Uncovering the Value of Circularity

Real Option Valuation of Detachable Aluminium Façade Components

Master Thesis

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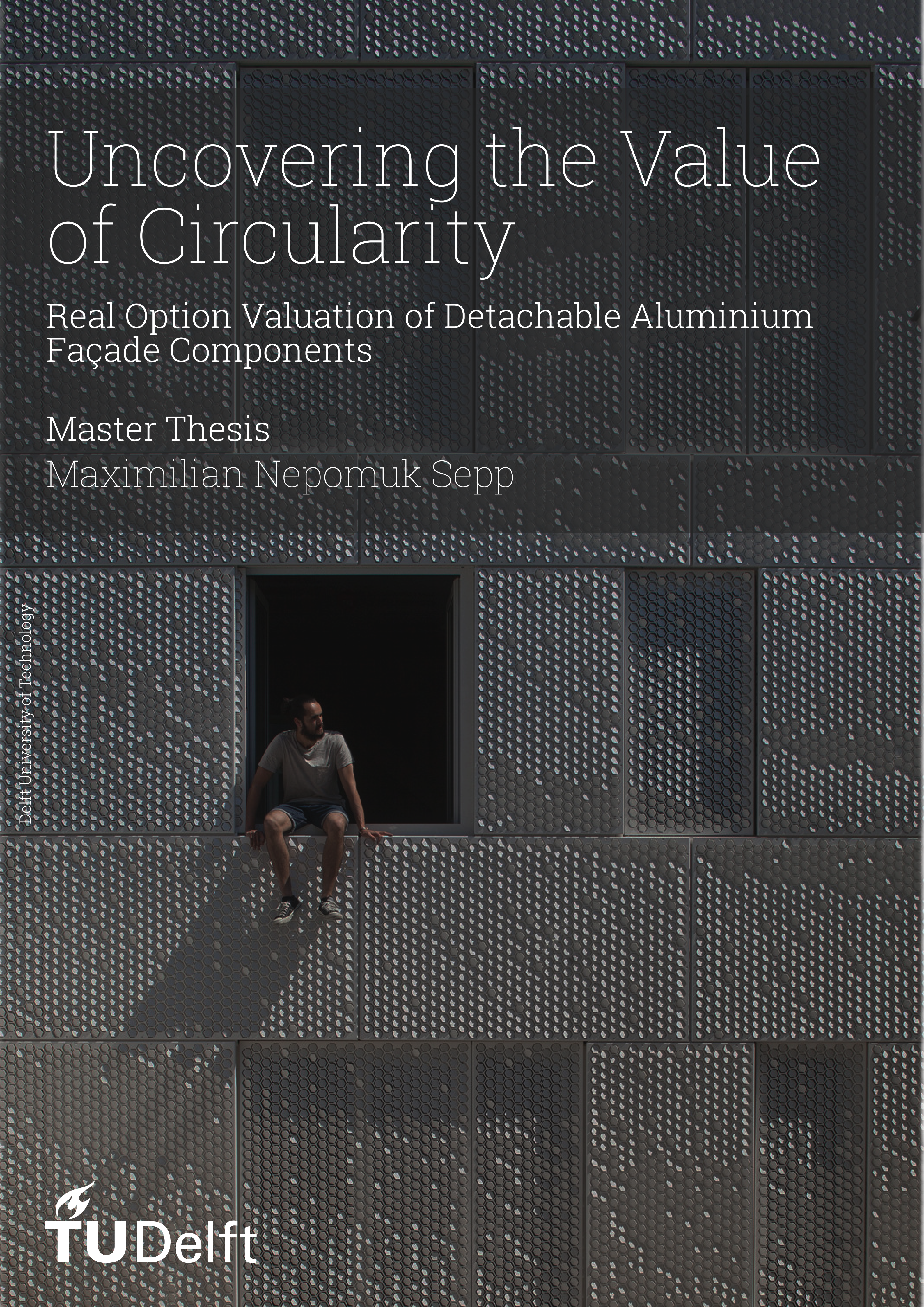

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by

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Abstract

This thesis explores the use of real option valuation to enhance the financial viability of circular real estate by valuing detachable aluminium façade components. The transition to a circular economy in the built environment is hindered by financial barriers: high upfront investment costs, and the absence of mechanisms to capture end-of-life value of building components. By applying option pricing models, including the Black-Scholes (1973) pricing model, binomial tree- and Heston (1993) option pricing, to a case study, this research uses aluminium commodity price data to value the option to recover raw aluminium embedded in a detachable façade system. A parallel qualitative study involving industry professionals assesses the willingness of market parties to adopt the researched valuation methods and to enter option contracts on detachable building components. Results indicate that real option valuation, as applied to aluminium building components, has the potential to fundamentally shift real estate valuation practices by introducing the concept of assessing buildings and components based on the "moneyness" of recovering embedded raw materials. In addition, by assigning a price to option contracts, this method enables both the demand side of building components to benefit from upfront cash inflows and the supply side to hedge against future material price volatility.

KEYWORDS – circular real estate | real options | valuation | raw materials

Preface

From the beginning, this thesis led me beyond familiar grounds. While challenging, this unfamiliarity became a source of motivation, encouraging me to learn along the way and take on a new academic journey after this wonderful project. What also kept me engaged was the sincere belief in the relevance and potential of the topic. Contributing a small part to an emerging conversation on rethinking real estate valuation has been a meaningful experience.

First and foremost, I wish to express my sincere gratitude to my mentors, Dr. ir. Michael U.J. Peeters and Prof. dr. ir. Vincent H. Gruis, who struck the perfect balance between encouraging exploration and guiding me to remain focused.

Drs. Maarten Donkers and Maurits Hilwig are gratefully acknowledged for their support throughout the research process and for providing the opportunity to gain meaningful perspectives through the internship.

Grateful thanks to Carl Caliva, Thomas Rothschopf, and Christos Zinelis for their support - in their own inimitable way.

I sincerely thank my family - my grandma Heidi, my parents Monika and Sebastian, and my sister Paulina - for always standing behind me and making this journey possible.

Lastly, I want to thank Leonie for being by my side every day with unwavering support.

Writing this thesis has been a deeply rewarding journey. However, I was reminded of how little graduation means when the life of a loved one is in danger. Although earning this degree might be my achievement, having my family witness it is a gift.

Maximilian Nepomuk Sepp
Delft, June 2025

Summary

Context

In March 2020, the European Commission launched the "Circular Economy Action Plan," aiming to enhance circularity in the built environment. In the same year, the COVID-19 pandemic disrupted supply chains and caused sharp increases in construction material prices, highlighting persistent price volatility as a major risk for the industry. While some perceive the EU's circularity agenda as a regulatory burden amid these pressures, it underscores the need to address material inefficiencies. Despite the significant value embedded in used building materials, real estate businesses have yet to fully seize this opportunity through circular practices and material recovery as a method to hedge against price volatility. EU regulations such as the "Critical Raw Materials Act" indicate that future material scarcity, especially for certain materials such as aluminium, will only intensify the need for a stable supply through used building components.

Hypothesis

This thesis identifies two key leverage points for unlocking the financial potential of circular real estate: reducing uncertainty around the end-of-life value of building components and integrating these benefits into initial investment calculations. These elements expose a critical disconnect between conventional valuation methods and the objectives of a circular economy. To bridge this gap, the thesis proposes a real options-based valuation method that enables the quantification of end-of-life value, incorporates expected material price volatility, and assigns an upfront value to circularity. This approach is designed to enhance the business case for circular construction by allowing option sellers to receive upfront payments and option buyers to hedge against future price and supply risks. Aluminium construction components were selected as the focus of this research due to availability of price data, high recyclability, anticipated future material scarcity, and environmental relevance. Analysing aluminium façade components is therefore providing a strong basis for testing the applicability and impact of real option valuation in the context of circular real estate opening up a path for broader research in the future.

Methodology

A parallel mixed-methods design was used, combining:

- *Quantitative Analysis: Application of three option valuation methods - Black-Scholes (1973), Binomial Tree, and Heston (1993) - to estimate the value of an option on a case study aluminium façade project. Each model was chosen based on different usability and underlying assumptions.*
- *Qualitative Analysis: Semi-structured interviews were conducted with professionals who are eligible to buy or sell an option on a façade or to finance a project where such an option is in place. An online workshop was held with a group of valuation professionals to present option valuation methods and to test potential application in real estate valuation reports.*

Key Findings

Two scenarios were analysed: a real-case based on actual project conditions, and a best-case with more favourable assumptions for strike price, volatility, and maturity. While the Black-Scholes (1973) and Binomial Tree models produced similar results, the Heston (1993) model yielded slightly lower valuations, reflecting a more stable outlook on aluminium prices. A key factor influencing valuation was the ratio of embedded aluminium value to recovery cost, which determined the option's "moneyness." Even under optimal conditions, option values accounted for only a small share of the total façade investment, as other cost factors remain dominant compared to the embedded raw material value of aluminium. Nevertheless, both scenarios demonstrate that real option valuation can assign an upfront value to material recovery at end-of-life. Assessing the "moneyness" of material recovery offers a practical method, however, the sensitivity analysis stresses that careful parameter selection is crucial, particularly when options are out of the money and more sensitive to input assumptions.

Consultation of industry professionals revealed a generally positive attitude toward the idea of incorporating option valuation to estimate the end-of-life value of building materials as an upfront value, especially in light of increasing concerns over future material scarcity. However, translating option valuations into contractual agreements is viewed as more problematic. Potential option sellers and financiers cited the open-end character of option contracts as an added risk while potential option buyers expressed the fragmentation of the material supply chain as a major barrier. This is because few actors can manage both material recovery, processing, as well as production and direct relationships with real estate owners.

Implications

In relation to the main research question

"To what extent can real option valuation enhance the business case for circular aluminium building components and subsequently circular buildings?"

real option valuation holds the potential to reveal how real estate valuation methods must generally evolve to define what truly constitutes a viable circular business case.

As applied to aluminium components in this thesis, real option valuation shows how the potential recovery of embedded materials can be priced. Translating this valuation into contractual agreements can benefit both supply and demand sides, whether by hedging against price volatility or enabling upfront financial gains. Most importantly, it may guide decisions toward a more circular and sustainable built environment.

Contents

List of Figures

Nomenclature

Abbreviations

Abbreviation	Definition
CBAM	Carbon Border Adjustment Mechanism
CE	Circular Economy
CRMA	Critical Raw Materials Act
DCF	Discounted Cash Flow
EU	European Union
MAD	Marketed Asset Disclaimer
NPV	Net Present Value
ROA	Real Option Analysis
ROG	Real Option Game
SCE	Sustainable Circular Economy

Symbols

Symbol	Definition	Unit
C	Option Value	[€]
d	Down-Factor - Binomial Tree	[Value]
$N(d1)$	Option Delta	[Value 0-1]
$N(d2)$	Risk adjusted Probability to expire ITM	[Value 0-1]
p	Risk Neutral Probability	[-]
r	Riske Free Rate	[%]
S	Current Asset Value	[€]
T	Time to Expiration	[years]
u	Up-Factor - Binomial Tree	[-]
v_0	Initial Variance	[-]
X	Strike Price	[€]
θ	Long-Run Average Variance	[-]
κ	Mean Reversion Speed	[-]
ρ	Correlation	[-]
σ	Volatility	[%]
σ_v	Volatility of Variance	[-]

1 Introduction

By publishing the ”Circular Economy Action Plan” in March 2020, the European Commission set a new agenda for transforming the built environment in Europe. The plan promotes measures to enhance circularity throughout the entire lifecycle of buildings and recognizes the pivotal role of the real estate and construction industry in the transition to a circular economy (CE), given that the sector consumes 50% of extracted materials and generates over 35% of the EU’s total waste (European Commission, 2020). In the same year the “Circular Economy Action Plan” was published, the construction industry in Europe was starting to feel the effects of the COVID 19 pandemic, which substantially influenced the entire supply chain and led to a significant price increase in construction materials (Haddad, 2022). The pandemic once again highlighted that enduring material price volatility is a consistent risk for market parties in the real estate and construction industry (Weidman et al., 2011), who are unable to take preventive measures. Although some may view the European Union’s circularity agenda as an additional regulatory burden in pursuit of sustainability goals, especially amid increasing pressures due to material price volatility, it underscores not only the need for sustainable real estate practices, but also the importance of addressing material inefficiencies. Despite a significant value embedded in used building materials, a considerable portion of this value is lost, and initiatives outlined in the “Circular Economy Action Plan” aim to tackle this issue by promoting material recovery measures. A report by Arup and the Ellen MacArthur Foundation (2020) estimates that the global material depreciation in the built environment accounts for approximately over two trillion euros of lost value each year, showing the significant financial potential in recovering the residual value of construction material. As EU regulations like the ”Critical Raw Materials Act” (CRMA) underscore the growing urgency of securing critical resources (European Parliament, 2023), material recovery and reuse may offer not only environmental benefits, but also a practical hedge against future supply disruptions.

Despite the opportunity to reduce dependency on material price volatility, businesses in the real estate industry have yet to fully capitalise on the residual value of pre-used building materials by adopting circular practices. This thesis explores how this gap can be addressed by strengthening the business case for recovering construction materials through the issuance of real options. It posits that creating options linked to the residual value of material embedded in pre-used building components - potentially tradeable on a secondary market - can enable market participants to hedge against price volatility while encouraging building owners and investors to embrace circular construction methods.

Employing a mixed-methods research approach, this study tested real option valuation techniques on case study data from a circular façade project to assess the applicability of existing pricing models to circular real estate. Quantitative findings from the case study are further contextualised through a series of semi-structured interviews and an online workshop with real estate valuation professionals, providing valuable insights into market parties' perspectives on option valuation of circular building components. Nonetheless, before the methods of this thesis are further explained, a comprehensive literature review will highlight current research on CE and real estate, as well as the status quo of circular real estate business practices showcasing critical barriers and enablers. In this context, an overview of real option theory and future outlook on raw material markets and policies within Europe will lead to this thesis hypothesis and research questions.

2

Literature Review

2.1. (SUSTAINABLE) CIRCULAR ECONOMY AND REAL ESTATE

The previously mentioned Circular Economy Action Plan puts the construction and real estate industry into critical focus for transitioning from linear to a circular economy and points to the sector accounting for approximately 40% of global green-house gas emissions (Larsen et al., 2022). This policy brief published by the EU establishes a direct link between environmental sustainability and the CE. Considering academic research such as the study by Nußholz et al (2023), which examined over sixty circular building cases in Europe, this link is certainly justified, as the study shows that circular approaches lead to a decrease in carbon emissions in new construction, renovation as well as demolition projects.

Nevertheless, the question of to what extent the circular economy supports environmental sustainability is still prevalent in academic research, which is demonstrated by Kirchherr et al. (2023) examining over two hundred different academic definitions of CE. Within this collection of CE interpretations they inter alia refer to the work of Blum et al. (2020), who showcase that a circular economy in the sense of enhanced resource efficiency does not necessarily lead to environmental sustainability in every case and can even cause negative environmental outcomes. To further clarify, Blum et al. (2020) introduce the concept of sustainable circular economy (SCE) as the intersection of environmental and economic benefits within the 'circular space' (Figure 2.1). Relating it back to the real estate sector and taking this definition into consideration, the transition from linear to circular real estate therefore should likewise aim at creating both environmental and economic value. Adding the latter as a prerequisite, Blum et al. (2020) follow the neoclassical growth paradigm arguing it is a prevalent precondition of the majority CE concepts (Blum et al., 2020). This thesis will similarly adhere to this approach and therefore considers economic value manifesting itself in the traverse from linear to circular real estate business models as a prerequisite for a functioning circular (real estate) economy. Considering the real option approach investigated, this can be seen as a fundamental assumption behind the application of option valuation theory to circular real estate cases.

While the environmental value of resource efficiency through decarbonisation, as it is being pursued with a circular real estate sector, is not a distinctive part of this literature review, it will further be brought up again in the context of raw material scarcity as part of the last sub-chapter. However, the following discussion will entirely revolve around economic factors, or more precisely, the transition from linear to circular real estate business. With this transition process being hindered by sector-specific barriers

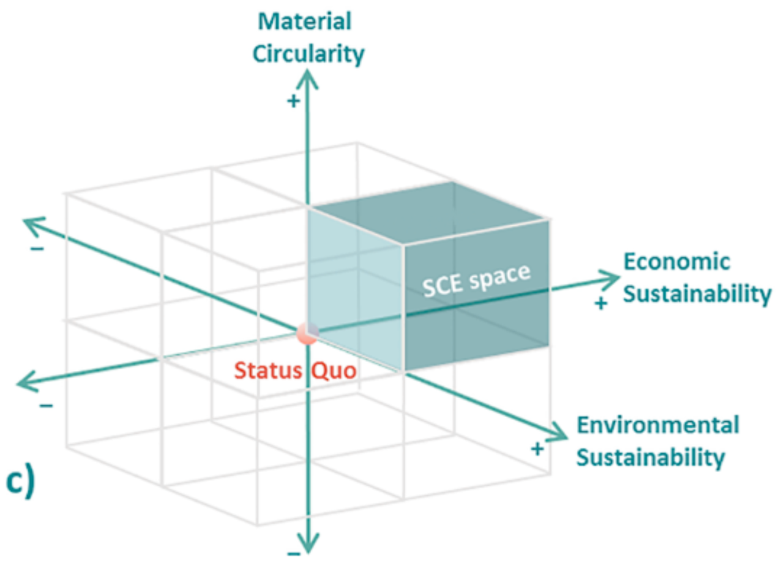


Figure 2.1: Sustainable Circular Economy Space (Blum et al., 2020)

that apply to the unique characteristics of the built environment (Hart et al., 2019), the subsequent paragraphs aim to provide a brief overview of the current state of research on hurdles implementing circular practices within real estate business practices. Ultimately, significant findings on enablers that could help overcome these barriers are discussed.

2.2. CIRCULAR REAL ESTATE BUSINESS: BARRIERS AND ENABLERS

2.2.1. Barriers – What is holding up Circular Real Estate Business?

Fundamental research has previously highlighted frameworks structuring and analysing what hinders the application of circular real estate practices in general. In 2018, the World Economic Forum presented a classification into four distinct categories: financial, social, institutional, and technological barriers. The proposal offers a comprehensive framework for addressing these challenges, including high transition costs, regulatory constraints, resistance to change, and the lack of metrics or infrastructure for circular processes, all of which demand innovative strategies and collective effort to overcome. Hart et al. (2019) not only outline barriers to implementing circular practices, but also identify enabling factors, grouping them into sectoral, regulatory, cultural, and financial categories. Highlighting more than 200 subcategories, their research points to cultural and financial challenges, such as limited supply chain collaboration and weak business cases, as key obstacles to a circular built environment. It becomes clear that fundamental categorisations have already been explored; however, a detailed analysis of each subsection would fall beyond the scope of this literature review. It is thus essential to set the focus towards a selection of barriers to better contextualise and comprehend the rationale behind the real option approach proposed in this thesis. In this regard, attention should be particularly focused on financial barriers.

Financial barriers to the circular economy in real estate and construction include high upfront investment costs for infrastructure and research compounded by low prices of virgin material and uncertain end-of-life values (Hart et al., 2019). These problems can be seen as core issues caused by the additional expenditure necessary to make a project circular, which are crucial but not necessarily unique to the real estate industry. However, as Adams et al. (2017) note, sector-specific issues, such as fragmented supply chain and competitive nature of the construction industry, pose significant additional challenges, with stakeholders highlighting concerns about the risks and costs associated with adopting innovative practices and business models such as leasing and performance-based contracts. Furthermore, Hart et al. (2019) argue that this short-term focus of the real estate business community, coupled with limited access to funding, hinders projects with broader social and environmental goals that go beyond the business as usual. Therefore, it is apparent that circular real estate practices not only face structural financial challenges inherent to the nature of circular business models, but are also significantly impeded by short-term thinking and a competitive business mindset. However, recent research also highlights a variety of enablers that offer promising opportunities to advance circular practices within the sector.

2.2.2. Enablers – Circular Real Estate Business Model Innovation

As previously highlighted, Hart et al. (2019) particularly emphasise the importance of financial hurdles in the application of circular practices in the built environment, compared to technical challenges. Supporting this view, Adams et al. (2017) report that although stakeholders recognise financial uncertainty and the lack of market mechanisms as major obstacles, they also identify the development of a clear and compelling business case as the most significant factor in enabling circular construction practices. Additionally, viable take-back schemes and the development of improved markets are viewed as major opportunities to advance circular business in the real estate and construction industry (Adams et al., 2017). This highlights the significant potential of not only solving financial barriers, but also rethinking existing business models. According to Zvirgzdins et al. (2019), this potential to improve existing revenue models is maximised when all stakeholders involved in the process perceive profitability and added value for their own purposes. At the same time, Haase et al. (2024) suggest to ultimately break down traditional roles identifying new stakeholder groups by using a stakeholder mapping approach in order to allow and develop new circular business models. Existing research therefore indicates that there is a high potential in distributed added value creating an equal incentive for all participants, while well-established processes must be rethought and stakeholder roles redefined.

The "status quo" of real estate business models shapes common work processes in the built environment and it is inevitably characterised by the respective legal frameworks that underlie business practices. Looking at the question of which possible circular business models can be better reconciled with existing legal structures, Ploeger et al. (2018) analysed the possibilities and restraints of different circular real estate business models within the legal context, specifically focussing on Dutch property law. Assuming that a lease-based business model is favourable for circular practices, their findings show that in numerous legal systems, components such as facades or windows are classified as fixtures, making their reuse within circular economy frameworks more challenging. To overcome these issues, models such as buy-back agreements and take-back schemes promoting reuse and recycling show greater potential, pointing to the need for alternatives to leasing concepts that align with circular economy objectives of reducing raw material dependency (Ploeger et al., 2018). However, while buy-back models have shown to potentially benefit both the suppliers and owners without legal constraints, multi-cyclic behaviour of materials beyond a single loop can still not be guaranteed within these business models (Ploeger et al., 2017). In summary, current research highlights that enhancing the business case for circular real estate presents a significant opportunity, particularly when profits are equitably shared among all stakeholders rather than concentrated on one side. However, achieving this requires redesigning business models and adopting a new understanding of participants in the real estate market.

2.2.3. Circular Real Estate Business Innovation and the Status Quo of Valuation Practices

As the previous section gave a brief look on current research on the barriers and enablers of transitioning to circular real estate business models, it has become clear that there is a demand for changing the short-term mentality of current practices by rethinking the way participants understand their role within the market. Yet, the work of Toxopeus et al. (2021) indicates that these efforts to innovate the real estate business are often hindered by limited access to debt financing. This is caused by the lack of pricing mechanisms for the residual value of circular assets, causing uncertainty and impaired transparency for financiers (Toxopeus et al., 2021). These common doubts about the feasibility of circular real estate projects bring the discussion back to two core financial problems mentioned before: high upfront cost and uncertain end-of-life values.

Common valuation practices such as the Discounted Cash Flow (DCF) method focussing on merely on construction cost, rental income, and exit yield combined with general depreciation methods neglecting the residual value of building components lead to this difficulty to justify circular construction (Franke, 2023). The way financiers and industry professionals currently analyse and evaluate buildings thus sheds light on the added cost and leaves the added value of circular construction in the dark, unable to quantify it. This leads to two main points of entry where changing practices has the potential leading market parties to realising the financial value behind circular real estate:

Changing valuation methods through:

a) Handling the uncertainty of building component end-of-life values

b) Incorporating end-of-life benefits into front-end investment costs

These two entry points mark the missing link between valuation practices established over decades of practice and the efforts to shift a whole economy sector from linear to circular. With the real option-based approach proposed in this thesis, a hypothesis is put forward to fundamentally rethink valuation processes by taking into account the end-of-life value of building material, quantifying and incorporating material price volatility and lastly and most importantly producing a numeric front-end value that can be incorporated into investment cost calculations.

The following section will further explain this approach and elaborate on the concept of real options, looking at the origin of the theory, presenting different approaches while discussing their use in practice, and finishing with an outlook on the relation between real options and real estate.

2.3. REAL OPTION VALUATION

„A real option can be defined as: „a right — not an obligation — to take an action on an underlying nonfinancial, real asset.“ (Kodukula & Papudeso, 2006). Applying the concept of real options to circular real estate could involve, for instance, an option granting the right to repurchase a building component at a predetermined price (the option's strike price) at a future date. Acquiring such an option would require the payment of a premium (Kodukula & Papudeso, 2006). The strike price of the option therefore quantifies the (estimated) end-of-life value of the circular building component, while the option premium represents a front-end added value of circularity.

Nevertheless, if one intends to apply this concept, the question naturally arises how to estimate the 'true' value of such an option. To address this, it is essential to recognise that the value of an option resides in the uncertainty and contingency of the decision made at that specific point in time, as the option provides flexibility and allows for delaying critical decisions until those uncertainties are resolved (Kodukula & Papudeso, 2006). Relating this back to the option on detachable building parts, uncertainty lies to a large extent within expected material price volatility and end-of-life value. With the increase in raw material prices being a fundamental assumption behind circular economy thinking (Ploeger et al., 2017), this thesis hypothesises that real options have the potential to identify this hidden value behind the added flexibility of circular construction enabling actors to hedge against price volatility. Toward the end of this literature review, a chapter on material scarcity will highlight the gaining importance of this hedging opportunities, relating it also back to environmental benefits associated with resource efficiency. The following section, however, first seeks to contextualise the hypothesis made by providing an overview of the theory on what option types exist, how real options can be priced, and to highlight the advantages and disadvantages of real option valuation compared to other valuation methods. The relationships between parties involved in the process of buying and selling real options will be explored with a short excursus on real option game theory before research on the connection between real option theory and real estate is discussed.

2.3.1. Real Option Types in the Context of Circular Building Components

Before designing and formulating a possible real option scenario for a circular building component it needs to be clarified which option style is potentially applicable. Common styles for real options are European and American options which are differentiated by the specific time-point when the option can be exercised (Kodukula & Papudeso, 2006). Given that triggering an option on a critical building component, such as a façade, may render the building partially or fully non-functional, the expiration date becomes a crucial factor. European options are characterized by a fixed maturity date where the option can be exercised (Kodukula & Papudeso, 2006) and therefore are well applicable to the scenario of a circular building component as the fixed time-point of exercising of the option leaves certainty for the option seller when to expect deconstruction of the building component. This is not the case, however, with American style options where triggering the option is possible at any time before the options expiration date (Kodukula & Papudeso, 2006). An American option on a building component would imply that the option seller has to expect deconstruction at any point in time until the option expires potentially disrupting the buildings functionality. Facing this problematic use-case as well as added complexity of valuation calculations, American style options will not be applied to case study data or researched in the context of this thesis. Still, even with a fixed maturity date (European

Option) the impact of recovering a building component while the building itself might remain in use must be assessed as option sellers need to consider dismantling the entire building or re-investing in order to replace the missing component to maintain building functionality.

Having established the applicability of European options as well as the problematic nature of American style options implemented on detachable building components it stands to reason to go one step further beyond the classic option styles into which is commonly considered as “exotic options”. Interpreting all possible exotic option styles would certainly exceed the boundaries of this thesis, however, specifically “Asian Options” deserve to be further investigated in the context of this research:

“The term Asian option is used for a financial option on the value of the arithmetic average of some underlying asset during a prespecified time interval.” (J. A. Nielsen & Sandmann, 2003, p. 449)

In order to write an Asian option on a detachable building component, it is necessary to calculate the arithmetic average of the component’s value, which requires establishing a clear method for valuation prior to creating the option contract. While valuation methods for financial assets are typically straightforward and transparent, real assets present multiple possible valuation approaches. One possibility could involve calculating the value of raw aluminium in a façade based on the average price of aluminium over a prespecified period. Even with this approach overlooking the functional value of the façade component, given the anticipated high volatility of raw materials such as aluminium, Asian options, allowing to hedge against price movements, may offer a distinct advantage over traditional European options, particularly when a market participant is heavily reliant on a specific commodity price (J.A. Nielsen & Sandmann, 2003). For a company specialised in detachable aluminium façade modules, an Asian option on buying back modules at an average aluminium price over a specified time span is therefore a certainly conceivable scenario. Aluminium, used here as a representative example, will serve as the central focus of this thesis, which will further be explained in a later subchapter. Before that, the following section outlines the valuation methods for European and other options, as identified in existing literature.

2.3.2. The Origin of Real Option Analysis Theory

The DCF method, introduced in the 1950s, represented a sophisticated approach to project valuation and became widely adopted with advancements in technology that simplified financial calculations (Brandao & Dyer, 2005). However, methods like DCF, overlook the value of flexibility and heavily discount for external uncertainties as most investments can often be delayed, modified, or divided into strategic phases (Carlsson & Fuller, 2003). While the DCF method still remains the standard tool, real options analysis (ROA) theory, developed from the foundational work of Black & Scholes (1973) and Merton (1973), does account for managerial flexibility (Brandao & Dyer, 2005) being critical for navigating uncertainties, such as fluctuating market conditions or technological advancements (Carlsson & Fuller, 2003). ROA complements rather than replaces the DCF method as decision trees and simulations are often integrated into the process that incorporate the investment cost and asset value derived from a “traditional” DCF analysis (Kodukula & Papudeso, 2006). Since the groundwork has been made in the 1970s, ROA theory has evolved to facilitate and to adapt to practical application and advancements in computational technologies forming different approaches (Brandao & Dyer, 2005; Copeland & Antikarov, 2005) which will be discussed in detail later. The key advantage of all these ROA approaches, however, lies in its ability to create dynamic models that not only provide quantitative predictions but also adapt to changing conditions. ROA can inter alia facilitate the valuation of investment projects and related contingent claims through replicating portfolios, akin to financial options pricing (Lambrecht, 2017). Additionally, ROA is able to bridge financial and strategic thinking and empowers managers to evaluate available options to make optimal decisions in the face of economic uncertainty (Lambrecht, 2017).

It becomes clear that in view of the objectives of this thesis, one can draw upon decades of research on real option analysis, which has undergone continuous development. Nevertheless, even though the theoretical advantages of ROA are beyond doubt, when examining the practical application of ROA, research shows that few managers fully leverage these benefits by formally applying ROA methods (Lambrecht, 2017). A study conducted by Block (2007) found that just over fourteen percent of respondents utilized real option analysis, citing several barriers: insufficient support from top management, the dominance of discounted cash flow as a well-established method, the perceived complexity of real options and concerns that their use might promote excessive risk-taking. Borison (2005) highlights the pervasive confusion surrounding real options analysis, attributing it to fundamental inconsistencies and contradictions among existing methodologies, which often result in conflicting outcomes and lead some practitioners to dismiss the approach entirely. Lambrecht (2017) argues that sophistication of ROA can lead to overconfidence in results, with insufficient attention paid to the accuracy of assumptions and input data. Ergo, it is evident that ROA shows clear limits in practical application connected to its complexity and the multifaceted nature of different approaches which will be discussed in detail in the following section. When determining how to price and analyze options for circular real estate, especially with it being a novel concept in an environment where market participants might have limited knowledge on option theory, it is essential to address this limitation to ensure the method is both applicable and effective. The following paragraph will dive deeper into the analytical practice of ROA and provide a short overview of calculation approaches to value real options based on Kodukula & Papudeso's (2006) and Borison's (2005) work to not only contextualize the methods chosen to be applied within the research framework of this thesis but also show the variety of possibilities ROA entails. The discussion on the development of real option theory concludes with a concise excursus into its connection to game theory.

2.3.3. Real Option Analysis: Calculation Methods and Valuation Approaches

Kodukula & Papudeso's (2006) categorise ROA calculation methods in three groups being partial differential equations, simulations and lattices. The partial differential equations method calculates option values by describing how market variables affect option pricing, with the Black-Scholes equation being the most notable solution for the case of European options. Simulations, similar to Monte Carlo valuation techniques, model the potential paths of an asset's value over the option life. This method is well-suited as well for European options with fixed exercise dates (Kodukula & Papudeso, 2006). Lattices (e.g. Binomial Trees) map out possible asset values over time, using up- and down-factors based on volatility. Binomial lattices are commonly used as they allow for backward recursion to determine option values. Out of the three calculation approaches the partial differential equation (e.g. a Black Scholes equation) is the simplest to conduct and can be done quickly with a handheld calculator, however this approach also lacks in visually mapping out the logic behind the process while the other approaches follow a comprehensible chain of calculations (Kodukula & Papudeso, 2006).

Now that the basic analytical “toolbox” of real option analysis is introduced the question remains which approach to follow applying these tools regarding the concept of real option analysis of circular real estate proposed in this thesis. To answer this question, the work of Borison (2005) can be considered as it introduces and compares a variety of possible ROA approaches.

The classic approach to real options builds on principles from financial option pricing theory, applying them to evaluate real investments. At its core, this method relies on the no-arbitrage assumption and the concept of a replicating portfolio, where a traded portfolio mimics the returns of the real option under consideration (Borison 2005). In his paper Borison (2005) argues that the assumption of a replicating portfolio is rarely tenable for real investments like manufacturing plants, research and development projects and also real estate. For attempting to price an option on a detachable building part, it can therefore be assumed that finding a correlated portfolio of traded assets that precisely replicates the returns of that option is similarly difficult. The possibility of relating to a replicating portfolio therefore needs to be considered before choosing a method testing to value circular real estate options.

The subjective approach to real options still uses replicating portfolio/no-arbitrage arguments and standard financial tools like Black-Scholes but replaces market data with subjective estimates for valuation inputs. It therefore simplifies data gathering by relying on expert judgment to estimate investment value and volatility, making it easier to implement than the classic approach (Borison 2005). As the market for detachable building components is in its infancy it can likewise be assumed that calculation the value of an option on such building-parts might require subjective estimates. The Marketed Asset Disclaimer (MAD) approach extends the progression of option valuation methods by discarding the reliance on a replicating portfolio (Borison 2005). This method is rooted in the premise that a project’s Net Present Value (NPV) is the best proxy for its market value if it were traded and it allows the use of real options analysis even when no market analog exists (Borison 2005). In case that the use of a replicating traded asset proves to be not possible utilizing the projects “traditional” NPV as a proxy could therefore potentially be taken into account justifying the decision to acquire an option on circular building parts or not. Lastly, the integrated approach addresses investments by acknowledging the coexistence of systemic risks (market-related, hedgeable) and ideosyncratic risks (corporate-specific, unhedgeable). This approach integrates methods from finance theory (real options) and management science (decision analysis) to evaluate investments more comprehensively and is according to Borison (2005) the most suitable for practical application, however also involves the biggest work load and highest degree of complexity.

It is evident that a diverse range of calculation methods and strategic approaches is present in theory for evaluating real options, each grounded in distinct conceptual frameworks and varying in sophistication and precision.

This literature review has thus far highlighted that valuing circular real estate options requires a careful consideration of the interplay between systemic and ideosyncratic risks. Recognizing the risks stemming from company-specific decisions and the actions of other stakeholders serves as an important addition to viewing real options on circular real estate components exclusively through the lens of price developments. Indeed, it can be assumed that the process of trading options on detachable building components involves a diverse group of stakeholders, each influencing the development trajectory of the real estate project in unique ways. The methods section of this thesis will delve deeper into these dynamics, presenting a stakeholder model that maps out the possible interconnections and potential influences among the various agents involved in a circular real estate option contract. However, to fully grasp how stakeholder actions in the trading of these options could affect the value of other stakeholders' options, it is necessary to take a further step—exploring the theoretical link between Real Options Analysis (ROA) and Game Theory.

2.3.4. Real Option Analysis & Game Theory

"In standard real options models, investment (and exercise) strategies are formulated in isolation, without considering the potential impact of other firms' exercise strategies. Agents are assumed to be perfectly informed, and the exercise of one agent's option is assumed to have no impact on the value of other agents' options." (Grenadier, 2000)

This quote by Grenadier (2000) illustrates why for the intent of this thesis to test real options on circular real estate it is necessary to consider the connection between ROA and Game Theory. The trading of real options on building components would require the involvement of at least two parties, each exerting influence on the process and consequently influencing the value of the option. A "standard" Real Options Game (ROG) describes a framework for evaluating investment decisions, often involving two firms competing over a single project (Azevedo & Paxson, 2014). The strategies employed in these models typically revolve around a zero-sum framework, meaning one firm's profit directly reduces the other's (Azevedo & Paxson, 2014). In the case of trading real options on circular building components it is surely debatable if this standard ROG is applicable, however, possible scenarios need to be considered with game theory offering a theoretical framework as it provides the foundation for analysing ROGs by identifying players (the firms), strategies (invest or defer), and payoffs (value functions). The characterisation of the game also includes the level of knowledge (complete or incomplete) and information (perfect or imperfect) available to players, the type of game (zero-sum, sequential or simultaneous) (Azevedo & Paxson, 2014). In particular, in contrast to zero-sum assumptions, circular business models may enable the creation and sharing of value among stakeholders, suggesting the potential relevance of cooperative game theory. The work by Savva & Scholtes (2005) suggests a framework for real options in partnership deals based on cooperative game theory investigating the effects of optionality on partnerships, a theoretical perspective that shows interesting parallels to the hypothesis proposed by this thesis.

Current game theory may not deliver a perfectly aligned real option game model tailored to the context of circular real estate option trading; nevertheless, it provides a robust theoretical foundation for designing such a model. However, doing so will go beyond the scope of this thesis, which is why the research will be conducted on a scenario that does not take into account the effects of competition in acquiring an option on a building component. This will be further detailed in the methods section. To close this sub-chapter on real option theory, an examination of the current state of research on the connection between real options and real estate will be presented.

2.3.5. Real Options and Real Estate

Real estate investments are marked by limited liquidity (Rocha et al., 2007), and the investment value depends on uncertainties such as material delivery, labour, and financing, which can cause delays but also offer opportunities (Ng & Björnsson, 2004). Lucius (2001) was one of the first to highlight the potential of considering these uncertainties and the value of flexibility and risk in real estate investment evaluation investigating the connection of real option theory and real estate developments. Research by Vimpari (2014), Ford et al. (2002), and Mintah et al. (2018a) underscores a key insight: Traditional valuation methods often overlook latent value in real estate projects. This can lead to undervaluation and missed opportunities which ROA can help uncover and address. Moreover, Vimpari (2014) emphasises the capability of ROA to enhance the life cycle analysis of real estate projects. Rocha et al. (2007) further highlight that the applicability and benefits of ROA are particularly pronounced in emerging markets, where elevated levels of uncertainty and risk prevail.

The possible applicability and feasibility of ROA for real estate investments have been researched over the last decades, producing positive evidence, however, showing parallels to general real option theory, practical application is limited, and traditional valuation methods are used more dominantly (Mintah et al. (2018). A circular real estate business model introduces a greater degree of flexibility through the detachability and interchangeability of building components. A factor that makes the use of ROA in such cases reasonable to investigate. At the time of this thesis, no research specifically addressing the application of ROA to circular real estate is available. Nonetheless, existing studies on the impact of ROA in material procurement and real estate with flexible interiors indicate promising outcomes:

Ng and Björnsson (2001) demonstrated that applying ROA in construction material procurement offers significant financial advantages by enabling flexibility in purchase volumes at predetermined prices. Similarly, Kim and Kim (2016) introduced a real options-based framework for evaluating purchase decisions of construction materials that are subject to high price volatility, highlighting a selection process that yields enhanced financial outcomes. Furthermore, Mintah et al. (2018b) illustrate that ROA reveals the added value of architectural flexibility in their analysis of Australian residential property developments.

These findings underscore the potential influence of real options on circular business models, particularly in valuing flexibility within multicyclic flows of construction materials. Having predominantly explored the added flexibility of circular real estate as a rationale for applying ROA, the following chapter will turn to another key factor: the rising volatility of material prices.

2.4. MATERIAL SCARCITY AND PRICE VOLATILITY: A FUTURE OUTLOOK ON ALUMINIUM

As the previous paragraphs shed light on real option theory including option types, calculation methods and research on real options applied in the real estate industry, this last section aims at drawing a line between both option theory and the discussed barriers hindering circular real estate business innovation. By sketching a future outlook on material scarcity and material price volatility, this discussion will not only put an even bigger emphasis on the economic relevance behind the option approach investigated, but furthermore come back to the potential environmental impact of efficient raw material flows. At this point, it should be noted that this thesis follows a European perspective discussing material scarcity in the context of European Union (EU) regulations and the dependency on raw material suppliers outside of the EU.

2.4.1. Aluminium as a Replicating Portfolio for Options on Building Components

In the first chapter of this literature review two main missing links between valuation practices and the efforts of shifting to circularity in real estate and construction have been identified, with one being the handling of uncertainty of end-of-life values. As Toxopeus et al. (2021) indicated this inconclusiveness around valuation methods is inter alia caused by a general lack of pricing mechanisms for circular building components. The analysis on real option valuation in the second chapter explained, how with an option, an underlying tradable asset is used to replicate a portfolio and therefore a pricing mechanism for the asset in question. On the assumption that there is not yet a market mechanism in place for a circular building component as tradable assets, one would thus need to resort to (tradable) raw materials embedded within the building component and utilise raw material price data as a replicating portfolio. This approach could then be conducted for each single component and possibly combined to estimate a value for the entirety of the building.

As the procedure based on raw material value is not addressing the functional end-of-life values of building components, it may be also considered to subjectively estimate this functional value taking into account possible reuse opportunities to go beyond (just) the raw material value. However, the subjective nature of this approach, again, causes uncertainty and a lack of transparency in the valuation process. Given that only limited academic research is available on the applicability of real option theory to circular real estate in general, fundamental investigations should therefore start at analysing the use of raw material prices as an underlying traded asset leaving different perspectives on how to determine other replicating pricing mechanism as an extension for further research.

This thesis will therefore apply option valuation methods based on raw material embedded within circular building components, specifically using aluminium as a commodity serving as an underlying traded asset. Other raw material types were likewise considered, however, four critical factors led to addressing aluminium specifically:

- Aluminium presents significant potential for advancing circular strategies, as it can undergo repeated reuse and recycling processes without compromising its mechanical integrity (World Economic Forum & McKinsey & Company, 2023).

- Aluminium Price Data such as the “London Metal Exchange Official Price” is publicly available for primary and secondary aluminium as well as hedging transactions (London Metal Exchange, 2025).
- Aluminium (combined with Bauxite and Alumina) is considered as a strategic and critical raw material under the EU Critical Raw Materials Act (European Parliament and Council of the European Union, 2024).
- A significant potential to reduce CO_2 emissions caused by construction aluminium through circular measures by up to eighty nine percent by 2050 (World Economic Forum & McKinsey & Company, 2023).

To summarise, these factors being the potential for reuse, availability of price data, material scarcity and environmental impact make aluminium a suitable starting field of research for investigating option valuation of circular building components. In addition to the remarks given above including that pricing data is available and there is generally high potential of aluminium to be reused, it should be reiterated why material scarcity plays a decisive role in the context of this research. As already explained in detail, a real options value resides in the uncertainty and contingency of the decision made at a specific point in time, meaning that under higher uncertainty the value of the option is likewise increasing. With aluminium as a commodity there are multiple factors that justify the assumption that the supply of raw material will become more uncertain and prices are expected to fluctuate to a greater extent.

2.4.2. Aluminium, a Scarce Material? A Future Outlook

As mentioned above, aluminium is considered a strategic and critical raw material under the EU Critical Raw Materials Act (CRMA) (European Parliament and Council of the European Union, 2024). With this regulatory framework, the EU aims to list materials that are vital to its economy and its green and digital transition, yet are limited and concentrated in supply, acknowledging the risks posed by rising demands and geopolitical tensions:

“The general objective of this Regulation is to improve the functioning of the internal market by establishing a framework to ensure the Union’s access to a secure, resilient and sustainable supply of critical raw materials, including by fostering efficiency and circularity throughout the value chain.” (European Parliament and Council of the European Union, 2024, p.17)

After bauxite, the ore necessary to produce aluminium, was already listed as a critical raw material in the predecessor of the act in the year 2020 (European Commission, 2020), aluminium was not included in the first proposal of the CRMA published in March 2023 (European Commission, 2023). The step of omitting both bauxite and aluminium was highly criticised by industry parties (Home, 2023) leading to the addition of both and the intermediate production form of alumina shortly after the introduction of the CRMA in November 2023 (European Parliament, 2023). This decision reflects the severity and growing importance of aluminium for the strategic economic sectors of the Union. A research report by the European Commission analysed that aluminium is the only critical raw material used in all of these key industry branches (Carrara et al., 2023), where it should be noted that construction was not considered as a strategic sector in the scope of the report. Carrara et al (2023) moreover expect the overall demand of aluminium within the EU to increase from about three hundred twenty tons per year in 2020 to over two million tons in 2050 for these critical sectors only. For the construction industry, the demand

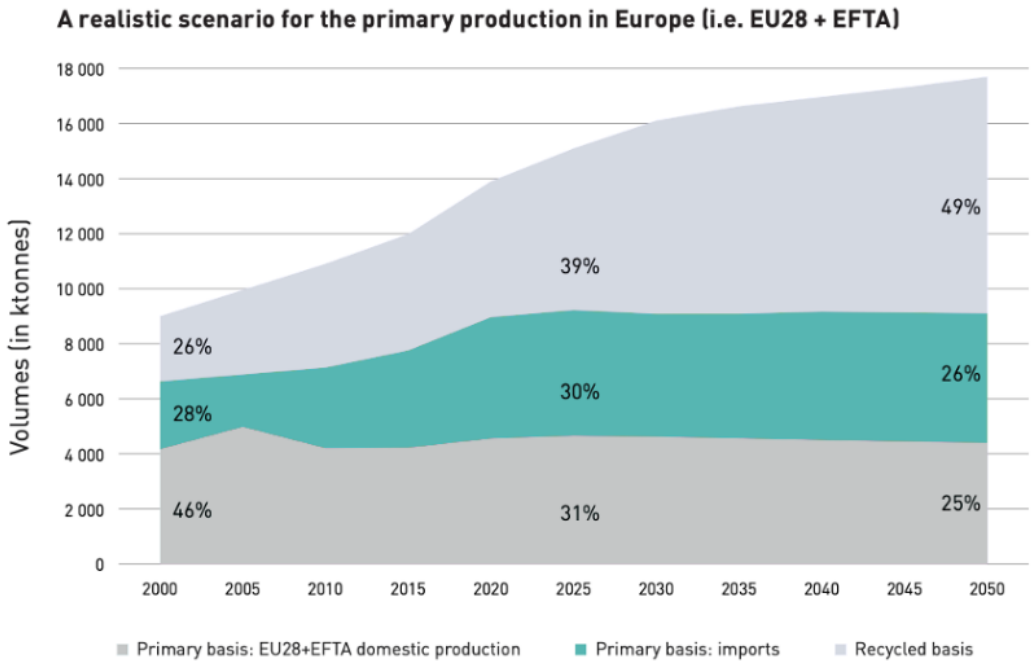


Figure 2.2: Projected primary Aluminium Production (European Aluminium, 2019)

for semi-fabricated aluminium is set to grow by twenty-eight percent by the year 2050 (European Aluminium, 2019). Therefore, it is evident that aluminium will play a progressively vital role in numerous sectors considered strategically important by the EU, even though the construction industry may not be explicitly included in this group. Nonetheless, beyond the general rise in demand, aluminium is also expected to likewise become increasingly significant in the construction sector, raising the question of how this growing demand will be met and how priorities will be set to supply different industry branches. In 2019, 'European Aluminium' projected, as shown in Figure 2.2, that the production of European primary aluminium (EU28 and EFTA) will remain relatively stable until 2050, with imported aluminium maintaining a similar level, while it is expected that the growing demand will be met primarily through increased supply of recycled aluminium (European Aluminium, 2019).

However, in Figure 2.3 it becomes clear that European primary production has already sunk to only supplying seven percent of the total share in 2023 due to high energy prices with an increase in net imports to meet demand (European Aluminium, 2025).

This development underscores the dependence of the European Union on external countries and the sensitivity of the market to geopolitical dynamics. In March 2025, the European Commission responded by launching the European Steel and Metals Action Plan, the urgency of the issue being made clear from the very outset of the proposal: " (…) the situation is already more worrying in aluminium (46%) and nickel (25%), especially considering the projected high growth in demand by 2030 for aluminium, copper and nickel." (European Commission, 2025a). Next to ensuring affordable energy prices for the industry and promoting circularity by retaining scrap metal and establishing recycling content requirements, a key point of the action plan is the prevention of carbon leakage through the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2025a). CBAM is a tool, with full implementation planned for 2026, set to ensure imported carbon-intensive goods are subject to the same carbon costs as EU-produced goods to prevent that EU based industries shift production to third countries with lower

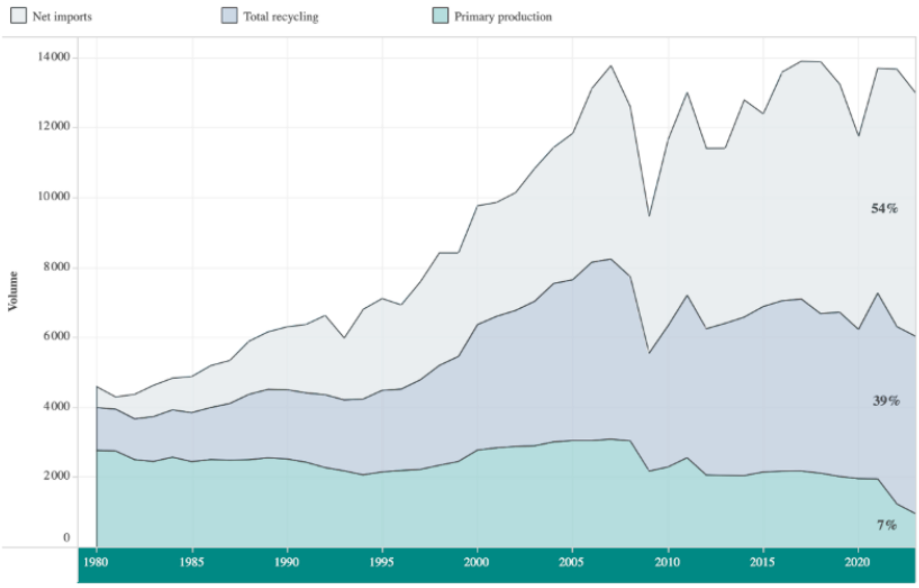


Figure 2.3: Dropping European Primary Production of Aluminium (European Aluminium, 2025)

carbon related standards (European Commission, 2025b). It can therefore be expected that aluminium importers will have to pay a fee under CBAM to equalise the lower carbon costs, possibly leading to overall price increases.

In conclusion, the European Union anticipates a substantial increase in aluminium demand due to its critical role in the majority of strategically important industries. The construction sector, possibly absent from this classification, may be disproportionately disadvantaged, as it competes for access to a material that is increasingly prioritised elsewhere. Addressing this rising demand will require significant enhancement of recycling capacities within the EU, as domestic production alone is expected to be insufficient. The resulting imbalance between supply and demand is likely to contribute to upward price pressure and market volatility, further intensified by policy instruments such as the CBAM.

Considering the projected future in which aluminium becomes an increasingly scarce resource, particularly in the construction sector while also serving essential functions in other strategic industries, the potential value of securing material from existing building stock through holding an option contract becomes evident to an even greater extent. As outlined earlier, in option valuation methods, this is reflected, where greater volatility, uncertainty, and anticipated price increases lead to a higher option value. The uncertain future sketched in this chapter underscores the relevance of testing these valuation methods on a circular construction case to determine the potential of a practical application of real option contracts, while it is still assured that structure and method follow scientific principles. Before the structure and method of the research conducted in this thesis are further elaborated in the methods section, a last subchapter will discuss the environmental impact of circular material flows referring to aluminium specifically.

2.4.3. Aluminium: the Environmental Impact of Circular Material Flows

CBAM was named as one factor potentially influencing aluminium price developments within the EU, yet, with Carbon Taxation another aspect should be discussed, moreover drawing the line between the expected scarcity of aluminium, the shift to a Europe-centred supply chain and the overall environmental impact caused by these changes. By the year 2024 globally thirty nine countries have implemented a carbon tax system including the Netherlands with a price of 66.50€ per tCO_{2e} (World Bank, 2025) and, being comparatively carbon intensive, aluminium products are expected to be significantly affected:

Comparing aluminium elements with other construction materials like showcased in Figure 2.4 it becomes apparent that they hold the unwanted spot at the top of the pyramid with high global warming potential values of 10.7 $CO_{2\ eq}$ / kg for aluminium sheets and 5.41 $CO_{2\ eq}$ / kg for aluminium frame windows. The carbon-intensive nature of aluminium products combined with a carbon taxation system therefore is expected to, again, influence price movements, potentially leading to long-term price increases.

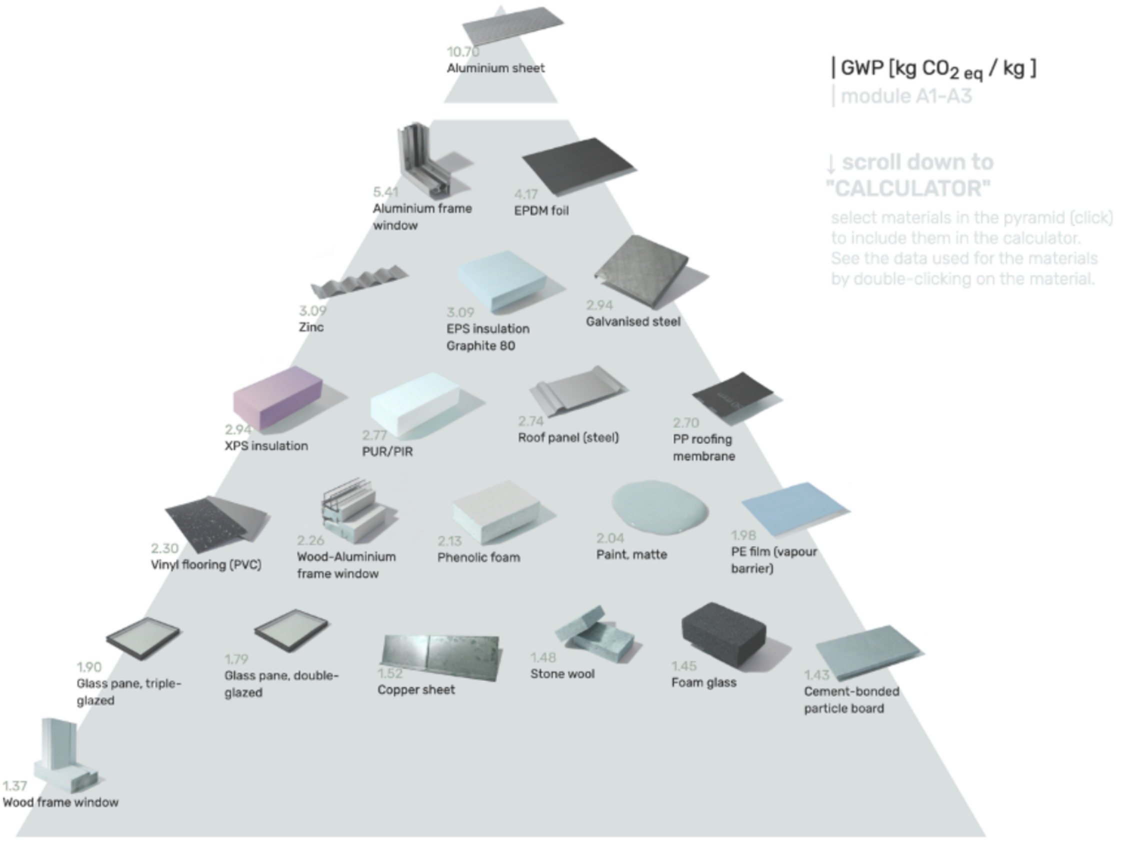


Figure 2.4: Global Warming Potential Pyramid – Selected Construction Materials (CINARK, 2025)

Therefore, it is established that aluminium construction elements show a high global warming potential, yet aluminium is the material often referred to as "green" or "green metal" as it contributes to environmental sustainability through direct means, with recycling, and indirect effects, such as, for example, reducing vehicle weight (Ferretti et al., 2007) having a decisive role in green energy technology or the automotive industry (Home, 2023). Nevertheless, it is essential to critically assess whether a material with such considerable global warming potential should retain, or even expand, its significance in future industrial and policy agendas. This, moreover, refers back to the beginning of the literature review, where the concept of the sustainable circular economy was discussed, asking the question what verifiable environmental impact will the shift to circular material flows (in the case of aluminium) have. Recent research by Specker et al. (2025) provides an in-depth analysis of this question, presenting a notably positve outcome:

"The findings indicate that shifting aluminium supply to domestic EU sources and enhancing recycling capacity can significantly reduce environmental impacts—particularly in terms of global warming potential, energy use, and water ecotoxicity—when viewed through the lens of EU footprint." (Specker et al. 2025, p.5) Numerically, the report of Specker et al. (2025) estimates that this impact for the aluminium industry will be a reduction of more than seven million tonnes of $CO_{2\,eq}$ per year or even more in a longer-term scenario. From a European perspective, a clearly positive impact can be expected but also globally for construction aluminium implementing circularity measures is estimated to potentially reduce CO_2 emissions by sixty two percent up to eighty nine percent by the year 2050 (World Economic Forum & McKinsey & Company, 2023).

2.5. A REAL OPTIONS APPROACH TO CIRCULAR REAL ESTATE

Prior to articulating the hypothesis of this thesis, it is essential to revisit the foundational concept of the SCE, as proposed by Blum et al. (2020), which situates itself at the intersection of economic and environmental value creation. The preceding section of this literature review explored the environmental dimension of circular material flows, with a particular focus on aluminium, and thereby established the rationale for the potential environmental benefits underpinning the investigation conducted in this thesis. The core of the literature analysis, however, focused on economic dimensions, emphasizing the financial barriers to implementing circular real estate business models. Notably, high initial investment costs and the uncertainty surrounding residual values at the end of the building life cycle emerged as particularly significant challenges. Subsequently, these challenges were addressed through an introduction to real options theory, which included an overview of its origins, option types, valuation methodologies, and its applicability within real estate practices. This provided the conceptual foundation for the methodological approach adopted in this research. In addition, the selection of aluminium as the main focus material was justified by examining projected scenarios of resource scarcity and price volatility, both of which underscore the relevance of incorporating option valuation into future real estate decision making.

2.5.1. Hypothesis

This thesis identifies two key leverage points for unlocking the financial potential of circular real estate: addressing uncertainty in end-of-life values of building components and integrating end-of-life benefits into initial investment calculations. These aspects highlight a critical gap between traditional real estate valuation methods and the circular economy goals of the real estate sector. Through a real options-based framework, this thesis proposes a fundamental reconsideration of valuation practices, enabling the quantification of circular construction components end-of-life value, the implementation of expected material price volatility and the incorporation of an added circularity value into upfront investment calculations.

The proposed approach is expected to enhance the circular real estate business case, while added value is shared amongst stakeholders involved through providing upfront cash in payments on the option seller side and the ability to hedge against price volatility and uncertainty of material supply on the option buyer side. Due to four key factors being, the availability of price data, the recyclability and reusability, expected material scarcity and environmental potential aluminium construction components were selected to be used as focus point of this fundamental research to set a clear research framework. Consequently, the following main research question and sub-questions are formulated:

2.5.2. Research Questions

Research question:

To what extent can real option valuation enhance the business case for circular aluminium building components and subsequently circular buildings?

Sub-questions:

SQ1: To what extent can real option valuation methods be utilised to value circular aluminium building components and be integrated in circular building valuations?

SQ2: To what extent can real option valuation of circular aluminium building components incentivise market parties to adapt circular practices in the construction and real estate industry?

SQ3: To what extent are market participants willing to BUY real options of circular (aluminium) building components?

SQ4: To what extent are market participants willing to SELL real options of circular (aluminium) building components?

3 Methodology

This section aims to illustrate the methodology applied to answer the research questions starting with a general description of the research paradigm and design. The different steps are then further discussed in individual sub-chapters.

3.1. RESEARCH PARADIGM AND DESIGN

As to the multifaceted nature of the proposed research question and sub-questions, this thesis follows the paradigm of pragmatism. Shifting the focus from abstract debates about reality to the practical interaction between beliefs and actions, pragmatism emphasises inquiry as a dynamic, context-driven process (Morgan, 2014). The flexibility in the use of theory and data collection allows one to follow a mixed-method research approach and provides an ideal framework for exploring and using preliminary hypotheses within a dynamic problem-solving process (Casula et al., 2020). To explore the financial applicability of real option valuation methods on circular aluminium components on one side and researching market-parties' willingness to adapt these methods on the other side, pragmatism serves a suitable model as it grounds itself in a purposeful inquiry aimed at addressing real-world problems (Casula et al., 2020). Subsequently, to test the hypothesis of this thesis, a convergent parallel mixed method research approach (triangulation) will be followed (Figure 3.1). This approach was selected ensuing the paradigm of pragmatism as the research question encompasses both qualitative and quantitative elements, and the hypothesis introduces a novel perspective that demands a robust and multifaceted research design to ensure valid interpretation.

Formulating the hypothesis that the selling of real options can enhance the business case for circular economy practices in the real estate industry, the research follows a deductive logic of inquiry (Blaikie & Priest, 2019) basing the hypothesis on general real option theory. Yet the exploration of a single case study and qualitative analysis of market parties' willingness to incorporate real option valuation as well as to buy and sell real options adds an exploratory logic of inquiry. The approach of this thesis can therefore be characterised as exploratory deductive. Casula et al. (2020) suggest working with adaptable hypotheses following this combined logic of inquiry serving as testable statements shaped by the research question and evaluated through action. Therefore, were the hypotheses of this thesis subject to change and were adapted following the progress of the research.

In preparation of the research a relational diagram will be introduced showcasing a scenario where a real option on a circular building component is sold.

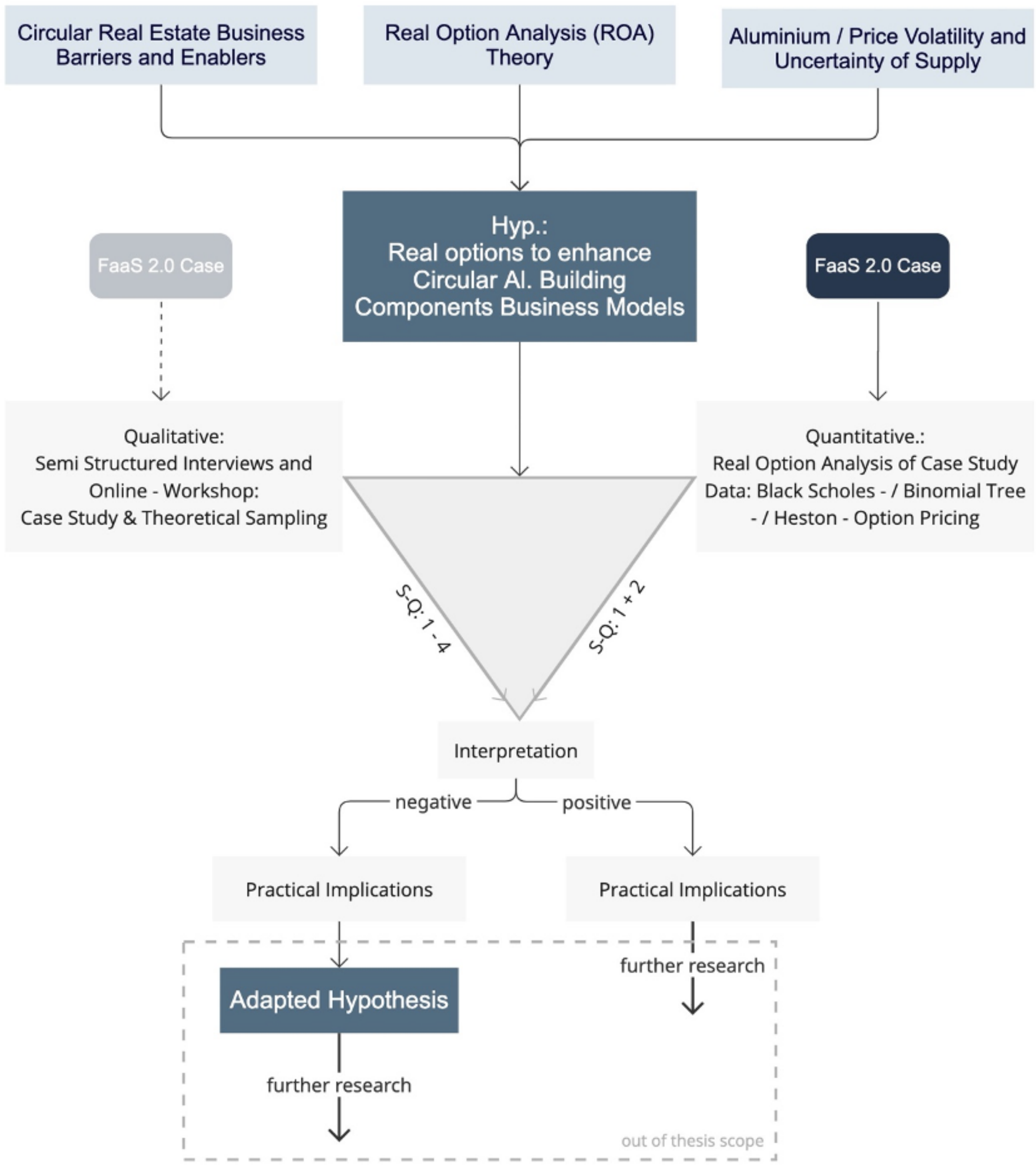


Figure 3.1: Conceptual framework of research design (own illustration)

As showcased in Figure 3.1 the research will be conducted in a parallel manner separated into quantitative and qualitative sections. Using a quantitative method while following a deductive logic to test hypotheses, it is recommended to operationalise concepts, collect relevant data, and analyse relationships through calculative techniques (Blaikie & Priest, 2019). This will be accomplished by applying three distinct real option valuation methods to the case study data, each varying in complexity and based on different assumptions. These approaches will be thoroughly examined in the section dedicated to quantitative data analysis. The qualitative section of the thesis entails a set of semi-structured interviews as well as an online workshop, which will likewise be further detailed in the corresponding subchapter.

In line with the exploratory deductive framework of this research, both the quantitative and partially the qualitative sections will focus on a single case study: the ”Facade as a Service 2.0” project, a collaboration between the Technical University of Delft and the companies CISKIN / Alkondor. Due to the uniqueness of the case being a detachable aluminium facade project with detailed data sets of material quantities and types available, it allows for in-depth testing. Since the research focusses more on the general applicability of real option valuation methods and less on a definitive assessment of the feasibility of this application, the decision was made to exclude the possibility of an empirical multi-unit study. The feasibility of real option application is inherently case-specific and thus warrants further investigation. Nevertheless, it can be anticipated that meaningful insights may be derived even from the analysis of a single illustrative case. To further support this, when useful variance across multiple units is unavailable or inadequate as is for circular aluminium component cases, single-unit studies such as single case studies can often yield more compelling insights (Gerring, 2004). Therefore, does the ”Facade as a Service 2.0” project serve as an ideal case study for the context of this research.

Additionally, regarding to the qualitative section of the research does the graduation internship at the Real Estate Finance Department of Rabobank serve as an opportunity to get access to connections to industry professionals in real estate finance and commodity trading, as well as other industry branches through the vast client network of the bank.

Table (3.1) gives an overview on the two parts of the investigation and the main data sources:

Research Part	Research Method	Research Design	Main Data Sources
a)	Quantitative	Embedded Single Case-Study	Case Study Data Sets + Material Pricing Data
b)	Qualitative	Embedded Single Case-Study + Theoretical Sampling	Semi-structured Interview Protocols + Online-Workshop Survey Protocols

Table 3.1: Overview Research Method, Design and main Data Source (own illustration)

3.2. REAL OPTIONS ON CIRCULAR BUILDING COMPONENT: A CALL OPTION SCENARIO

To lay the groundwork for both the quantitative and qualitative research of this thesis, a short section will identify key participants in a scenario in which real options are applied to circular aluminium building components. This analysis begins with the development of a real option relational diagram showcasing the general functional connections of the option scenario followed by a stakeholder analysis trying to identify stakeholder groups matching these relations and mapping out stakeholder interest and power.

3.2.1. A Scenario for a Real Option on Circular Aluminium Façade Components

Figure 3.2 presents a relational diagram for a call option on a detachable aluminium building component:

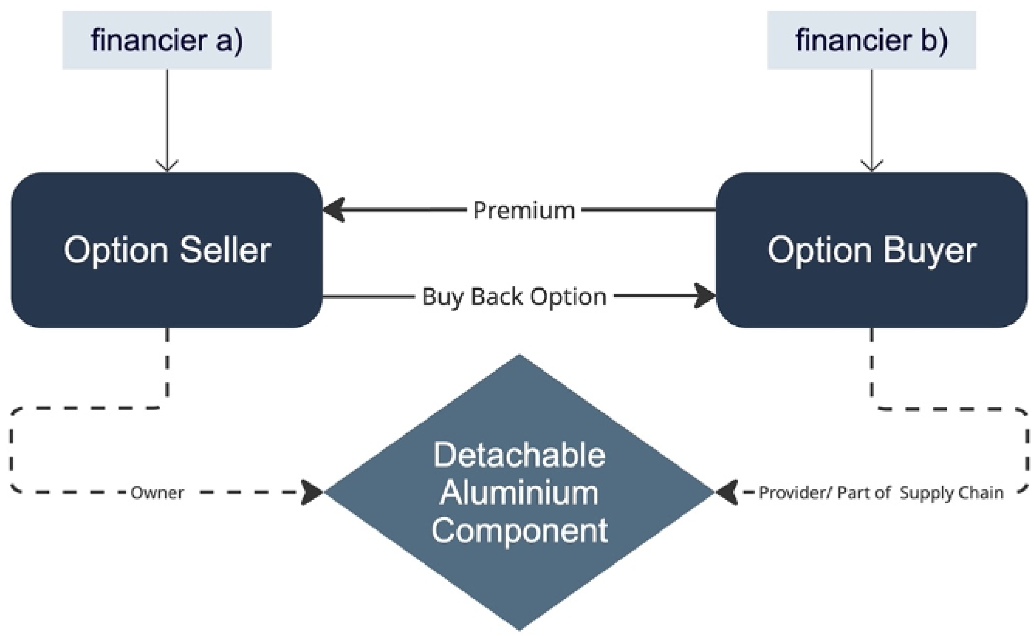
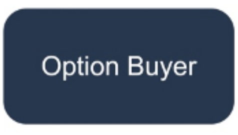
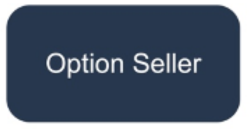


Figure 3.2: Relational diagram for a call option on a detachable aluminium building component (own illustration)

The diagram presented illustrates a call option; however, put options on circular building components may also be possible, altering the roles of the ”option buyer” and ”option seller”. As previously discussed in the literature review, different option styles come into consideration, yet it was decided to limit the research to a European call option with a fixed date of expiry. The following paragraphs will discuss the different roles shown in Figure 3.2 in more detail:



The option buyer can, but may not necessarily be, the provider of the detachable aluminium building component being, for example, a façade producing and mounting company. As the goal of the option buyer is to hedge against aluminium price increases or uncertainty in supply by securing existent material stored in a building, the option could likewise be bought by a demolition company or a party that specialises in aluminium recycling, smelting, producing or extruding. As such an option can, moreover, be traded on a secondary market, it is not certain that the option holder might change and will therefore not have any other relationship to the original option seller next to the option contract itself. The option buyer or holder will trigger the option once the value of the raw aluminium embedded within the detachable aluminium components is higher than the strike price of the option, while the cost of deconstruction and recovery of the material need to be taken into account. This is further visually explained in Figure 3.3.



The option seller can be considered as the owner of the detachable aluminium building component for the moment the option contract is fixed, however, leading to the moment of expiry, the ownership might change with the option contract still in place. This would, for example, be the case for a developer establishing the option contract to partially finance a circular construction project and then selling the building after completion. At the moment of expiration, once the option is triggered, the ownership of the detachable aluminium building component will be transferred to the option holding party. Next to developers, like in the example used, multiple parties developing or holding real estate can be considered as potential option sellers such as general real estate investors, pension funds, housing associations and more. The option sellers goal is to use the option premium as a cash in to finance the additional cost of circular construction.

There is a broad spectrum of potential building components suitable for this purpose; however, it may be assumed that key considerations in writing the option contract include the quantity of raw aluminium contained within the components, the quality of the material, and the associated costs of dismantling and material recovery.

financier a)

A party financing the option seller, such as a bank or other funding provider, would need to take into account, if the option contract carries added risk to the project and subsequently react to mitigate this risk. This may involve looking at scenarios how to react if the option is triggered and the detachable aluminium components are deconstructed and recovered.

financier b)

A party financing the option buyer, such as a bank or other funding provider, would likewise need to take into account if the option contract carries added risk to the project and subsequently react to mitigate this risk. This may involve looking at the probability of the option falling in the money (as showcased in Figure 3.3), capacities to pay the option premium and strike price and the ability to recover and store material at the time of expiration.

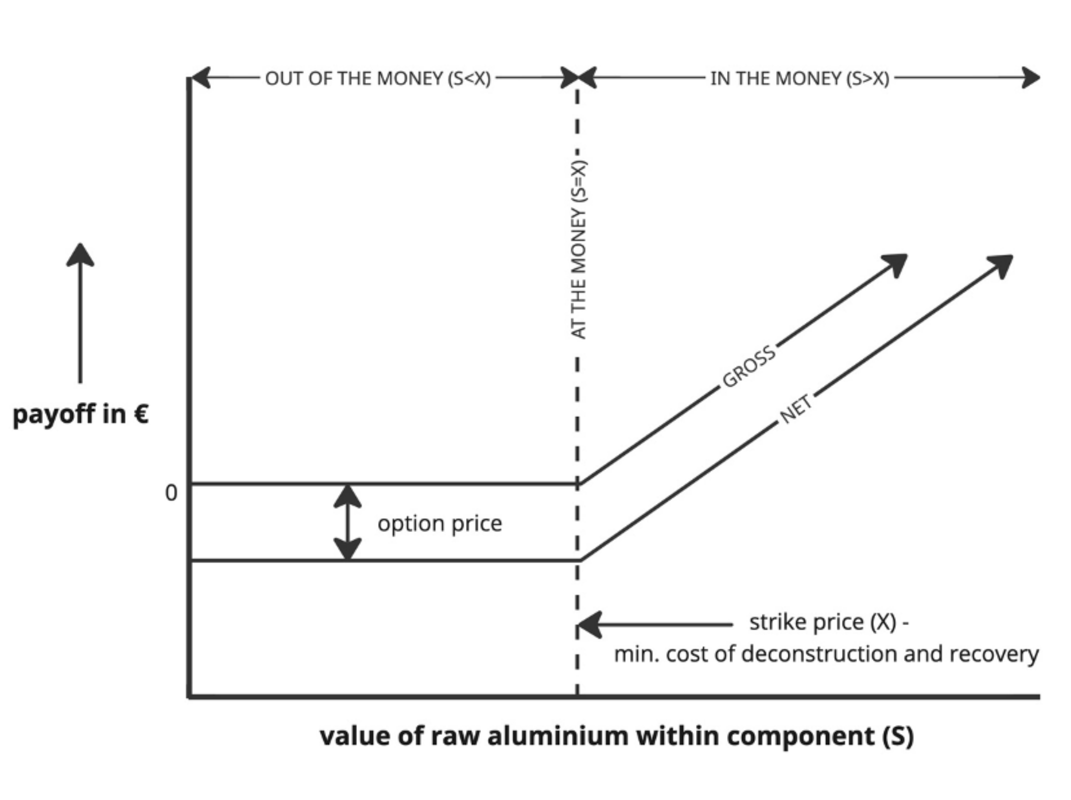


Figure 3.3: Payoff diagram for an option on a detachable aluminium building component (own illustration, adapted from Kodukula & Papudeso, 2006)

3.2.2. Excursus: The Role of Valuation Experts

As the first sub-question of this research looks at to what extent real option valuation can be utilised to value detachable aluminium building components and subsequently circular buildings it is significant to additionally discuss the perspective of valuation experts even if they might not directly be engaged in the structuring or execution of an options contract on detachable aluminium components. In case of such an option contract being in place, valuation professionals would potentially be expected to take this into account estimating the market and investment value of a building. Next to that, as proposed in the literature review, real option valuation methods might be used by valuation experts to determine and implement an end of life value of building components using material price developments and a front-end added value of circularity making use of the option premium as an estimate. In view of these considerations, valuation experts are regarded as key stakeholders and are accorded a high priority, particularly in the qualitative research section of this thesis.

For the purpose of presenting the call option framework for a detachable aluminium building component described to industry professionals as part of the qualitative analysis of this thesis, an example scenario was created to be shown as an explanatory video before interviews. This will further be explained in the sub-chapter on semi-structured interviews and the online workshop.

3.2.3. Stakeholder Analysis

The analysis of the general relations within the real option model opens up the question how actors in the real estate industry, matched to those roles described, influence the option contract. To answer this matter, a stakeholder analysis was conducted partly based on previous research done by Caputo (2013) who analysed key stakeholders in the real estate industry and Haase et al. (2024) who map out stakeholders specifically in the context of circular real estate.

The result is a power-interest matrix adapted to the context of the real option scenario presented previously (see Figures 3.4 and 3.5). The power-interest matrix looks at two specific moments: the period before an option contract is entered, and the moment before the date of expiration of the option, showcasing how the influence and interest of different stakeholder groups changes over the option life. In addition, the matrix maps out different potential stakeholders that match the groups introduced in the previous scenario. The influence of different groups shifts notably over the life of the option, as the option seller typically has limited control over the contract's outcome once the agreement is in place.

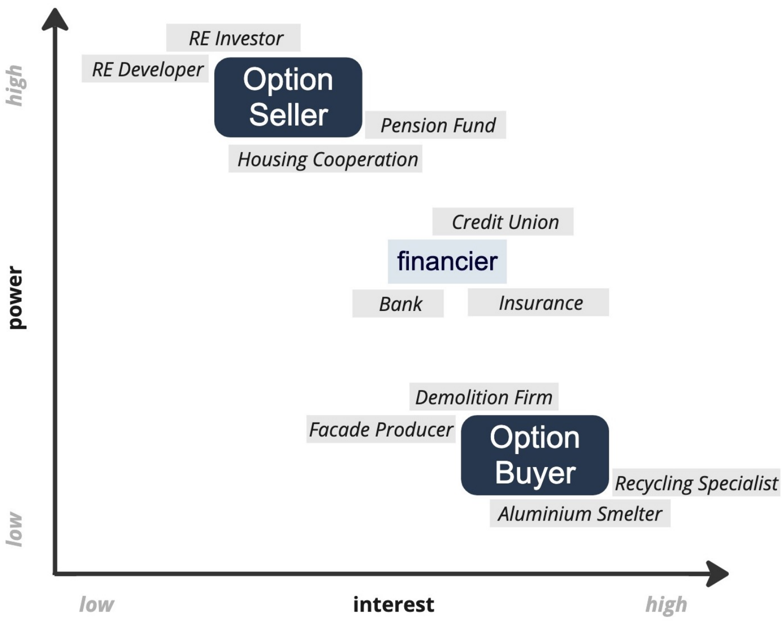


Figure 3.4: Power-Interest: before entering Option Contract (own illustration)

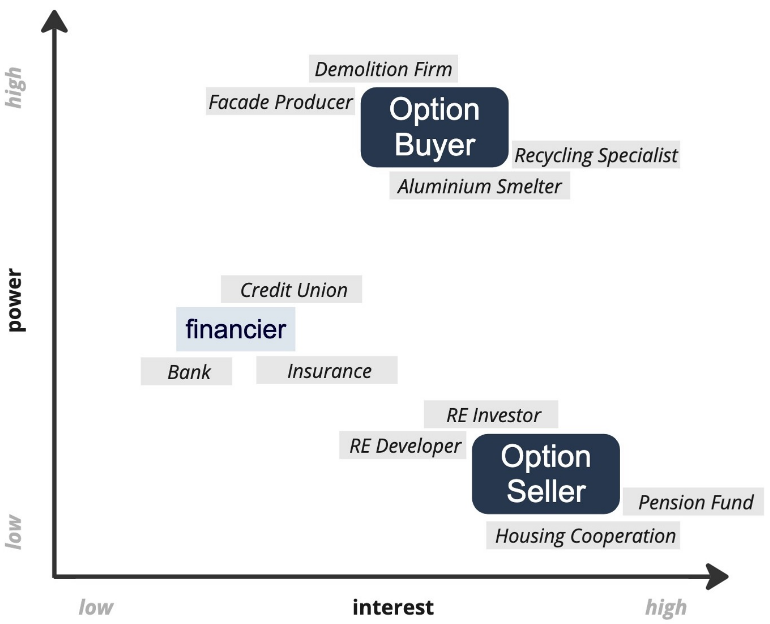


Figure 3.5: Power-Interest: before Option Expiry (own illustration)

This stakeholder analysis marks the final part of setting up a basic real option scenario for both parts of the mixed method research approach. The following section will outline specifically how the case study data will be analysed within the quantitative part of this thesis.

3.3. QUANTITATIVE CASE-STUDY DATA ANALYSIS

Building on the case study data, a Real Options Analysis (ROA) for a detachable aluminium façade will be conducted using two distinct approaches and three applied calculation techniques, with a subsequent comparison of the results from each method. As highlighted in the literature review, ROA approaches vary in complexity and theoretical perspective, incorporating elements such as no-arbitrage principles or explicitly accounting for both public and private risks. To ensure a comprehensive evaluation of the case study, it stands to reason to employ multiple approaches and critically assess their outcomes in relation to one another. This section outlines the methodologies that will be applied in each step, providing further detail on their implementation. The first ROA method chosen is the "Classic Approach" (Borison ,2005) utilising an underlying tradable asset, testing option pricing methods based on the formula developed by Black & Scholes (1973), constructing a recombining binomial tree (Kodukula & Papudesu, 2006) and lastly the model of Heston (1993). The exact differences between these option pricing approaches will be elaborated in subsequent subchapters. Next to that the "Integrated Approach" based on the comparative work done by Borison (2005) will be discussed as an excursus with the construction of a decision tree applicable to the case of an detachable aluminium façade. However, it should be noted that for this approach an exemplary decision tree framework will be illustrated, yet no quantified option value will be determined using case study data.

Before giving a short introduction about the case study and delving into the application of calculation approaches , it is important to first address why the "Classic Approach" (Borison 2005) has been chosen to be the focus of the research and not been excluded as a method to evaluate an option on circular building components, as, inter alia, suggested by theory. As previously highlighted in the literature review, a key requirement of this approach is the identification of a replicating portfolio comprising traded financial assets whose risk and return characteristics align closely with those of the investment under consideration. However, given the relatively novel nature of circular building components and their associated business model, identifying such a portfolio might be particularly challenging. This aligns with Oppenheimer's (2002) critique, which generally questions the existence of a dependable comparable value for real estate assets that can effectively be utilised in option valuation modelling. Yet, as previously touched upon in the context of the literature review, the aim of this research is to, firstly, showcase the value of circularity in terms of added flexibility and to investigate a starting point of real option valuation of detachable building components that is applicable in real-world conditions, assuming that there are not yet traded assets existent comparable to detachable building components. This is achieved by breaking it down to the embedded raw material as a tradable underlying asset.

3.3.1. Case study: Façade as a Service 2.0

The initiative "Façade as a Service" (FaaS) marks an effort in translating circular construction principles into practice. Developed through a collaboration between TU Delft, InvestNL, and façade specialist CISKIN / Alkondor Icon, FaaS aims to redefine building facades by offering modular, service-based products rather than static components (Ciskin & TU Delft, 2024). A key milestone in the development of FaaS is the pilot project undertaken at TU Delft's Civil Engineering building, referred to as FaaS 2.0. Encompassing more than 2,700 square metres of façade, the project provides an opportunity to test the real-world feasibility of CISKIN's modular and prefabricated façade system within a service-oriented model. Beyond the technical implementation, the pilot focuses on evaluating alternative procurement and operational framework such as full-service leasing and hybrid models combining initial purchase with ongoing maintenance services (Ciskin & TU Delft, 2024).

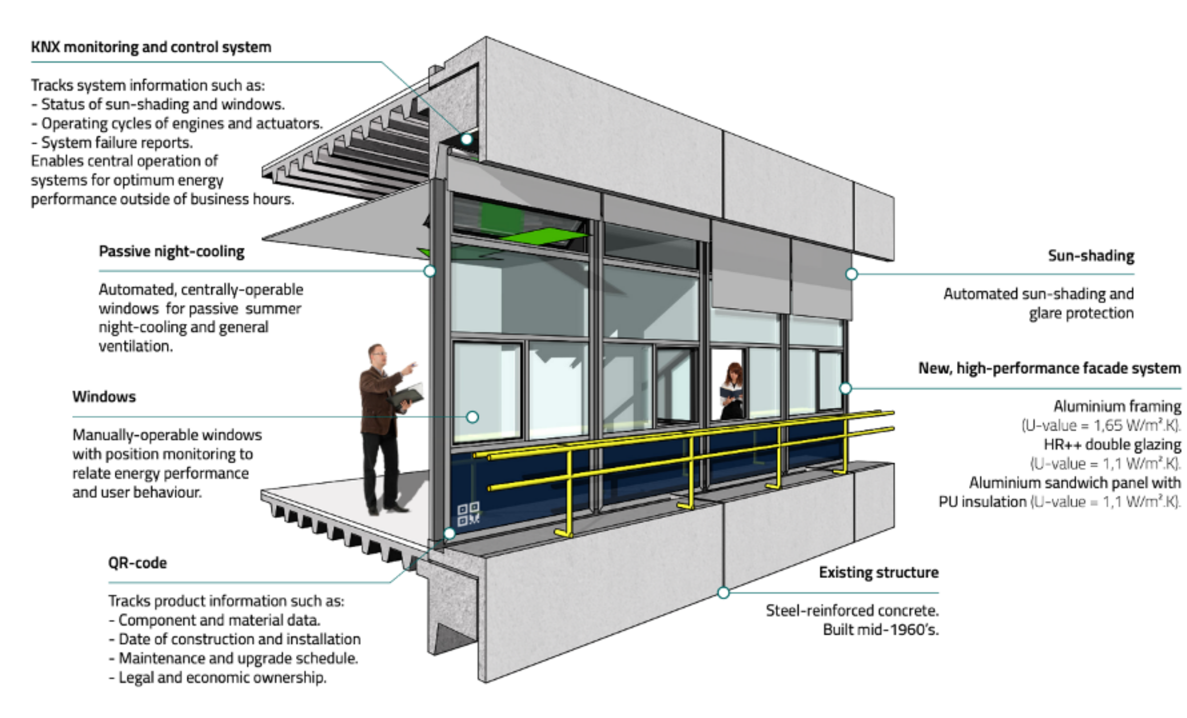


Figure 3.6: Rendering of FaaS 2.0 project (Azcarate Aguerre et al., 2020)

As real options scenario described previously prerequisites a transfer of ownership of the façade at option expiry this research focuses on a "traditional" case where the façade is first sold and owned by the building owner, while "as a Service" models are not taken into consideration. In the context of this thesis the pilot project at the Civil Engineering building, even when intended for "as a Service" based research, will be used as a case study providing data on the quantity of aluminium components, the embedded raw aluminium within those components, the investment costs of these components, their financial and functional life and more. How the data is implemented in the real option calculation methods will further be discussed in the following subchapters looking at the "Classic Approach" to ROA starting with Black & Scholes (1973) option pricing.

3.3.2. Valuation of Real Option on a Detachable Aluminium Façade: The "Classic Approach"

As already touched upon in the overview of real option approaches given in the literature review the "Classic Approach" applies traditional financial option pricing methods, such as for example the Black-Scholes model (1973), to real asset investments (Borison, 2005). Central to this approach is the assumption that a replicating portfolio of traded financial assets exists which mirrors the risk profile of the real investment. Practical application involves identifying such a portfolio, estimating its volatility and size relative to the investment, and applying financial option pricing models accordingly (Borison, 2005). For the case study the replicating portfolio used will be aluminium commodity prices drawn from market data, while case study data will inform the estimation of the current value of raw material embedded in the façade. The strike price will be based on the estimated cost for dismantling and recovering the material, likewise based on case study data. These estimates are therefore derived from actual case and historical market data. However, given the assumption that aluminium price volatility is expected to increase, as described in the literature analysis, this research incorporates not only a "real-case scenario" but additionally a "future best-case scenario", allowing for a more robust examination of how these future changes would impact the options value.

Key Parameters of the "Classic Approach"

The following paragraphs will guide through and give an overview of the main parameters used following the "Classic Approach" of ROA. The parameters are discussed and then presented in the following scheme, highlighting in addition how different values are altered for a future scenario in contrast to available case or market data:

PARAMETER

Value	Source or assumption behind value choice
Alteration for "future scenario"	Assumption behind changing the value for "future scenario"

Additional parameters will be introduced separately that are specifically needed for the different calculation methods Black & Scholes (1973), binomial tree (Kodukula & Papudesu, 2006) and lastly Heston (1993). Further information regarding the parameters can be found in the calculation tables (Appendix A).

Current Asset Value (S): The current asset value is an estimation for the value of raw aluminium embedded in the entire façade. For the case study project a total weight of 40,00 tons of aluminium is calculated which has an estimated residual value of 1.500,00€ per ton resulting in a Current Asset Value of 60.000,00€. In a future scenario this value might increase (at the same level of total investment cost) as recycling processes become more efficient and production develops to a higher degree of automation. However, to ensure better comparability of both scenarios the current asset value will not be altered for the future "best-case scenario".

CURRENT ASSET VALUE

S_f = 60.000,00€	Case Study Data FaaS 2.0: 40t * 1.500,00€
no alteration	-

Time to expiration (T): The time to expiration, so the period from a starting date to the date of expiry, will be based on the functional asset life of the façade being 30 years as listed in case study data. This decision was made to set the option expiry close to general maintenance schedules to get a realistic timespan when a façade component generally needs replacement. For a future scenario of a more dynamic, circular flow of materials or building components a shorter value for T at 15 years is assumed.

TIME TO EXPIRATION

T = 30 years	Case Study Data FaaS 2.0: equals functional asset life
15 years	more dynamic, circular flow of materials and building components

Strike Price (X): As mentioned previously the strike price should be set at the estimated cost of dismantling the façade and recovering the raw material as a minimum. As the strike price is paid at the date of expiry the estimated cost of dismantling needs therefore to be indexed for T to take into account inflation.

The cost of dismantling the façade is estimated using indicators for (traditional) deconstruction from (Bouwkosten.nl, 2025) showing a value of about 10,00 €/m^2 for facades leading to an estimated total cost of 24.877,00 € for the case study. However, to take into account the added complexity of dismantling and separating circular building components this cost is multiplied with a factor of four (leading to 99.509,00€ total cost). For the "future best-case scenario" however it is assumed that dismantling processes become technically advanced and have a higher degree of efficiency leading to a cost values comparable to today's regular deconstruction. Therefore the factor for the future best-case scenario is set at one (24.877,00 € total cost). Indexed for inflation with a CPI Index of 2,0% both cost estimation can then be translated in the following starting strike prices: 180.248,00 € (real-case scenario) and 33.482,00 € (future best-case scenario).

STRIKE PRICE

X_f = 180.248,00 €	est. Cost of dismantling; Inflation indexed for T = 30; Circularity factor of x4
= 33.482,00 €	est. Cost of dismantling; Inflation indexed for T=15; Circularity factor of x1

Volatility (σ): "Volatility is defined as a measure of the variation in the price of an asset over time." (De Silva et al., 2018, p. 365). For the case study of the aluminium façade a volatility factor representing the variation of the price of raw aluminium needs to be determined.

For this a publicly available volatility index can be used, such as the CVOL^{TM} Index which showed a value of 20,39% for aluminium at the starting date of the quantitative research, 11.03.2025 (CME Group, 2025). This, moreover, implies that the volatility might be subject to change over time. If this is taken into account or the volatility is assumed to be constant, is discussed in the individual subchapters on the option calculation methods. To have a more robust estimate of a starting volatility value, an analysis of historical price data was performed (see Appendix A) showing a value of 22,21%. For the case study, an estimated volatility value for the aluminium price development will therefore be set at the average of both values being 21,30%. For the future scenario, as previously discussed, it is assumed that the volatility of raw aluminium price will rise significantly due to uncertainty of supply. This is taken into account by setting a volatility factor of 30,00% for the future "best-case scenario".

VOLATILITY

σ = 21,30 %	based on CVOL Index / own analysis of historical data
= 30,00 %	assumed rise in volatility of raw aluminium price

Risk Free Rate (r): The risk-free rate can be defined as the expected return on an investment assumed to have no risk of loss over a set period (Kenton, 2023). For the option valuation methods applied in this thesis the risk free rate will be used to discount future payoffs to present values, which will be further explained in the relevant individual sub-chapters. To set a risk-free rate for the case study analysis a triple A rated European Bond Yield was used matching the value of T (see above) with a 30 year maturity showing a value of about 2.8% (European Central Bank, 2025). A risk free rate of 2.8% per annum is therefore assumed and will be used for further analysis. For the "future best-case" scenario the risk free rate is not altered to ensure better comparability, even though a rising risk free rate can be argued under the future scenario described previously.

RISK FREE RATE

r = 2.8 %	based on AAA European Government Bond Yield - 30 Years
no alteration	-

Total Investment - Façade Components: The total investment for the façade components (excl. VAT) needs to be taken into account, not as a parameter to calculation option values, but more to put on the one hand the residual raw material value and on the other hand the calculated option value into perspective of the total project to assess the significance of the calculated result. The cost for, glass, screens, and electrical components are not taken into account. For the "future best-case" scenario the total investment is not altered to ensure better comparability, even though a lower total investment can be argued under the future scenario described previously as to higher efficiency and automation in production.

TOTAL INVESTMENT - FACADE

2.840.000,00€	based on Case Study Data FaaS 2.0
no alteration	-

As the most significant parameters have been discussed in detail, an overview of these parameters is presented in Figure 3.7. At this point it should be noted that the parameters shown are partly based on assumptions, which are well informed by data and have been reviewed and adapted multiple times in the research process of this thesis. Yet, it stands to reason to test their effect on the outcome of the analysis by conducting a sensitivity analysis. This ensures comprehensive findings allowing for a profound discussion of the applicability of real option valuation methods on a detachable aluminium façade case. The sensitivity analysis will therefore be incorporated in the findings chapter.

PARAMETER	Case Study	"Future Best-Case Scenario"
CURRENT ASSET VALUE	60.000,00€	no alteration
TIME TO EXPIRATION	30 years	15 years
STRIKE PRICE	180.248,00 €	33.482,00 €
VOLATILITY	21,30 %	30,00 %
RISK FREE RATE	2.8 %	no alteration
TOTAL INVESTMENT - FACADE	2.840.000,00€	no alteration

Figure 3.7: Overview Parameters Option Analysis (own illustration)

Before presenting the option valuation methods, it is appropriate to briefly outline the anticipated results - specifically, the key output values of the analysis and their intended interpretation.

Option Value (C): The options "price" or "value" is the result value of the calculation methods tested on the case study data such as e.g. the Black-Scholes model (1973) and is therefore the key indicator analysed. Interpreted in the context of the case study, C is the value of the option at T=0 to buy back the façade at T for the set strike price (X) and to recover the embedded raw aluminium. The option value therefore gives an estimation of the amount an "option buyer", as elaborated in the scenario given earlier, could pay as a premium to acquire the option as well as an estimation of the added cash-in the "option seller" could use to finance the façade investment.

The option value can further be analysed in relation to the starting asset value (C/S) or in relation to the total investment in the facade to indicate the significance of the calculated option price influencing the business case of the façade project. This can be interpreted as the potential 'discount' on the embedded raw material or 'discount' on the total project made possible by setting up an option contract.

Other key result values such as the options 'Delta' or 'Risk Neutral Probability' for the option to fall into the money will be described in the following subchapter, introducing the application of the Black-Scholes model (1973) to the case study.

3.3.3. Following the "Classic Approach": The Black Scholes (1973) Model

After the introduction to the methodology has already outlined the main parameters generally used for option pricing, they will now be brought into context of the Black-Scholes (1973) option pricing formula:

Figure 3.8 shows the formula connected to the input parameters discussed previously for a better understanding.

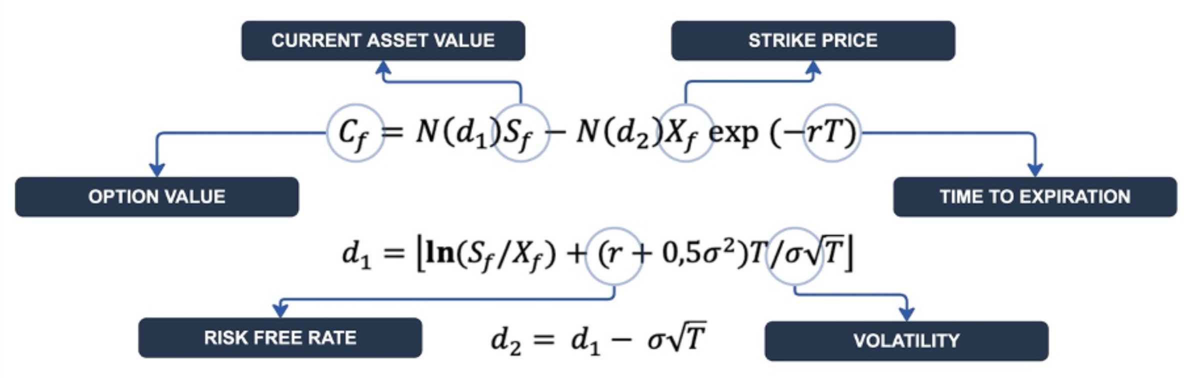


Figure 3.8: Black-Scholes (1973) formula – adapted with input parameters (own illustration)

A detailed explanation of the assumptions and mechanisms underlying the model lies beyond the scope of this thesis; therefore, only the most essential aspects will be addressed:

The fundamental assumption made by Black and Scholes (1973) is that the price of the underlying follows a geometric Brownian motion, meaning that the volatility is a constant value, which in real market cases might not be the case. The parameter to assess volatility in the context of this research was already discussed previously, e.g. the CVOL^{TM} Index for aluminium. Continuous changes of this index (CME Group, 2025) strengthen the argument that the Black Scholes (1973) assumption is not applicable for this case study. Yet, the model stands out as a simple and efficient method to estimate option values and to interpret key option characteristics, especially for European options, making it still particularly well-suited as a main focus point to the quantitative research context of this thesis. With the Heston model (1993), another method is introduced in a subsequent chapter that takes into account changes of volatility over time to allow for a comparative analysis.

Analysing the $N(d1)$ and $N(d2)$ value for an option on a detachable aluminium façade:

After highlighting the main parameters of the Black and Scholes (1973) formula, two key values used to identify the options price are now discussed (see Figure 3.9) being $N(d1)$ and $N(d2)$. As the values of the normal distribution at d_1 and d_2 they can simply be calculated using Microsoft Excel® and be utilized to interpret and characterize the option making them a vital addition to the analysis.

For European call options, $N(d1)$, being a value between 0 and 1, can likewise be called the option Delta and "is defined as the rate of change of the option price with respect to the price of the underlying asset." (Hull, 2007, p.352). The closer the value is to 1, the more the option price behaves like the underlying asset price (Hull, 2007). In option trading the Delta is, inter alia, used for so called "Delta Hedging" strategies to balance out portfolios to being insensitive to price movement to mitigate risks

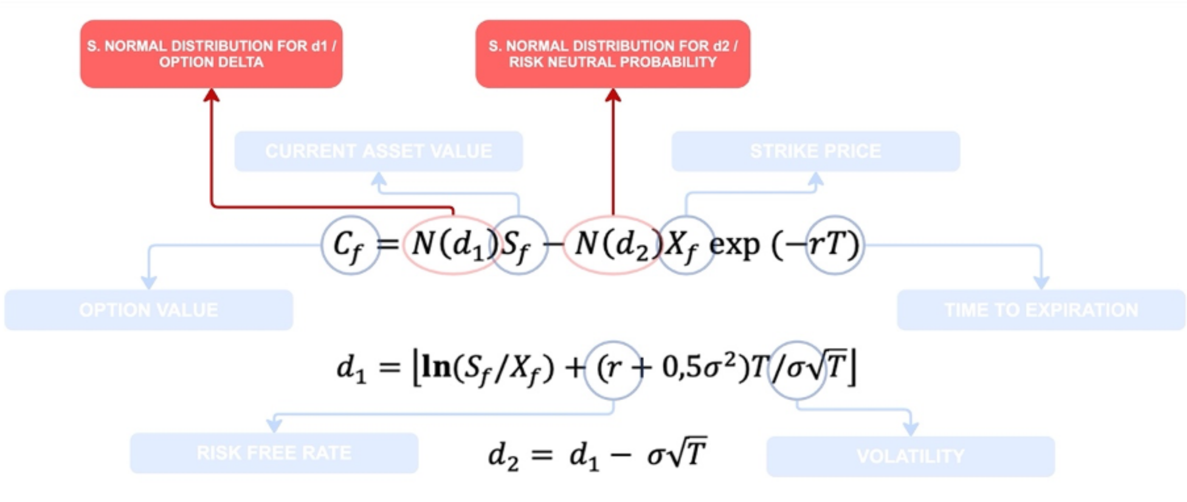


Figure 3.9: Black-Scholes (1973) formula – adapted to illustrate Nd1 and Nd2 (own illustration)

(Hull, 2007). Now, the question arises how the Delta value can potentially be interpreted for an option on a detachable aluminium façade: In particular, it can be utilised to categorise the option for being a “in the money”, “at the money” or “out the money” option (see Figure 3.10).

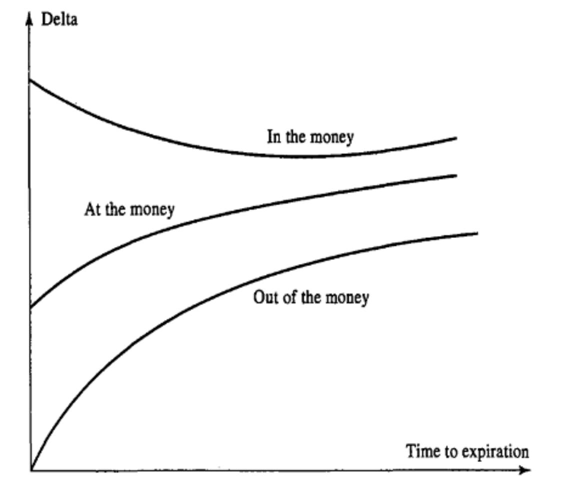


Figure 3.10: Characteristic Delta Curves for different option categories (Hull, 2007)

An in-the-money option on the façade might be interpreted to be attractive for hedging, yet require a high option price so a high premium that has to be paid to the façade owner to acquire the option, while an out-the-money option might be more speculative, yet requiring only a small option premium to be paid, while having little chance to be exercised by the time of expiry. Still, it has to be noted that with a real option on a facade, not allowing for liquid trading, hedging strategies like described by Hull (2007) cannot directly be applied: This is due to the fact that one cannot simply “buy more façade option exposure” like it would be the case with a hedging strategy on a financial market as each façade is unique effecting dismantling processes and therefore cannot be scaled up or down into units. Nevertheless, the options delta can be seen as an useful value for strategic decision making analysing the potential acquiring of a real option on an aluminium façade and will therefore be analysed in the findings.

The $N(d2)$ value “is the risk-adjusted probability that the option will be exercised.” (L.T. Nielsen, 1993, p 1). Risk adjusted, meaning that it takes into account the risk-free rate to assume a world where investors do not take into account and require a premium for risk. $N(d2)$ can therefore be interpreted as a risk-adjusted chance that it will be economically viable to recover the material embedded in the façade at the time of expiration.

Before the following chapter introduces the binomial tree method it stands to reason to illustrate why no threshold values are set for an option value, the option delta or risk-neutral probability beforehand. Discussions about, for example, a “sufficient” risk neutral probability for the option to be feasible might be imaginable; however, the transferability to other cases is limited. Even looking at the same case, interpretation of various parameters can differ depending on what strategy lies behind acquiring an option. The research is therefore specifically intended to test the application of the method, while still leaving room for a comparative interpretation of the results and for further investigation across, for example, a multiple unit study to investigate the feasibility in real-world cases.

3.3.4. Following the "Classic Approach": Constructing a Binomial Lattice

After illustrating how the formula of Black Scholes (1973) will be used to analyse the case study data now the second method, being the construction of a Binomial Lattice or likewise referred to as Binomial Tree, will be introduced.

It is the nature of partial differential equations like the one used by Black Scholes (1973), that the way a result is achieved is not a particularly transparent process, especially for users in practice (Kodukula & Papudesu, 2006). Even if the assumptions behind the model are similar compared to Black Scholes (1973) likewise assuming a constant volatility (Hull, 2007), does the Binomial Tree method solve this issue to a certain extent by mapping out a path to receiving a final option value estimation (Kodukula & Papudesu, 2006). This section will guide through how the method will be applied to the aluminium façade case step by step, illustrating how the Binomial Tree is constructed and the option value of T = 0 is determined working backwards to the trees starting point. The majority of the description is based on the method described by Kodukula & Papudesu (2006) and Hull (2007), but slightly altered to follow the logic of the aluminium façade case.

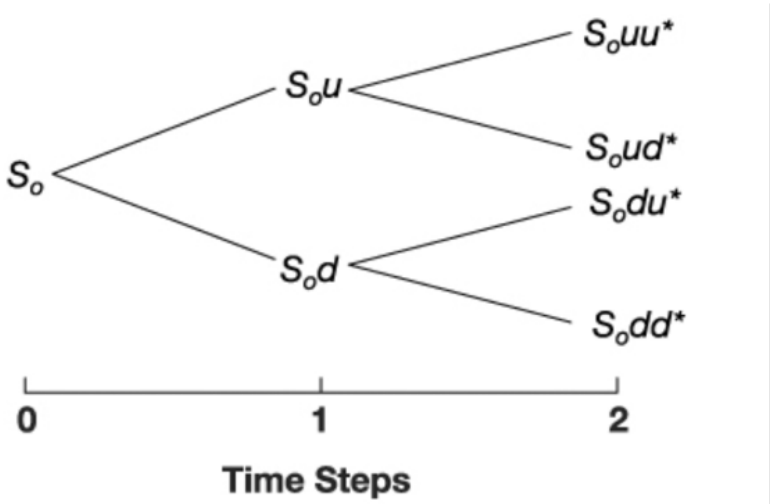


Figure 3.11: Example for generic nonrecombining Binomial Lattice (Kodukula & Papudesu, 2006)

The first step of the analysis is to construct the Binomial Lattice starting with the Current Asset Value, being the value of aluminium embedded in the façade at T = 0. Figure 3.11 showcases a simple Binomial Lattice for two time steps, where the starting value is multiplied with an up-factor (u) and a down-factor (d) to estimate price movements for the first time step, which could for example be one year. This is then likewise done for the second time step resulting in now four resulting values and can be continued further depending on what time-span is intended to be analysed.

To calculate the up (u) and down (d) factors the following formulas are used (Kodukula & Papudesu, 2006):

$$u = \exp(\sigma\sqrt{\delta t}) \tag{3.1}$$

and

$$d = \frac{1}{u} \tag{3.2}$$

The factors influencing the up- and downward movement of the asset price are therefore determined using the estimated volatility factor, meaning that with higher volatility results, stronger movements of the asset price with each node of the Binomial Tree will be calculated. The value for T determines how many nodes are constructed and what time-intervals are analysed.

Figure 3.12 connects this method with the parameters already introduced in this chapter to give an overview of how the asset values of raw aluminium for each time step can be determined starting with the current value at T=0:

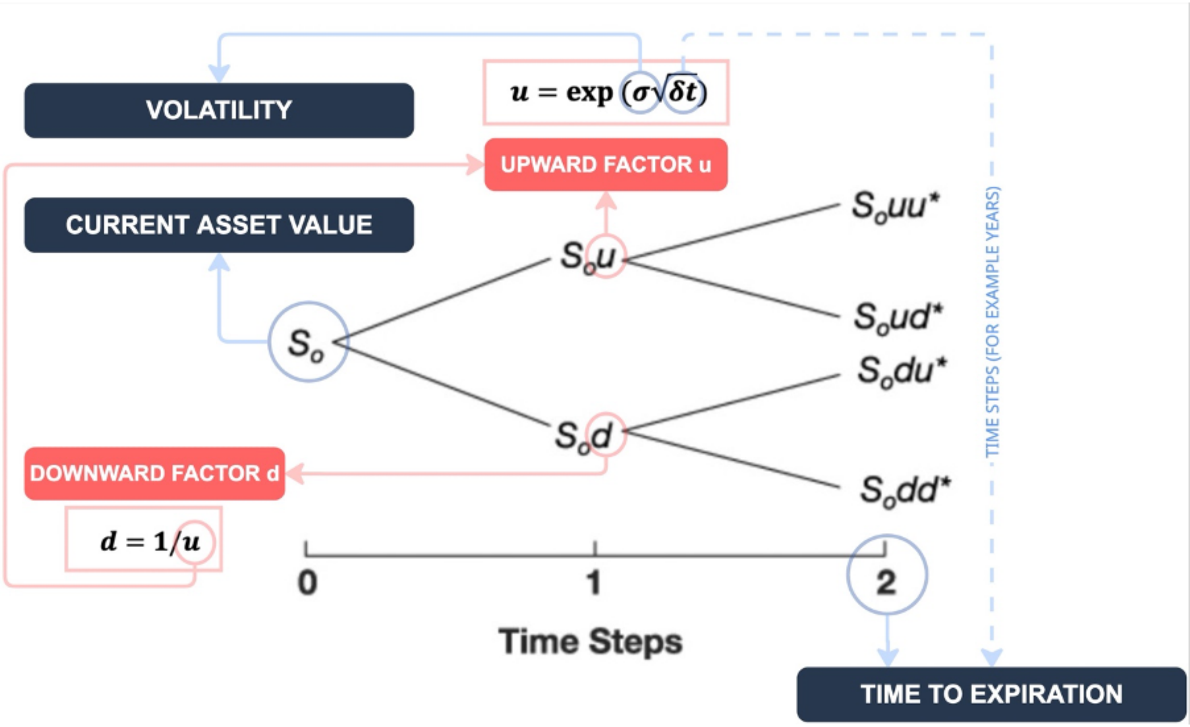


Figure 3.12: Binomial Lattice (Kodukula & Papudesu, 2006) – adapted to illustrate input parameters (own illustration)

After the tree has been constructed the value of the option is then calculated by working backwards from the ending nodes to the starting point. To determine the option value of intermediate notes the expected value to keep the option open at this specific point in time needs to be calculated which is a discounted weighted average of potential future options (Kodukula & Papudesu, 2006). This is achieved using the risk neutral probability (p) as shown in Figure 3.13:

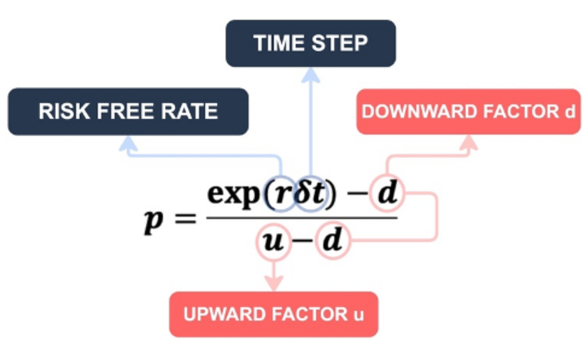


Figure 3.13: Formula for (p) (Kodukula & Papudesu, 2006) – adapted to illustrate input parameters (own illustration)

At this point, it stands to reason to clarify that the variable p is not directly comparable to the previously discussed $N(d2)$ value, which represents the risk-neutral probability of the option expiring in the money. Rather, p denotes the probability of an upward movement at each individual time step within the binomial model and does not account for the full duration of the option's lifespan. Nevertheless, calculating a cumulative risk-neutral probability of the option ending in the money remains valuable, both as an independent metric and as a means of validating the result derived from $N(d2)$. To that end, the method for estimating this cumulative probability will be described in greater detail in a subsequent paragraph.

After this short clarification, the chapter now proceeds with a detailed explanation of the method used to determine the option value by applying the risk-neutral probability parameter (p): At the terminal nodes of the binomial tree, the option value is determined by deducting the strike price from the asset value (see Figure 3.14). Subsequently, the option values at preceding time steps are repetitively derived using the formula presented in Figure 3.13, with the parameter p serving as the determining factor (Hull, 2007). This backward induction process continues until the option value is obtained at T = 0.

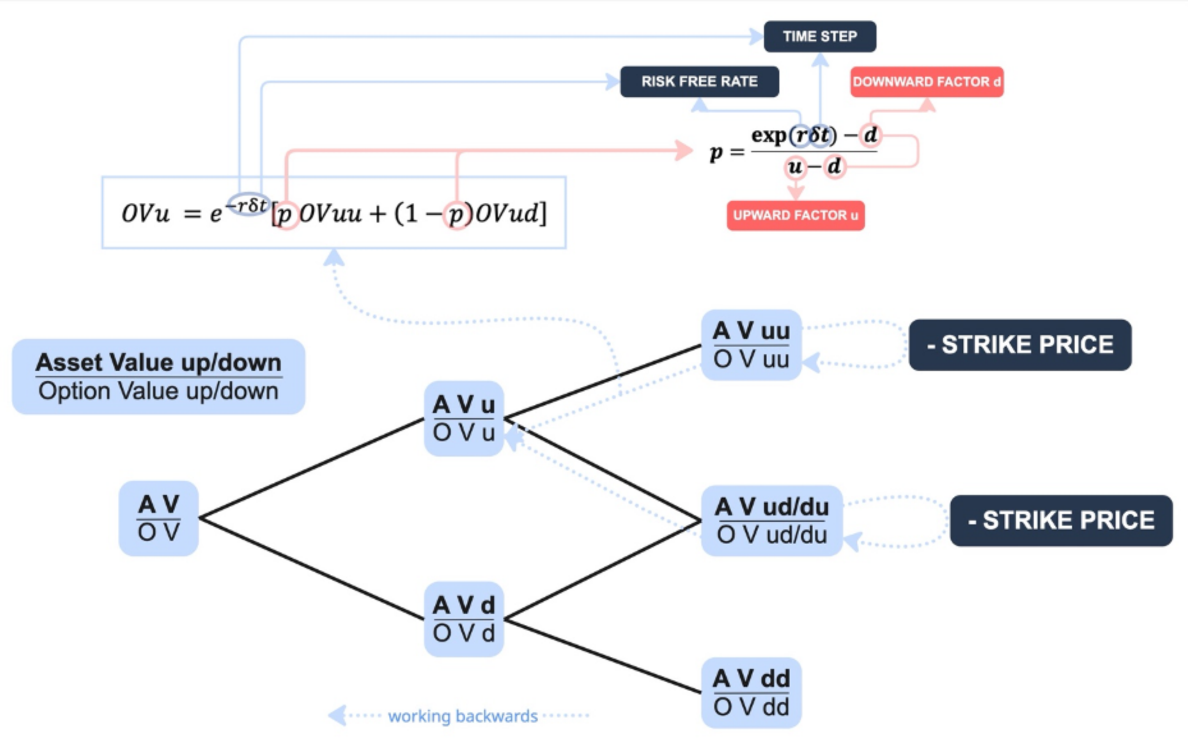


Figure 3.14: Working back the Binomial Tree (own illustration based on Hull (2007))

Having introduced the method, it is relevant to briefly consider the interpretation of intermediate nodes within the context of the façade case. At any given time step, such as year 20 within a 30-year option lifespan, each node's option value reflects the value of holding the right to recover the embedded aluminium at that moment, conditional on the specific price path of raw aluminium up to that point. For companies operating in construction-related aluminium markets, the binomial tree thus might provide a visual framework to map potential future price trajectories alongside the corresponding option values, offering strategic insight into the timing and value of material recovery.

Before introducing the Heston (1993) model as the final method employed within the “classic approach” of real option valuation, this section briefly outlines the procedures for deriving the option’s delta and the risk-neutral probability within a binomial tree structure. The delta is computed using a formula based on Hull (2007), modified to align with the scheme illustrated in Figure 3.12.

$$\Delta = \frac{OV_u - OV_d}{AV_u - AV_d} \tag{3.3}$$

The risk-neutral probability of the option expiring in the money is derived by summing the probabilities of all terminal paths within the binomial tree that result in a positive option value. These in-the-money paths are identified by looking at the option values at the final nodes of the tree. To keep the methodology section concise, a detailed explanation of the binomial probability distribution is not provided. For the application of this methodology, the BINOM.DIST function in Excel® was be used to calculate the individual path probabilities. Once the in-the-money terminal nodes are identified based on their option values, the corresponding probabilities are summed to determine the total risk-neutral probability of the option being exercised at expiry (under risk neutral measures).

Following the detailed examination of two real option valuation methods applied to the aluminium façade case, both of which are based on the assumption of constant volatility, the subsequent chapter introduces an alternative approach that incorporates the possibility of changes in volatility over time.

3.3.5. Following the "Classic Approach": Heston (1993) Option Pricing

To maintain conciseness in this already extensive methodology section, the explanation of the mathematical framework underlying the Heston (1993) model will be limited to the most relevant elements necessary for contextualising its application to the aluminium façade case and for drawing comparisons with the previously discussed Black & Scholes (1973) model and the binomial tree approach. This will be structured by first outlining the core assumptions established by Steven L. Heston (1993) in developing the model, then examining the stochastic differential equations with reference to the case study and associated parameters, and finally presenting the specific parameters applied in the subsequent option pricing analysis.

“I offer a model of stochastic volatility that is not based on the Black-Scholes formula. It provides a closed-form solution for the price of a European call option when the spot asset is correlated with volatility (…).” (Heston, 1993, p. 328)

The key insight from Heston’s (1993) quote is the shift from assuming constant volatility to modelling volatility as a stochastic process correlated with the price of the underlying asset. To contextualise this within the case study, it is necessary to examine the implications step by step. In contrast to the Black-Scholes and binomial tree models previously discussed, the Heston model incorporates a mean-reverting volatility process (Hull, 2007), whereby fluctuations in volatility are continually ’pulled back’ towards a long-term average, which is further visually illustrated in Figure 3.15. This tendency of volatility to revert to its average level is governed by what is referred to as the *drift* term (Hull, 2007).

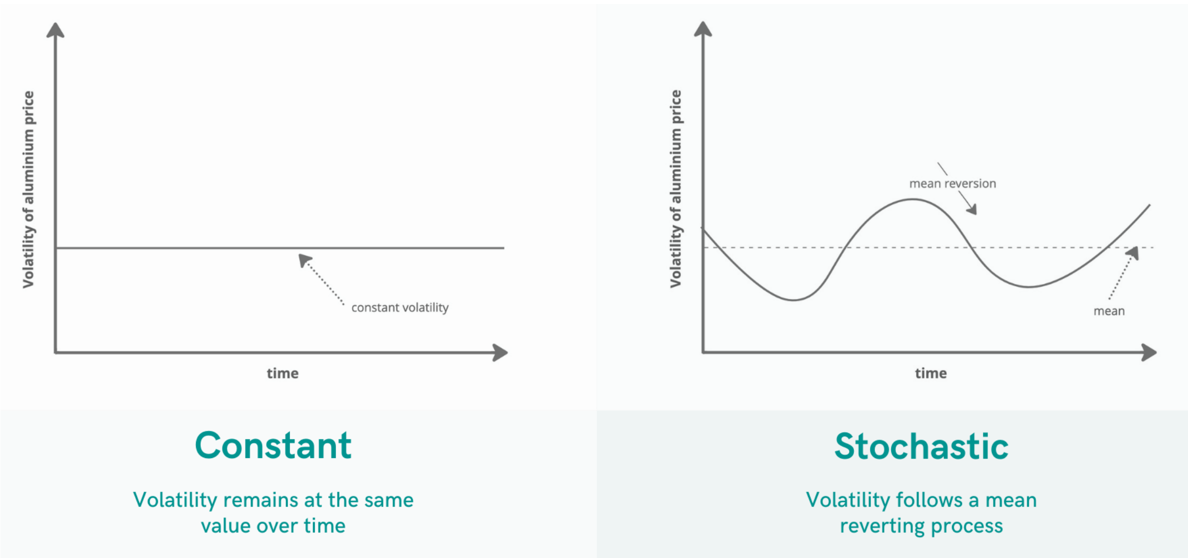


Figure 3.15: Sketch: Mean Reverting Volatility (Own Illustration)

In the context of aluminium pricing, the Heston model accommodates fluctuations in volatility that may arise from various sources such as geopolitical instability, shifts in energy costs, or evolving regulatory frameworks. At the same time, it anchors these variations around a predetermined long-term average and defines the rate at which volatility reverts to this mean. This approach, therefore, provides a more flexible framework for evaluating options on aluminium façade components, enabling the analysis of a broader range of more realistic market scenarios and their influence on the options valuation. It also aligns more closely with the underlying assumptions that support the relevance of this research being a long term change in volatility of aluminium prices.

"For options that last less than a year, the impact of a stochastic volatility on pricing is fairly small in absolute terms (although in percentage terms it can be quite large for deep-out-of-the-money options). It becomes progressively larger as the life of the option increases." (Hull, 2007, p. 589-590)

Given the extended time horizons defined for (T), the assumption of stochastic volatility is expected to have a notable influence on the resulting option values. This effect will be explored through the application of the Heston (1973) model to the case study data.

The correlation between asset price and volatility reflects the premise that price movements influence volatility dynamics. This relationship may be either positive or negative, depending on the market context, and is intended to capture shock effects (Heston, 1993). For aluminium, it appears plausible that under rising prices due to, e.g. high demands, a shortage of supply, and fluctuating energy prices, volatility likewise tends to increase caused by higher market uncertainty, which would be expressed in a positive correlation.

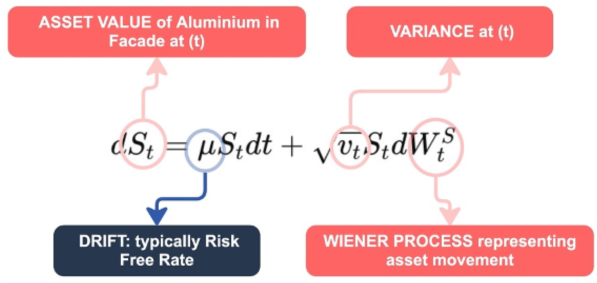


Figure 3.16: Stochastic Differential Equation for Asset Price (Heston, 1993) - altered to illustrate parameters (own illustration)

The stochastic dynamics of both the asset price and its volatility are described in Heston's (1993) model through stochastic differential equations, as illustrated in Figures 3.16 and 3.17. Parameters highlighted in blue correspond to those previously introduced, such as the risk-neutral probability and the long-run average variance θ (theta) with the latter being the square root of the volatility. These can be defined under the same assumptions to those applied in the earlier models that assumed constant volatility, which will further be clarified looking at each input value specifically.

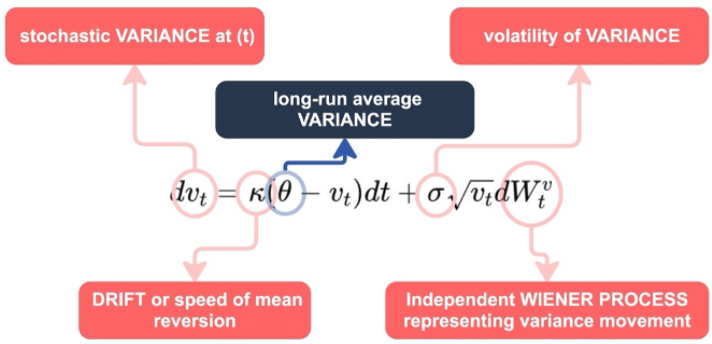


Figure 3.17: Stochastic Differential Equation for Volatility (Heston, 1993) - altered to illustrate parameters (own illustration)

It is evident that the stochastic evolution of both variance and asset price is described by two independent Wiener processes (or geometric Brownian motions). The previously discussed correlation between these two processes is captured by the parameter ρ (rho). Together with rho other input factors such as the volatility of variance (σ) and the speed of mean reversion κ (kappa) have not yet been introduced and thus require definition within the context of the case study. For clarity and consistency, given that σ previously denoted standard volatility, this thesis will refer to the volatility of volatility as σ_v. The following section provides a step-by-step discussion of the key inputs required for the Heston (1993) option pricing model, outlining the basis on which each input has been determined. The current asset value (S) and strike price (X) remain at the same values assumed in previous chapters. The risk free rate (r) and time to expiration (T) are likewise not altered compared to previous chapters to ensure comparability. The fundamental inputs defining the option remain unchanged and are altered depending if the real-case scenario or best-case scenario is analysed; however, as previously outlined, volatility is no longer treated as a constant. This necessitates the following revised assumptions:

v_0 initial variance

The initial volatility at (T = 0) will be set at an equal level of the previously defined 21.30% to ensure comparability to the previous models which used this value as the standard volatility. To be used in the Heston model as initial variance value v_0 the volatility is squared. Therefore a value of v_0 = 0.0454 will be plotted into the model as initial variance. For the "best-case scenario" the initial volatility and therefore variance will be altered accordingly.

θ long-run average variance

It is assumed that the current starting volatility at (T = 0) is near the long run average and therefore is set at σ = 21.30%. In case the option analysis is conducted in times of known high volatility levels for aluminium prices, a lower value should be chosen. The value for theta will therefore likewise be specified at θ = 0.454. For the "best case scenario" also the long run average volatility will be altered accordingly.

κ mean reversion speed

To not go beyond the scope of this thesis it was decided to refrain from modelling a value of kappa based on historical aluminium price data and to assume a speed of mean reversion κ = 0.7 per year with the volatility reverting halfway to its long-term mean in about 1 year.

σv volatility of variance

For the volatility of variance a high value of σ_v = 1.0 is assumed to capture large unpredictable swings in variance and to align with the objective of adding the Heston (1993) model to the analysis to test for potential difference between constant versus stochastic volatility outcomes.

ρ correlation

As previously outlined can a positive correlation be assumed for the case of aluminium prices and the value of rho will therefore be set at ρ = 0.2 to model a slightly inverse leverage effect. For comparison, a value of ρ = 1 would mean that the asset price and volatility are correlated perfectly.

The input parameters discussed (Figure 3.18) will be plotted in the MATLAB *optByHestonNI* function to compute and price a call option for T of both case scenarios and to perform a sensitivity analysis, which will be discussed in the Findings section. The MATLAB script used can be found in Appendix B.

Heston PARAMETER	Case Study	Best-Case Scenario
σ0 initial variance	0.0454	0.09
θ long-run average variance	0.0454	0.09
κ mean reversion speed	0.7	no alteration
σv volatility of variance	1.0	no alteration
ρ correlation	+ 0.2	no alteration

Figure 3.18: Parameters for Heston (1993) option pricing – overview (own illustration)

The Heston model concludes the three approaches being part of the classic approach to real option valuation utilising an underlying traded asset to price the option. The next chapter, while still being a valuable addition to this thesis research, can be seen as an excursus to a more complex yet also realistic approach to real option valuation presenting the “integrated” method.

3.3.6. Excursus: Valuation of a Real Option on a Detachable Aluminium Façade: The "Integrated Approach"

As highlighted in the previous chapter, the integrated approach combines financial modelling with management theory, specifically decision analysis. Borison (2005) discusses this approach in his paper on various ROA methods, building on the foundational work of Smith and Nau (1995) and Smith and McCardle (1998). These authors view the integrated approach not as a single methodology but as a fusion of option pricing and decision analysis. As touched on in the literature review, the integrated approach begins by explicitly identifying systemic and idiosyncratic risks, forming the first step of the analysis process. Systemic, market-driven risks include factors such as material price fluctuations, shifts in demand and regulatory changes. In contrast, idiosyncratic risks are firm-specific and encompass uncertainties related to the costs of recovering the façade, as well as the firm's ability to efficiently manage the logistics and processes involved in recovering façade components. The methods discussed before being part of the "Classic Approach" focus exclusively on aluminium price developments as a systemic risk and do not incorporate specific project or company risks into the valuation process. The only exception is the strike price, which reflects dismantling costs unique to the project. The integrated approach, by contrast, aims to address these individual risk factors in greater detail.

Applying this integration within the research context of this thesis will entail the following steps: The integrated approach is structured to evaluate the value of at least two distinct strategies. In the context of selling an option on the case study façade, this, for example, involves evaluating two potential strategies for a façade producing company: building, selling, and potentially repurchasing the façade with or without obtaining a formal buy-back option.

Now the actual analysis is conducted by construction a decision tree that integrates a binomial model to account for both systemic and ideosyncratic risks (Figure 3.19):

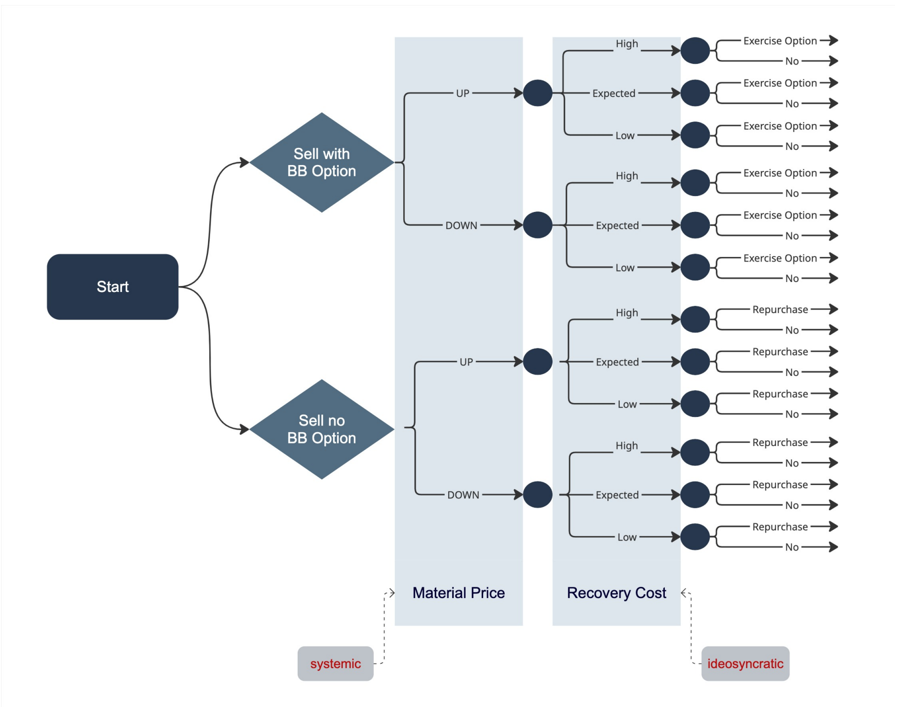


Figure 3.19: Simplified Example Decision tree including binomial model (own illustration)

By performing a backward induction through the tree, from the terminal nodes to the root, the value of each strategy can be determined. At each decision point, the expected value is computed using the probabilities of various outcomes and their corresponding payoffs, while accounting for both public and private risks. As indicated in the literature review, the integrated approach is regarded as the most sophisticated and practically applicable method. However, it is also the most intricate and labour-intensive. In the context of this thesis's research question, this approach enables a valuable addition to the "classic approach" showing how option valuation methods can be applied to more case specific contexts. However, a detailed examination and application of this approach to the case study data lie beyond the scope of this thesis. Therefore, it is included here as a brief excursus and proposed as a direction for future research.

3.4. QUALITATIVE DATA COLLECTION AND ANALYSIS

The quantitative component of this mixed-method research approach is designed to evaluate the feasibility of valuing an option on a detachable aluminium component by applying real option valuation theory to case study data. However, as highlighted in the literature review, while the theoretical and mathematical advantages of ROA are well-established, significant barriers persist that hinder its adoption by practitioners - not only in real estate but generally across multiple industries. In alignment with the exploratory deductive nature of this research, qualitative data was gathered concurrently to capture perspectives of industry professionals on the application of the real option model to circular real estate components. This analysis intends to identify potential enablers and barriers to real option application within circular real estate business and financing as well as serve as a anti pole to the real option calculations made within the quantitative section showcasing differences in the perceived risks and decision-making processes adapted by industry professionals.

3.4.1. Data Collection: Semi-Structured Interviews

The qualitative section will be divided in two parts starting with a set of semi-structured interviews. To sample interview candidates as a first step case study sampling was applied focusing on practitioners involved within the “Façade as a Service” project. According to Diefenbach (2009) researching case studies through a set of semi structured interviews allows for investigation based on qualitative relevance and nuanced understanding of different perspectives, however, to shift away from mere narrating a case study, limitations need to be addressed by contextualising findings. This is the main reason why after sampling interviewees from the case study additional interviews were conducted following a theoretical sampling strategy, meaning that data will be collected in a continuous process and interviewees will be chosen based on findings made progressing with the research (Blaikie & Priest, 2019).

With the option scenario introduced earlier in this chapter and the subsequent stakeholder model, a framework was set to map out industry professionals matching the different roles identified and select interview partners. The graduation internship at Rabobank presented a significant opportunity to engage with and invite industry professionals for interviews, extending beyond the stakeholders directly involved in the “Façade as a Service” project. This sampling approach allows both the intended comparative ’qualitative view’ on the case study and further investigation of practitioner perspectives to ensure internal and external validity of the results. It needs to be clarified that as regards the scope of this thesis and the already comprehensive quantitative analysis, it is not the goal of the qualitative research section to produce empirical evidence of the feasibility of the real option approach. More, it intends to collect potential limitations or enablers of real option application across different sectors and stakeholder roles and entails therefore a widespread group of interviewees.

For semi-structured interviews, a default set of interview protocols was developed for different stakeholder groups which could then be adapted for each individual interviewee. This default set of questions can be found in Appendix (C). In the early stages of the investigation, it was observed that presenting a real option scenario for an aluminium façade to stakeholders with limited knowledge of financial theory and, respectively, option mechanisms was a potential limitation to the quality of the interview findings due to misunderstandings. To ensure a simple and visual explanation of the topic, a ’whiteboard style’ explanation video was developed that would be shown to the interviewee before asking questions regarding the use of option contracts or option valuation methods.

While figure 3.20 shows screenshots of the video used, can the .mp4 file be found in Appendix D.

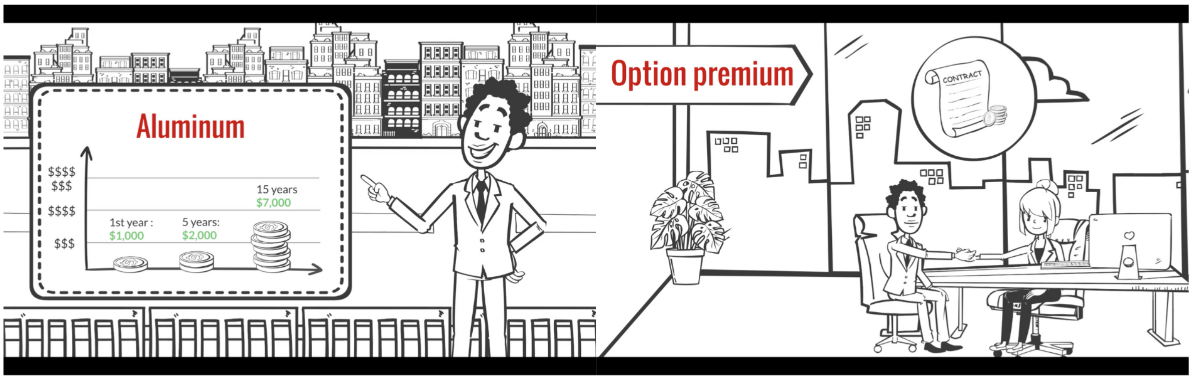


Figure 3.20: Screenshots – White Board Explanation Video (own illustration)

The semi-structured interviews were audio recorded, transcribed to intelligent verbatim and then analysed within the respective stakeholder groups to identify and compare different perspectives on the option concept and its potential application to valuation practices and option contracts.

3.4.2. Data Collection: (RE) VALUE Online Workshop

The previous subsection on the real option scenario and involved stakeholder groups identified valuation experts fulfilling a specific role, while not necessarily being an active part of an option contract on a aluminium façade component, but being the ones to value a building with such a contract in place and/or adapting the valuation methods presented themselves.

To grant this group an integral role in the qualitative investigation, an online workshop was set up embedded in the (RE)VALUE research series to present option valuation methods to a number of multiple valuation professionals and to subsequently obtain data via intermediate surveys integrated in the workshop. As a research method, a workshop is of particular value if topics are un-defined and future orientated (Ørngreen & Levinsen, 2017) which is the case for the option valuation methods used, as they are assumed to be not a common practice in real estate valuation, which was, likewise, set to be verified through the workshop.

The (RE)VALUE research group at TU Delft aims to advance real estate valuation by integrating sustainability, technology, and social impact into innovative, future-orientated valuation models and offers regular online sessions (REVALUE, 2025). The subject of this thesis was therefore highly aligned with the overarching objectives of the (RE)VALUE project, making the integration of the online workshop into the regular meeting series a well-suited and coherent addition.

To guide participants from a general understanding of the option concept to the detailed mechanics of option valuation methods, the workshop was structured into four distinct segments. The session began with an introductory part featuring the explanatory video mentioned above, followed by a brief survey to assess participants' comprehension and gather initial feedback on the concept. The central section presented the option valuation approach using a practical example, deliberately leaving out mathematical formulations at that point, and was complemented by a forward-looking discussion on material scarcity and aluminium supply uncertainty. Both segments concluded with short follow-up surveys to capture immediate reactions. The survey was developed to ask workshop participants for feedback during the session looking at potential implementation of the option contract in a valuation report, adaptation of the presented valuation methods, their subjective view on gaining importance of embedded raw materials and more. The full question list for the survey can be found in Appendix E, and the results will be discussed in detail in the Findings chapter. An optional fourth section offered a detailed walkthrough of the Black & Scholes (1973) valuation method, supported by a visual framework (see Figure 3.21 and Appendix F) and some exemplary calculations using the Excel® model developed for the quantitative analysis (Appendix A). The presentation slides used for the workshop can be found in Appendix G.

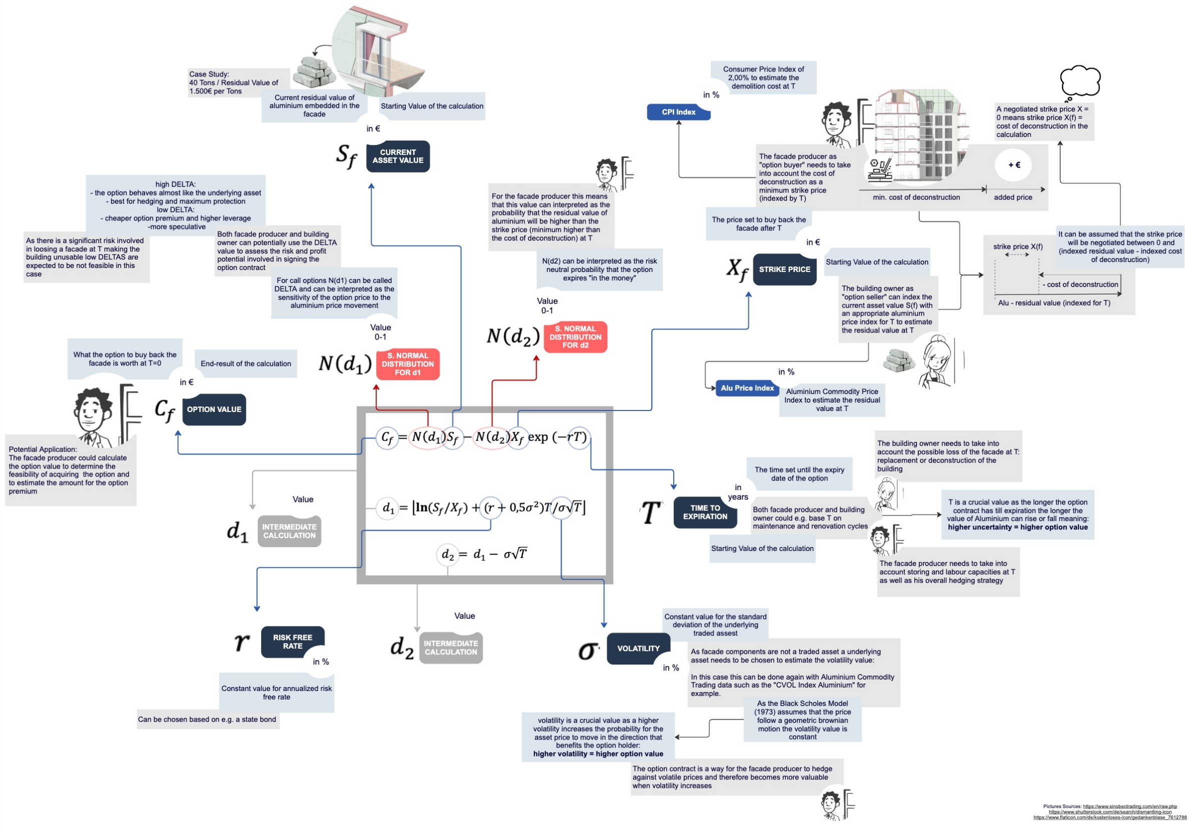


Figure 3.21: Explanatory framework based on Black & Scholes (1973) for the (RE) VALUE online workshop (own illustration)

4

Research Ethics and Data Management

To maintain both methodological integrity and ethical compliance throughout the research, respective risks and corresponding counteractions are defined in the subsequent section. External and internal validity of this thesis proposal is discussed followed by a brief summary of participant protection measures. The chapter concludes with an overview of the data management plan designed to ensure sufficient data handling and storage.

4.1. RELIABILITY AND VALIDITY OF THE RESEARCH

This sub-chapter evaluates whether the research proves to be valid according to the scientific community's requirements, distinguishing between internal and external validity (Price & Murnan, 2004). Internal validity assesses the extent to which the study effectively investigates the specific questions it initially aims to explore (Price & Murnan, 2004). The chosen research design follows a mixed method approach investigating the research questions in a parallel manner (triangulation) allowing to combine and compare results from both quantitative and qualitative methods. The literature review has shown that barriers to apply circular practices in the real estate industry are both structural but also behavioural due to the unique nature or real estate business models. The method chosen therefore ensures to target both barriers, testing the financial applicability of real options as well as investigating market parities subjective view on the topic. Possible limitations for the quantitative section are the subjective choice of input data possibly having a significant impact on the results. A sensitivity analysis was therefore included to evaluate input data and counteract possible misleading interpretation of calculation outcomes. For the qualitative section limitations might lie in participants not being familiar with financial theory and therefore the concept of real options. Interview questions and case study information therefore were formulated in an understandable way targeted to each interviewee's profession.

External validity, or generalisability, is achieved when the findings accurately reflect the outcomes that would have emerged if the entire population had been included in the study (Price & Murnan, 2004). As highlighted in the chapter on methodology, the single case of the FaaS project was chosen, as circular construction projects are still rare, and the availability of necessary data within this specific project is satisfactory. However, it needs to be emphasised that the exploratory deductive nature of the chosen research method limits generalisability significantly. However, the concept proposed within this thesis can be considered novel as there is only limited research available concerning similar topics at this point in time, which justifies the choice of an exploratory logic of inquiry.

Ultimately, acknowledging the researcher's role is crucial to recognising and reducing any potential impact of biases. For the quantitative section, possible bias in the choice of approach are counteracted by following three different approaches allowing for sufficient variety in results. For the design and data analysis of semi-structured interviews and workshop, the researcher should make sure to remain objective to avoid framing questions in a biased manner and strive to minimise interference during the workshop by designing a setup that requires little to no intervention.

4.2. PROTECTION OF PARTICIPANTS

To ensure ethical handling of data gathering involving human participants, the research will adhere to established protocols guided by the Human Research Ethics Committee (HREC) Checklist. Informed consent will be obtained from participants, verifying they are fully aware of the study's purpose, procedures and risks. Participation in the interviews and workshop is fully voluntary and participants have the option to withdraw from the research at any point in time. Since case study sampling will be employed to identify candidates for interviews and the workshop group, full anonymisation may not be feasible due to the recognisability of the case study, which could potentially reveal participants' identities. Consequently, personal data will be thoroughly pseudonymised, and participants will be informed about this limitation. Lists used for administrative purposes as well as audio recordings and transcripts containing personal data will be destroyed after the end of the research. For further information please refer to the data management plan (Appendix H).

4.3. DATA MANAGEMENT

Appendix H contains the data management plan, which underpins the explanations discussed below. It defines the scope and origin of the data to be collected, the criteria guiding its selection, and the procedures for both analysing and securely storing the information (Blaikie & Priest, 2019). Furthermore, this plan is designed with research ethics in mind, ensuring that all data handling practices align with ethical standards.

As the data collected contains confidential data from commercial parties, the Project Data Storage (U:) drive was chosen to store all research data of this thesis assuring the appropriate level of security. Only the research team including the researcher and the main mentors had access to the storage. In order to pseudonymise the interview transcripts it is necessary to store data shortly on the researches private drive. Only pseudonymised data can be distributed within the research team, and participants were informed in the consent forms about the possibility of data leaks. For the interviews, participants were requested to provide consent regarding the use of direct quotes in the publication and whether their professional role can be referenced. If consent was not granted, the data were excluded from the final publication.

5

Results

5.1. QUANTITATIVE RESULTS

The results presented in this chapter are extracted from the calculations conducted in Appendix A using Microsoft Excel® and were edited for clearer presentation. For further detailed information please refer to Appendix (A).

5.1.1. Results from applying the Black & Scholes (1973) Model

In this subchapter, the results derived from applying the Black & Scholes (1973) model are examined, beginning with the real-case scenario and followed by a sensitivity analysis. Subsequently, these findings are contextualised through a comparative evaluation against the best-case scenario.

Case Study – Calculated Values:

CALCULATED OPTION VALUE: C	C_f = 22.099,00 €
C / CURRENT ASSET VALUE	36,8 %
C / TOTAL INVESTMENT - FACADE	0,78 %
DELTA - N(d1)	0,640
RISK-NEUTRAL PROBABILITY - N(d2)	0,210

Figure 5.1: Main Findings Black Scholes – Real Case Study (own illustration)

Figure 5.1 shows an overview of the main results using the Black & Scholes formula for the real-case scenario. An option value C of 22.099,00€ was determined making up for 36,8% of the current asset value of the raw aluminium within the façade and 0,78% of the total investment of the case study façade. As it is not the primary intention of the research conducted to test the feasibility of the option in the context of the façade projects business case, it is not further interpreted if the option value in relation to asset value and total investment may be of financial significance. However, within the qualitative research data a “circularity premium” for the project of about 10 up to 20 percent was mentioned by professionals involved in the case, meaning that the option price would only have a very limited impact on financing this premium. Yet, the threshold to significantly change an aluminium facades business case might be interpreted differently in other cases leaving the possibility open to test the approach used in this thesis on an empirical multi case study, further investigating this question.

Furthermore, a risk-adjusted probability of 0,210 was calculated, as well as an option Delta of 0,640. As discussed previously, the interpretation of these values is strongly dependent on the goals that may be behind planning to acquire an option and how risk is taken into account in a specific case. Yet, it can be concluded that the risk neutral probability is more likely to be seen in the lower range, indicating a higher risk that the option will not be in the money at expiration, meaning that the value of raw aluminium at T would be lower than the cost of recovering the façade (strike price). The options delta, however, shows a moderately high sensitivity of the option price to the underlying asset, suggesting that the option has a relatively balanced risk-reward profile, but might also react strongly to changes in volatility (Malz, 1997), which is tested, inter alia, in the sensitivity analysis:

Case Study – Sensitivity Analysis:

As outlined in the methodology chapter, the calculation relies significantly on assumed parameters, making it essential to critically assess these assumptions through a sensitivity analysis and to examine how variations in input values influence the results. Figure 5.2 distributes the option value over a change of the volatility measure.

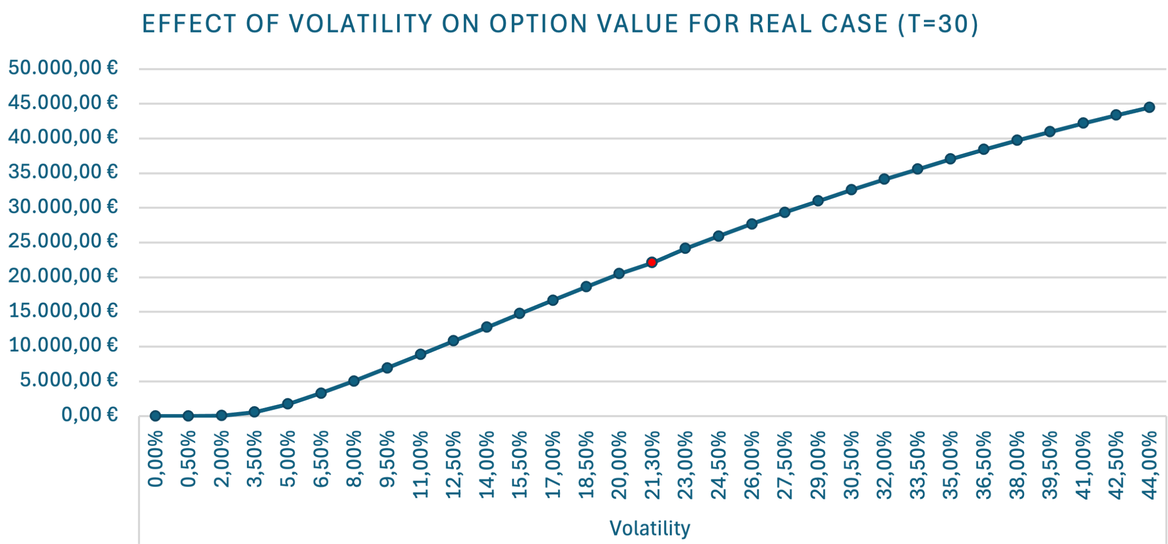


Figure 5.2: Sensitivity Analysis – Black and Scholes (1973) – Effect of Volatility (own illustration)

It becomes clear that option on the case study façade reacts significantly to changes in volatility with a linear increase in option value, which was already suggested by the moderate value for Delta. This indicates that the value of having the option to buy back the aluminium facade would be significantly higher if a strongly volatile price behaviour of raw aluminium is assumed in the future.

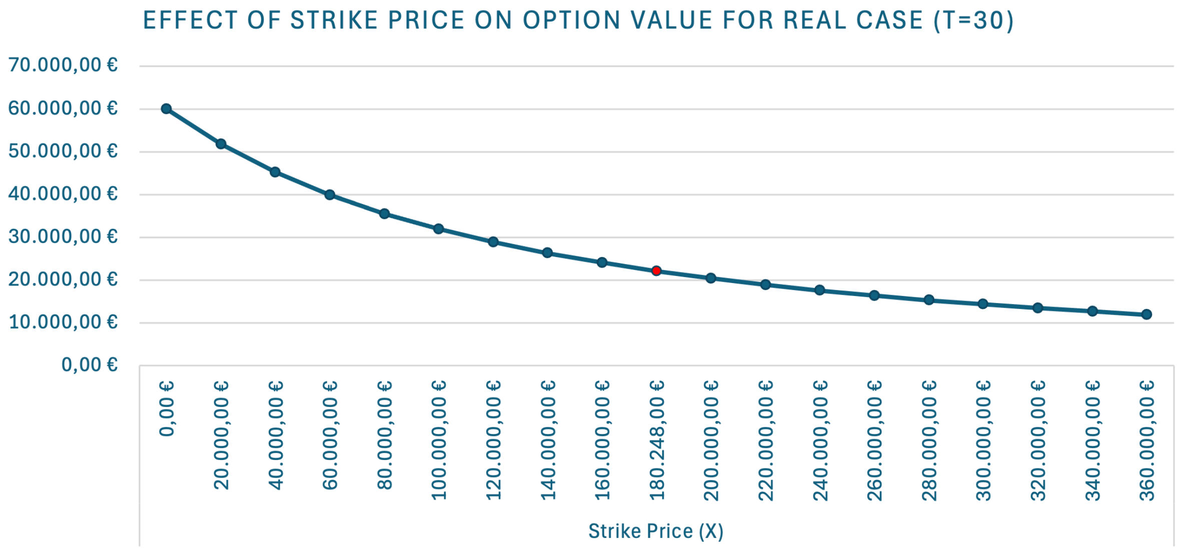


Figure 5.3: Sensitivity Analysis – Black and Scholes (1973) – Effect of Strike Price (own illustration)

As can be seen clearly from Figure 5.3 the strike price naturally influences the option value resulting in a decline under rising values for X. However, the rate of decline is dropping likewise, causing the curve to steadily flatten out, showing the potential in reducing the strike price resulting in significantly higher option prices. This could potentially be achieved by reducing the cost to dismantle the façade and to recover the material.

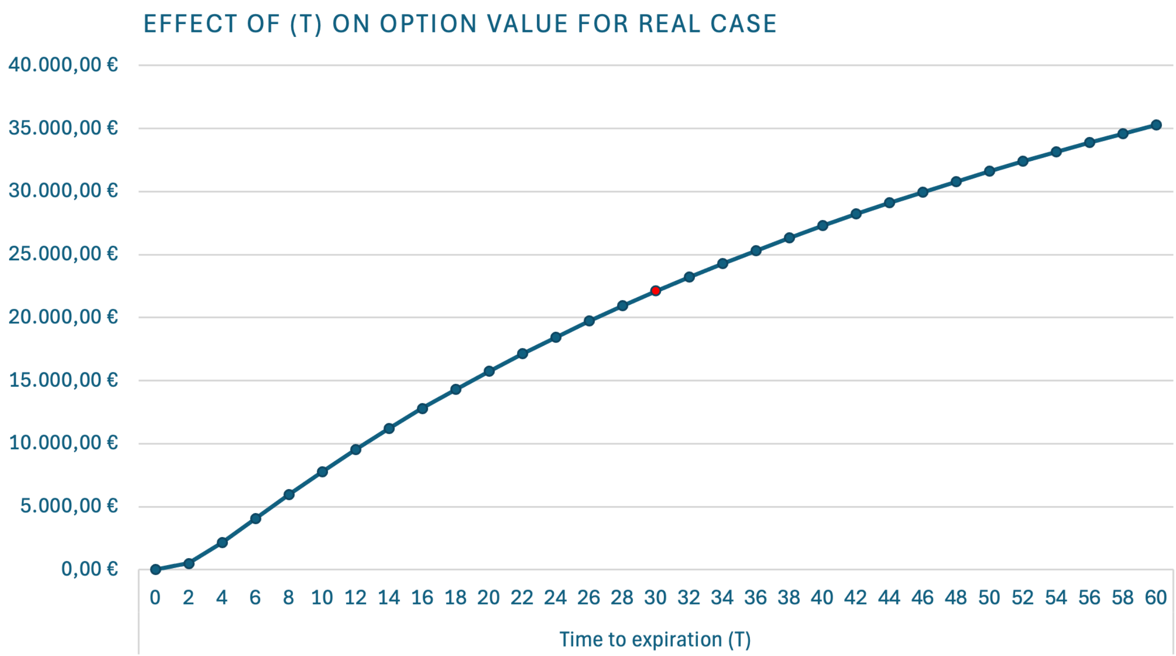


Figure 5.4: Sensitivity Analysis – Black and Scholes (1973) – Effect of Time (own illustration)

Figure 5.4 illustrates the change in option value for different periods for the time to expiry value, indicating, what can be expected, that the option gains in value for longer time spans, as there is more time for the value of raw aluminium embedded in the facade to exceed the cost of dismantling and recovering the material (strike price).

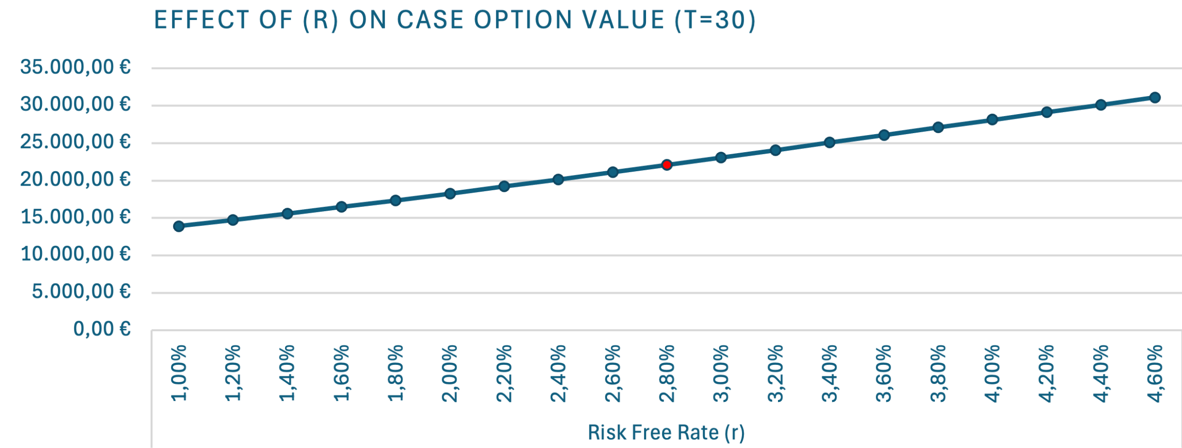


Figure 5.5: Sensitivity Analysis – Black and Scholes (1973) – Effect of Risk Free Rate

The effect of the risk free rate, as indicated by figure 5.5, reflects an increased value of the option at higher risk free rates as the present value of the cost to dismantle and recover the facade is discounted more heavily.

Real-Case Option vs. Best-Case Option – Comparative Analysis:

For a more nuanced interpretation of the findings, the best-case scenario is now considered in comparative perspective, providing insights into how option valuations for a detachable aluminium façade may evolve in response to future developments. Both, real-case and best-case scenario, are then further analysed to identify key differences considering behaviour under changing volatility, the option Delta value, or differences in risk neutral probabilities.

Parameter	Real Case	Best Case
CALCULATED OPTION VALUE: C	22.099,00 €	42.095,00 €
C / CURRENT ASSET VALUE	36,8 %	70,2 %
C / TOTAL INVESTMENT - FACADE	0,78 %	1,5 %
DELTA - N(d1)	0,640	0,925
RISK-NEUTRAL PROBABILITY - N(d2)	0,210	0,611

Figure 5.6: Black and Scholes (1973) – Results: Comparison Real Case vs. Best Case (own illustration)

It stands to reason to shortly revise the key differences between the real-case scenario option and the best-case scenario option being a significantly lower strike price (33.482 € vs. 180.248 €), a higher value of volatility (30% vs. 21,3%), and a shorter time to expiry (T=15 vs. T=30). The direct comparison of the calculation results (as depicted in Figure 5.6) show a clearly higher option value at 42.095,00€ making up for 70,2 % of the current asset value and 1,5% of the total investment on the façade. In relation to the total raw aluminium used for the project the results can be interpreted as an even higher "discount" possible on raw material, while the impact on the total investment on the façade is still limited. However, looking at a aluminium façade project the latter is significantly influenced by what share of total cost might be for instance labour, non-aluminium products and other outside the raw aluminium used. The Delta value was determined to be at 0,925 making it characteristically for a strongly in-the-money option which will is also set to be verified later interpreting the delta curve over time. The risk neutral probability is significantly higher at 0,611 showing a greater chance that the option will fall in the money meaning that the value of aluminium will exceed the cost of dismantling at T. To further asses the behaviour of both the real-case option and best-case option under changing parameters a comparative sensitivity analysis will be conducted:

Real-Case Option vs. Best-Case Option – Comparative Sensitivity Analysis:

As both real-case option and best-case option have significantly different assumptions behind the multiple input parameters used to determine the option value, it can be expected that the result behaves similarly differently when one parameter is changed.

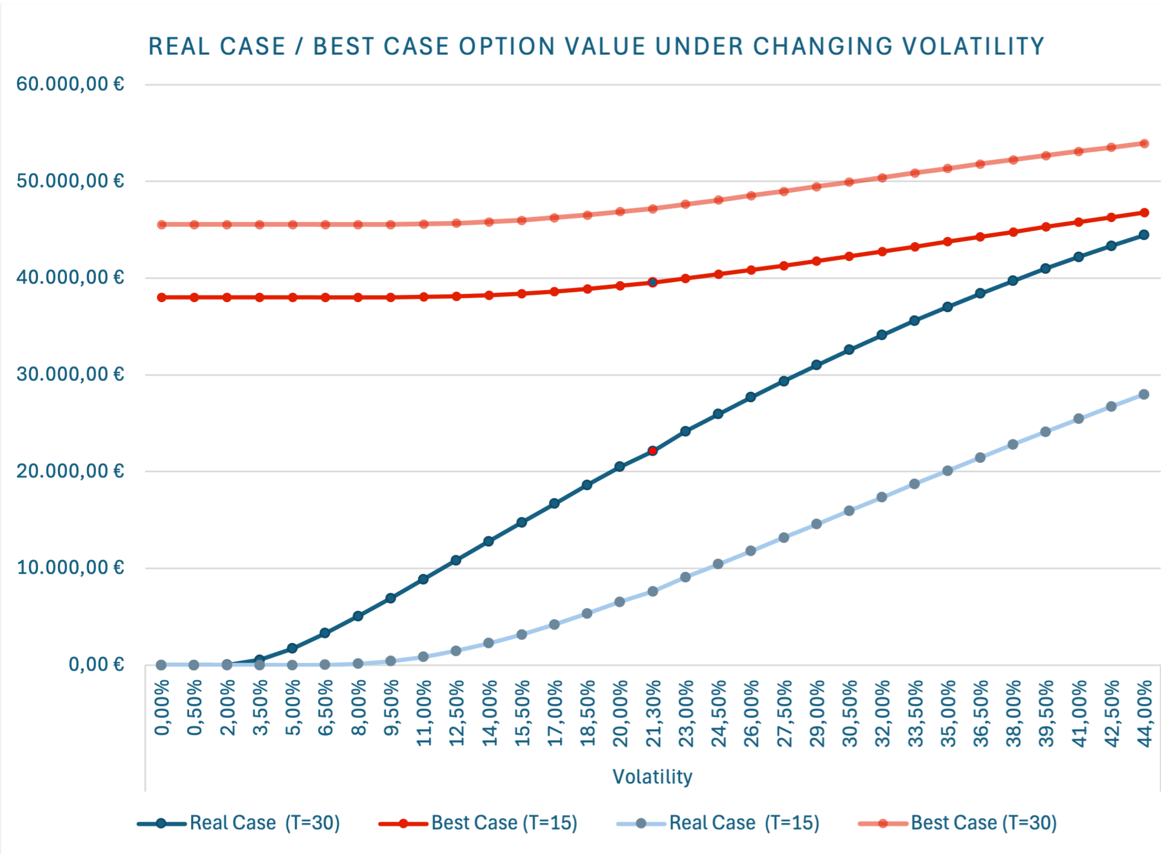


Figure 5.7: Black and Scholes (1973) – Comparison Real Case vs. Best Case – Volatility (own illustration)

Figure 5.7 distributes both cases result for option value over a change of volatility. For better comparability two alterations to the options with their correspondent numbers of (T) were added. It becomes apparent that the best-case option value reacts significantly less strongly to changes in volatility having a stable and high option price even at values close to zero only moderately rising with an increase in volatility. As the best-case options strike price, so the cost to recover the material, is lower than the aluminium value at T = 0 this result appears to be plausible as it cannot be expected that higher volatility will affect the option in favour compared to the real-case option being reliant on market price changes for the recovery of the material to be economically viable. Still, Figure 5.7 moreover clearly depicts that at very high volatility parameters the price of the real-case option nearly reaches the level of the best-case option.

As previously discussed in the methodology section on the Black Scholes (1973) model, the Delta value of the option can be utilised to categorise the option to a certain degree into being 'in the money', 'at the money' or 'out of the money':

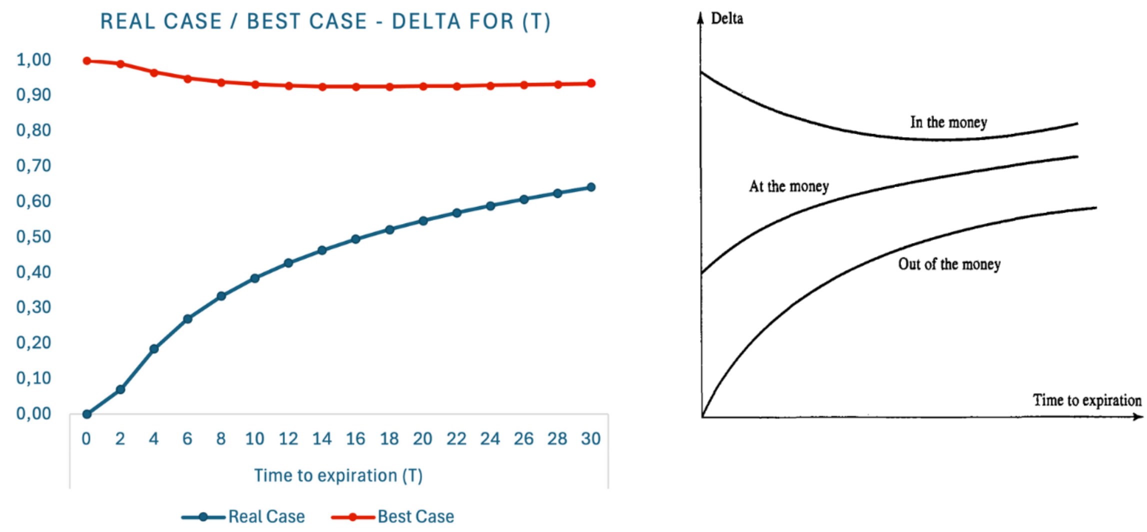


Figure 5.8: Black and Scholes (1973) – Comparison Real Case vs. Best Case – Delta (own illustration) + Delta Curves (Hull, 2007)

Figure 5.8 brings together the characteristic curves for European call options based on (Hull, 2007) and the results of the case study comparison. The parallels become clearly visible emphasising once more that the best-case option can be seen as a clear in-the-money option, while the real-case option shows the pattern of a out-of-the-money option.

Examining the results of the change of risk neutral probability, so the $N(d2)$ value, showcased in Figure 5.9, it is surely remarkable that the probability to fall into the money for the best-case option is declining for higher time values T while it is rising for the real-case option. This, again, is plausible when it is considered that with the strike price being lower than the current asset value for the best-case option time does not work in favour of the option, while it does for a case where the strike price is significantly higher as for the best-case option.

In considering the insights derived from the case comparison and their relevance to aluminium façade projects, particular attention should therefore be given to the strike price – defined as the cost of dismantling the façade and recovering the material – as a key determinant, alongside time to expiration and assumed price volatility. The sensitivity analysis suggests that options linked to façades with a relatively high underlying aluminium value compared to the strike price are likely to be in the money at maturity, rendering them attractive for hedging purposes. However, such options exhibit limited sensitivity to increasing aluminium price volatility. Conversely, options with a comparatively high strike price,

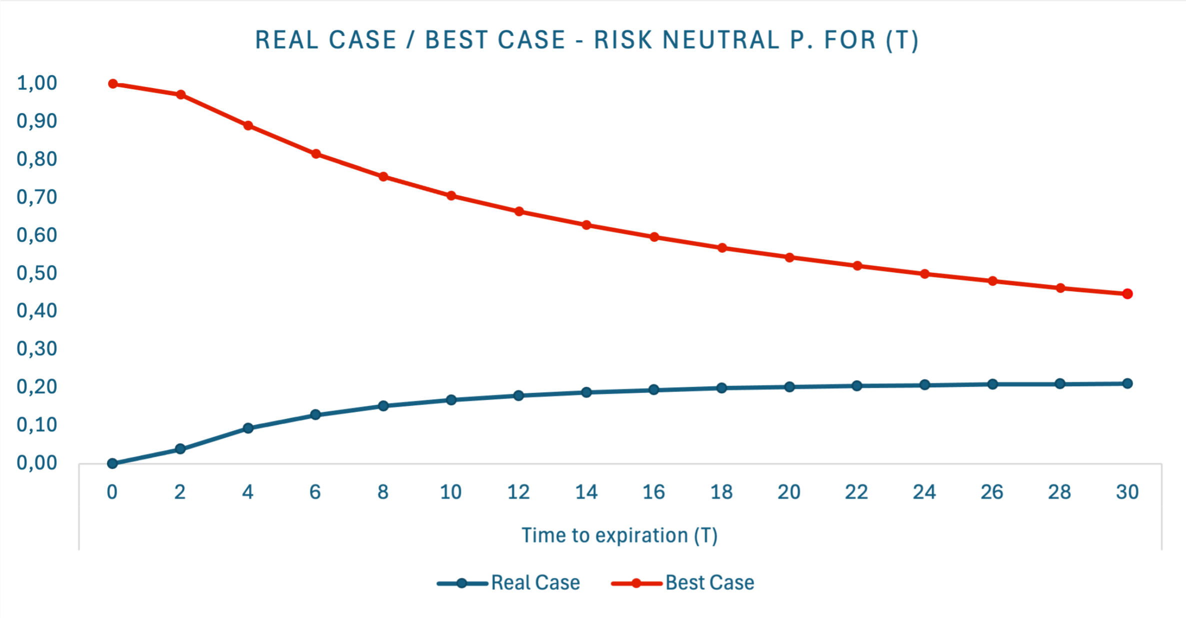


Figure 5.9: Black and Scholes (1973) – Comparison Real Case vs. Best Case – Risk neutral probability (own illustration)

reflecting substantial deconstruction costs, are more likely to remain out of the money and possess lower intrinsic value, yet they stand to benefit more significantly from heightened volatility in aluminium prices, particularly over extended time horizons. It follows that, the interplay between the embedded aluminium value in a façade and the corresponding dismantling costs emerges as a key factor influencing the option's valuation. The discussion section will, at a later stage, place these findings within a broader context and distill the key implications that emerge from the analysis by making the connection to the qualitative findings.

5.1.2. Results from applying the Binomial Tree Model

This section presents and discusses the findings derived from the application of the Binomial Tree Model. Given that the model's underlying assumptions, most notably a constant volatility, are closely aligned with those of the Black & Scholes (1973) framework, the results obtained here also serve to validate the outcomes presented in the preceding chapter. Figure 5.10 illustrates the constructed Binomial Tree for the real-case option over a time horizon of T = 30, as implemented in Microsoft Excel® to estimate the corresponding option value.

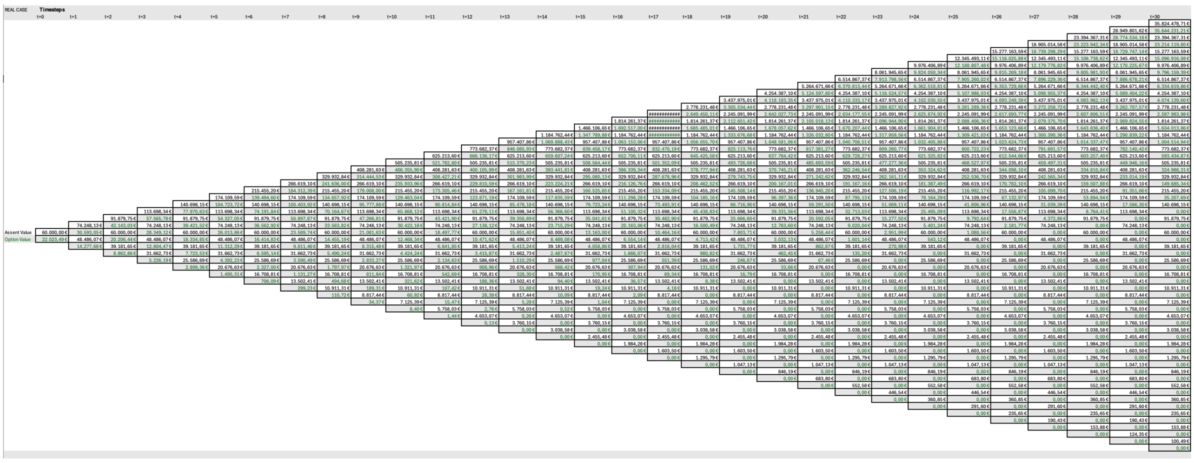


Figure 5.10: Binomial Tree Excel® Sheet – Real Case (own illustration)

To obtain the option value at the starting node the option values where discounted back using a calculated value for risk neutral probability (p) of 0,51 for upward and downward movements. It is important to recognise, like mentioned in the method section, that this (p) value is not comparable to the $N(d2)$ value discussed in the previous section. While likewise called risk neutral probability, it does not reflect the probability that the option will be in the money at expiry but only targets the probability of an upmove at each step. From discounting the option values back from the end note at T = 30 the following results were calculated (Figure 5.11):

CALCULATED OPTION VALUE: C	C_f **= 22.023,00 €**
C / CURRENT ASSET VALUE	36,7 %
C / TOTAL INVESTMENT - FACADE	0,78 %
DELTA - N(d1)	0,633
RISK-NEUTRAL PROBABILITY - N(d2)	0,221

Figure 5.11: Binomial Tree – Results Real Case (own illustration)

With a computed option value of €22,023.00—representing approximately 36.7% of the current asset value and 0.78% of the total investment—the results exhibit only marginal deviations from those obtained using the Black & Scholes (1973) model. A similar conclusion can be drawn for the Delta, which, at 0.633, indicates a moderate level, reflecting, again the option prices notable sensitivity to volatility changes. As outlined in the methodology, the risk-neutral probability for the option to fall in the money was derived by aggregating the probabilities of ending in the money across all terminal nodes. Although calculated via a different mathematical approach, the resulting value of 0.221 remains broadly consistent with that of the Black-Scholes framework, which substantiates the methodological soundness and consistent application of both modelling frameworks.

Case Study – Sensitivity Analysis:

The findings of the sensitivity analysis for the real-case option are presented in a more concise manner, as they closely align with the results discussed in the preceding chapter on the Black & Scholes Model (1973):

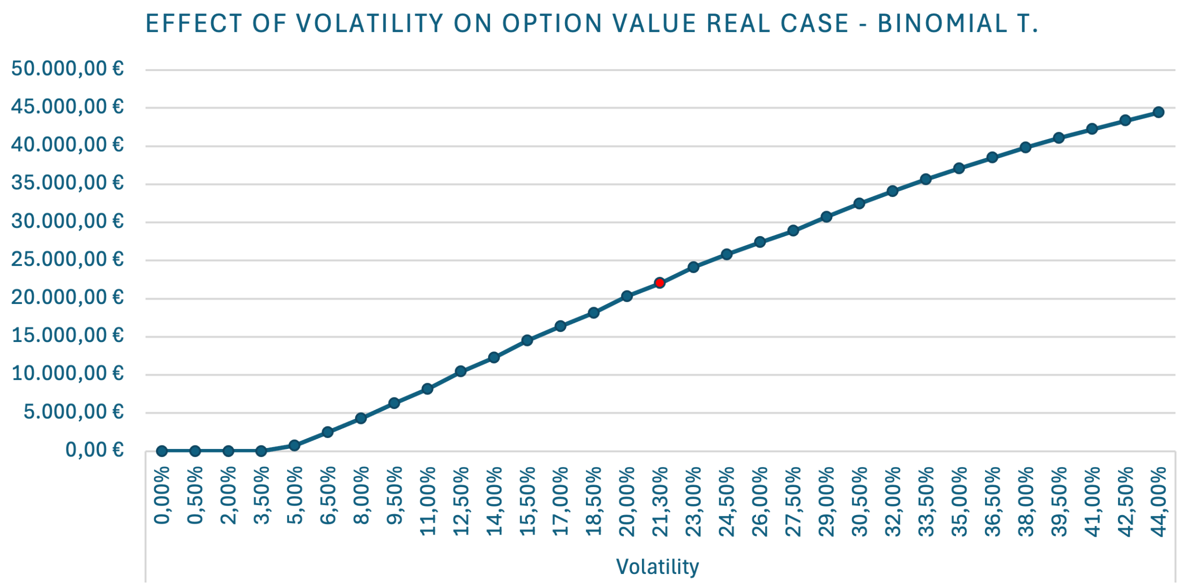


Figure 5.12: Binomial Tree – Sensitivity Analysis Real Case – Volatility (own illustration)

As illustrated in Figure 5.12, the option price exhibits a similar response to changes in volatility – characterized by a generally gradual, near-linear increase and a slightly more pronounced curvature approaching lower and higher volatility values, suggesting a convex-to-concave transition in its behaviour. Under changes of the strike price (X) the option value presents a convex decline, like observed previously with the Black Scholes model (Figure 5.13).

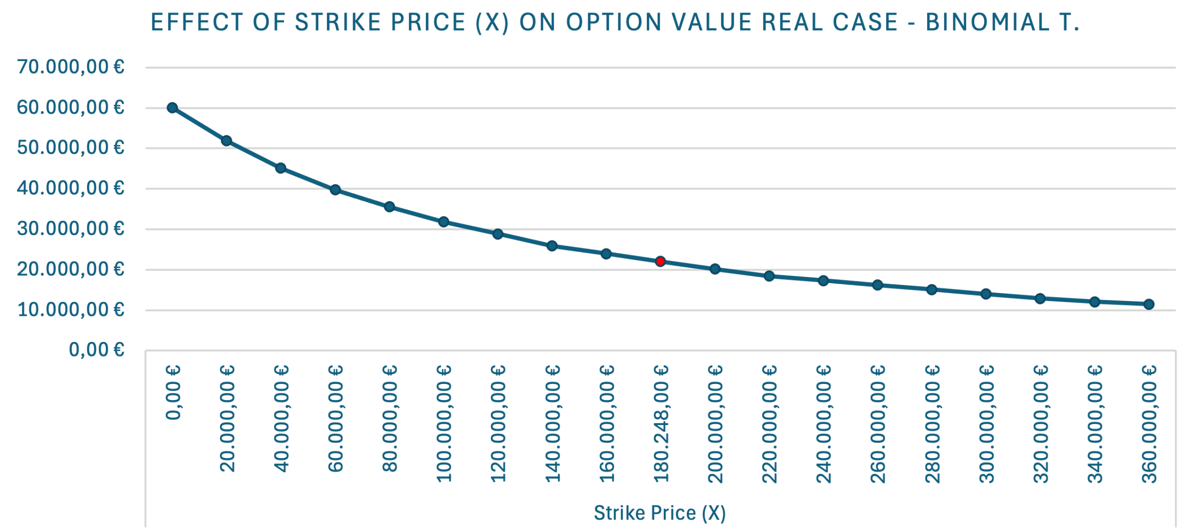


Figure 5.13: Binomial Tree – Sensitivity Analysis Real Case – Strike Price (own illustration)

Real Case Option vs. Best Case Option – Comparative Analysis:

For the best-case option, a binomial tree was similarly constructed and evaluated using backward induction to determine the corresponding option value. The tree appears notably more compact (figure 5.14), reflecting the reduced time horizon of 15 years defined for this scenario, which entails half the number of time steps compared to the previous real-case option.

BEST CASE	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12	t=13	t=14	t=15
																5.407.689,87 €
															4.005.785,98 €	5.374.208,24 €
														2.967.315,38 €	3.973.229,32 €	2.967.315,38 €
													2.198.060,65 €	2.935.658,15 €	2.198.060,65 €	2.933.833,74 €
												1.628.229,57 €	2.167.278,00 €	1.628.229,57 €	2.165.504,00 €	1.628.229,57 €
											1.206.123,01 €	1.598.297,34 €	1.206.123,01 €	1.596.572,34 €	1.206.123,01 €	1.594.747,93 €
										893.444,47 €	1.177.017,70 €	893.444,47 €	1.175.340,36 €	893.444,47 €	1.173.566,35 €	893.444,47 €
									661.825,55 €	865.143,25 €	661.825,55 €	863.512,24 €	661.825,55 €	861.787,25 €	661.825,55 €	859.962,84 €
								490.252,14 €	634.306,19 €	490.252,14 €	632.720,25 €	490.252,14 €	631.042,91 €	490.252,14 €	629.268,90 €	490.252,14 €
							363.157,87 €	463.493,04 €	363.157,87 €	461.950,91 €	363.157,87 €	460.319,91 €	363.157,87 €	458.594,91 €	363.157,87 €	456.770,50 €
						269.011,86 €	337.160,51 €	269.011,86 €	335.638,51 €	269.011,86 €	334.052,57 €	269.011,86 €	332.375,22 €	269.011,86 €	330.601,22 €	269.011,86 €
					199.272,51 €	243.839,53 €	199.272,51 €	242.296,55 €	199.272,51 €	240.710,63 €	199.272,51 €	239.079,63 €	199.272,51 €	237.354,63 €	199.272,51 €	235.530,22 €
				147.612,57 €	175.076,80 €	147.612,57 €	173.483,27 €	147.612,57 €	171.838,46 €	147.612,57 €	170.167,21 €	147.612,57 €	168.489,86 €	147.612,57 €	166.715,85 €	147.612,57 €
			109.345,10 €	124.626,99 €	109.345,10 €	122.988,12 €	109.345,10 €	121.263,60 €	109.345,10 €	119.477,57 €	109.345,10 €	117.680,35 €	109.345,10 €	115.955,35 €	109.345,10 €	114.130,94 €
		80.998,18 €	87.847,16 €	80.998,18 €	86.204,78 €	80.998,18 €	84.437,16 €	80.998,18 €	82.548,50 €	80.998,18 €	80.563,65 €	80.998,18 €	78.562,45 €	80.998,18 €	76.788,44 €	80.998,18 €
Assent Value	60.000,00 €	61.256,72 €	60.000,00 €	59.673,87 €	60.000,00 €	57.939,94 €	60.000,00 €	56.038,61 €	60.000,00 €	53.956,49 €	60.000,00 €	51.696,95 €	60.000,00 €	49.340,96 €	60.000,00 €	47.516,55 €
Option Value	**42.226,67 €**	44.445,44 €	40.767,17 €	44.445,44 €	39.152,38 €	44.445,44 €	37.355,27 €	44.445,44 €	35.340,25 €	44.445,44 €	33.059,05 €	44.445,44 €	30.446,78 €	44.445,44 €	27.443,34 €	44.445,44 €
		27.476,05 €	32.923,29 €	26.048,33 €	32.923,29 €	24.453,18 €	32.923,29 €	22.652,58 €	32.923,29 €	20.589,11 €	32.923,29 €	18.165,76 €	32.923,29 €	15.183,61 €	32.923,29 €	10.963,80 €
			17.065,26 €	24.388,17 €	15.728,06 €	24.388,17 €	14.227,70 €	24.388,17 €	12.521,99 €	24.388,17 €	10.542,21 €	24.388,17 €	8.157,43 €	24.388,17 €	5.033,80 €	24.388,17 €
				9.947,91 €	18.065,71 €	8.769,48 €	18.065,71 €	7.456,95 €	18.065,71 €	5.979,48 €	18.065,71 €	4.289,93 €	18.065,71 €	2.311,17 €	18.065,71 €	0,00 €
					5.312,67 €	13.382,31 €	4.358,80 €	13.382,31 €	3.327,33 €	13.382,31 €	2.219,68 €	13.382,31 €	1.061,12 €	13.382,31 €	0,00 €	13.382,31 €
						2.506,30 €	9.913,04 €	1.821,93 €	9.913,04 €	1.133,93 €	9.913,04 €	487,19 €	9.913,04 €	0,00 €	9.913,04 €	0,00 €
							984,03 €	7.343,16 €	573,33 €	7.343,16 €	223,68 €	7.343,16 €	0,00 €	7.343,16 €	0,00 €	7.343,16 €
								287,43 €	5.439,50 €	102,70 €	5.439,50 €	0,00 €	5.439,50 €	0,00 €	5.439,50 €	0,00 €
									47,15 €	4.029,35 €	0,00 €	4.029,35 €	0,00 €	4.029,35 €	0,00 €	4.029,35 €
										0,00 €	2.984,77 €	0,00 €	2.984,77 €	0,00 €	2.984,77 €	0,00 €
											0,00 €	2.210,99 €	0,00 €	2.210,99 €	0,00 €	2.210,99 €
												0,00 €	1.637,81 €	0,00 €	1.637,81 €	0,00 €
													0,00 €	1.213,22 €	0,00 €	1.213,22 €
														0,00 €	898,70 €	0,00 €
															0,00 €	665,72 €
																0,00 €

Figure 5.14: Binomial Tree Excel® Sheet – Best Case (own illustration)

The overview of the results given in Figure 5.15 once more emphasises the similarity between both approaches showing only minor differences in results coming from the binomial tree method for both the real-case as well as the best case option. This suggests that, when assuming a constant volatility, both methods are interchangeably able to produce an option value with minor differences , while the binomial tree has the advantage, as mentioned previously, to map out a more transparent approach on how this value is obtained which might be useful, when e.g. calculation are presented to investors.

Parameter	B. & S. Real Case	Binom. Real Case	B. & S. Best Case	Binom. Best Case
CALCULATED OPTION VALUE: C	**22.099,00 €**	**22.023,00 €**	**42.095,00 €**	**42.227,00 €**
C / CURRENT ASSET VALUE	36,8 %	36,7 %	70,2 %	70,4 %
C / TOTAL INVESTMENT - FACADE	0,78 %	0,78 %	1,5 %	1,5 %
DELTA	0,640	0,633	0,925	0,924
RISK-NEUTRAL PROBABILITY	0,210	0,221	0,611	0,616

Figure 5.15: Binomial Tree vs. Black & Scholes (1973) – Results Real Case and Best Case (own illustration)

However, the binomial model requires greater computational effort constructing trees for varying values of (T), whereas the Black-Scholes formula allows for a more rapid evaluation across different parameters. Accordingly, the selection between the two methods should be guided by the specific analytical objectives and the desired level of detail in the results.

Now that the results for models assuming constant volatility have been discussed, the findings of the Heston (1993) model will be presented in the following section, leading to a final comparative analysis evaluation of all three models under the 'classic approach' of real option valuation.

5.1.3. Results from applying the Heston (1993) Model

To maintain clarity and conciseness in the analysis of the Heston model results, both the real-case option and the best-case option will be examined in parallel from the outset. The MATLAB code scripts used to compute the following results can be found in Appendix (B).

Case Study & Best Case Study – Results:

Parameter	**Real Case**	**Best Case**
CALCULATED OPTION VALUE: C	**20.119,00 €**	**41.368,00 €**
C / CURRENT ASSET VALUE	33,5 %	68,9 %
C / TOTAL INVESTMENT - FACADE	0,71 %	1,46%
DELTA	0,565	0,9438
RISK-NEUTRAL PROBABILITY	0,177	0,6940

Figure 5.16: Heston (1993) – Results Real Case and Best Case (own illustration)

Figure 5.16 illustrates the option valuation results derived from the Heston (1993) model, based on the parameters introduced in the methodology chapter. For the real-case scenario, the computed option value (C) is €20,119.00, accounting for approximately one-third of the asset value and 0.71% of the total investment, which aligns closely with, yet remains slightly below, the results obtained using the Black-Scholes (1973) and binomial tree models. Similarly, in the best-case scenario, the option value reaches €41,368.00, representing 68.9% of the underlying asset value and 1.46% of the total investment in the façade. Although the differences are relatively minor, the real-case produces a lower Delta of 0.565 and risk-neutral probability of 0.177, indicating a more moderate sensitivity and likelihood of finishing in the money compared to previous results. Conversely, the best-case displays a Delta of 0.9438 and a risk-neutral probability of 0.6940, both slightly higher than those calculated under the previous models, suggesting greater responsiveness to the underlying asset's movements and a stronger probability of exercising the option profitably.

As the results indicate that applying the Heston (1993) model and therefore incorporating stochastic volatility produces slightly lower option values compared to the Black-Scholes (1973) and Binomial tree models, it can be suggested that, under the chosen parameters, aluminium prices are modelled to be relatively stable, reflecting a lower risk and consequently lower option premiums. Comparing the delta and risk-neutral probability between the real-case and best-case options reinforces this interpretation. The higher delta and risk neutral probability of the best-case option, compared to the lower delta and probability for the real-case option, indicate that assumed limited fluctuations in volatility profit the option that is considered in the money. Yet, is the option that is considered out of the money relying more heavily on higher volatility levels to become valuable, negatively affected by this stable volatility prediction.

To further evaluate how the selected parameters of the Heston (1993) model influence the option value, the following sensitivity analysis illustrates the variation in option pricing corresponding to adjustments in each individual parameter.

Case Study & Best Case Study – Sensitivity Analysis:

Figures 5.18 and 5.19 present the variation in option value for both scenarios across different strike prices and times to expiry, depicted in mesh format. A comparative evaluation of both figures reveals that the best-case option demonstrates a steeper value increase over longer maturities, particularly at higher strike prices. This trend aligns with earlier findings, suggesting that the best-case scenario—characterised by higher assumed volatility—benefits more significantly from extended time horizons, as it allows greater potential for the underlying aluminium value to rise, thereby enhancing the option's worth.

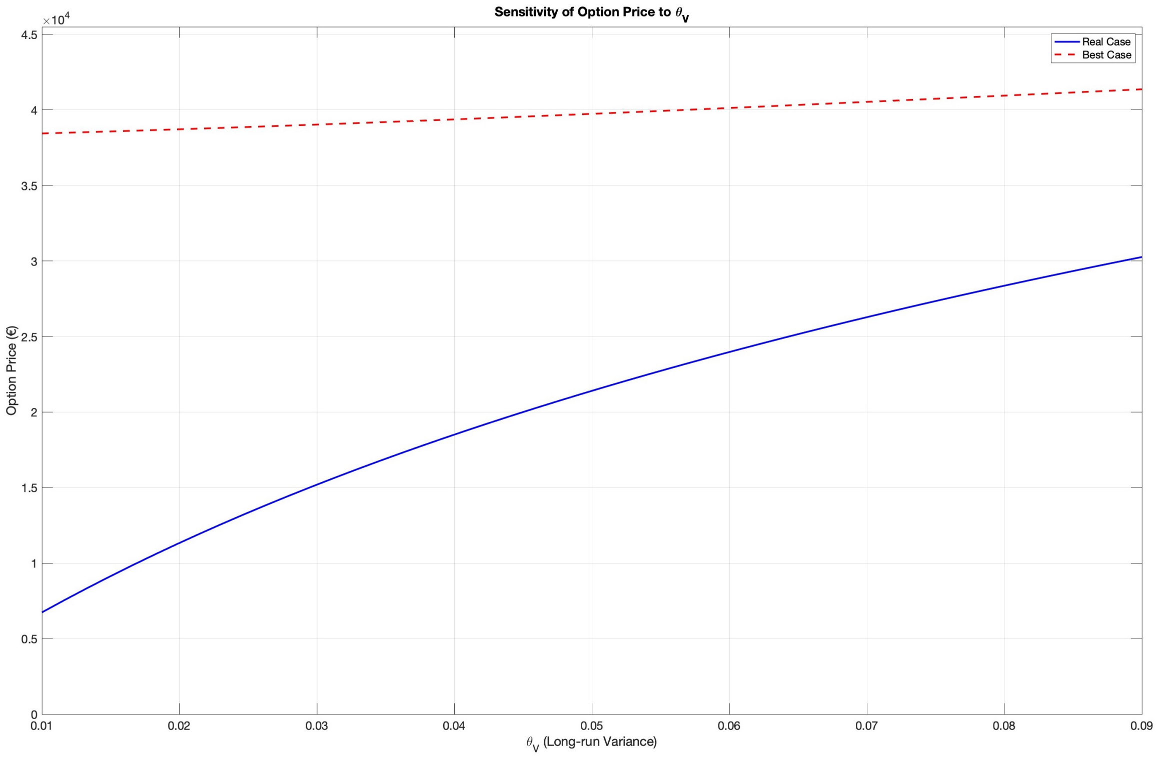


Figure 5.17: Heston (1993) – Real- and Best-Case Option – Sensitivity Option Value to Theta (own illustration)

It is thus evident that the assumed volatility has a substantial influence on the option's value dynamics, a relationship further illustrated in Figure 5.17, which depicts the effect of long-term variance θ on the options valuation.

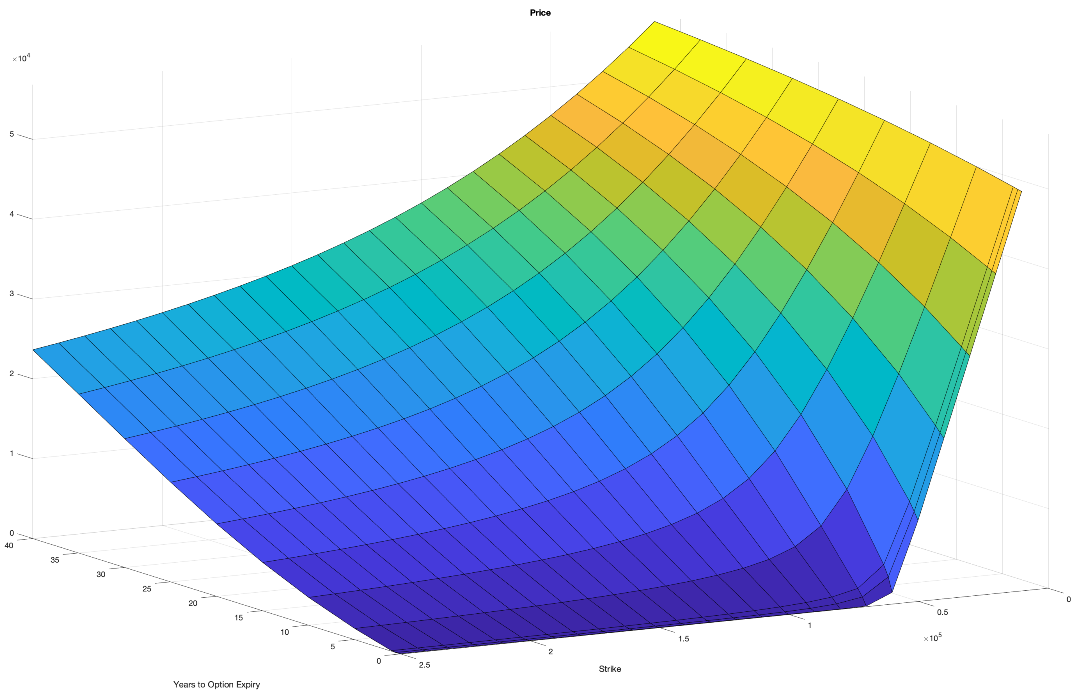


Figure 5.18: Heston (1993) – Real Case Option – Sensitivity Option Value to T and Strike Price (own illustration)

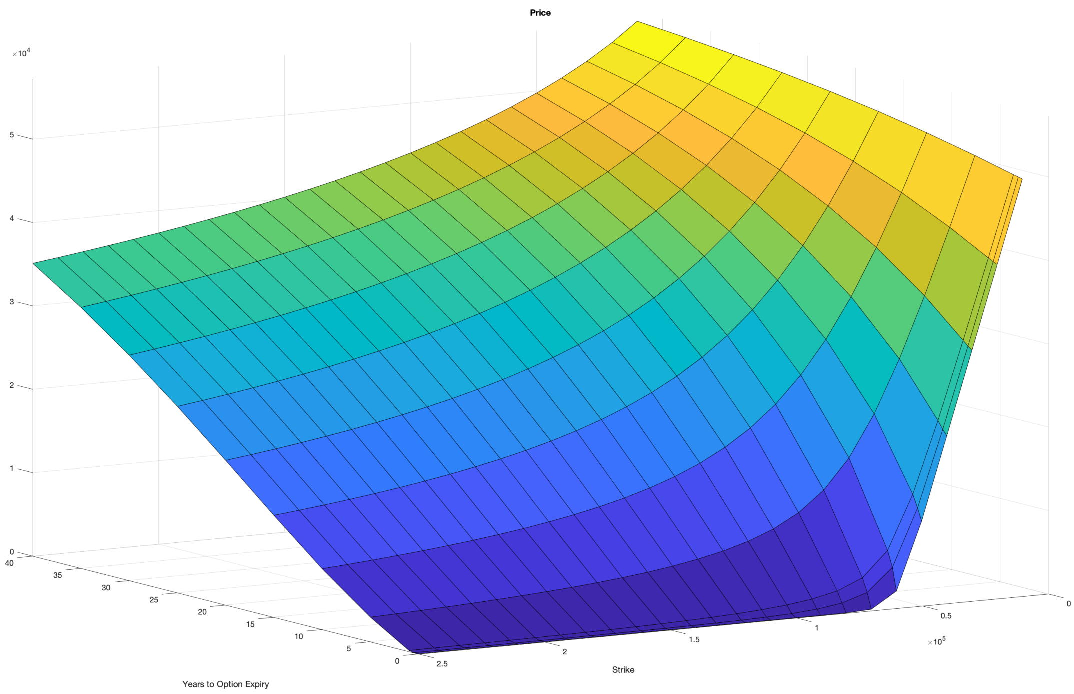


Figure 5.19: Heston (1993) – Best Case Option – Sensitivity Option Value to T and Strike Price (own illustration)

Similar to the constant volatility assumptions in earlier models, the long-term variance parameter, Theta, exhibits a notably greater influence on the real-case option, which is positioned further out of the money. In contrast, the option value in the best-case scenario remains relatively stable across varying assumptions of average variance over the option's lifespan. This reinforces previous findings that when deconstruction costs significantly exceed the embedded aluminium value, the resulting option becomes more sensitive to price volatility. While such scenarios benefit more from high market fluctuations, they produce ever decreasing option values under more stable conditions.

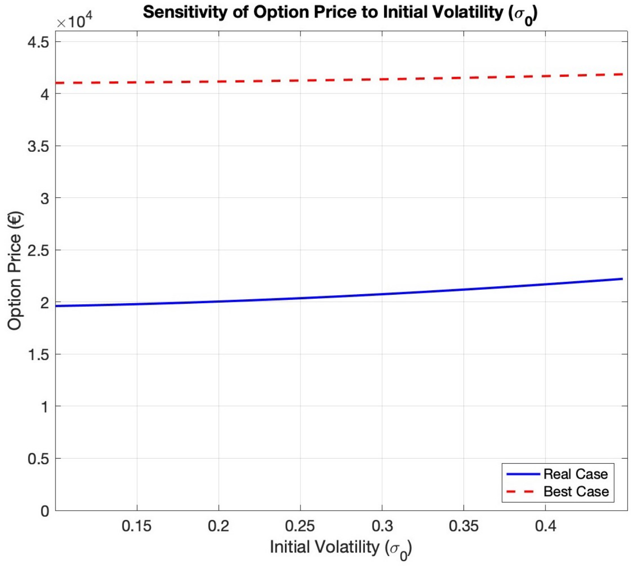


Figure 5.20: Heston (1993) – Real- and Best-Case Option – Sensitivity Option Value to initial volatility (own illustration)

A higher initial volatility leads to an increase in option value, as demonstrated in Figure 5.20. While the effect is moderately pronounced for the best-case option, it is somewhat more substantial for the real-case scenario. This suggests that even though volatility reverts to the long-term average θ, the choice of initial variance still influences the volatility trajectory and, consequently, the option's valuation. Therefore, this parameter must be carefully considered when pricing an option on an aluminium façade.

As described in the methodology chapter, the parameter kappa controls how quickly the volatility reverts to its long-term average, starting from the previously discussed initially assumed variance. The influence of kappa is illustrated in Figure 5.21. The results indicate that lower values lead to slower mean reversion, allowing volatility to remain subdued for longer periods, and as a result, the expected variability of returns decreases, which translates into significantly lower option values. The data displayed in Figure 5.21 furthermore suggest that this effect is particularly pronounced for options that are initially out of the money, such as the real-case option, where the probability of expiring in the money is already low. In such scenarios, sustained low volatility further reduces the potential for an economically viable recovery of raw aluminium, thereby diminishing option value. In contrast, when kappa is high, the variance reverts more quickly to the mean, yet the resulting increase in option value plateaus, indicating that beyond a certain point, further increases in kappa have limited effect. Comparing the two case options confirms that the sensitivity to kappa is markedly stronger for the out-of-the-money scenario, underlining the importance of this parameter when pricing options on an aluminium building component with a lower comparable asset value.

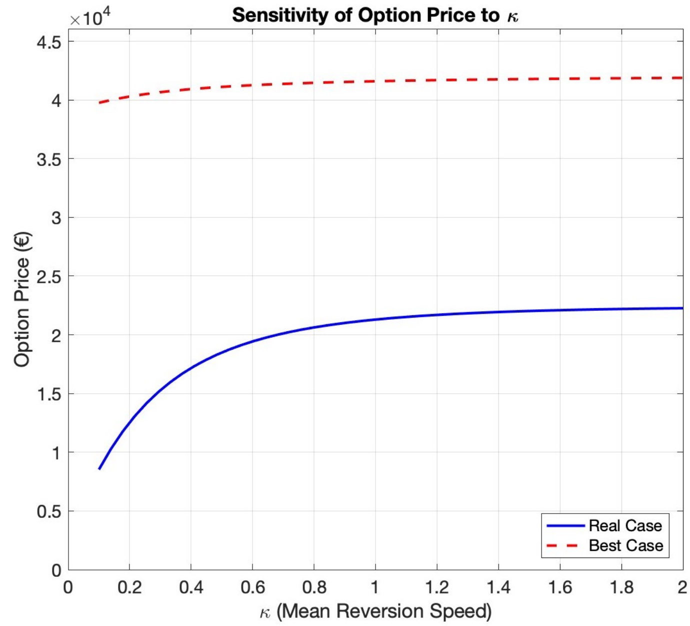


Figure 5.21: Heston (1993) – Real- and Best-Case Option – Sensitivity Option Value to Kappa (own illustration)

With increasing values of the volatility of variance or σ_v the variance of the underlying asset becomes more erratic or unstable over time. While intuitively one might expect that more uncertainty should increase an option's value, can the exact opposite pattern be observed from figure 5.22. It can be inferred that, due to the mean-reverting nature of volatility, sharp increases in volatility tend to be short-lived; consequently, higher values of σ_v may result in lower average effective volatility over time. This potential dynamic should be carefully considered by valuation professionals when estimating the volatility of variance for an option on an aluminium building component.

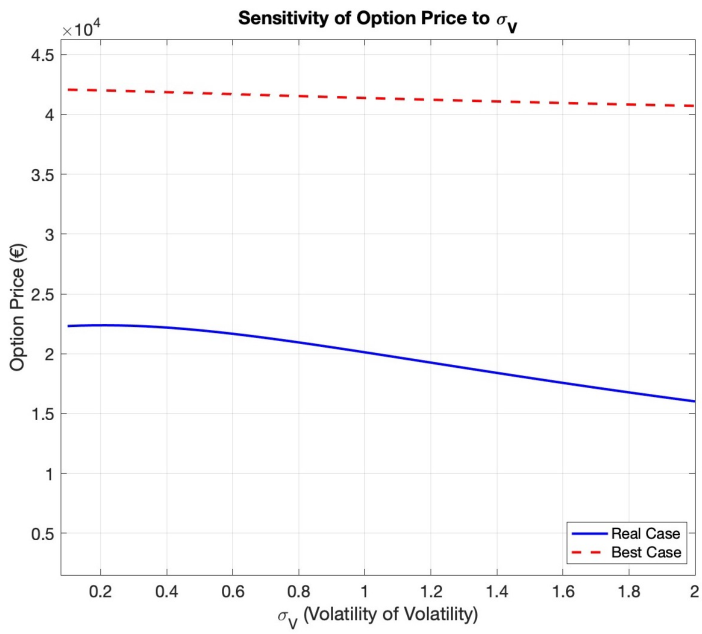


Figure 5.22: Heston (1993) – Real- and Best-Case Option – Sensitivity Option Value to Volatility of Variance (own illustration)

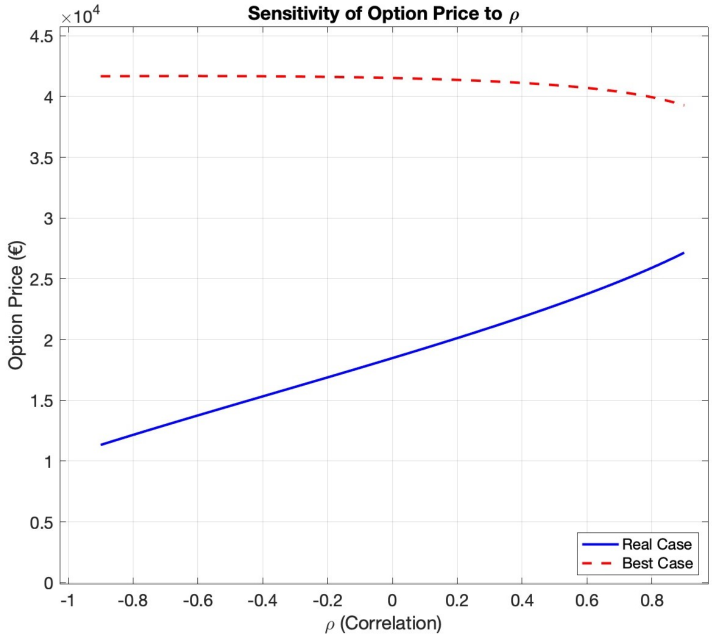


Figure 5.23: Heston (1993) – Real- and Best-Case Option – Sensitivity Option Value to Correlation (own illustration)

For different values of correlation both cases show very distinct differences in behaviour (figure 5.23). This result suggests that in the real-case scenario, where the aluminium façade option is out of the money, a higher ρ (positive correlation between aluminium price and its volatility) increases the likelihood of the option reaching profitability. This is because rising aluminium prices are now accompanied by increased volatility, enhancing the potential for further upward movement beyond the strike price. With negative correlation this effect would be inverted which is indicated by the slight concave to convex transition of the curve. Conversely, in the best-case scenario, where the option is already in the money, Figure 5.23 indicates that a high ρ diminishes its relative advantage in the event of a price decline, volatility also tends to fall, potentially reducing the chance of a price rebound and weakening the option's resilience to adverse market movements.

5.2. QUALITATIVE RESULTS: BRIDGING THEORY AND THE STATUS QUO OF PRACTICE

The quantitative results of this thesis have thoroughly examined the use of real option valuation methods to assess an option on an aluminium façade component, producing a range of multifaceted outcomes. In this chapter, these results are now complemented by the evaluation of the qualitative research, beginning with the key insights from the semi-structured interviews. The interviews are primarily intended to first validate stakeholder interest in options on aluminium façades and the overall innovativeness of the idea. Secondly, potential barriers to buying, selling or financing option contracts are set to be identified.

5.2.1. Results from Semi Structured Interviews

This section first provides an overview of the interviews conducted, followed by a more detailed analysis of the findings according to the respective overarching respondent groups. Overall ten interviews were conducted each targeting a slightly different professional role belonging to the stakeholder groups showcased in figure 5.24. The interview transcripts can be found in Appendix I.

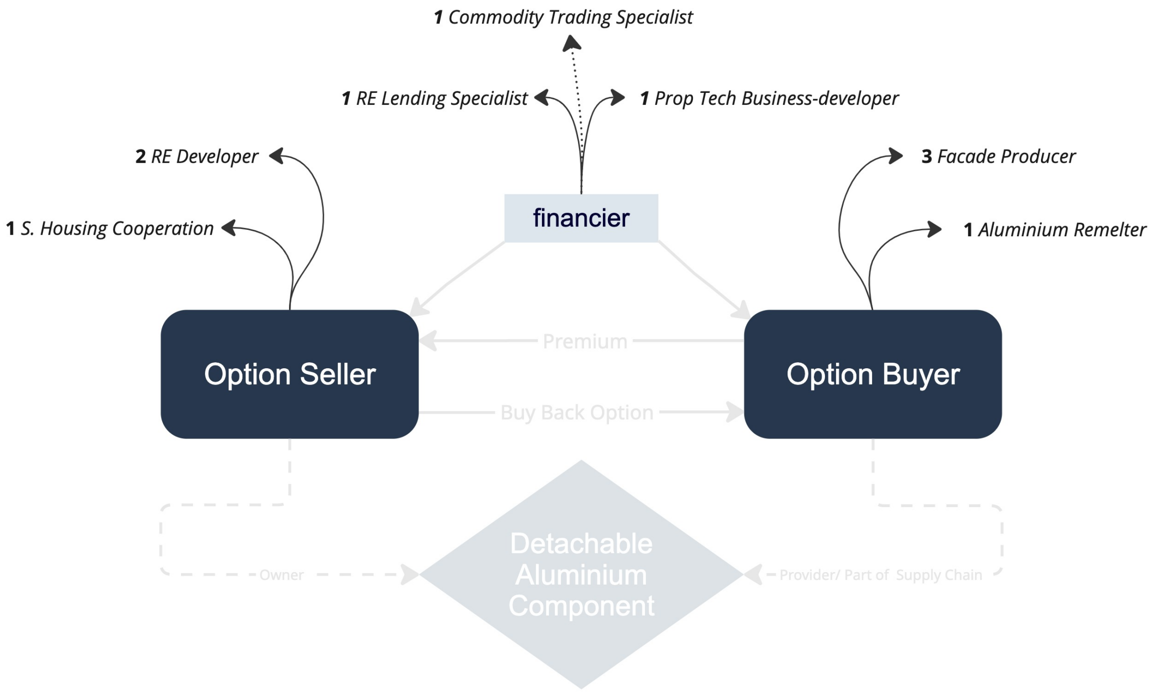


Figure 5.24: Semi-structured interviews overview (own illustration)

Group 1: Option Seller

Within the category of market participants likely to issue an option on a detachable building component integrated into a property they own or develop, three interviews were conducted. These included two real estate developers and one housing association. The housing association (Group 1 / Interview 1) was selected to represent a stakeholder involved in both development and long-term ownership, positioning them as a particularly relevant case for evaluating the applicability of the option concept. The first interviewed real estate developer (Group 1 /Interview 2) specialises in modular and temporary buildings, which are retained in the company's ownership under temporary ground leases – an approach that inherently demands long-term planning and strategic foresight. The second developer (Group 1 / Interview 3) primarily focuses on timber construction, which may seem out of place given this thesis's focus on aluminium. However, due to the exploratory nature of the study and the aim to assess the broader applicability of option valuation to other raw materials, this interview was included to offer an alternative perspective, particularly in light of the potential for timber to serve as a substitute material in scenarios where aluminium becomes increasingly scarce. The interview highlighted parallels with aluminium and notably the potential to link an option to the value of stored carbon in timber building components. This presents a promising stimulus for future research, though it falls outside the scope of this thesis.

In the opening segment of the interview, participants were invited to share their general approach to circular construction, their expectations regarding future material prices, and whether end-of-life values are currently considered in their planning or investment strategies:

For the housing association, circularity was described as a strategic objective aligned with the organisation's societal role; however, no specific KPIs have been established. The implementation of circular measures is evaluated on a project-by-project basis, contingent on the viability of the business case and the need to maintain tenant comfort standards. For the developer specialising in modular buildings, the ability to detach and reuse both individual components and entire units is regarded as a fundamental aspect of the company's business model.

Group 1 - Option Seller | Interview 2

" (…) we are in fact circular in a way that we can move the houses to another spot (…)"

However, all interviewees expressed that while end-of-life values of building components might be considered in most projects, a key barrier remains the difficulty of quantifying them accurately.

Group 1 - Option Seller | Interview 1

"From a financial perspective, it's difficult to take into account the value of a house for 50 years in the calculations we make now."

While preliminary efforts to incorporate material end-of-life values were noted (Interview 2), there was also mention of limited investor acceptance, with such valuations often confined to educational purposes (Interview 3). All interviewees in this group emphasised that the significant additional costs remain a major barrier to implementing circular measures which restricts action to what can be justified within the boundaries of a defined business case.

After viewing the explanatory video outlining the option scenario, all three interviewees expressed interest in the concept of entering into an option contract for a façade they own.

Group 1 - Option Seller | Interview 3

"I think it's a very nice idea."

Yet next to general interest and openness towards the idea multiple concerns and potential barriers were identified.

Group 1 - Option Seller | Interview 2

"It would be certainly something I would look into. Maybe somewhat earlier for installation or maybe also kitchens or a bathroom instead of something that's directly linked to moving of renters. Yeah, I would be interested."

While the quote reflects strong interest, it also illustrates a recurring concern among interviewees: the potential loss of building functionality if the option is exercised and the façade is reclaimed. A closely related issue raised was the inherent uncertainty of options—specifically, not knowing whether the holder will ultimately choose to exercise their right.

Group 1 - Option Seller | Interview 1

"The main risk is that we don't know whether a supplier will take back the building part at the end of its lifetime. That's a big risk."

Another concern raised was the long time horizon, which makes it challenging to predict future façade replacement costs and to accurately assess the option's strike price and premium (Interview 3). To address this uncertainty, both interviewees from development firms (Interviews 2 & 3) proposed linking the option contract to a binding offer for a replacement façade, should the original be recovered by the option holder. This approach was seen as a way to reduce the risk of losing the façade during a period of high material prices - when the option becomes more attractive to the buyer - while avoiding the financial strain of reinvesting at an inopportune time.

Interestingly, some interviewees (Interview 2 & 3) initially interpreted the option concept as akin to an 'as-a-service' model or needed clarification that ownership of the building component remains with them until the option is exercised. This suggests that, although legally untrue, entering into an option contract may be perceived as a partial loss of ownership, which is closely tied to the uncertainty of whether the option holder will ultimately exercise their right, overall contributing to the perceived risk of such agreements from an real estate owners perspective.

In summary, while the idea of selling an option to a supplier was met with interest by the interviewees, the option price would need to be sufficiently high to compensate for perceived risks, particularly the potential loss of rental income and uncertainty surrounding future replacement investments. The perspective of potential option buyers and their willingness to meet this price will be examined in the following sub-chapter.

Group 2: Option Buyer

Four semi-structured interviews were conducted with stakeholders who could potentially purchase an option on aluminium façade components to benefit from material recovery or hedge against price volatility. These included three façade producers and one aluminium smelter. The first façade producer (Group 2 / Interview 1) is a company focused on assembling prefabricated façade profiles and circular, detachable systems. In contrast, the other two producers (Group 2 / Interviews 2 & 3) are part of globally operating firms that cover all or most stages of the supply chain. The aluminium smelter (Group 2 / Interview 4) is focused on remelting scrap aluminium to produce billets for extrusion mainly to be used in the construction sector.

At the beginning of the interview, prior to introducing the option scenario, the participants were invited to share their perspectives on the future of aluminium supply and demand in Europe, potential price trends, and the influence of EU regulations on these developments.

Although expressed in different ways, all participants indicated that future developments will be characterised by rising uncertainty, e.g. caused by geopolitical shifts and climate influences and that this will be reflected in price developments. It can be inferred from the statements of Interview 1 & 4 that this will possibly affect smaller companies more, as they have less control over the market and only cover part of the value chain, therefore, expressing an even more pessimistic outlook on future developments.

Group 2 - Option Buyer | Interview 4

“I mean already in the Netherlands the energy prices are far beyond the average of Europe and we see a lot of industries going down and, well, that combined with more expensive scrap… Yes, there’s all kind of reasons to be pessimistic.”

Group 2 - Option Buyer | Interview 3

“The other story, where I actually see the added value of urban mining in particular, is that we are increasingly living in unstable times, which is not the right word, but in dynamic times where things change quickly.”

The latter quote complements a perspective that sees rising market volatility as a reason to adopt a strategic approach to material recovery, using it as a safeguard against supply instability. Only Interviewees 2 and 3 indicated that material recovery from buildings falls within their strategic and operational scope, whereas the smaller façade producer (Interview 1) and the aluminium smelter (Interview 4) stated that they are not directly involved in recovery processes, or only provide advisory support.

Group 2 - Option Buyer | Interview 1

“ (…) we only are kind of the mediator between the client and the party who is recycling. We don’t charge anything for that.”

When asked about measures to counteract future price volatility the smaller façade producer (Interview 1) as well as the aluminium smelter (Interview 4) indicate a limitation in the possibility to plan ahead.

Group 2 - Option Buyer | Interview 1

"Our common business is just selling facades, so we look to the price for today in a little bit the price over half a year. But further than that we cannot watch because we have no idea."

Group 2 - Option Buyer | Interview 4

"Let's say also our extrusion plants are selling and pricing material not further ahead as let's say 6 to 9 months. And in case a large order is being booked for the future for, let's say nine months something like that, then it might be that I already purchase a certain amount of primary with a fixed price. But that's about it."

The strategic priorities lie more in enhancing internal production capabilities (Interview 1) and improving scrap sorting processes (Interview 4), rather than in securing stable prices. The interviews with professionals from larger companies (Interview 2 & 3) also show that, although as previously mentioned aluminium recovery from buildings for recycling is already an integral part of their strategy, no concrete steps have yet been taken to secure material for the future. Both interviewees stated that 'as a service' approaches have been tested or are currently being explored as a way to keep ownership of materials, but have not yet been implemented.

Group 2 - Option Buyer | Interview 3

"Are we endeavouring today to secure this for tomorrow? At the moment no, we're not quite there yet. At the moment it's more of a, I don't want to say gold-rush mood - no, that would be too much to say - but actually more of an approach of how do I get the existing material back into the market."

Group 2 - Option Buyer | Interview 2

"I think it would be great if we can try this out on building, but it's like I said there was product as a service. The same thing for us. And we ran into issues at the last or we couldn't get the contract to go."

After being introduced to the option scenario, the professional from the smaller façade production company (Interview 1) responded with strong interest, acknowledging the growing importance of preparing for increasing aluminium price uncertainty. However, concerns were raised about the already narrow profit margins in the business, which could be further reduced by covering the cost of an option respectively offering a discount for future material recovery. Another challenge mentioned was the lack of direct relationships with both building owners and recycling firms, making it difficult to establish such contracts. When the conversation shifted to options on detachable façade components intended for reuse and resale as a complete component rather then recycling, the professional saw greater potential in the concept but also pointed out the difficulty in forecasting the future functional value of these components compared to simply valuing the raw materials. Interview 2, conducted with a representative from a large, Europe-wide operating façade producer, reflected similar concerns, particularly regarding the challenge of identifying suitable partners to establish an option contract and a preference for long-term reuse of windows and façade components over raw material recycling. However, the participant also noted that, as a larger company, they are better positioned to engage in long-term agreements to provide greater price stability while at the same time, concerns about maintaining fair competition were raised. Overall, the level of interest in the concept was high showing openness to test in on a pilot project.

Group 2 - Option Buyer | Interview 2

"If this would be a feasible solution, would we be open to a solution in this way? Yeah, I think 100% yes."

Interview 3 involved a representative from a major aluminium production and recycling company operating across the entire value chain. The option scenario was met with strong interest, though concerns were raised about financial feasibility

Group 2 - Option Buyer | Interview 3

"Now we've already taken the step of bringing it back, but we haven't had it on our radar for 30 years. The next step would be to have options to bring it back in 30 years. This is logic, as you have presented it, makes sense to me, but I can't tell you what the financial figures look like and what the finances are like."

A key concern was the relatively low share of aluminium in total façade costs, reflecting similar observations from the case study discussed in the previous chapter. Emphasis was placed on the importance of a sufficiently high option premium to make such agreements attractive for building owners. At the same time, the model was viewed as an opportunity to build long-term customer relationships by securing future replacement contracts early in an already common renovation cycle, offering mutual benefit. However, the option model was also questioned in comparison with an as a service approach, while the participant agreed that an option-based approach could be more feasible for existing businesses, as it avoids inflating the balance sheet through retained ownership of large façade portfolios.

The representative of an aluminium smelter operating in central Europe (Interview 4), focused on the remelting of scrap aluminium, acknowledged the growing scarcity of scrap and future supply challenges, but showed comparatively limited interest in entering an option contract for aluminium façades. The primary concerns related to the extended time horizon of such contracts, as existing agreements typically span no more than nine months. The inherent uncertainty of long-term arrangements was seen as a significant barrier. In addition, large-scale operations at the smelter require substantial volumes to maintain furnace efficiency amid high energy costs. Recovering material from individual buildings was viewed as insufficient to meet demand, while coordinating recovery across multiple sites was considered logistically unfeasible.

Group 2 - Option Buyer | Interview 4

"I mean that's only very small amounts. I mean we use at the moment let's say 50.000 to 60.000 tonnes of scrap. That's what we need to fill the furnaces and ok, if there may be a project in 15 years or in 20 years with some aluminium which is coming, it doesn't bring anything."

Overall, while the option concept was well received, its adoption depends on clear financial benefits and structural alignment within the supply chain. The latter puts larger entities in a favourable position to enter option contracts as they are supported by strong client and recycling company networks or even are able to process recovered aluminium entirely inhouse. To explore how such contracts might be perceived and handled from a financing perspective, the following chapter presents insights from professionals with expertise in lending, finance business development and commodity trading.

Group 3: Financier

In total, two interviews were conducted with representatives from national banks in the Netherlands. The first interview (Group 3 / Interview 1) involved a specialist in commercial real estate, with particular expertise in real estate lending and valuation. After being presented with the option scenario the participant was asked to imagine the evaluation of a proposal for a real estate project where such an option contract is in place and to reflect on how this contract would be viewed from a banks perspective. Several factors were highlighted as potentially influencing financing conditions in the context of an option contract on a façade. A key concern was the inherent uncertainty of the arrangement, particularly whether the option would be exercised and how this could affect future rental income, which plays a central role in determining the value of the collateral.

Group 3 - Financier | Interview 1

"So if it's a closed-end situation, you know what the risk are and what the scenario is, but if it's an open-end situation that's what a bank doesn't want."

Although ownership remains with the building owner, the involvement of a third party was viewed as an additional risk. To reduce this risk, the interviewee suggested establishing clear contractual provisions for both possible outcomes. These provisions could become mandatory for lenders to consider financing a project that includes such an option contract.

When discussing option valuation as a methodological approach separate from actual contractual agreements, the participant cited the 2008 global financial crisis as a key reason why current regulations restrict the use of future assumptions in real estate valuation. While acknowledging that promoting sustainability and circularity may require changes to these boundaries, the interviewee also cautioned that incorporating raw material values could risk overvaluation and potential opportunism. Another point mentioned was the impact of idiosyncratic risks being involved in the valuation such as changing surroundings of buildings that are not foreseeable but occur, especially in urban environments.

Group 3 - Financier | Interview 1

"But also if you have a new built project and it's at the edge of the city where it's quite easy to have access to the place. And the option is for 15 years and after 15 years you come to the same place and it's a very crowded area with buildings on all sides and it's not very easy to remove a facade."

Nonetheless, the linkage to transparent price data and the potential to structure option contracts as financial products were seen as compelling strengths of the concept.

The second interview was held with a bank representative specializing in business development with a focus on real estate and property technology (Group 3 / Interview 2). This participant was also partially involved in earlier research discussions and was therefore well acquainted with the option concept explored in this thesis. From a business perspective, the idea was seen as highly promising. However, the participant identified significant obstacles in the prevailing short-term mindset of the market and the slow adoption of innovative financing methods within a banks risk departments. The evolving field of property technology was seen as a potential driver for enabling option trading on building components. At the same time, the limited impact of focusing solely on aluminium was noted, especially when compared to more widely used construction materials. The participant also highlighted the regulatory potential of integrating raw material-based valuation into bond structures as a complement to existing green bonds.

Group 3 - Financier | Interview 2

"We have green bonds. So we give green bonds obligations based on assets like real estate with a green certificate. But what would happen if we would have a new material bond with raw materials or scarce materials that you could invest in for the future, that could be something that would be very interesting."

5.2.2. Results from the (RE) VALUE Online Workshop

After the findings from the semi structured interviews have been analysed, this sub-section will specifically dive into the results of the (RE) Value workshop intended to capture the perspective of valuation professionals on the impact a real option contract on a detachable aluminium building component would have on valuation practices and on the application of real option valuation methods.

In total twenty-two participants joined the session, while the response numbers of the surveys were lower and fluctuated between all three survey sessions.

Although the structure of the (RE)VALUE meeting and the corresponding segmentation of the survey were already outlined in the methodology section, a detailed reiteration is now provided to contextualise the findings for a better understanding of the immediate reaction of the participants. The analysis is presented in accordance with the chronological progression of the workshop.

The first part of the workshop served as an introduction guiding the participants towards the scenario of an option contract being written on a aluminium façade. To ensure sufficient understanding, the presentation was conducted in a 'story-like' narrative leading to the explanatory video (Appendix D) which was shown at the end of the introduction. The survey following this section was intended to verify understanding, check on participants' experience on option contracts, and capture immediate reactions on the topic. For the first part, eleven respondents responded to the survey (Figure 5.25):

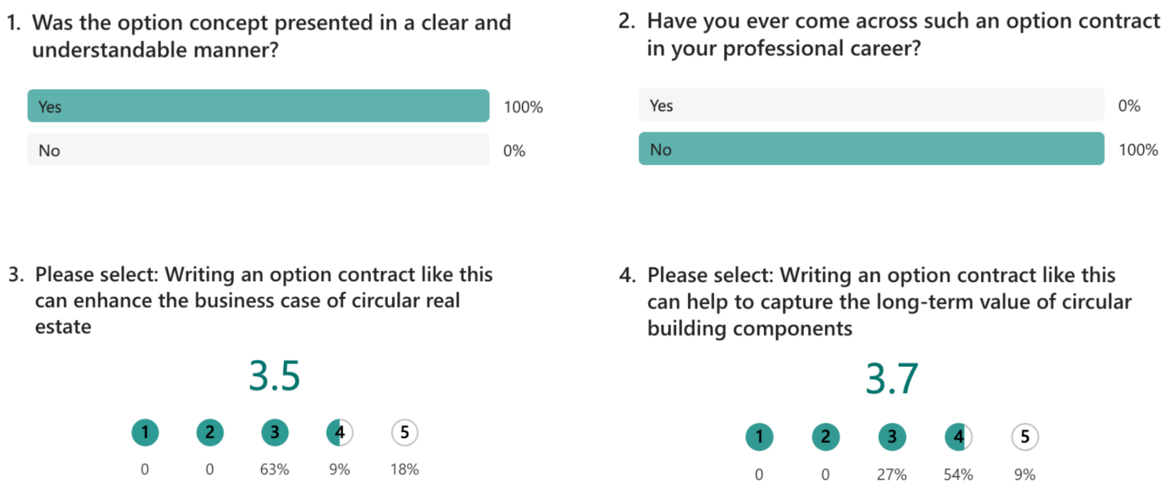


Figure 5.25: Results – Survey Part 1 (RE) VALUE workshop (own illustration)

The first question shows a clear result indicating that the topic was presented understandably. Naturally, this result does not serve as definitive evidence of participants' actual understanding which should be regarded as a limitation. However, to avoid creating hesitation or discomfort among participants, comprehension-check questions were intentionally omitted. An equally clear result was obtained from question two showing that none of the participants was ever in touch with an comparable option contract in their professional career. Regarding the potential of an option contract enhancing the business case of circular real estate respondents reacted with an overall score of 3.5 out of 5 while the majority with 63% gave a more neutral answer and 18% viewed it strongly positive. With an overall average score of 3.7 and 54% of respondents selecting a rating of 4, the potential to capture the long-term value of circular building components was perceived more favourably compared to question three. This outcome suggests that, as an initial response, valuation professionals recognise greater promise in the concept as a valuation method trying to capture end of life values than in the feasibility of real option contracts to enhance the business case for circular real estate—for instance, by supporting the financing of higher upfront costs.

Following the introduction, the workshop proceeded to its main segment, maintaining a narrative style to clearly convey how a real option valuation could be applied to the previously discussed scenario. At this stage, no mathematical formulas were introduced; instead, the essential core parameters for real option analysis were presented as a basic conceptual 'recipe'. A sample valuation was then used to demonstrate the resulting option value, both as a potential cash-in for the real estate investor and as a quantifiable present value of the option. Building on this, the focus shifted from the façade element alone to the broader task of valuing an entire building incorporating such an option contract, leading to the second survey session. For the second part, ten respondents reacted to the poll (Figure 5.26):

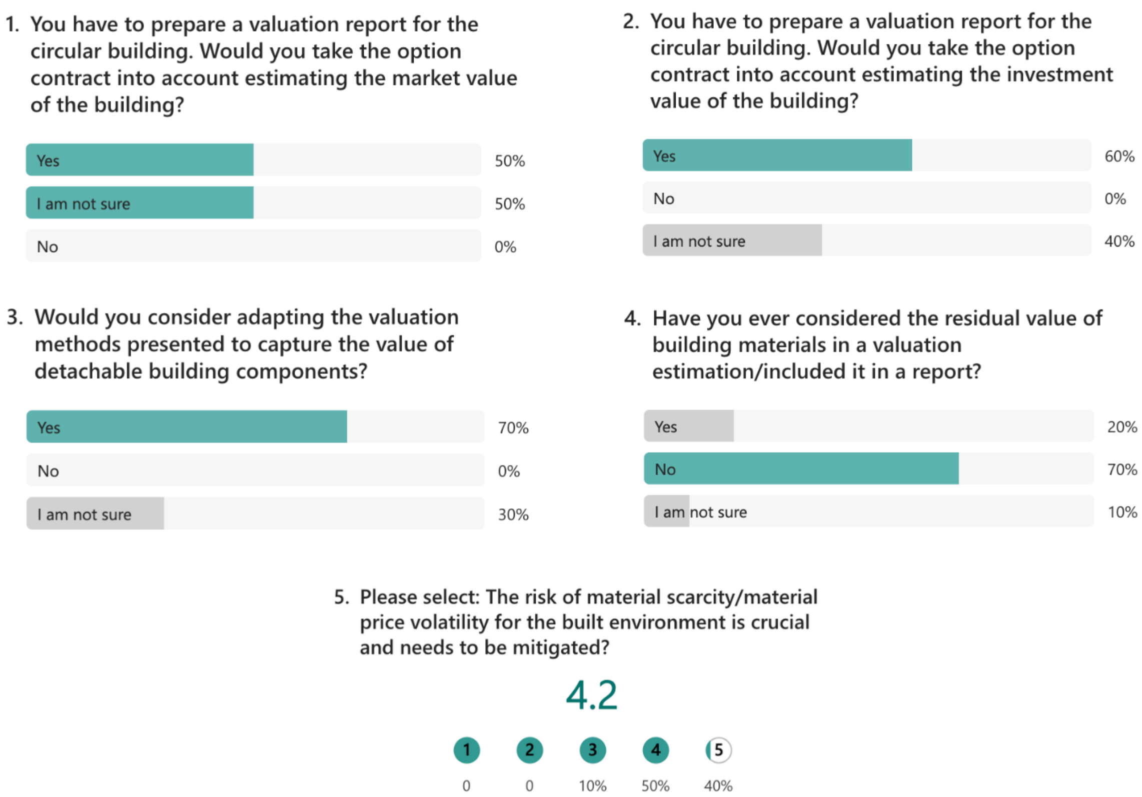


Figure 5.26: Results – Survey Part 2 (RE) VALUE workshop (own illustration)

The first two questions aimed to assess whether valuation professionals would consider incorporating such an option contract into a valuation report, and to distinguish whether they believed it would influence market value, investment value, or both. While 50% indicated market value and 60% investment value, the difference – though modest given the limited sample size – suggests a slightly stronger inclination to view the option's relevance for investment value. Notably, no participants opposed including the option contract altogether. However, a degree of uncertainty remains, with 50% and 40% selecting "I am not sure" for questions one and two, respectively.

Question three revealed a more confident response, with 70% expressing support for adopting the valuation method, and 30% uncertain, yet no participant rejected the idea, indicating an overall openness to integrating the valuation of real options as a means of quantifying the residual value of raw materials. Question four reinforced this view, showing that 70% of the respondents currently do not account for such residual material value in valuation reports, yet 20% confirmed that they do, which points to emerging practice in this area.

Finally, responses to question five produced a strong positive consensus, with an average rating of 4.2 out of 5, underlining the perceived importance of addressing risks associated with material scarcity and price volatility within the valuation process.

The third and final scheduled segment of the presentation – prior to the optional demonstration of the real option valuation method for a façade case based on Black & Scholes (1973) – was designed to offer participants a forward-looking perspective. This section focused on key developments in EU policy, including the 'EU Critical Raw Materials Act', the 'Carbon Border Adjustment Mechanism' and the 'Steel and Metals Action Plan', along with broader geopolitical changes. The objective was to underscore the growing importance for market participants to mitigate supply risks associated with aluminium and other building materials, risks for which an option contract could offer a viable hedging strategy. The session concluded with three survey questions, to which nine participants responded (Figure 5.27).

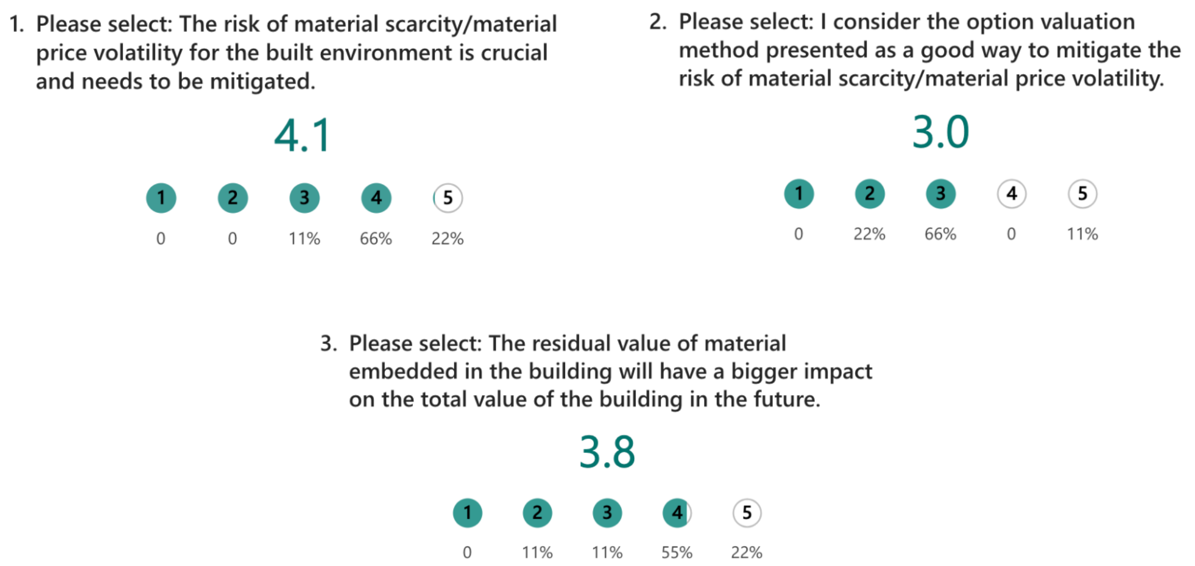


Figure 5.27: Results – Survey Part 3 (RE) VALUE workshop (own illustration)

Question one, which had also been posed during the second part of the workshop, aimed to assess whether the future outlook presented had influenced participants' perception of the importance of mitigating risks related to material scarcity and price volatility. The resulting average score of 4.1 out of 5 – slightly lower than before – may reflect the reduced number of respondents or suggest that the already strong consensus remained unchanged. Question two revealed a more sceptical stance regarding the potential of real option valuation as a tool for mitigating such risks, with an average score of 3.0 and 22% of participants selecting a rating of 2, indicating disagreement. Conversely, the third question concerning the future relevance of the residual value of materials embedded in buildings received strong support, with an average score of 3.8 and 55% selecting a value of 4. These responses indicate that while there is broad recognition of the need for risk mitigation and an increasing awareness of raw material value in real estate, there remained a degree of neutrality or scepticism among valuation professionals regarding the practical application of real option valuation as a solution.

The outcomes of the (RE) Value session represent the concluding component of the presented findings and will be further examined in the subsequent discussion section.

6
Discussion

6.1. INTERPRETATION

At the outset of this research, a comprehensive review of the literature identified two key leverage points as critical to unlocking the financial potential of circular real estate: managing the uncertainty of end-of-life values for building components and integrating these future benefits into upfront investment appraisals. Aiming to address this fundamental disconnect between established valuation practices and long-term sustainability objectives central to circular economy efforts in the built environment, this thesis tested utilising real option valuation methods to account for end-of-life material values, to capture price volatility, and to ultimately generate quantifiable upfront values of circular construction. Aluminium was chosen as the raw material in the focus of this research due to its price data availability, recyclability, projected scarcity, and its environmental potential:

SQ1: *To what extent can real option valuation methods be utilised to value circular aluminium building components and be integrated in circular building valuations?*

&

SQ2: *To what extent can real option valuation of circular aluminium building components incentivise market parties to adapt circular practices in the construction and real estate industry?*

In the quantitative analysis, two overarching methods were applied to estimate the option value of an aluminium building component case, the Façade as a Service 2.0 project. The primary focus was on the ”Classic Approach,” which bases its valuation strictly on an underlying traded asset, while the ”Integrated Approach” was added as a complementary perspective incorporating project-specific risks.

In total, three methods were tested under the “Classic Approach” to real option valuation, being the Black & Scholes (1973) model, the Binomial Tee model, and finally the Heston (1993) model. Based on case study data and using aluminium commodity data as underlying price, two option scenarios were calculated: A real-case scenario where the assumed parameters were fully based on the case study conditions and a best-case scenario where the strike price, maturity time, and assumed volatility were altered to simulate more favourable conditions. The results indicate that the option is out of the money in the real-case and in the money under the best-case assumptions, resulting in substantially different option values and behaviour under changing parameters such as volatility, maturity time and strike price. The categorisation of “moneyness” of the results of both cases is further emphasised by the determined option delta and risk-neutral probability to expire in the money. Central to this outcome is the ratio between the initial value of the asset and the strike price, interpreted in this context as the relationship between the value of embedded aluminium in the façade and the cost of dismantling and material recovery. This ratio proves to be a critical determinant of whether the option can be considered in the money and thus suitable for hedging at higher risk while paying high option premiums. This distinction also explains why out-of-the-money options, which are generally considered to offer a speculative upside in volatile conditions, as are predicted for the aluminium market, may be less relevant in practice for detachable building components. For the option seller to agree to such a contract today, the option value must be sufficiently high to justify parting with a building component at a future date. This would not be the case for out-of-money options with a low option premium, which prevents a low ’entry level’ for market participants to buy low-risk low-price speculative options; an assumption strongly supported by the qualitative analysis, which asked both potential option buyers and option sellers. Moreover, the results of the quantitative analysis suggest that even in the best-case scenario, the option value remains a relatively small share of the total façade investment. This limited contribution reflects the low proportion of raw material costs compared to other cost drivers such as labour or non-aluminium components in the case analysed.

Still, from a valuation methodology perspective, judging from the findings obtained in this thesis, both scenarios, whether the option is in or out of the money, can be effectively assessed and included in a valuation report, offering a means to account for embedded material value and future price uncertainty. Importantly, the categorisation of the moneyness of the option can potentially serve as a practical decision-making tool when planning circular construction projects. For example, a façade with a high aluminium content and relatively low dismantling costs may yield an in-the-money option, offering a stronger financial justification for detachable design and long-term reuse strategies. Conversely, if the material recovery costs outweigh the embedded value, the option may be out-of-the-money, prompting reconsideration of material choices or recovery methods in an early design stage. However, as demonstrated by the sensitivity analyses across all three models used in this thesis, parameter selection requires careful consideration, and valuation professionals should be aware of the substantial influence these assumptions can have on the resulting option value. The findings suggest that this impact becomes particularly pronounced when the option is out of the money, with parameters such as assumed volatility or long-term average variance (in models incorporating stochastic volatility) having a notably greater effect on the valuation outcome.

When considering the general applicability of option valuation methods, it is reasonable to reflect on the suitability of the three calculation models employed in this thesis to value an aluminium building component. While the Black-Scholes (1973) model and the Binomial Tree produced nearly identical results, the Heston (1993) model showed moderately lower valuations, indicating a relatively stable aluminium price behaviour, as discussed comprehensively in the results chapter. Based on these findings, it is not possible to promote one model as more suitable than another. However, each model has distinct advantages and limitations that must be carefully considered. The Black-Scholes (1973) model offers a fast and straightforward approach but relies on the assumption of constant volatility, making it less suitable for capturing complex price trajectories. However, under similar assumptions, the binomial tree provides greater transparency by illustrating a range of potential paths for the material value embedded in the façade, which may enhance communication with stakeholders unfamiliar with option theory. The Heston (1993) model, while more complex, enables a more nuanced representation of underlying price dynamics by incorporating stochastic volatility. However, as shown in the sensitivity analysis, its output is dependent on a combination of parameter values, such as the speed of mean reversion, volatility of variance, and correlation between price and volatility, each of which must be set with a clear understanding of its influence on the option outcome. Ultimately, the choice of model should align with the specific context, availability of data, and purpose of the valuation exercise.

Shifting away from the technical point of view of choosing and applying different pricing models, it is worth considering once again whether these models can actually be used for real (estate) assets. One significant point here is the assumption of risk neutrality central to models like Black-Scholes (1973) and Heston (1993), which posits that all investors are indifferent to risk and value assets solely based on expected returns discounted at the risk-free rate. While this simplifies pricing in liquid financial markets, its applicability becomes problematic in the context of illiquid, long-term, project-based real assets such as aluminium façades. In such settings, stakeholders like building owners or aluminium suppliers may perceive and price risk quite differently from financial investors.

To this end, it is essential to further reflect on and discuss the extent to which the models referenced and applied in this thesis account for systemic and idiosyncratic risks and how this might influence real-world applicability as an valuation method. As noted previously, the classic approach to real option valuation as used in this thesis primarily captures systemic risks such as macroeconomic changes or regulatory shifts, which affect the entire market or material class. However, there are further distinctions between the models. Black-Scholes (1973) and binomial tree approaches assume constant or predefined volatility, which may under-represent real-world systemic price swings in aluminium caused by geopolitical developments or supply chain disruptions. The Heston (1993) model improves upon this by allowing for stochastic volatility, making it more appropriate for capturing long-term systemic fluctuations in commodity prices. Nonetheless, real-world applications may require an added scenario analysis or time-varying parameters to more accurately reflect shifting risks over multi-decade horizons. Systemic risks are therefore captured to different extents, depending on the model used. This raises the question of how idiosyncratic risks, which are specific to a project or firm, can be effectively incorporated into these valuation approaches. For financial assets, option valuation models abstract away from idiosyncratic risks under the assumption that they can be diversified. However, in the way these methods were used in the context of the aluminium façade case in this thesis, idiosyncratic risks are already partly taken into account by connecting the option strike price (X) to the projected costs of dismantling, which is a case-specific parameter. When using this method, it should therefore be borne in mind that these idiosyncratic assumptions influence the option value significantly. This shifts the focus even more to a sufficient sensitivity analysis and reflection on the input parameters used. The excursus on the “integrated approach” to option valuation demonstrated an example of how a project-specific decision tree can be used to create a more tailored valuation method. This approach allows for the inclusion of idiosyncratic risks, such as changes in the project’s environment or unforeseen façade degradation; risks that multiple experts also noted during interviews.

Another commonly identified challenge among the different stakeholder groups interviewed in the qualitative research section of this thesis was the difficulty of estimating the end-of-life value of building components over long time spans and integrating this into valuation reports. This was highlighted as a key barrier to the financial justification of circular construction measures. The findings of this thesis suggest that this need can be partially addressed through real option valuation methods. However, it should be noted that these methods focus on specific raw materials as underlying traded assets and therefore do not account for other materials or the functional end-of-life value of components.

The presentation of real option valuation methods to valuation professionals during the (RE) VALUE meeting revealed a general openness toward integrating end-of-life values of raw materials into valuation reports, along with a growing awareness of the risks associated with future material scarcity. Participants also expressed interest in the potential application of real option valuation techniques in professional practice. However, when it came to the practical implementation of actual option contracts within building valuation, responses were more cautious. Despite being considered too critical to be ignored, the results indicated a notable degree of uncertainty amongst participants regarding if and how an existing option contract on a building component should be effectively incorporated into market and investment value estimations. In line with previous findings, this reinforces the need to distinguish between using real options on detachable building components purely as a valuation method and taking the additional step of formalising these valuations into contractual agreements between market actors and their willingness to enter such contracts:

SQ3: *To what extent are market participants willing to BUY real options of circular (aluminium) building components?*

&

SQ4: *To what extent are market participants willing to SELL real options of circular (aluminium) building components?*

As this thesis is based on a single case study, the implications for the broader feasibility of implementing an option contract remain limited. Nonetheless, as previously outlined, the quantitative findings suggest that the option value represents only a small fraction of the total façade investment, which makes it less appealing to a potential option seller, since the initial cash inflow would likely have minimal financial influence. Yet again, different outcomes may arise in other case contexts.

Interviews with market actors who could potentially adopt option contracts on building components to hedge against rising material prices and increasing volatility revealed the fragmented nature of the construction supply chain as a key barrier. Since an option contract involves both a future long-term relationship with the building owner and the very initiation of a recycling process (the starting point of the supply chain), only a limited number of actors are currently able to manage both (supply chain) ends. Although situated near the end of the supply chain, façade producers interviewed typically operate under main contractors in the Dutch context, meaning that they still lack direct contractual relationships with building owners and do not handle material recovery themselves. An interview with an aluminium smelter further revealed major scalability issues, as scrap is typically procured in large volumes, and recovering materials from numerous buildings would impose considerable additional logistical effort. However, for smaller demolition firms, buying such an option may be more feasible and practical. In addition, supply chain-related challenges could potentially be mitigated by developing secondary markets that enable scalable option portfolios and standardised contracts across building portfolios, allowing actors to participate that are not directly involved in demolition or real estate in general.

Another overarching insight that limits the practical application of option contracts is the short-term mindset prevalent within the industry with respect to price developments. This is reflected in the absence of substantial hedging strategies and a general scepticism toward long-term price forecasting, as shared by the professionals interviewed. Aluminium prices are taken “as they come” and a more strategic focus is set on improving production efficiency and capacity. Nevertheless, certain interview participants, particularly those representing larger and more established firms, demonstrated a willingness to engage with long-term planning horizons. Due to their scale and market influence, these firms are comparatively well positioned to operationalise option contracts in practice. The concept was regarded as both conceptually sound and practically viable, particularly in contrast to service-based models. Furthermore, representatives from the financial sector acknowledged the potential merits of real options when framed as financial instruments, noting their suitability for integration into financing structures under specific conditions.

Although long-term real estate owners, as potential sellers of option contracts, are naturally inclined to take a future-orientated view, the concept of granting an option on a detachable building component was nonetheless perceived as an additional risk. Although legal ownership of the asset remains unchanged, many interviewees saw such a contract as a partial surrender of control. This, coupled with the uncertainty as to whether the option would be exercised, contributed to a sense of reluctance. On the buyer side, barriers were both structural and behavioural; however, when evaluating the seller's willingness to engage in such contracts, behavioural hesitation played a more significant role. This highlights the critical importance of the option premium being financially attractive enough to offset perceived risks.

From the financier group, particularly from a real estate lending perspective, the involvement of a third party through an option contract was viewed as an additional risk. It is therefore reasonable to assume that short-term option agreements may initially increase real estate transaction costs due to the need for supplementary legal arrangements to mitigate such risks. Option contracts may increase complexity by introducing new layers of legal, financial, and technical analysis. This includes costs associated with drafting bespoke agreements, evaluating the option's fair value, and managing additional due diligence requirements. Yet again comparing with an 'as a service' model, where the ownership of the building is separated, buyback agreements such as an option contract prove to be less complex and more feasible in existing legal frameworks, as already discussed in the literature review. Looking ahead, if option contracts are standardised and widely adopted, they could play a significant role in facilitating more liquid material markets, potentially lowering long-term transaction costs in real estate.

When considering the perspectives of different stakeholders entering an option contract, it is also reasonable to reflect on the decision to focus on a call option rather than a put option, and to ask what potential changes this would entail. In the context of applying real options to circular construction, a put option on an aluminium façade allows the building owner to sell the façade at a predetermined strike price at the end of its life cycle. This serves as a hedge against future price uncertainty, providing the owner with a minimum guaranteed value for the aluminium, regardless of market fluctuations. In this scenario, the building owner assumes the role of the option holder and would therefore be responsible for paying the option premium. The premium acts as a cost of securing this downside protection and is paid to the counterparty - a supplier or material processor - who commits to purchasing the façade material at the agreed price should the option be exercised. Instead of receiving additional upfront cash to finance the added cost of circularity, the building owner aims to reduce the risk of circular investments by agreeing to a higher upfront investment in exchange for securing a fixed value for the raw materials embedded in the building. Switching from a call option to a put option does not fundamentally alter the underlying strategy of hedging against price volatility, yet it clearly shifts the perspective and incentives of the stakeholder pursuing this strategy. This thesis focuses on the call option as a starting point; however, exploring the application of a put option on a façade presents a compelling direction for future research following a similar research design to identify differences in not only option valuation approaches, but also perceived barriers and enablers to enter put option contracts. The same principle also extends to strategies that involve combinations of call and/or put options with varying strike prices and maturities.

Lastly, when reflecting on the willingness of stakeholders to enter into an option contract, the option type should be considered, building on what has already been discussed in the literature review chapter of this thesis. In the context of this thesis, a plain vanilla European option was analysed, to ensure a simple valuation approach as well as to provide clarity on the exercise date of the option. Doing so, however, leaves open the question of whether alternative option types may offer more suitable solutions. As discussed in the previous interview findings, uncertainty regarding the timing of exercising the option was a frequently expressed concern, particularly among potential option sellers, such as building owners. Introducing an American option could amplify this uncertainty, given that it allows the holder to exercise the option at any point up to expiration. It's use is therefore questionable compared to the European option, especially considering the higher valuation complexity. However, an American option may offer the option holder greater flexibility to respond to favourable aluminium prices. This suggests that the balanced benefit assumed with the European option may shift more strongly towards the holder, which would likely require significantly higher option premiums to compensate the seller.

For Asian options, the payoff would be based on the average price of the underlying asset over a specific period. As suggested by statements in semi-structured interviews, Asian options or swaps are commonly used in commodity trading and, therefore, might show higher potential. Averaging the price would mitigate the impact of short-term price volatility, which may align well with the long-term nature of options on aluminium facades. As the outcome can be considered more stable or predictable, an Asian option might also allow for more flexibility around the exact timing of recovery, providing better solutions for planning renovation scenarios, for example. Interviews with all stakeholder groups, especially the financing side potentially allowing a loan on a project where an option contract is in place, showed that agreements should allow for different fixed scenarios mitigating the open-end nature of an option contract. Moving beyond the standard categorisation of option types, European, American, or Asian, it can be argued that tailored option contracts are likely to be an effective approach. Such contracts would retain the core structure of a conventional option type while incorporating specific sub-agreements to address different scenarios. This would enhance clarity and reduce uncertainty for all stakeholders, and present another possible path for further research.

In summary, while exploring different option types can offer greater flexibility, it is important to recognise that increasing contractual complexity also results in more intricate and demanding valuation processes. Therefore, the benefits of increased adaptability in agreements must be carefully weighed against the challenges of achieving more accurate and reliable valuations.

6.2. CONTRIBUTION AND IMPLICATIONS

The research presented in this thesis is a step toward new real estate valuation practices that accompany the transition to a circular built environment economy. In real estate projects, professionals are required to consider extended time horizons, often exceeding thirty years, where uncertainty makes it difficult to assess how current decisions will affect outcomes at the end of life of a building. By deconstructing building components into their embedded raw materials, this thesis introduces an approach to address such uncertainty and to estimate the upfront value of having the option to recover specific materials, based on publicly available commodity price data. Through the application of real option valuation methods, valuation experts can assess the 'moneyness of material recovery' across different time spans, thereby providing a basis to justify additional costs associated with circular construction or alternative material selections. Market parties can use the real option valuation approach presented to assess option contracts either to gain an upfront cash in for a real estate investment or hedge themselves against rising prices and price volatility of raw materials. To achieve this, a broader mindset shift is required, particularly among suppliers of materials and building components, toward embracing a longer-term perspective and a more active strategy regarding raw material price fluctuations. The successful integration of real option valuation into real estate practice depends not only on methodological development but also on increased financial literacy among valuation professionals and other market actors. As real option valuation is not yet widely adopted even within traditional financial sectors, building confidence in its outcomes will require financial education and greater familiarity with financial modelling tools to support informed decisions.

This thesis proposes a method to monetarily evaluate the added flexibility of circular construction in real estate by applying real option valuation techniques. While this offers promising potential, it is essential to reflect critically on possible unintended consequences. Effectively capturing the value of embedded raw materials through valuation may shift perceptions of buildings from long-term functional assets to repositories of recoverable resources, which could potentially lead to incentivising premature dismantling and generally reducing the overall lifespan of buildings.

By focussing solely on the raw material content, the reuse potential of building components may be undervalued. This creates a tension between two fundamental circular strategies: Product Life Extension and Recycling and Recovery (Lacy & Rutqvist, 2015). Prioritising the latter risks weakening the former. As outlined in the literature review, aluminium is a material high in demand across multiple strategic industries. This growing competition may further reduce incentives to pursue reuse, as recycling offers quicker access to raw materials.

To avoid this imbalance and support a more holistic approach to circularity, it should be a future objective to develop valuation methods that incorporate not only the value of raw materials, but also the functional end-of-life potential of components.

6.3. LIMITATIONS

While the approach adopted in this research is limited by its narrow focus on raw material value, excluding considerations of reus, a similar constraint arises from the exclusive emphasis on aluminium as the underlying material. Applying the same option valuation methods to other materials, for which market data availability, price volatility, or recyclability differ, could lead to significantly different outcomes. Furthermore, a key limitation lies in the partially subjective assumptions used to define the numerous parameters required for the option valuation models and the two case scenarios. Although sensitivity analyses were performed to assess the impact of individual variables, the complexity and volume of parameters made it impractical, at least in the scope of this thesis, to evaluate the potential effects of interaction between multiple variables simultaneously. Although appropriate within an exploratory research context, a significant limitation of this thesis is its reliance on a single case study, which restricts the generalisability of the findings. This is compounded by the limited number of participants in the (RE) Value workshop and the relatively small sample size of interviewees within each stakeholder group. As a result, the qualitative component of the study offers suggestive insights into stakeholder concerns and potential risks rather than robust empirical evidence. Additionally, the complexity of the topic of real option valuation posed challenges in ensuring full comprehension among the participants. Despite efforts to simplify the concept through a visually supported 'whiteboard-style' explanatory video, misunderstandings persisted, with some respondents confusing the option structure with leasing models or failing to grasp the nature of optionality at the time of expiration. Combined with a general lack of familiarity with financial hedging among stakeholders, this represents a further constraint on the qualitative findings presented in this thesis.

6.4. FURTHER RESEARCH

Future research should build upon the exploratory findings of this thesis through more comprehensive empirical investigations. A possible research direction would be to conduct a large-scale stakeholder survey across the real estate, construction, and materials-based sectors to assess the willingness to adopt real option valuation methods in greater depth and to produce empirical evidence. This could help validate or challenge the insights gathered from the limited number of interviews conducted in this study. In parallel, a quantitative empirical multi-unit case study would offer stronger evidence by applying the option valuation methodology across a portfolio of buildings or façade components, allowing for comparative analysis and assessment of context-specific feasibility of computed option value outcomes. Expanding the methodological framework is another promising direction. This could involve using alternative or advanced real option models, such as simulation-based approaches or further developing and applying the decision tree model introduced in the method section of this thesis. Assessing the valuation of a put option, rather than a call option, could offer new insights into scenarios where material buyers seek protection against price drops or reduced residual value. Additionally, testing the application of American or Asian option types could reflect more realistic market conditions, such as flexible exercise timing or average price mechanisms, and thus enhance the practical robustness of valuation models. Furthermore, investigating the applicability of real option valuation to other materials, such as steel, glass, or timber, or to combinations of materials, could broaden the relevance of this approach within circular construction and open a path to comprehensive option analyses of complete building components and subsequently whole buildings. Lastly, a systemic analysis of the entire supply chain is crucial to understanding the structural and contractual barriers to implementing option agreements. This includes identifying which actors are best positioned to hold or trade option contracts, how responsibilities and ownership might shift, and how secondary markets could be structured. Together, these research directions would provide a more robust foundation for integrating real option valuation methods and the application of real option contracts into circular economy strategies within the built environment.

7 Conclusion

“*And so Fisher and I started talking about options … And we started working together, and we very quickly came to a theory of how to solve the option by setting up the replicating portfolio. (….) So then Fisher and I said, well, let’s make an assumption, which is false, that the interest rate is constant, and that the volatility is constant. And we got and the option was European, and therefore, we can get a closed form solution. So that we got a closed form solution and that became known as the Black Scholes option pricing model.*

(…..) Now we know that every model has an assumption, every model has an error, every model is an incomplete description of reality. How well does the model do in making predictions? And that’s the key. Basically the model has done very well over time. There’s a lot of people who say the model doesn’t do this, the model doesn’t do that, but it does pretty darn great.“

– Myron Scholes, interviewed by Taylor (2025).

Concluding this thesis, the underlying statement of Myron Scholes’ quote should be transferred to what has been found and discussed: When attempting to model reality and to make predictions, the true value of a model lies in its ability to guide decisions over time rather than in its exact precision. Trying to model and predict what it is worth today to construct a circular building and while doing so breaking the building down into its individual components and further into its raw materials overlooks a wide range of factors that could – or most definitely should – be considered.

Yet, how should the uncertainty surrounding the value of the building components at the end of the buildings life be addressed, if not by simplifying the matter? How, if not by making false assumptions just like Fisher and Scholes did when developing their option pricing model?

A building truly is not just the sum of its embedded raw materials, but viewing it from this perspective is a starting point for redeveloping the general understanding of real estate valuation practices; practices that inform decisions every day and influence how buildings are designed and built.

In perspective to the main research question of this thesis,

”*To what extent can real option valuation enhance the business case for circular aluminium building components and subsequently circular buildings?*”

it would go too far to view real option valuation as the simple and overlooked solution to enhance the business case of circular real estate. However, real option valuation has the potential to uncover how valuation methods need to evolve in order to truly define what forms a viable business case for circular real estate in the first place. Only what is valued and considered valuable can justify additional cost. Real option valuation is a starting point to quantify the added value and therefore justify the added cost of circular real estate:

Real option valuation, as applied to aluminium building components, has the potential to redefine real estate valuation by demonstrating how buildings or building components can be assessed by estimating the "moneyness" of recovering embedded raw materials. It has the potential to put a price tag on option contracts, allowing both the supply and demand sides to profit by either hedging against price movements or receiving an upfront cash-in. But most importantly, it has the potential to guide decisions towards a more circular and sustainable built environment. If applied, time will tell whether it will do so.

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Use of AI Tools - Disclaimer: Open AI "Chat GPT" was used to shorten and rephrase writing in this thesis report. "Deepl" translating tool was used to translate writing and sources to English.

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Reflection

REFLECTION

From the beginning, it was clear that the topic of this thesis would bring me out of my comfort zone not having any background in financial studies and being a relatively extensive mixed method research approach. This, however, was also the kind of challenge that kept me motivated to pursue the work further and to get an even deeper understanding of what I am doing and what would be possible. What also kept me and still keeps me passionate about the idea is, that I truly believe in the significance and the potential impact of real option valuation to fundamentally change real estate valuation practice and I am very happy to have the chance to deliver a small contribution to that change.

Being a novel concept with nearly no previous academic research the possibilities to explore this topic were plentiful and it took multiple cycles of reiteration to narrow the approach down to a concise framework. My mentors played a significant role in helping me to stay on the path and to not stray too far from what is feasible to be included. The feedback was always the right mix of steering me towards exploring new and different perspectives like focusing more on valuation or qualitative aspects and reminding me to stick to the core of the research framework.

Looking at the end product at this stage I have the feeling that the final approach produced results that have significance and open a variety of paths for further research. Looking forward to the end stage I hope to enhance the findings so far by adding a bit more depth to both quantitative and qualitative sections.

I have very much enjoyed working on this thesis and putting aa lot of effort into it and I will continue to do so for P5. One moment, however, reminded me that graduation is nothing more than irrelevant when the life of one of your loved ones is in danger. Graduating might be my own achievement. To have my whole family witness it is a gift.