over a twenty-year horizon. The two-way table therefore shows under which parameter combinations a corporation's financial position favours one strategy over the other.

4.4 Application to the existing case

The Generaal Swartlaan portfolio comprises a total renovation budget of approximately €35.7 million, distributed across the nine component groups in proportions that reflect the renovation scope. The construction cost volatilities range from $\sigma \approx 2.6\%$ (BKT) to $\sigma \approx 5.4\%$ (Fire safety). Component-level option values are shown in Table 4.14a and risk-neutral probabilities at the horizon in Table 4.14b.

Table 4.14a. Base case component-level results

	Total Costs	Weigthed σ (annual)	Option Value	Option value / component investment	Option value / total investment
	K_g	σ_i	OV_g	OV_g / K_g	$OV_g / \Sigma K_g$
1 - Standard works	€ 3.360.000	3,2055%	€ 24.540	0,7%	0,07%
2 - Substructure	€ 3.248.000	3,5957%	€ 32.688	1,0%	0,09%
3 - Façade	€ 7.302.400	3,9849%	€ 94.453	1,3%	0,26%
4 - Roof	€ 1.904.000	4,4837%	€ 31.864	1,7%	0,09%
5 - Installations	€ 2.788.800	3,9445%	€ 35.227	1,3%	0,10%
6 - Bathrooms, kitchens and toilets (BKT)	€ 6.272.000	2,5652%	€ 19.664	0,3%	0,06%
7 - Finishes	€ 2.217.600	4,0809%	€ 30.285	1,4%	0,08%
8 - Fire safety	€ 2.240.000	5,3841%	€ 53.344	2,4%	0,15%
9 - Other	€ 6.372.800	3,9945%	€ 82.885	1,3%	0,23%
Total	**€ 35.705.600**		**€ 404.949**		**1,13%**

Table 4.14b. Base case component-level risk-neutral probabilities

	Risk-neutral probability ITM op T	Risk-neutral probability ATM op T	Risk-neutral probability OTM op T
1 - Standard works	0,04%	0,15%	99,80%
2 - Substructure	0,18%	0,53%	99,29%
3 - Façade	0,49%	1,18%	98,33%
4 - Roof	1,18%	2,33%	96,49%
5 - Installations	0,45%	1,10%	98,45%
6 - Bathrooms, kitchens and toilets (BKT)	0,00%	0,00%	100,00%
7 - Finishes	0,60%	1,37%	98,03%
8 - Fire safety	3,20%	4,84%	91,96%
9 - Other	0,50%	1,20%	98,30%

All logical patterns observed in the fictional case carry over. The option value per unit of component investment (OV_g/K_g) correlates with σ: Fire safety produces the highest at 2.4%, whilst BKT and Standard works produce the lowest at 0.3% and 0.7%. In absolute terms, the Façade group contributes the largest component option value (€94,453), driven by its substantial weight in the renovation budget rather than by a larger per-unit value. The OTM probabilities at T remain high across all components: above 91% in every case and effectively 100% for BKT.

Table 4.15. Aggregate financial valuation

		Value (discounted)
Totale option value	€	404.949
Total option value / total investment		1,13%
NPV Integral	-€	37.936.652
NPV Phased	-€	35.273.304
Expanded NPV Phased	-€	34.868.355
Value of Flexibility	€	3.068.297
Of which option value	€	404.949
Of which deferral effect (time-value)	€	2.663.348

At the aggregate level (Table 4.15), the integral strategy has an NPV of - €37.94 million, whilst the phased strategy yields - €35.27 million before the option contribution and - €34.87 million once the option value is added. The resulting value of flexibility is €3.07 million, equivalent to approximately 8.1% of the integral NPV. The decomposition into its two elements shows that the deferral effect contributes €2.66 million (87%) and the option value €0.40 million (13%).

Discussion

5

The model developed in this thesis quantifies one dimension of the renovation investment decision (the financial value of flexibility under construction cost uncertainty) within deliberately set boundaries. This discussion examines those boundaries critically, in order to make explicit what the model and the thesis cannot tell a corporation, so that the contribution of the model is located accurately within the broader decision space.

5.1 The scope of uncertainty

A first point of discussion is the choice of construction cost volatility as the single stochastic driver of the model. Renovation decisions in the Dutch social housing context are exposed to many sources of uncertainty: in addition to construction costs, the most prominent uncertainties are energy prices, the discount rate, regulations, subsidies, technology costs and tenant-side dynamics such as mutation rates. Each of these could in principle generate its own source of option value. Three of these alternatives were scoped at the proposal stage before the present uncertainty was settled. Energy price volatility was the initial candidate but was discarded once the first analysis showed that energy costs in Dutch social housing are borne by the tenant rather than by the corporation, which removes the channel from the corporate cash flow scope altogether. Regulation and subsidy-uncertainty was reviewed through the interview material, where interviewees framed this type of uncertainty as a corporate risk: one carried at the organisational level instead of the project level. Finally, the cost of technology was considered. This was a valid alternative, but construction cost uncertainty already absorbs technology cost movements to some extent through the same BDB renovation cost-index from which the model's volatility is calibrated: installations, photovoltaic systems and similar components are themselves part of the index's labour and material composition.

5.2 Component-level simplifications

Several interviewees observed that certain component groups require tenant displacement regardless of whether the work is integral or phased. The most prominent example is the BKT group: when this group has to be replaced, the dwelling becomes uninhabitable for the duration of the work, because these are the only such facilities the tenant has. Similar logic applies to works such as internal demolition that exposes structural elements. Under phased execution, these components still require temporary rehousing, although perhaps for shorter periods than under integral execution, but at non-trivial cost per dwelling. Several options regarding temporary sanitary facilities at the site were also mentioned by some interviewees as a solution, but in practice, this is rarely realised.

Furthermore, the model's binary treatment of relocation and rent loss (full cost and loss under integral, zero cost and loss under phased) therefore overstates the relocation-cost advantage of phasing. If the phased strategy were charged with a partial relocation cost for BKT execution (even at half the integral rate) the resulting reduction in the value of flexibility would be of the same order of magnitude as the base-case flexibility value itself. This indicates that the relocation-cost channel is one of the more vulnerable elements of the base-case verdict, and that a component-by-component treatment of relocation requirements would be a high-value refinement of the model.

5.3 Component independence and contractor logistics

The model treats the nine component groups as independent groups which can be renovated at the moment the technical lifespan demands. The interview material identified two real-world dependencies that this abstraction omits.

The first is physical interdependence. Replacement of façade insulation typically requires removal and reinstallation of the window frames; replacement of window frames requires re-tiling or re-painting of the surrounding interior; roof work may require temporary removal of solar panels. The optimal exercise moment for one component could therefore be constrained by the chosen moment for the components it interacts with, and the assumed independence per component overstates the achievable optionality.

The second is contractor mobilisation. The site setup, scaffolding, tenant communication, permits and project management are fixed costs that are incurred every time work starts. A phased strategy that spreads execution across many years pays these (partial) costs repeatedly, whereas an integral strategy pays them only once. The current model does not capture this: the costs of the component only depend on scope, regardless of how often the contractor returns to site. A refinement would add a fixed cost per renovation event, so that the model weighs the benefits of phasing against the extra mobilisation costs it generates.

5.4 Volatility

The calculation of the volatility relies on a single external index ranging from 2021 to 2026. The window is short by financial-market standards and has its own specific price movements that do not accurately depict long run price volatility. Therefore, the calibrated volatility can over- or understate the longer-run volatility of construction costs. A better calibration would draw on a longer time series spanning multiple economic cycles, and would cross-check the BDB result against alternative cost indices. It should be noted, however, that the volatility would have to change by a substantial amount (in the order of several tens of percent) before the moneyness of the options would shift in a meaningful way. The component-level options analysed here are deeply out-of-the-money at the horizon for both the fictional and existing case: the terminal ITM probabilities remain below 5% for every component and approach 0% for several. Modest recalibration adjustments of 2% or 5% therefore have only a small effect on the option values. This deep out-of-the-money result is the dominant feature of the configuration and should be kept in mind when interpreting both the absolute option values and their robustness.

A second (related) limitation concerns the empirical base on the case side: the fictional case is, of course, fictional, and the existing case is a single observation in a specific city. A broader empirical base with multiple case studies conducted would increase confidence in the generality of the findings.

5.5 Interpretation of different methods

In this thesis, two main calculation methods are combined in order to create the model that calculates the value of flexibility: the DCF method and the BOPM method. This is accompanied by a discount-rate asymmetry between the calculation methods. The BOPM uses the risk-free rate r under the risk-neutral measure, and the discounted cash flow scenarios use the WACC under the real-world measure. The combination is theoretically defensible: each side of the model is applied correctly within their ow respective frameworks. However, the asymmetry creates a presentational vulnerability, because a practitioner who is unfamiliar with the technical distinction between the two measures is likely to perceive the two rates as inconsistent. There is no methodologically clean way to use a single rate throughout the model whilst retaining the risk-neutral pricing of the option.

5.6 Practical implementation considerations

The model assumes that corporations can observe changes in renovation costs and respond accordingly and within a short timeframe. The interview material suggests that this assumption is optimistic. The decision-making process in many corporations is subject to bureaucratic lag: board cycles, tenant consultation rounds and procurement processes. These processes can create delays of months, if not years, between the moment when an exercise condition is met and the moment when execution begins; possibly resulting in a new change in renovation costs. Furthermore, exercising early during a downturn in construction costs would be optimal but would require the social housing corporations to commit capital ahead of a financial year in which other projects compete for the same funds.

5.7 Confidence in the conclusions

Taken together, the points of discussion set out in this chapter do certainly not invalidate the conclusions reported in §6, but they locate those conclusions within a specific zone of applicability.

The points of discussion do however show that the quantitative result from the model is more fragile than the results-section suggests. The base-case value of flexibility of approximately 1% of total budget is small relative to several of the parametric and structural revisions discussed above. For instance, the BKT relocation-cost adjustment alone is significant, and a more refined treatment of contractor mobilisation costs would shift the result in the same direction. This means that the direction of the result is reliable; its exact size is not. The appropriate way to use the model in practice is therefore as a structured exploration of the strategic space, not as a definitive financial calculation or guideline.

The methodological contribution (the extension of Real Options Analysis to mandatory-investment problems with timing flexibility within a finite horizon) is independent of the case-specific quantitative result, and is a durable output of the thesis. The model framework, the option-type framing, the component-level decomposition and the option-value/deferral-effect diagnostic are reusable in other application domains with appropriate recalculation. The principal contribution of this thesis should therefore be seen as the framework itself, not the exact headline numbers that the model produces.

Conclusion

6

This chapter draws together the findings of the literature review (§2), the methodological framework and interview data (§3), and the quantitative results (§5) in order to answer the research questions formulated in §1.2. The four sub-questions are addressed in turn, with each answer grounded in the specific evidence base most appropriate to it: SQ1 is mainly answered with reference to the literature and to the methodological reasoning of the model; SQ2 is answered with reference to the volatility-side sensitivity analyses in §4.2.1; SQ3 is answered with reference to the base case results in §4.1 and to the qualitative interview material; and SQ4 is answered with reference to the full set of one-way and two-way sensitivity analyses in §4.2 and §4.3. The main research question is then addressed in §6.5 as a synthesis of these four partial answers.

6.1 Application of Real Options Analysis to renovation decisions (SQ1)

SQ1: How can Real Options Analysis be applied to residential renovation investment decisions with renovation costs as the primary variable?

The Real Options literature is largely built around investments in which an actor holds the right but not the obligation to commit to a project. The standard reference is the deferral logic of McDonald & Siegel (1986)), in which the value of waiting arises from the ability to wait for favourable conditions before investing. This framework does not transfer directly to Dutch social housing: the corporation is not free to abandon the investment. The Housing Act maintenance obligation and the EFG phase-out under the National Performance Agreements (RVO, 2024) both impose a deadline, or horizon, within which the renovation must be executed. The question is therefore not whether to invest, but when and how, which is a different option-theoretic problem.

The model in Chapter 3 builds the framework around this when-and-how problem through four methodological choices: the option type, the underlying uncertainty, the level of decomposition, and the incorporation of the resulting value. The first of these is the adaptation of the McDonald & Siegel (1986) logic to the mandatory-investment setting; the others specify the inputs and outputs needed to make that adaptation operational.

The first is the option-type framing. The renovation programme is modelled as a series of American puts on construction costs with forced terminal exercise. The put-on-cost framing reflects the corporation's position as an obligated payer, for whom the right to act on favourable cost realisations carries the value. The American option-style reflects the ability to act at any annual node instead of only at a fixed expiration date. The forced-terminal-exercise constraint reflects the fact that the option cannot be abandoned at the horizon: at T=20, the renovation must be completed regardless of the cost level. This framing departs from the standard deferral-call logic of McDonald & Siegel (1986) and is the central adaptation needed to align option theory with the Dutch social housing context.

The second is the choice of the underlying uncertainty. Using construction cost as the stochastic uncertainty has an impact on the model in three ways. First, the variable is calibrated from observable data: log-returns on the BDB renovation cost index ranging from 2021 to 2026 give an annualised volatility (σ) across the nine component groups, and a drift (μ) of approximately 4.9% taken as the CAGR from the same series. Both parameters are estimated from data rather than assumed. Second, the renovation cost uncertainty enters the cash flow directly: the corporation pays the construction cost in full, so every movement in cost translates one-on-one into the renovation budget. Third, this type of exposure also fixes the option type: the corporation gains when costs fall, which corresponds to a put on construction cost.

The third is the level of decomposition. The renovation programme is split into nine component groups, with each treated as an independent option with its own σ, strike, and remaining technical lifespan. This decomposition reflects variation in remaining technical lifespans and in labour (w_i) to material composition. Treating the whole budget as a single option would hide this variation and mask which components matter most. Because the nine options are separable, their values can be added together (Trigeorgis & Reuer, 2017).

The fourth is the decomposition of flexibility value into an option-value component and a deferral-effect component. The option value is added to the phased strategy's NPV to produce an Expanded NPV, following Angelou & Economides (2009). The value of flexibility is then the difference between the phased E-NPV and the integral NPV. This split isolates the share of phasing's financial advantage that comes from optionality from the share that comes from spreading investment over time. As §4.1.3 shows, one can be negative whilst the other is positive, in which case the choice for phasing rests on the option-value alone. Without this decomposition, the distinction would be invisible to the corporation.

The answer to SQ1 is therefore that Real Options Analysis can be applied to residential renovation through a binomial-lattice model in which construction cost is the underlying stochastic variable, the programme is decomposed into component-level American puts with forced terminal exercise, and volatilities that are calibrated from an external cost index. This combination gives an interpretable framework that incorporates both the theory and workings of option pricing and the reality of the Dutch social housing sector.

6.2 The influence of cost uncertainty on the value of flexibility (SQ2)

SQ2: How does renovation cost uncertainty influence the value of flexibility in phased renovation strategies?

The two volatility-side sensitivity tables and graphs in §4.2.1 provide the answer. The first graph (*see* Graph 4.1) shows that the option value per component investment amount rises approximately linearly with the volatility, from less than 2% at the calculated base case to nearly 40% at $\sigma + 30\%$. The second graph (*see* Graph 4.2) shows that the risk-neutral probability of the cost path ending below the strike at the terminal node (in the money) rises from around zero at the base case to between 60% and 63% at $\sigma + 30\%$.

However, as discussed in §5.4, it is unlikely that the volatilities of the components will increase with the percentages seen in the sensitivity analyses. The volatilities calibrated from the BDB index fall within the 2.6% - 5.9% range, and a shift to the $\sigma + 30\%$ regime would require changes in the Dutch construction sector well beyond anything observed.

The answer to SQ2 is therefore that the value of flexibility in phased renovation strategies rises approximately linear with renovation cost volatility. Within a realistic volatility range for Dutch renovation costs, however, this mechanism translates into a modest option value contribution: cost uncertainty does influence the value of flexibility, but the level of that influence is bounded by the volatility range that the BDB data supports. The option value only becomes a dominant driver of flexibility under volatility that recent historical records do not justify.

6.3 The phased-versus-integral comparison in returns and risk (SQ3)

SQ3: How does a phased renovation strategy compare to an integral renovation strategy in terms of expected returns and risk exposure under renovation cost volatility?

The comparison consists of two aspects: phased and integral strategies differ both in their expected return profile (the difference in cash flows over the horizon) and in their risk exposure (the shape and timing of the corporation's commitment to investments). The model mainly addresses the return profile, and the interviews provide qualitative insight into the accompanying risks.

In expected return terms, the two strategies are nearly even under the calculated fictional case. The phased strategy yields a slightly higher E-NPV than the integral strategy, with a value of flexibility of approximately 1.4% of the total renovation budget. The decomposition in Table 4.2 shows the structure of this advantage: the option-value component is positive and quite large in size, while the deferral-effect component is mildly negative. In other words, pure postponement is unfavourable under base parameters: the combined extra investment cost due to construction cost inflation and delayed rental income exceeds the discounting benefit of phasing the investment. However, the option to act on cost developments generates enough value to compensate for this. The discussion in §5.2 elaborates on several variables that have a high one-sided impact on the net present values, meaning that the results can differ greatly case by case. It can therefore not be concluded that the integral strategy has a great structural advantage or disadvantage on the phased strategy; it is only at a disadvantage on the option value, where it has no value to offer.

In risk exposure terms, the difference between the strategies is better observed through qualitative data rather than quantitative data. The integral strategy commits the full investment in year zero and is therefore fully exposed to whatever the cost level is at that moment. The phased strategy retains the right, but not the obligation, to delay any individual component group within its own window in response to cost developments. The corporation is thereby exposed to cost variation only at the moment of exercise of each component option, not at one single point in time. This is the structural source of the option value, and optionality means, at its core, asymmetric risk exposure.

The qualitative interview material relates to this argument indirectly rather than directly. The professionals did not identify construction cost volatility as the main risk facing their renovation programmes. The more frequently mentioned uncertainties and risks were rising interest rates, investment-capacity constraints under the National Performance Agreements, and regulatory limits on rent increases. Where construction cost was discussed, the general view was that costs rise predictably rather than fluctuate up and down: several interviewees observed that they had not seen a sustained decline in construction costs in recent decades.

Phased execution, where it was discussed, was described as a response to budget capacity or as a way of preserving flexibility for unresolved technology choices such as possible future heat-network connections, rather than as a strategy for managing cost uncertainty.

The answer to SQ3 is therefore that under the fictional case, the phased strategy slightly outperforms the integral strategy in expected NPV terms, with the entire advantage coming from the option-value rather than from the deferral-effect. The risk under the low construction cost volatility and a sustained historic rise in costs can be described as low; interviewees mentioned that these aspects of construction costs makes them predictable. Phasing does provide an advantage when it comes to dealing with budget capacities or preserving the flexibility to implement future technologies together with renovation measures.

6.4 The conditions for outperformance (SQ4)

SQ4: Under what conditions does phased renovation financially outperform integral renovation, and vice versa?

The results in §4.1 indicate that the phased strategy is preferred for both the fictional case and the existing case, but it must be acknowledged that it does so with parameter uncertainties identified in Chapter 5. The full set of sensitivity analyses in §4.2 and §4.3 is therefore needed to establish the conditions under which either strategy outperforms the other. The conditions can be expressed through the one-way and two-way analyses.

At the one-way level, each parameter shifts the value of flexibility in a clear direction. Phased renovation outperforms integral renovation when any one of the following conditions strengthens: construction cost volatility (σ) rises, the cost of capital (WACC) rises relative to the inflation rate, the renovation cost inflation rate (μ) falls relative to the cost of capital, or the relocation costs per dwelling rise. Integral renovation outperforms phased renovation under the opposite conditions: low volatility (which lowers the option value), high inflation relative to the WACC (making deferral expensive), and low relocation costs (removing a one-sided penalty on integral execution). The risk-free rate (r) has impact through the option value in the phased strategy but with a much smaller magnitude than σ; the return rate in the integral strategy is the weakest of all parameters tested.

At the two-way level, the $\sigma \times \mu$ table in §4.3.1 demonstrates that, once volatility is sufficiently high, phased outperforms integral across the entire tested range of inflation rates, even when the deferral effect is unfavourable. The WACC × μ table in §4.3.2 demonstrates that, along the diagonal where the WACC is close to μ, the value of flexibility is positive. The two variables therefore have an impact on the comparison in the following way: volatility σ is the strategic parameter on the option value channel: when σ is high enough, phased wins regardless of the deferral effect. The gap (WACC - μ) is the strategic parameter on the deferral channel: when this gap is positive (WACC > μ) or even slightly negative (<1%), phased benefits from deferral; when it is negative, phased is penalised by deferral.

The answer to SQ4 is therefore that the conditions under which phased renovation financially outperforms integral renovation is governed by three structural variables: the renovation cost volatility σ and the gap between the cost of capital WACC and the cost inflation rate μ. The σ variable acts on the option-value channel and, when the variable is sufficiently high, dominates all other parameters; the WACC - μ gap acts on the deferral side and determines the size of the time-value contribution to the value of flexibility. In conclusion, phased renovation is preferred when σ is high and it is disfavoured when σ is low and the WACC - μ gap is strongly negative. Under the fictional case, the flexibility value sits in a ‘knife-edge’ region where the option value and the deferral effect are close to cancelling each other out. Here, secondary parameters such as relocation cost and mutation rate become decisive.

6.5 Answer to the main research question

Main research question: How does a phased investment approach compare to a single upfront renovation financially and in risk terms for Dutch social housing corporations?

Synthesising the four sub-question answers, the comparison can be stated as follows.

Financially, the two strategies are close to equivalent under the fictional case parameters, with a small advantage to phased renovation arising from the value of the option to respond to construction cost developments rather than from any intrinsic time-value-of-money benefit of postponement. The model decomposition into the option value and deferral effect shows that, under parameter values that are most representative of current Dutch social housing conditions, the deferral effect is unfavourable to phasing whilst the option value is favourable. The financial case for phasing (under the fictional case study) is therefore a real-options case instead of a time-value case: it depends on the recognition and quantification of the optionality within the model, not on the standard logic of discounting future expenditures. The size of the advantage is mainly a function of the volatility of the construction costs, and rises sharply as that volatility increases. Due to the low component-level volatilities calculated in the model, the occurrence of in-the-money is low at the horizon. This in turn is caused by a positive construction cost drift ($\mu \approx 4.9\%$), which pushes most realised cost paths above the initial strike. The option value advantage is therefore realised in only a small amount of futures, and should be weighed against the extra costs of phased execution, which are incurred regardless of how the cost path develops.

In risk terms, the difference between the strategies is the timing of the corporation’s commitment. The integral strategy commits to the full renovation cost in year zero; the phased strategy has the right to delay each component group in response to cost developments, exposing the corporation to cost variation only at the moment of each partial renovation rather than at one point. The interviews moderate the practical weight of this advantage: the professionals identified rising interest rates, investment-capacity constraints, and regulatory limits on rent increases as more pressing risks, and described phasing primarily as a response to budget capacity rather than to cost uncertainty. The asymmetric cost exposure is therefore real but bounded, and materialises in only a small amount of futures under the realistic volatility range.

The comparison does not give an unconditional recommendation for either strategy. Instead, it provides a conditional framework. In environments characterised by high renovation cost volatility and a cost of capital that exceeds renovation cost inflation, the phased approach is highly preferable. In an environment characterised by low cost volatility and an inflation rate that exceeds the cost of capital, the integral approach may be preferable. Most realistic Dutch social housing renovation programmes are likely to sit in the second environment, with volatilities between 2.6% - 5.9%, and with renovation cost inflation greater than the cost of capital. However, the financial preference between the two strategies depends sensitively on the configuration of all parameters.

The contribution of this thesis to the main research question has two sides. First, the work shows that the comparison between phased and integral renovation is conditional instead of absolute, and that it is mainly impacted by three variables: the construction cost volatility σ and the gap between the cost of capital WACC and renovation cost inflation μ. Second, the work shows that this conditional framework can be quantified using a binomial-lattice real options model that is calibrated to available cost-index data. The practical implications of these findings and the further direction of future research are developed in §6.6.

6.6 Implications and recommendations

The findings have implications at three levels: for corporate decision-making, for sectoral and policy actors, and for the academic literature.

The principal implication for individual housing corporations is that they should not select phased renovation in expectation of a substantial optionality premium. Rather, they should weigh that bounded premium against the parameters that the model and the interviews identify as more decisive for the outcome: among others the cost of capital, the renovation cost inflation rate, the relocation cost per dwelling, and the mutation and return rates. Still, a conventional single-NPV comparison understates phasing in environments with material cost uncertainty, but the present results indicate that, under realistic Dutch conditions, the gap between an NPV and an E-NPV comparison is unlikely to be the variable on which a renovation strategy is chosen.

For sector-level actors (Aedes, the Ministry of Housing, WSW), the interview material points to a collection of uncertainties that are not included in the current modelled volatilities, but that the professionals consistently identified as more pressing. Rising interest rates affect the cost of capital and the investment volume that a corporation can commit to. Regulatory limits on rent increases, especially the restrictions on passing energy-related improvements on to sitting tenants, further reduce the corporation-side benefits that can be realised with a renovation. These uncertainties affect whether a programme is feasible at all, rather than how it should be phased. Any sector-level intervention aimed at improving renovation outcomes for housing corporations is therefore likely to have a larger effect through these channels than through the renovation cost volatility channel that the option-pricing framework isolates.

For the academic literature, the principal implication is that the American-put-with-forced-terminal-exercise framing extends the methodology of standard real option literature to the class of investment problems characterised by mandatory investment with a finite horizon. Three directions for further research follow from this. First, the framework can be refined and extended to incorporate the additional risk channels that the interview material identifies. The most prominent option for this extension would be the implementation of the cost of capital as the stochastic variable, which would allow interest-rate uncertainty to enter the valuation individually or alongside construction cost uncertainty. Second, the framework would benefit from application to a broader set of case studies, covering projects of varying sizes, portfolios in different cities, and different sets of unique parameters, in order to test the generality of the results derived here. Third, the component-independence assumption could be adjusted by introducing cross-component dependencies to assess the robustness of the current method.

Two concrete recommendations follow. First, corporations considering phased renovation should not justify the choice primarily on optionality grounds under current Dutch volatility conditions. The more defensible justifications are the management of investment-capacity constraints, the preservation of flexibility for new technology implementations such as future heat-network connections, and the alignment of renovation moments with component-specific end-of-life dates. Second, sector bodies and researchers should jointly investigate the risk channels that the interviews identified as more pressing than construction cost uncertainty: in particular interest-rate uncertainty and the binding effect of the National Performance Agreements on investment capacity, and develop valuation tools that address these risks directly.

6.7 Reflection

This reflection engages with what the result actually means. The process of writing the thesis itself is treated briefly: the early reframing from energy price volatility to construction cost volatility, and the corresponding shift from a deferral call option to an American put with forced terminal exercise, was the single most consequential methodological decision of the project. It was the right choice in retrospect, but it cost time that might otherwise have been spent on case-study breadth.

The thesis began with the implicit hope that something new could be discovered: Real Options Analysis would reveal a substantial, previously underappreciated financial argument for phased renovation. That hope rested on the standard real-options intuition: where there is uncertainty and irreversibility, there is value in the right to wait. Construction costs are uncertain. Renovations are largely irreversible. The expectation should therefore be a meaningful number: an amount large enough to call for a re-examination of how Dutch housing corporations view renovation strategies. The model, however, returned a flexibility value of approximately 1% of the total budget, with important side-notes. Across the entire range of plausible volatilities calculated from the BDB index, the result remained modest; only under volatility regimes well beyond anything the Dutch construction sector has historically produced did phasing begin to look preferable on uncertainty-grounds alone.

Regardless of the final result, the research did its job. It asked a clear question, applied a method, and returned a defensible answer. A small flexibility value is still an answer: it places phased renovation in its proper conditional zone, and it warns practitioners against justifying the strategy on optionality grounds when the conditions for substantial optionality are not present. In that sense the scientific contribution is intact, but an interesting question opens up: if construction cost uncertainty is not the variable around which a corporation should organise its phasing decision, then what should it organise that decision around? This is the question on which the rest of this reflection turns.

The Dutch social housing sector operates under a dual mandate: financial viability and social return. The cost-minimisation logic is a constraint, not an objective. If that constraint is satisfied, that is, if the choice between phased and integral renovation is roughly financially equivalent, as the present model suggests under most realistic Dutch conditions, then the appropriate decision criteria are the criteria that increase the social return. Several deserve mention.

The first is the tenant experience of the renovation itself. The interview repeatedly mentioned the cost of disruption: temporary relocation to *wisselwoningen* or *logeerwoningen* for weeks at a time, the trouble of living through a phased renovation programme that returns the contractor to the building every few years, and the participation processes that are needed to get the renovation processes started. These are not just financial items. They are part of how a corporation relates to its tenants in practice. Choosing between phasing and integral execution on the basis of which approach produces less disruption, or distributes that disruption more fairly across households, is a criterion that a financial model cannot take into account.

The second is energy poverty and household resilience. Social housing serves a population disproportionately exposed to energy cost shocks (Llera-Sastresa et al., 2017). The model considered here treats energy costs as outside of the corporate cash flow because the tenant pays them (and that is technically correct) but the corporation's social mandate does not stop at its cash flow. A phasing decision that prioritises the worst-performing dwellings, or that sequences insulation works ahead of installation upgrades for the households that are most at risk of energy poverty, is a phasing decision made on social grounds. It does not have to be a financial argument.

The third is a long horizon. The thesis uses a twenty-year window, but other problems sit beyond that: climate adaptation in a country that is getting hotter and wetter, an ageing tenant population that needs suitable housing, biodiversity in residential neighbourhoods, and the next renovation cycle that will follow this one. Phasing decisions can be tested against these longer horizons rather than against a twenty-year cash flow, and the answers may perhaps be different.

None of these criteria can be quantified in the way option value can. That is the point. The contribution of this thesis is not a number that decides the renovation question, but a number small enough that the question can perhaps be decided on other grounds. When the optionality premium is large, it deserves attention; when it is small, the corporation can legitimately look elsewhere. An outcome of this research is therefore an invitation to look harder at the criteria the financial model cannot express.

The personal lesson is related. A thesis is, in this case, partly an exercise in learning to be wrong about what you expected to find, and to accept the result without trying to inflate it. The model returns what it returns. The work of building it correctly, calibrating it carefully, and reporting its output truthfully is what justifies it, in spite of the headline number. This is perhaps the most useful thing the project has produced: a demonstration that financial flexibility is not always where the value lies.

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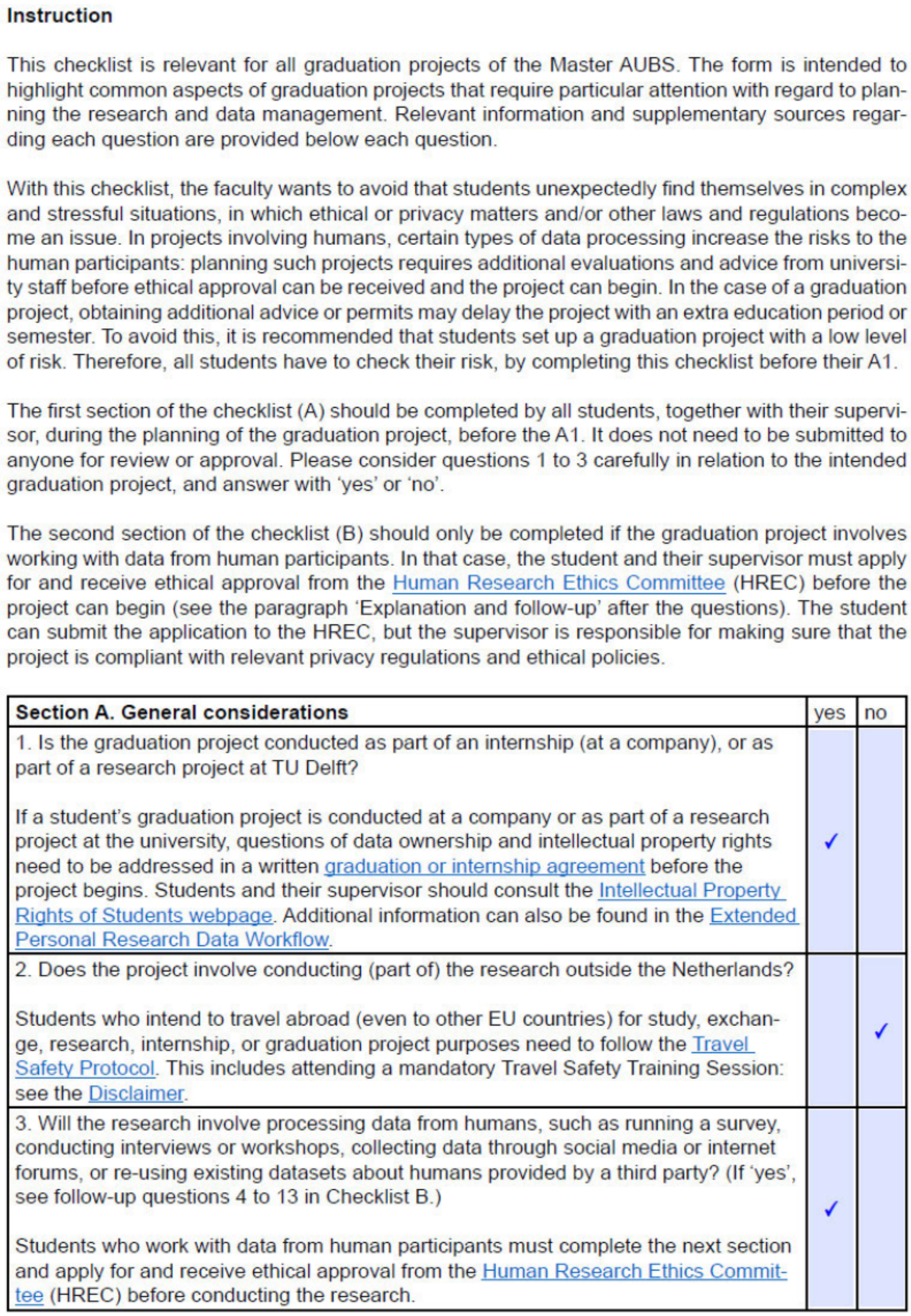
Appendix I | Data Management Checklist



Instruction

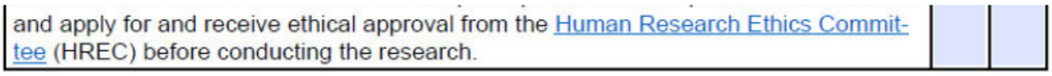
This checklist is relevant for all graduation projects of the Master AUBS. The form is intended to highlight common aspects of graduation projects that require particular attention with regard to planning the research and data management. Relevant information and supplementary sources regarding each question are provided below each question.

With this checklist, the faculty wants to avoid that students unexpectedly find themselves in complex and stressful situations, in which ethical or privacy matters and/or other laws and regulations become an issue. In projects involving humans, certain types of data processing increase the risks to the human participants: planning such projects requires additional evaluations and advice from university staff before ethical approval can be received and the project can begin. In the case of a graduation project, obtaining additional advice or permits may delay the project with an extra education period or semester. To avoid this, it is recommended that students set up a graduation project with a low level of risk. Therefore, all students have to check their risk, by completing this checklist before their A1.

The first section of the checklist (A) should be completed by all students, together with their supervisor, during the planning of the graduation project, before the A1. It does not need to be submitted to anyone for review or approval. Please consider questions 1 to 3 carefully in relation to the intended graduation project, and answer with 'yes' or 'no'.

The second section of the checklist (B) should only be completed if the graduation project involves working with data from human participants. In that case, the student and their supervisor must apply for and receive ethical approval from the Human Research Ethics Committee (HREC) before the project can begin (see the paragraph 'Explanation and follow-up' after the questions). The student can submit the application to the HREC, but the supervisor is responsible for making sure that the project is compliant with relevant privacy regulations and ethical policies.

Section A. General considerations	yes	no
1. Is the graduation project conducted as part of an internship (at a company), or as part of a research project at TU Delft? If a student's graduation project is conducted at a company or as part of a research project at the university, questions of data ownership and intellectual property rights need to be addressed in a written graduation or internship agreement before the project begins. Students and their supervisor should consult the Intellectual Property Rights of Students webpage. Additional information can also be found in the Extended Personal Research Data Workflow.	✓	
2. Does the project involve conducting (part of) the research outside the Netherlands? Students who intend to travel abroad (even to other EU countries) for study, exchange, research, internship, or graduation project purposes need to follow the Travel Safety Protocol. This includes attending a mandatory Travel Safety Training Session: see the Disclaimer.		✓
3. Will the research involve processing data from humans, such as running a survey, conducting interviews or workshops, collecting data through social media or internet forums, or re-using existing datasets about humans provided by a third party? (If 'yes', see follow-up questions 4 to 13 in Checklist B.) Students who work with data from human participants must complete the next section and apply for and receive ethical approval from the Human Research Ethics Committee (HREC) before conducting the research.	✓	



and apply for and receive ethical approval from the Human Research Ethics Committee (HREC) before conducting the research.

Section B. Extended risk factors (only if question 3 has been answered with ‘yes’.)	yes	no
4. Will the project involve participants who may be considered vulnerable, such as the elderly, refugees or asylum seekers, ethnic minorities, patients, or people with disabilities? Participants who may suffer very adverse consequences (for instance, due to discrimination) if their personal data became publicly available can be considered vulnerable.		✓
5. Will the project involve participants who cannot themselves give informed consent for taking part in the project, but for whom consent must be obtained from a legal guardian? Participants who cannot give informed consent can include, for instance, children or participants with intellectual disabilities, mental disorders, or dementia. Such participants are also considered vulnerable in the context of the General Data Protection Regulation (GDPR).		✓
6. Will the project involve processing any of the special categories of personal data below? - Race - Ethnicity - Criminal offence data - Political opinion - Union membership - Religious or philosophical beliefs - Sex life and/or sexual orientation - Health data (including measurements such as heart rate) - Biometric or genetic data (including fingerprints, iris scanning, facial recognition) The General Data Protection Regulation (GDPR) defines a stricter rules for processing special categories of personal data. If it is necessary to process these data in a project, it is it is important to provide additional safeguards.		✓
7. Will the project involve processing personal data that could be considered sensitive, such as the ones listed below? - Information about a person’s income, debts, or other payments - Information about a person’s (un-)employment status - Information about a person’s performance at school or work - Information about relationship problems or (gambling) addiction - Information about poverty, domestic violence, or youth welfare/social work involvement Some types of personal data are considered sensitive, because they can have a high impact on the privacy of the data subject if other persons gain access to these data. Sensitive personal data should only be processed if necessary: in such cases, additional safeguards need to be put in place.		✓
8. Will the project involve processing video-recordings, or photographs of participants? TU Delft considers photographic and video-materials of research participants to be sensitive personal data. If such data need to be processed, additional safeguards must be put in place.		✓

Section B. Extended risk factors (only if question 3 has been answered with 'yes'.)	yes	no
9. Will the project involve sharing or transferring personal data between multiple partners or collaborating organisations involved, such as between TU Delft and an internship company? According to privacy law, sharing personal data between organisations requires a privacy agreement to be in place: setting this up takes time, and requires support from additional university staff. Furthermore, personal data sharing can potentially expose research participants to different types of risks: these risks must be considered in the ethical application.		✓
10. Will the project involve deception, or covert observation of participants? In some types of research, obtaining informed consent for processing participants' personal data is not an option: for instance, if the research involves deception, or the research is covert (conducted without participants knowing about it). In such situations, the steps to mitigate risks to participants are important, and an alternative legal basis for processing the participant's data needs to be established with the help of additional support staff.		✓
11. Will the project involve working with social media data? Social media data are personal data, but since it is usually not possible to ask for informed consent for processing social media data, another legal basis for processing the participant's data needs to be established. Processing of social media data also involves legal considerations related to terms of use of data from third-party platforms: therefore, research with social media data requires expert support on privacy, ethics, and legal matters.		✓
12. Will the project involve using learning algorithms or other AI to analyse, combine, or otherwise process data from participants? The use of AI in research involves many considerations in terms of data protection, ethics, security, and intellectual property: for more information, see TU Delft's Instructions for use of Generative AI.		✓
13. Will the project involve participants who are based in a country or countries outside of the EU? Students affiliated with TU Delft must comply with Dutch and EU regulations of personal data processing (GDPR). Furthermore, the student and their supervisor must make sure that the research complies with local (privacy) legislations of any foreign destinations. Additional support from an external (local) expert may be required.		✓

Explanation and follow-up

If you have answered 'no' to all questions 4 to 13, your project is likely to be considered low or minimal-risk: see the paragraph 'Projects with minimal or low-risk' on the next page.

If you have answered 'yes' to one or more of the questions 4 to 13, your research likely involves extended or high risks to participants, according to the General Data Protection Regulation (GDPR) and TU Delft's privacy and ethical policies: for information regarding such projects, see the paragraph 'Projects with extended or high-risk' on the next pages.

Appendix II | Interview Protocol

1. Zou u kort uw functie kunnen omschrijven en wat uw dagelijkse werkzaamheden inhouden?
    a. Hoe lang bent u al werkzaam in de sociale huursector?
2. Heeft u in uw carrière ervaring opgedaan met de renovatie van sociale huurwoningen?
    a. Zo ja, kunt u aangeven om welke typen gebouwen het ging?
    b. Betrof het voornamelijk naoorlogse woningen *(1945–1975)*?
3. Heeft u ervaring met gefaseerd renoveren, dus het stapsgewijs uitvoeren van renovatiemaatregelen over meerdere jaren?
    a. Zo ja, kunt u een concreet voorbeeld noemen?
    b. Zo nee, is dit een strategie die binnen uw organisatie wordt besproken of overwogen?
4. Hoe wordt binnen uw organisatie bepaald welke woningen worden gerenoveerd en wanneer?
    a. Welke criteria spelen de grootste rol?
5. Welke financiële methoden of instrumenten gebruikt uw organisatie om renovatiescenario's te beoordelen?
    a. Wordt er gebruik gemaakt van netto contante waarde, terugverdientijd, of andere rekenmethodieken?
    b. Hoe wordt de disconteringsvoet bepaald?
    c. Worden er specifieke softwaretools of modellen gebruikt? *(bijv. Ortec Finance, Fakton, eigen modellen)*
6. In welke mate wordt onzekerheid of risico expliciet meegenomen in de huidige besluitvorming?
    a. Worden er scenario-analyses of gevoeligheidsanalyses uitgevoerd?
    b. Hoe gaat de organisatie om met het feit dat toekomstige energieprijzen, regelgeving en technologie onzeker zijn?
7. Wat is momenteel de voorkeursstrategie van uw organisatie: alles in één keer renoveren, of stapsgewijs over meerdere jaren?
    a. Wat zijn de belangrijkste redenen voor deze voorkeur?
8. Wat ziet u als de voornaamste voordelen van een integrale renovatie?
    a. En wat zijn de belangrijkste nadelen of risico's?
9. Wat ziet u als de voornaamste voordelen van een gefaseerde renovatieaanpak?
    a. En wat zijn de belangrijkste nadelen of risico's?
    b. Biedt gefaseerd renoveren volgens u de mogelijkheid om in te spelen op nieuwe ontwikkelingen, zoals dalende technologiekosten of veranderende regelgeving?
10. Welke hindernissen of barrières ervaart u bij het implementeren van een gefaseerde renovatiestrategie?
    a. Zijn er technische belemmeringen?
    b. Zijn er organisatorische of financiële barrières?

    c. Speelt draagvlak bij bewoners een rol in de strategiekeuze?
11. Kent u concrete gevallen waarin een corporatie spijt heeft gehad van de gekozen renovatiestrategie?
    a. Wat ging er mis en wat had achteraf beter gekund?
12. Welke renovatiemaatregelen worden doorgaans toegepast bij naoorlogse sociale huurwoningen met een slecht energielabel *(D–G)*?
    a. Kunt u aangeven welke maatregelen doorgaans als eerste worden uitgevoerd?
    b. Zijn er maatregelen die technisch gezien samen moeten worden uitgevoerd?
13. Hoe zou u de renovatiemaatregelen groeperen in logische pakketten voor een gefaseerde aanpak?
    a. Welk pakket zou u als eerste uitvoeren, en waarom?
    b. Welke tijdsintervallen zijn realistisch tussen de fasen?
14. Welke energielabelsprongen zijn realistisch per fase?
    a. Wat kost gemiddeld een stap van label D/E naar label B of A?
    b. Hoe verhoudt de kostenefficiëntie van de eerste fase zich tot die van de laatste fase?
15. In hoeverre beïnvloeden schaalvoordelen de keuze voor integraal versus gefaseerd renoveren?
    a. Zijn de kosten per woning aanzienlijk lager bij grootschalige integrale renovatie?
    b. Hoe groot schat u de extra kosten in bij gefaseerd renoveren?
16. Wat beschouwt u als de grootste onzekerheden waarmee woningcorporaties te maken hebben bij het nemen van renovatiebeslissingen?
17. In welke mate beïnvloedt de onzekerheid rondom energieprijzen uw renovatiebeslissingen?
    a. Wordt in uw organisatie rekening gehouden met verschillende energieprijsscenario's?
    b. In welke mate bepaalt de energieprijsontwikkeling de terugverdientijd van renovaties?
18. Welke rol speelt beleidsonzekerheid in de besluitvorming?
    a. Heeft recente beleidswijziging geleid tot aanpassing van de renovatiestrategie?
19. Hoe kijkt u aan tegen de onzekerheid rondom technologische ontwikkelingen?
    a. Verwacht u dat de kosten van warmtepompen, PV-panelen of isolatiematerialen significant zullen dalen in de komende jaren?
    b. Wordt er bewust gewacht met bepaalde maatregelen in afwachting van betere of goedkopere technologie?
20. Hoe kijkt u aan tegen de onzekerheid rondom renovatie kosten?
21. Als u de volgende onzekerheden zou moeten rangschikken naar impact op renovatiebeslissingen, hoe zou u dat doen?
        i. Energieprijzen
        ii. Beleids- en regelgevingsontwikkelingen
        iii. Technologiekosten
        iv. Bouwkostenontwikkeling
        v. Overig *(huurdersgedrag, rente, etc.)*
22. Welke disconteringsvoet hanteert uw organisatie voor investeringsbeslissingen in renovatie?
    a. Sluit deze aan bij de WSW-richtlijnen of worden eigen percentages gehanteerd?
23. Wat zijn naar uw ervaring realistische kosten per woning voor een integrale renovatie van een naoorlogse portiekflat naar energielabel A of B?
    a. Kunt u deze kosten ook uitsplitsen naar type maatregel?
    b. Hoe verhouden de kosten van een gefaseerde aanpak zich tot die van integraal?
24. Hoe schat u de energiebesparingen in na renovatie, uitgedrukt in kWh of euro's per jaar?

    a. Komt de daadwerkelijke energiebesparing overeen met wat vooraf werd voorspeld?
25. Hoe lang is de gemiddelde levensduur of exploitatietermijn die wordt gehanteerd voor renovatiemaatregelen?
    a. Verschilt dit per type maatregel?
26. Heeft uw organisatie ervaring met renovatieprojecten waarbij de kosten of opbrengsten aanzienlijk afweken van de verwachting?
    a. Wat waren de oorzaken van deze afwijkingen?
    b. Hoe heeft dit het besluitvormingsproces achteraf beïnvloed?
27. In mijn onderzoek pas ik Real Options Analysis toe: een methode uit de financiële wereld die de waarde van flexibiliteit (het recht om een investering uit te stellen, te faseren of aan te passen) expliciet waardeert. Bent u bekend met dit concept?
    a. Zo ja, in welke context bent u hiermee in aanraking gekomen?
    b. Zo nee: Hoe kijkt u aan tegen het idee dat het uitstellen of faseren van maatregelen op zichzelf financiële waarde kan hebben?
28. Denkt u dat een methode die de waarde van flexibiliteit expliciet meeneemt, nuttig kan zijn voor woningcorporaties?
    a. In welke situaties zou een dergelijke analyse het meest waardevol zijn?
    b. Welke barrières ziet u voor de adoptie van een dergelijke methode?
29. In het model vergelijk ik twee scenario's: een integrale renovatie in jaar 0 versus een gefaseerde renovatie. Vindt u dit een realistische vergelijking?
    a. Mist u scenario's of factoren die relevant zouden zijn?
    b. Hoeveel fasen acht u realistisch vanuit de praktijk?

Appendix III | AI Usage

In line with the disclosure requirements of Delft University of Technology, this appendix describes the use of generative AI tools during the process of this thesis. AI tools were used in three capacities: in the initial topic-exploration phase, in the refinement of academic language in the written report, and in the execution of repetitive calculations supporting the sensitivity analysis. All substantive content, methodological decisions, results, and conclusions in this thesis are the author's own.

Initial topic exploration. Before the research direction was settled, generative AI was used as a brainstorming partner during the early scoping of the topic. This included questions about which parts of ROA and renovation practice had received the most academic attention, and where the existing literature appeared to leave gaps. The outputs were treated as starting points for further reading rather than as academic sources, and every research direction that emerged from this phase was verified against the academic literature before being incorporated into the proposal.

Example prompts used in this phase:

- "What are the main trends in literature applying Real Options Analysis to building renovation, and where do the apparent gaps lie?"
- "Which institutional features of the Dutch social housing sector might be most relevant to a Real Options framing of renovation timing?"
- "What are the standard objections to applying option-pricing methods to non-traded assets such as housing stock?"

Language refinement. During the writing phase, AI tools were used to assist with the academic tone and clarity of selected passages that the author had already drafted in full. Suggestions concerning sentence structure, register, and concision were made. No conceptual content was introduced through these edits.

Example prompts used in this phase:

- "Suggest a more concise phrasing for the following sentence without changing its meaning: [sentence]."
- "Make the following sentence less messy and more academic: [sentence]."
- "Check whether this paragraph contains any spelling errors: [paragraph]."
- "Check whether this paragraph has a logical structure: [paragraph]."

Sensitivity analysis calculations. The most extensive use of AI in this thesis was computational rather than intellectual. The sensitivity analyses presented in Chapter 4 require the systematic re-running of the binomial-lattice model under a range of parameter combinations, and the population of the corresponding one- and two-way sensitivity tables. The design of these analyses (the choice of parameters, the ranges tested, the structure of the tables, and the interpretation of the results) was the author's own. The AI tool that was used for this is called Claude AI, and was deployed within the Excel file, with the BDB index removed. It was only used to execute the calculations within the Excel workbook: applying parameter combinations specified by the author and writing the resulting outputs into the appropriate table cells. This avoided the writing of a macro script within Excel or the manual transcription of several hundred values from the model into the sensitivity tables, a process that would otherwise have been mechanical and error-prone. No analytical judgement was delegated to the AI at this step.

Example prompts used in this phase:

- "Re-run the model with σ values of +5%, +10%, +15%, +20%, +25%, and +30%, and populate the corresponding cells in the sensitivity table."
- "Apply the parameter combinations from Table 4.3 to the model and enter the resulting flexibility values into the table."

AI tools were used as assistive instruments only, in the three ways set out above.