MASTER THESIS

TU Delft
CME
Robin Mueller
5633958

AN AGENT-BASED SIMULATION OF CONTRACTOR BIDDING IN CONSTRUCTION PROCUREMENT UNDER DIFFERENT SUSTAINABILITY CRITERIA

CHAIR: DAAN F.J. SCHRAVEN
FIRST SUPERVISOR: RANJITH K. SOMAN
SECOND SUPERVISOR: GEESKE SCHOLZ
DATE: 21.01.2025

CONTENTS

EXECUTIVE SUMMARY

The procurement step has always been central to projects in the construction sector, more so than in other sectors, because of the uniqueness of each project and the long-life time. Each construction project often presents specific requirements and challenges, necessitating tailored solutions and coordination among various stakeholders. Over the years, researchers and practitioners have focused on improving procurement methods to enhance efficiency, collaboration, and value delivery. Recently, incorporating environmental sustainability into procurement has become increasingly important as the construction sector seeks to reduce greenhouse gas emissions. Green Public Procurement (GPP) has emerged as a policy tool to advance sustainability goals by leveraging public purchasing power to influence market behavior and drive the sector toward more sustainable practices.

This research investigates how sustainability criteria affect contractor bidding behavior and dynamics in construction procurement. Building on existing models using auction theory, specifically expected utility theory, as the primary theoretical foundation, the research employs Agent-Based Modeling (ABM) to simulate contractor bidding decisions. ABM allows for modeling individual contractor decisions and interactions within a competitive bidding environment. By integrating sustainability aspects into the model, the research examines the emergent bidding behaviors resulting from the auction scenarios that evaluate multidimensional bids with different sustainability criteria scoring rules instead of price-only bids. Through this, the research was able to identify potential barriers and opportunities associated with the different sustainable bid selection criteria, providing insights into how they might influence contractor markups, sustainability and competitiveness.

The first phase of the study developed a baseline model representing traditional contractor bidding behavior in the absence of sustainability influences. This model was built using existing auction models from construction management literature, based on utility theory. It was then tuned using empirical data and validated through pattern-oriented modeling (POM) to reflect real-world contractor decision-making processes accurately. Contractor agent logic in this model was governed by established auction utility theory. Factors such as risk aversion or profit variance were modeled, which in turn are affected by competitive pressures, project complexity or contractor financial factors. This foundational model served as a benchmark for testing and validating contractor bidding behaviors in first price sealed bid auctions, the same auction design most contracting scenarios employ, ensuring a robust starting point for introducing sustainability elements in subsequent phases.

The second phase introduced sustainability into the model, reflecting real-world practices like Green Public Procurement. The incorporation and scoring of sustainability elements in construction procurement was studied and the most common mechanisms were chosen to be modeled. This included minimum requirements, flat discount incentives, and scaling discount mechanisms, were incorporated to simulate their impact on contractor decisions. By adopting a simplified modeling approach for this phase, the study focused on isolating the fundamental effects of sustainability criteria on contractor behaviors. The model's validation ensured that these changes aligned with observed industry patterns and theoretical expectations, offering a credible representation of the evolving construction procurement landscape.

The final phase expanded the model to test various sustainability criteria adoption schemes as policy scenarios. This phase also accounted for contractor bid/no-bid decisions and evolution, where agents could decide to bid or not-bid and therefore invest or not-invest in sustainability projects over time, which affects their capability to meet environmental criteria. Simulations revealed how these criteria influenced contractor participation, bid markups, and market competitiveness. Minimum sustainability requirements encouraged contractors to adopt greener practices but excluded those with limited capabilities, reducing competition while maintaining relatively low bid prices. This method achieved moderate sustainability outcomes due to its inclusivity but did not incentivize significant investment. In contrast, scaling discount mechanisms allowed contractors to maximize project sustainability in accordance with their own profile, leading to high sustainability scores but higher bid prices and a less even playing field. Contractors with advanced sustainability capabilities consistently outperformed others, resulting in high levels of participation but reduced-price competitiveness. The flat discount mechanism aimed to balance inclusivity and competitiveness while maximizing sustainability results within a defined range. However, simulations revealed that its downsides were also amplified. The mechanism was neither highly inclusive nor did it effectively level the playing field, except at the extremes, where contractors with either very high or very low sustainability capabilities benefited. Despite these limitations, the flat discount method outperformed the others in maximizing sustainability while encouraging lower bid prices. Unlike the pure scaling discount, contractors appeared to absorb more costs to remain competitive, and compared to minimum criteria the sustainability scores were often higher and optimized to the contractor profile.

The model also highlighted the benefits of market segmentation, where niches for highly sustainable contractors emerged, in these niches contractors would regularly win contracts against one another and create a small but competitive pool of contractors. This segmentation maintained the price-reducing effects of competition while ensuring that the most qualified contractors were awarded contracts. Validation through expert interviews further contextualized these findings within the construction sector.

The findings demonstrate that sustainability criteria significantly influence market behavior, shaping contractor participation, bid pricing, and overall competitiveness. Overall, the results suggest that a balance can be achieved by tailoring criteria to encourage investment in sustainable technologies among contractors that are willing and eager to compete in that space, making sure to maintain a competitive pool of contractors. The recommendations derived from the model experiments suggest that procurement specialists and policymakers should adopt adaptive strategies that accommodate varying contractor capabilities without diluting sustainability goals to appease the broader market. Notably, the results show that even a small group of highly capable contractors can generate significant downward price pressure, while simultaneously driving innovation and cost efficiency.

This study focuses on environmental sustainability, excluding social and economic dimensions. Additionally, it assumes lump-sum contracting and first price sealed bid auctions, and does not account for collaborative delivery methods or project-specific characteristics. Future research could address these gaps, incorporating broader sustainability dimensions, exploring other auction designs or collaborative approaches to procurement. Expanding the scope in this way would provide a more comprehensive understanding of sustainability in construction procurement.

Keywords: Green Public Procurement, Construction Industry, Agent-Based Model, Bid Selection, Sustainability Criteria, Policy Recommendation

1. INTRODUCTION

1.1 BACKGROUND

1.2 PROBLEM STATEMENT

1.3 LITERATURE OVERVIEW

1.1 BACKGROUND

Construction Sector in Context

Construction is a pivotal sector in the global economy, responsible for a significant portion of economic activity, around 13% of the global GDP (Ribeirinho et al., 2020). It is poised to keep growing in importance with population growth and housing demand, among many other factors, continuing to fuel the sector globally. It, however, faces persistent challenges related to efficiency, sustainability, and innovation adoption. Despite its importance, the sector remains notoriously slow to change, with high investment requirements, low profit margins, intense competition, and long project timelines contributing to its vulnerability and resistance to innovation. Efficiency gains have also eluded the sector, and costs remain high and productivity growth in construction has lagged behind other industries (The Economist, 2017).

Given these characteristics, the sector it is striking that the sector is also particularly climate-unfriendly, accounting for almost 40% of global energy-related carbon emissions, with buildings alone responsible for nearly 20% and projected to increase (The Economist, 2022). Governments are attempting to address these issues, with policies addressing operational efficiency of buildings, but also embodied carbon of new construction.

Environmental Sustainability and Emissions

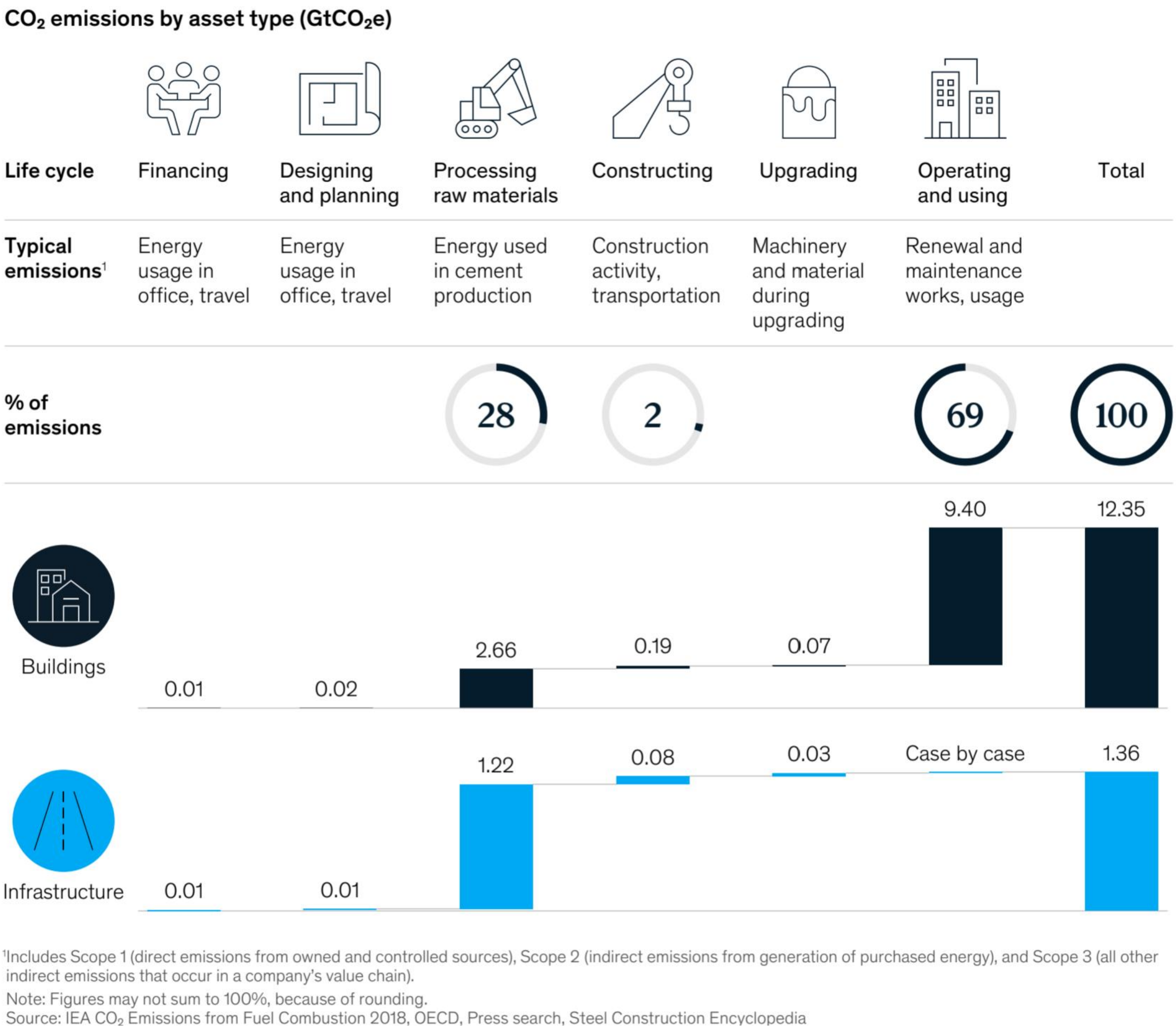


Figure 1: CO2 emissions by asset type and lifecycle step (Blanco et al., 2021)

The GHG footprint of a construction project over its entire lifetime is driven by three factors as seen in *Figure 1* with operation and processing raw materials making up the majority while construction activity and transportation makes up a much smaller part. This is, however, dependent on the case. Noticeably, a lot of the focus on addressing the unsustainable practices of the sector is focused on increasing operational efficiency. While technological progress in heating, cooling and lighting has been great over the past three decades advances in building energy efficiency are stalling; the global rate of annual improvement fell by half between 2016 and 2019. Less than 1% of buildings are currently net-zero, and total greenhouse gas emissions from homes have decreased by only marginal amounts in major economies. American household emissions have fallen by just 2% since 2005, far less than the 7% reduction consistent with the Paris Agreement goal (The Economist, 2022). In modern construction embodied carbon and even construction activity constitutes a growing share of the total GHG emissions and policy measures should reflect that. A number of policies have been addressing this, and procurement practices are changing, opening up the possibility of addressing environmental sustainability for all phases of a construction project's lifetime.

Changing Procurement Practices

The landscape of procurement practices in the construction industry has undergone significant transformation over the past three decades and is still changing. Since around the 90s, highlighted by the publication of the Latham Review (1994), a seminal report on the UK construction industry, there has been a paradigm shift in procurement practices. It advocated moving away from awarding contracts based solely on the lowest price, towards considering quality and collaborative practices (Latham, 1994). This shift progressed further in following years, leaving behind the singular focus on cost, by adding quality considerations, to a more comprehensive multi-criteria approach, to finally incorporating sustainability and even social aspects. 20 years later in 2014, the European Commission codified this progress through Directive 2014/24/EU, introducing the concept of the Most Economically Advantageous Tender (MEAT) criteria which encourages and allows public contracting authorities (CAs) to make contract award decisions based on a broader set of factors beyond cost and price considerations, specifically by: “[...]basis of criteria, including qualitative, environmental and/or social aspects, linked to the subject-matter of the public contract in question" (European Parliament, 2014, p. 134). The Directive represents a pivotal change in procurement practice, but also use of procurement practices as policy tools.

The Role of Public Procurement

Public procurement plays an especially important role in the context of the construction sector as government expenditure is significant and therefore steering investments becomes very impactful. A major share of construction is driven by public investment, especially in Infrastructure where public spending accounts for 87-91 per cent globally (World Bank, 2019). Given this scale, Green Public Procurement (GPP) has gained traction, as governments use their purchasing power to influence the behavior of other organizations and drive broader policy objectives. As Halonen (2021) notes, "public procurement can be a lever to deliver broader government objectives, such as stimulating innovation in supply markets, using public money to support environmental or social objectives, and for supporting domestic markets." The nature of public sector purchasing differs from commercial practice. In addition to the practice of using it as a policy instrument to promote green practices, public procurement also must be guided by “principles of transparency, accountability, and achieving value for money for citizens and taxpayers". In addition to that, policy makers also have a responsibility to support a healthy private market with fair competition, promoting innovation and maintaining monetary stability.

Private Procurement Practices

The evolution towards sustainable procurement practices is not limited to the public sector. Geach (2016) provides insights into private sector practices, noting that there has been a wider cultural shift in how we view sustainability. The concept has become increasingly important. This has manifested in various ways: The rise of zero-carbon buildings, Increased demand for eco-labeled buildings, and preference for local and responsible sourcing of labor and materials. The role of eco-labels and environmental benchmarking certifications such as BREEAM, LEED, or SKA in private-sector procurement has become increasingly important for maximizing letting potential and rents for landlords. Geach (2016) notes that private sector clients are under increasing pressure from various policy measures to achieve net-zero emissions or reduce their carbon footprint. This pressure is driving changes in procurement and contract awarding. However, the focus in the private sector is often on operational sustainability and emissions, because these also benefit financial performance by reducing operating costs and increasing property values.

Challenges

The adoption and these practices has not been without challenges, the implementation of MEAT criteria reflects this. Despite the potential benefits, a report commissioned by the European Parliament revealed that many member states continue to award tenders primarily based on the lowest price (Caimi & Sansonetti, 2023), as the provisions in Directive 2014/24/EU were not made mandatory. This hints at an existing gap between policy intentions and actual practices in the construction sector. Further examples of this can be seen across the Europe, officials aim for nearly half of a building's energy to come from renewable sources by 2030. Over ambitions policy goals, for example, new energy-efficiency standards in England and Wales rendered one in ten offices in central London obsolete for lacking standards in 2023, with nearly 60% potentially unusable by 2027 (The Economist, 2022a). Therefore, concerns about potential unintended consequences in public but also private procurement such as policy displacement effects or sustainability-driven market exclusion are warranted. The policy displacement effect refers to the possibility that emphasizing sustainability criteria in procurement might inadvertently sideline other important policy objectives. For instance, there could be trade-offs between environmental sustainability and social sustainability goals, such as local job creation or support for small and medium-sized enterprises (SMEs). Sustainability-driven market exclusion, on the other hand, raises questions about whether stringent sustainability requirements might create barriers to entry for smaller or less technologically advanced firms. Potentially leading to a less competitive market, which could in drive costs higher.

Opportunities

Still, the importance of this shift in procurement practice toward a sustainability focused selection presents an opportunity for a win-win situation for policymakers: it offers a pathway to reduce GHG emissions across the whole lifetime of construction projects while simultaneously stimulating change and innovation in the desired direction. Procurement has long been identified as an important lever to drive industry-wide changes in construction. As McKinsey (2021) notes, "procurement will likely play an even greater role in decarbonizing construction," which is especially true because of the growing potential for curbing emissions on embodied carbon.

1.2 PROBLEM STATEMENT

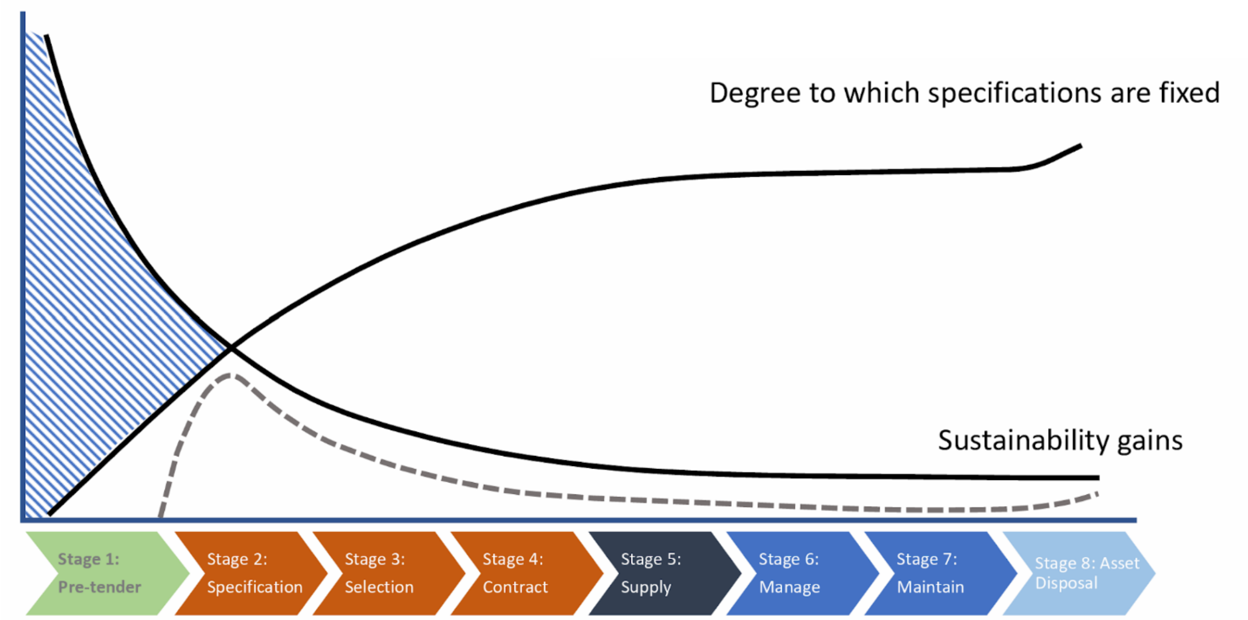


Figure 2: Sustainability gains and change management (Rijkswaaterstaat, 2022)

The problem facing industry and policymakers is twofold. Not only is the construction sector very wasteful and polluting, but it is also notoriously slow to adopt innovations and change. The impulse to change and create a more sustainable future and built environment has come in the form of various goals and policies. A number of them address the owners and CAs and the procurement practices, but not only is public procurement seeing a trend toward sustainability criteria, but also private procurement is directly and indirectly affected. It is common wisdom in construction change management that decisions be made at the outset of a project to avoid high costs that come with changes in planning (Project Management Institute, 2008). The earliest instance of this is procurement. Sustainability criteria can play an important role in the bid selection of the procurement process and in the sustainability of construction projects and the sector as a whole. In the effort to guide change, it is also important to consider potential side effects and minimize their negative impact. However, the slow pace of the industry economic cycles and combined with the general challenge of measuring policy impacts, creates a unique situation. Feedback to assess the effects of new policies or sustainability criteria are very difficult to measure. Therefore, careful analysis is essential to guide the sector towards more sustainable practices while minimizing unintended consequences, allowing informed decisions despite these challenges.

1.3 LITERATURE OVERVIEW

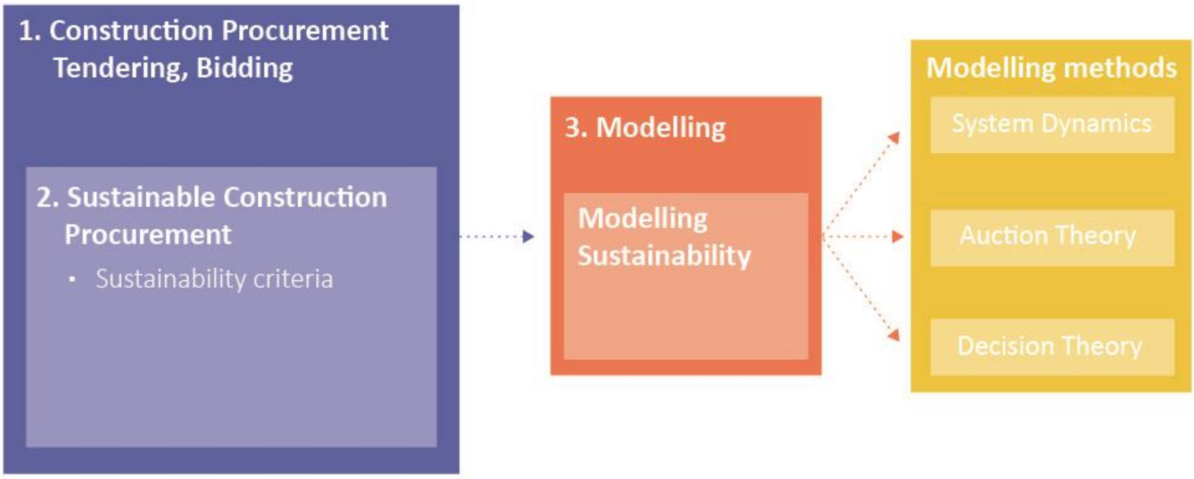


Figure 3: Topic Overview and Relationship Diagram

Antecedent to the findings of the literature review, the scope, the topics themselves and their relationship to each other are laid out in an overview in this section to help establish a definition of terms and describe the current body of knowledge leading up to the research gap.

As seen in *Figure 3* this research focuses on an intersection of three areas that are related to each other: construction procurement, sustainability, and modeling. Construction procurement and the subset sustainable construction procurement reflects the reality of the process; economically, socially and environmentally, through which most construction projects are realized. While the modeling these systems, besides predicting and helping plan for outcomes, can help develop an understanding for them.

Firstly, and at the broadest level there is the research area of Construction Procurement, Tendering, and Bidding. Procurement in construction is defined as the comprehensive process of acquiring the necessary goods and services essential for a construction project. It links an often fragmented supply side (contractors, engineers, suppliers, etc.) with the project owners and representatives and covers everything required from project inception to completion. There are many definitions of construction procurement but according to Ruparathna and Hewage (2015) they can be represented in two groups:

1. The mere purchasing transaction of obtaining a constructed facility; and
2. The holistic process of satisfying potential clients with a need for constructed facilities.

Tendering is a subset of procurement and involves a critical step: inviting and evaluating bids from potential contractors to carry out specific parts of the project. The project owners and representative contracting agency, from here on out just referred to as owners, initiates tendering by initiating bidding and inviting contractors to place bids for work, based on the tender documents issued by the owners. Among the final steps of the tender procedure the bid is selected based on a selection criteria that is decided on by the owners.

The research in construction procurement encompasses a large and complex body of knowledge. It is characterized by its diversity, with many studies focusing on specific contexts, locations or aspects of procurement processes. While valuable for depth, this presents challenges in synthesizing a comprehensive understanding of the field. The scope of this research will focus mainly on construction procurement through first price sealed bid auctions and lump sum contracting. This is still the most common way of construction procurement. However, the reality is that while construction procurement works similarly around the world, differences can be found and should be considered.

The second area, sustainable construction procurement, represents a growing focus in the industry, aiming to integrate environmental, social, and economic considerations into the procurement process. In this report the focus will lie on environmental sustainability in the construction industry. It refers to the adoption of practices and strategies that minimize negative impacts on the environment. However, the performance of a project in this regard is hard to measure. Lima et al. (2021) review the literature on sustainability in the construction industry and find a lack of taxonomy and quantitative methodologies to assess sustainability in the civil construction industry. The most used methodology are life cycle assessments (LCA) and the most used environmental certification is Leadership in Energy and Environmental Design (LEED). The literature discusses the environmental impacts of different building materials, design and energy usage, maintenance needs and construction methods (Lima et al., 2021). The integration of sustainability into procurement practices represents a significant shift in the construction industry. It requires new evaluation criteria, different skillsets from contractors, and often involves navigating complex trade-offs between various sustainability goals and traditional project objectives.

The third component of the literature study looks at the use of simulations and modelling in construction procurement, without and with sustainability aspects. In construction procurement, the most common method is still the lump-sum contract, often awarded through a single-stage tendering process. This approach is equivalent to a first-price sealed-bid auction, where contractors submit confidential bids, and the lowest bidder wins the contract at their bid price. Auction theory is a field that has long examined auction designs and bidder behavior, developing a theoretical basis for understanding and analyzing this process. It utilizes different approaches such as expected utility theory, prospect theory or game theory, to model and predict bidder behavior. Auction theory has been instrumental in analyzing how different auction formats impact bidder strategies and outcomes.

These modelling approaches have not been so thoroughly applied to construction procurement. The research can broadly be categorized into three main types: contractor decision models, system dynamic models (contractor ecosystem models), and in between, auction models. Contractor decision models focus on individual firm-level choices, such as bid/no-bid decisions and markup determination. These models often employ techniques like utility theory, neural networks, or fuzzy logic to capture the complexity of decision-making under uncertainty (Bagies & Fortune, 2006). Contractor ecosystem models, on the other hand, aim to simulate broader competitive dynamics using methods such as system dynamics modelling. Auction models are in between on the scale and attempt to bridge individual and market-level dynamics. Agent-Based Modelling (ABM), has the capacity to model on this in between scale by starting with a decision model, simulating multiple auctions, and through that, emerging market behavior.

ABM is a computational approach used to simulate real-world complex systems through the simulation of interacting autonomous decision-making entities called agents and their environment. ABM employs a bottom-up methodology, focusing on individual-level behaviors to understand system-level outcomes. ABMs are able to generate a deeper understanding of systems like markets compared to, for example, system dynamics models, because market behavior emerges out of the adaptive and changing behavior of the individual agents (Bonabeau, 2002). ABM has also been applied to auction modelling and tendering process in construction. Models have been developed to simulate the behavior of bidders, the impact of different bidding strategies on project outcomes, and the dynamics of the bidding market (Awwad et al., 2014; Asgari & Kandil, 2016; Awwad & Ammoury, 2019; Elsayegh et al., 2020). The theoretical and empirical basis of these models has been limited, however, and there have been no models that simulate construction procurement with sustainability aspects.

Further details of the literature review are discussed and analyzed in each of the corresponding chapters. The basis of the split is rooted in both the context of the topics themselves and the methodology of the model building. This will be elaborated upon in chapter 3. This part of the review helped define and describe the current body of knowledge, whereas the following parts within the chapters will identify the state of current practices and associated challenges and opportunities, find patterns and trends and pick out relevant economic theory and empirical data to base the models on.

1.4 RESEARCH GAP

In the previous chapter, we defined key terms and provided a comprehensive overview of the existing literature. This section narrows the focus to highlight the gaps within the current body of knowledge and illustrate how addressing these gaps can advance both academic and practical understanding of sustainable construction procurement.

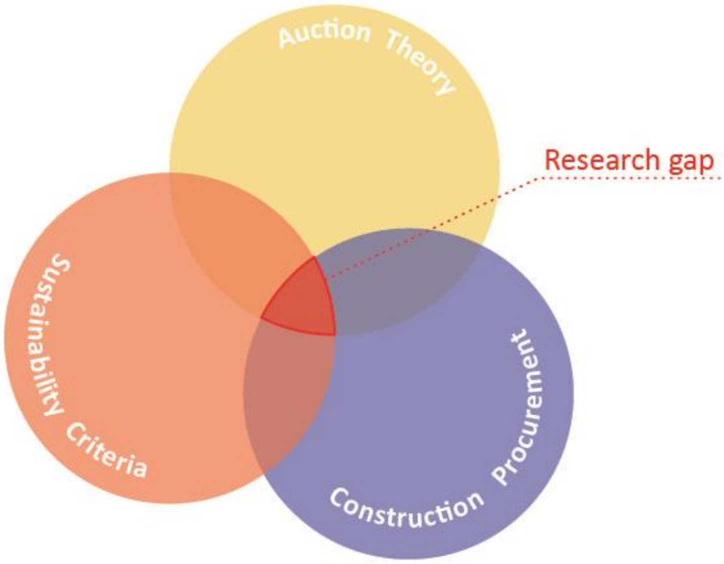


Figure 4: Research Gap Diagram

The literature gap is twofold, spanning three key areas of research: auction theory, construction procurement, and sustainability criteria. The first gap lies in the application and integration of auction theory and data into construction bidding models. The second gap relates to the limited research on sustainability criteria and their impact on construction procurement and auctions. Currently, there is neither robust empirical research nor sufficient theoretical exploration in these areas. In the following sections, the research gap will be clearly outlined through a critical review of existing studies in these three key areas, highlighting their limitations and synthesizing them into a coherent research gap.

Auction Theory

The first body of knowledge that needs to be explored is auction theory. Auctions are mechanisms for allocating resources by matching supply with demand (principle of efficient allocation). At their core, auctions aim to maximize the seller's revenue while ensuring goods or services are allocated to those who value them most (principle of surplus maximization). This happens by driving competition among bidders, auctions reveal each participant's valuation of the auctioned object. Where then the participant with highest valuation wins the auction.

Frameworks such as game theory, utility theory, and prospect theory provide the analytical tools to evaluate bidder behavior. Game theory models rational, risk-neutral decision-making in competitive settings, while utility theory incorporates individual preferences and risk attitudes. Prospect theory extends this by accounting for psychological biases like loss aversion and regret, offering a deeper understanding of real-world bidding behavior.

Most auction theory research is non-context-specific, focusing on general auction formats. But the theory has been applied in practice for mechanism design of auctions in fields like spectrum auctions. However, its application to construction procurement remains rare. One hurdle is that, even though the most common auction format in construction procurement, sealed tender or first-price sealed-bid auctions, are well researched, the theorems describing the behaviour under these auction conditions are under idealized conditions (Milgrom 2003). These tools offer a theoretical baseline for understanding auction dynamics but must be adapted to address the complexities of construction procurement. There are many deviations and complications from standard auction formats and theory in construction procurement that are worth mentioning.

In construction procurement, auctions involve elements of both common value models, meaning auctions where the true, noiseless valuation of the object should be the same for every participant. In construction shared information, like project specifications and material costs, influences valuations. In auction theory these are called shared signals. However, there are also many elements of private value models, meaning the valuation of auction participants are independent of each other. There are for example private adjustments for factors such as risk perceptions, profit margins, and firm-specific efficiencies, these are called private signals. This leads to fuzzy valuations, where subjective estimations further complicate the analysis of the auction behaviour.
Another deviation from standard auction models is that construction contractors also differ in their risk preferences and experience, creating significant asymmetries. Experienced contractors might for example bid more aggressively.
Lastly there is another aspect that differentiates this research case from typically researched auction formats. In construction procurement, particularly sustainable construction procurement, bids are evaluated based on both price and non-price attributes, differing from pure price-only auctions by incorporating qualitative factors such as sustainability. In auction theory these are referred to as auctions with scoring rules as opposed to price-only auctions. Researchers even in auction theory have not extensively researched auctions with scoring rules, this is where a significant gap remains (Milgrom 2003). Only Che (1993) and Rezende (2002), have looked into scoring auctions and shown that in an auctions sellers can sometimes benefit by biasing the scoring rules to increase competition in the auction.

While traditional auction theory models have limitations, like struggling to capture nuanced contractor behaviours in competitive environments, for instance, classical Neutral Bayesian-Nash Equilibrium frameworks fail to explain phenomena such as overbidding and "throwing away," as demonstrated by Cox et al. (1988), empirical and behavioural extensions of auction theory can be an important tool for understanding and bettering allocation mechanisms in construction procurement. Studies such as Campo (2012), Hartono (2010) and Wang & Guo (2017) provide important groundwork by applying utility theory, prospect theory and bounded rationality to construction contexts, respectively. These works offer insights into contractor decision-making by incorporating contractor-specific factors, such as financial stress and risk aversion or factors like regret, conservatism, and cognitive limitations influence bidding behaviours. While these studies expand the theoretical lens of auction theory, their primary focus has been on understanding bidder behaviour rather than the broader auction framework.

Construction Procurement
Construction procurement is widely researched, focusing on processes, methods, and policies, yet significant gaps remain. Studies exploring aspects like contracting strategies and selection criteria (Ruparathna & Hewage, 2015) are often fragmented and lack integration into broader theoretical frameworks. Despite the industry's emphasis on proper procurement for project success, the literature reveals a lack of a unified perspective on procurement processes, with practices remaining diverse and fragmented. Many procurement methods are explored in detail, including lump-sum contracting, design-build, and integrated project delivery (Ruparathna & Hewage, 2015; Kowet & Ozumba, 2019). Similarly, selection criteria, ranging from price-based methods to multi-criteria approaches, have been studied extensively, often highlighting the benefits of incorporating non-price factors such as contractor experience and technical capability (Olaniran, 2015; Konno, 2018; Waara & Bröchner, 2006; Khoso et al., 2021). However, the often-fragmented and project-specific understanding makes it challenging to determine the most effective strategies for specific project needs.

Several studies have attempted to apply auction theory to construction procurement models, offering promising insights into contractor dynamics. Utility theory remains the dominant approach (Awwad et al., 2014; Asgari & Kandil, 2016; Awwad & Ammoury, 2019; Elsayegh et al., 2020), while game theory has been explored less frequently (Ahmed et al., 2016; Asgari & Shaafat, 2016). These models typically focus on contractor behaviors such as markup strategies and competitive dynamics. However, many of these efforts make simplifying assumptions or fail to engage with foundational research, such as Campo (2012), which connects auction theory to real-world construction bidding. This disconnect has left gaps in understanding how procurement policies, including sustainability criteria, shape competitive bidding environments. Bridging these gaps requires integrating insights from both contractor-focused studies and the broader auction design and scoring rules of selection criteria.

By integrating auction theory into agent-based modeling (ABM), this research bridges the gap between theory and practical applications. ABM allows for the simulation of selection criteria scoring rules' impact on contractor participation, competitiveness, and price development. This approach has been explored in studies such as Idrees et al. (2023), which analyzed the impact on owner utilities when switching between different bid price selection criteria. Additionally, earlier research has used ABM to investigate various contractor strategies, and owner decision-making frameworks (Awwad et al., 2014; Asgari & Kandil, 2016; Awwad & Ammoury, 2019; Elsayegh et al., 2020). However, these models often lack integration with the broader auction theory literature, which remains underutilized in construction procurement research.

Sustainability Criteria

Research on sustainable construction procurement has led to the development of many frameworks and policies aimed at embedding environmental sustainability into construction practices. These frameworks—such as certification systems like LEED and BREEAM, or methodologies like Life Cycle Assessment (LCA)—provide structured tools to assess and rate environmental performance (Lima et al., 2021; Kjerulf and Haugbølle, 2021). Recent trends show a noticeable shift from purely economic winner selection in procurement to multi-criteria evaluation, where sustainability considerations play a critical role. Studies and case analyses across frameworks and locations have highlighted their potential to promote greener practices while offering insights into their implementation in different contexts (Bohari et al., 2017; Ruparathna & Hewage, 2015b; Wiik et al., 2020).

Despite the abundance of sustainability frameworks, the integration of sustainability criteria into procurement auctions remains underexplored. There is limited research on how these frameworks and certification systems are implemented within the procurement process and into incentive structures. Most existing studies rely on qualitative methods, such as case studies and interviews, to identify barriers to sustainable procurement—such as high costs, complexity, and market resistance (Ruparathna & Hewage, 2015; Prier et al., 2016). However, there remains a research gap in exploring the specific mechanisms for implementing sustainability frameworks into procurement processes, even though, in practice, the choice of which mechanisms to use remains a key consideration for owners and policymakers.

The few studies that have attempted modeling sustainability in construction procurement focus on other aspects. For example, ABMs have been used to simulate broader market responses to sustainability policies, such as the diffusion of green practices or contractor adaptation over time (Attallah et al., 2013; Li et al., 2022). While these studies offer valuable insights, they do not address the tendering or bidding process directly, leaving a gap in understanding how sustainability-driven policies affect auction design and outcomes. This research seeks to bridge these gaps by integrating sustainability criteria into procurement auction models. By simulating their effects on contractor participation, pricing, and auction outcomes.

Combined approach

The gaps identified at the intersection of auction theory, construction procurement, and sustainability criteria reveal a need for more integrative approaches in both research and practice. Auction theory has been applied to construction procurement, yet its connection to procurement policies, particularly sustainability criteria, remains underdeveloped. Similarly, while construction procurement research offers detailed insights into methods and frameworks, these often lack the theoretical and systemic integration necessary to assess their broader impacts on competitive environments. Sustainability criteria, while central to modern procurement policies, are rarely examined through the lens of auction theory, leaving their effects on contractor behaviour, market dynamics, and project outcomes largely unmodeled. By leveraging auction theory and ABM, this study provides a framework to analyse how sustainability criteria interact with procurement policies and market dynamics. ABM's ability to simulate emergent behaviours allows for the exploration of nuanced policy effects, from contractor participation and pricing to the achievement of sustainability goals.

Practical examples from other sectors highlight the transformative potential of such approaches. For instance, spectrum auctions (Milgrom, 2004; Cramton, 1997) and carbon trading schemes (Cramton & Kerr, 2002; Hepburn et al., 2006) demonstrate how well-designed auction mechanisms can simultaneously achieve economic efficiency and policy objectives. Adapting these insights to construction procurement offers a pathway to balance environmental goals with competitiveness and inclusivity, providing actionable insights for a more sustainable industry.

1.5 RESEACH AIM, QUESTION AND SCOPE

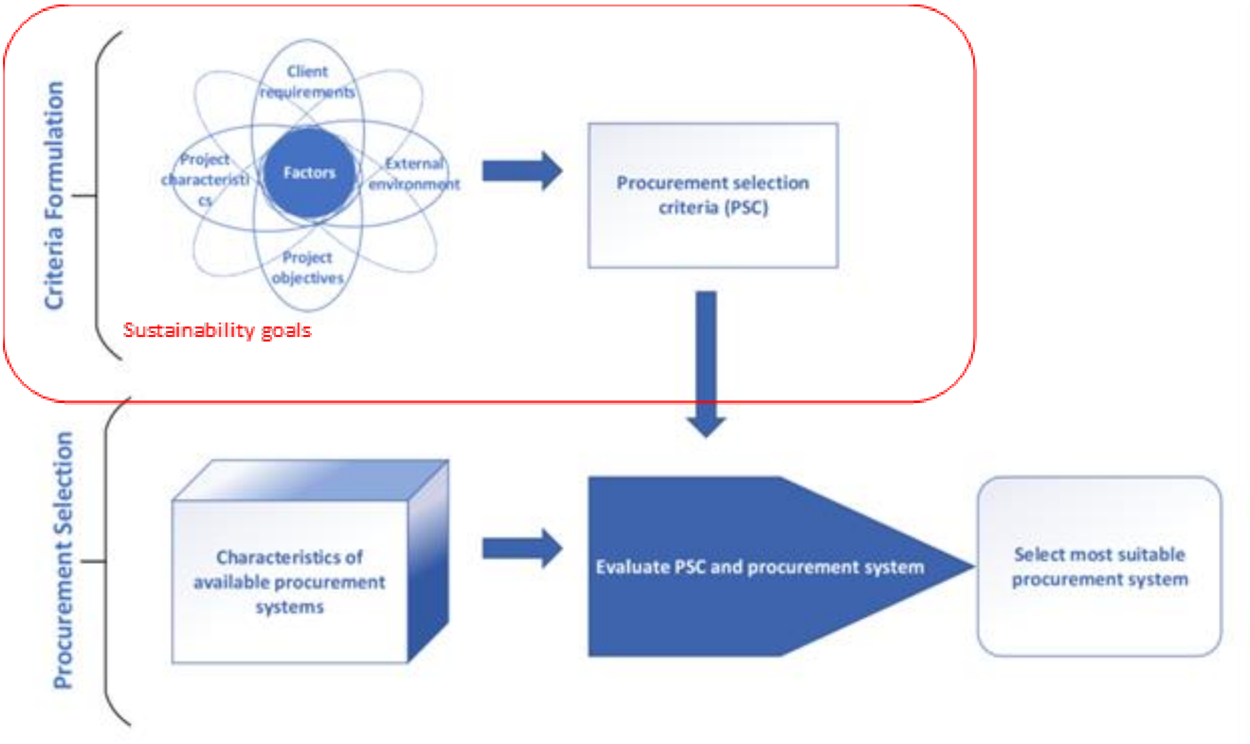
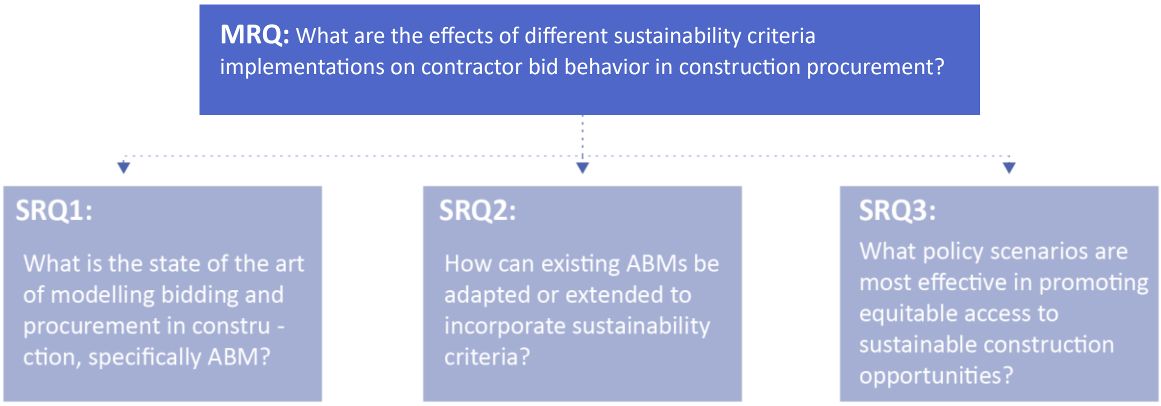


Figure 4: Construction Procurement Selection Process (Zhao et. al., 2022)

The procurement process in construction is influenced by numerous factors and characteristics that vary across projects. This research focuses specifically on sustainability criteria, highlighted in red in *Figure 4*, and their economic implications, such as bid pricing, contractor participation, and competition. Other aspects of procurement, such as project-specific characteristics, procurement systems, remuneration schemes, and project delivery methods, are outside the scope of this study. The study assumes a lump sum contracting approach with tendering processes aligned to first-price sealed-bid auctions. By narrowing the focus to sustainability selection criteria and their implementation mechanisms, this research aims to address critical questions around their role in shaping contractor behavior and procurement outcomes.

The primary aim of this research is to assess the current state and explore the effects of sustainability selection criteria in construction procurement, specifically focusing on their mechanisms of implementation. To achieve this aim, an ABM is developed to simulate and compare existing implementation mechanisms, policies, and formulas. The ABM facilitates experimentation to evaluate their impact on key economic factors, including bid price development, contractor participation, and market competition.



The question follow from the methods used and will be explained in more detail in the following chapter.

2. RESEARCH METHOD

2.1 METHODOLOGY

This research combines a number of methods to ensure a comprehensive answer to the research questions. The use and reason behind them will be laid out in the following.

Agent-Based Modeling (ABM): As introduced in the previous chapter, ABM is a computational approach designed to simulate complex systems by modeling interactions between autonomous, decision-making agents and their environment. In this thesis, the ABM serves as the primary method of modelling and bridging individual contractor decision-making models with broader market-level phenomena. It is particularly suited for simulating the dynamics of construction procurement auctions, where contractors make decisions, such as whether to participate in tenders or adjust bid markups, that collectively influence market competitiveness and sustainability outcomes.

In research, ABMs have been widely applied to study models of competition and cooperation (Axelrod 1997). They have been especially instrumental in modeling auction mechanisms and market dynamics, exploring how bidding strategies and contractor behaviors evolve under different conditions. These models allow observation of emergent patterns and testing of policy scenarios in a controlled environment, providing insights without the cost or complexity of real-world experimentation.

However, ABMs while insightful, are models that are challenging to validate and sometimes criticized as "Toy Models" (Tesfatsion, 2022). The criticism often stems from the perception that ABMs oversimplify complex real-world systems. Critics argue that the simplifications necessary to make ABMs computationally tractable may strip away essential complexities, potentially leading to misleading results. Additionally, the large number of parameters and the sensitivity of outcomes to initial conditions in ABMs can make it challenging to distinguish between genuine insights and artifacts of the model design. This shows that even more so than in other modelling methods it is important to find optimal modeling complexity with ABMs.

Auction Theory (Expected Utility Theory): The agent logic within the ABM is based on expected utility theory, a well-established framework in economic modeling. This theory helps simulate rational decision-making, where agents evaluate the expected benefits and risks of their actions to maximize their utility. The strength of expected utility theory lies in its alignment with empirical studies and its practical applications in construction management. It avoids some of the pitfalls of game theory, which fails to explain some phenomena such as overbidding and "throwing away" (Cox et al., 1988), while offering a solid theoretical and empirical foundation for modeling contractor behavior. The literature briefly mentioned in the previous chapter offers good knowledge to build on. By incorporating expected utility theory, the ABM ensures that contractor behavior is grounded in economic principles that reflect real-world bidding strategies.

Step-by-Step Model Development: To address the complexities inherent in modeling contractor bidding behavior and the integration of sustainability criteria, this research adopts an iterative modeling approach grounded in both literature and existing models. Each iteration of the model incrementally incorporates new aspects, informed by parallel literature reviews and research efforts. This iterative process allows for continuous refinement of the model, providing multiple opportunities for validation and verification at each stage.

- **Initial Model**: The first version of the ABM is constructed based on existing literature on construction bidding models and auction theory. This version represents a conventional bidding environment without sustainability considerations, focusing on standard contractor decision-making and market dynamics. Empirical data supports this baseline model to ensure its accuracy and relevance.
  In this phase, the "Keep It Descriptive, Stupid" (KIDS) approach is employed (Edmonds & Moss, 2005). Given the availability of empirical data and well-established theories, a more detailed and descriptive model is appropriate. The KIDS approach advocates for including sufficient detail to ensure the model accurately represents the phenomena under investigation. The model is grounded in empirical data to ensure its validity and relevance. By incorporating

detailed representations of contractor decision-making processes, risk preferences, and market behaviors, the model accurately simulates the baseline behaviors observed in construction procurement.

- **Sustainability Integration**: The second version of the model incorporates environmental sustainability criteria, reflecting real-world practices and policies like Green Public Procurement (GPP). This version simulates how sustainability factors influence contractor decisions, markups, and participation in tenders.
  Due to the limited precedent and lack of comprehensive data on how sustainability factors influence contractor bidding behavior, the "Keep It Simple, Stupid" (KISS) approach is adopted in this phase (Axelrod, 1997). The rationale for this shift is due to the limited precedent and lack of accurate, comprehensive data, sustainability factors in construction procurement. Given these uncertainties, a simpler model is advantageous. The KISS approach enables a focus on the most critical elements of sustainability integration. By simplifying the sustainability components, we can explore the fundamental impacts of different sustainability criteria capturing essential insights while maintaining model tractability.

- **Enhanced Features for Policy Analysis**: The final iteration of the model includes additional features such as bid/no-bid decision-making processes and a mechanism for sustainability learning, where contractors improve their sustainability capabilities through investments. These additions allow the model to run policy scenarios that test different sustainability criteria implementations and assess their effects on market behavior and competitiveness. The model evolves from a closed bidding environment to an open market setting, allowing for more dynamic interactions and competition among contractors. For this phase, validation is achieved through interviews with industry professionals—both owners and contractors. These interviews provide real-world verification of the model's assumptions and outputs, helping to interpret the results in the context of industry knowledge and experience.

Literature Review and Data Collection: Throughout the modeling process, an ongoing literature review and data collection are conducted, serving three main purposes. Firstly, a system analysis for building a comprehensive understanding of the underlying system. This involves researching current practices and gaining insights into how the construction procurement system operates, including procurement systems, selection and evaluation methods, and market behaviors. Secondly, model building support requires collecting empirical evidence, quantitative and qualitative data, and theoretical insights to inform model development and parameterization. This ensures that the model is representative of real-world phenomena and grounded in factual data. Lastly, pattern finding focuses on identifying qualitative and quantitative patterns observed in the industry. This step is essential for ensuring the model is fit for purpose and aids in validation through Pattern-Oriented Modeling (POM). By aligning the model with known patterns and behaviors, we enhance its credibility and ensure it accurately reflects the dynamics of construction procurement.

Pattern-Oriented Modeling (POM): To validate the models in their respective phases, a pattern-oriented modeling approach is employed. POM focuses on replicating multiple qualitative and quantitative patterns observed in real-world systems, thereby ensuring the model's structural realism and robustness. This method serves as a qualitative validation tool that aligns model behavior with known empirical patterns.

A POM approach is adopted for partial validation of the model (Grimm et al., 2005). POM provides a method for qualitative validation by using multiple patterns observed in real-world systems, preferably at different scales and levels. This approach helps reduce parameter uncertainty through inverse modeling—recreating patterns observed in reality to decode information on internal organization or agent behavior.

By incorporating a POM step, structural realism of the model can be partly ensured. As Epstein (2008) notes, any prediction or projection found in research or practice involves running some model, typically with implicit assumptions and unknown logical consequences. By using POM to guide the development of an explicit ABM, assumptions are made transparent and testable against observed patterns. This allows for examining the implications of different theories about contractor behavior and market dynamics in the construction industry.

POM also addresses the trade-off between model complexity and tractability. By focusing on replicating multiple real-world patterns, we can develop a model that captures essential dynamics without becoming overly complex. This aligns with the KISS principle in later stages while ensuring the model remains grounded in empirical observations.

However, while POM provides a robust approach to model development and partial validation, it is not sufficient for full model validation. Therefore, for the final validation of findings, expert interviews are used to provide an additional layer of real-world verification and to help interpret the model's results in the context of industry knowledge and experience.

Expert Interviews: To complement the POM validation, expert interviews with industry professionals, from both the owners and contractor side, are conducted. Overall, five semi structured interviews were conducted with one owner, one owner consultant and three contractors of different sizes. The interview outline can be seen on *Appendix 1.* These interviews provide an additional layer of validation by comparing the model's outputs and assumptions with the practical experiences and insights of those actively engaged in the industry. These interviews serve multiple purposes:

- **Validation of Model Assumptions**: Comparing the model's outputs and underlying assumptions with practical experiences and insights from professionals actively engaged in the industry.
- **Interpretation of Results**: Gaining deeper understanding and context for the simulation findings, particularly in areas where empirical data is limited.
- **Policy Implications**: Gathering perspectives on the practical applicability of the findings and potential policy recommendations.

This mix of methods helps deal with a lack of empirical data, while allowing to build on what is known, while systematically exploring new models. Together these methods make up the methodology of this research and aim to produce a robust and reliable analysis of the research questions.

2.2 THESIS STRUCTURE

The thesis structure aligns with the methodology outlined, ensuring a logical progression from problem identification to solution development and validation. Chapters 1 and 2 introduce the topic, establish context, and provide a roadmap for the research. Chapters 3, 4, and 5 form the core of the investigation, each addressing one phase of the research and corresponding to a sub-question (SQ1, SQ2, SQ3). Each phase follows a structured approach involving data collection, model development, and validation, with distinct differences in focus and content.

Phase I and Sub-question 1: Initial Model

Phase I centers on developing the initial version of the ABM, which models conventional contractor bidding behavior without sustainability considerations. This phase begins with data collection through a literature review and semi-structured interviews to gather insights on procurement systems, contractor decision-making, and market behavior. The goal is to create a foundational model anchored in existing literature and empirical evidence. The model is then validated using POM to ensure its fit with observed real-world behavior and practices.

Phase II and Sub-question 2: Sustainability Integration

Phase II extends the initial model by incorporating sustainability criteria, reflecting current policies and practices such as GPP. This phase also starts with a literature review and industry interviews, focusing on sustainability in construction procurement, relevant frameworks, and contractor strategies for integrating sustainability. The model is adapted to simulate how sustainability criteria affect contractor decisions, participation, and market dynamics. Validation through POM continues in this phase to maintain structural realism and reliability.

Phase III and Sub-question 3: Enhanced Features

Phase III focuses on advancing the model with enhanced features, transitioning from a closed bidding environment to an open market setting. This phase explores the dynamics of contractor competition and sustainability learning through investment. Building on the insights and findings from the previous phases, the final model includes bid/no-bid decision-making processes and contractor learning mechanisms. Validation for this phase is achieved through expert interviews, providing real-world verification and contextualizing the model's outputs.

Final Chapters

The last two chapters synthesize the findings and reflect on their broader implications. Chapter 6 serves as a comprehensive validation, integrating insights from POM and expert interviews to assess the reliability and practical relevance of the model. Chapter 7 discusses the results, presents conclusions, and suggests directions for further research, emphasizing the applicability of the research outcomes to both academic and industry practices. This structure ensures a cohesive approach that answers the main research question through a combination of theory, modeling, and practical validation.

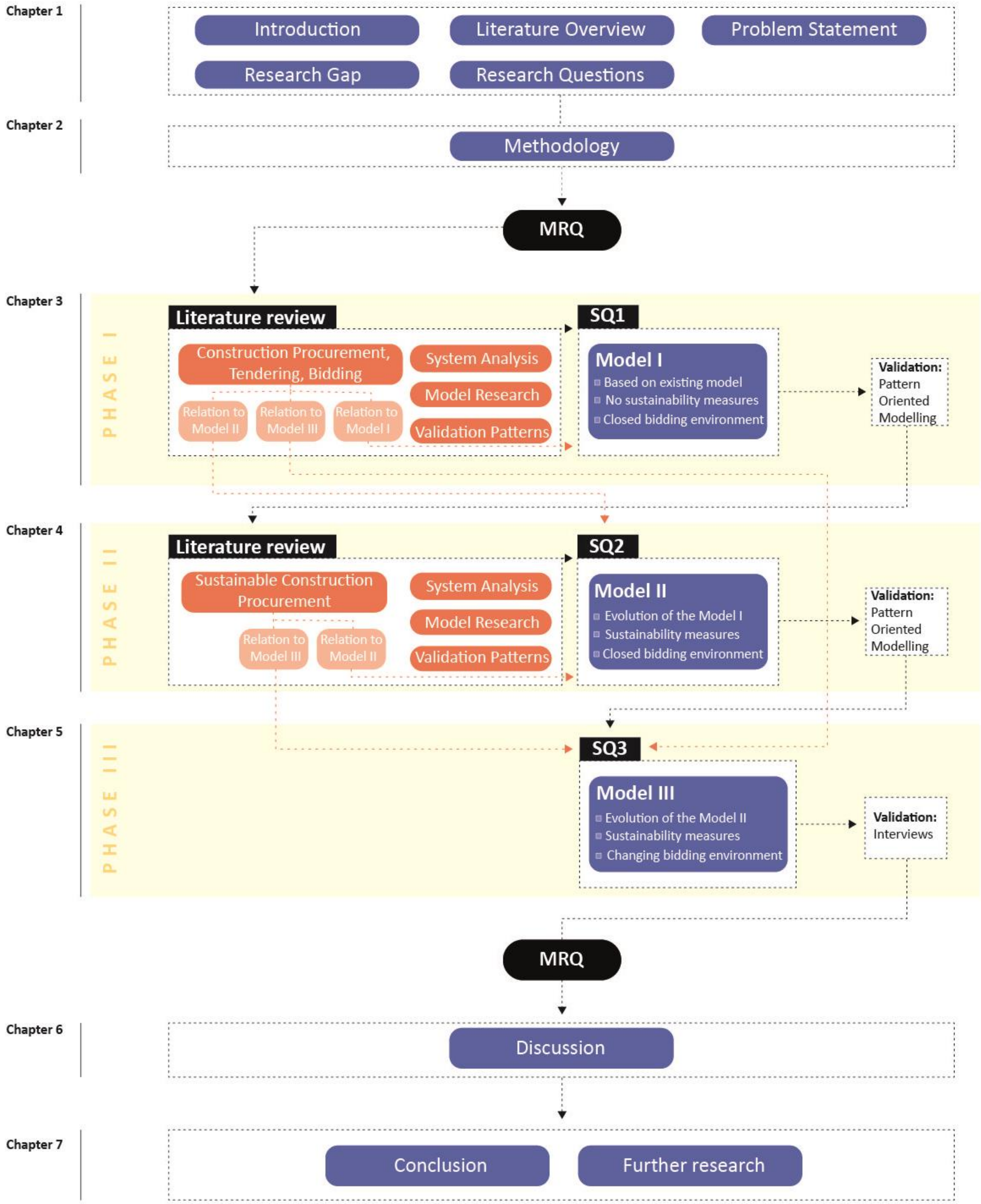


Figure 5. Flowchart of Thesis and Report Structure

2.3 LITERATURE REVIEW METHOD

This section outlines the systematic method for conducting the literature review, loosely based on the quantitative methodology proposed by Seuring and Müller (2008). The process is comprised of four stages: category selection, material collection, analysis, and pattern identification.

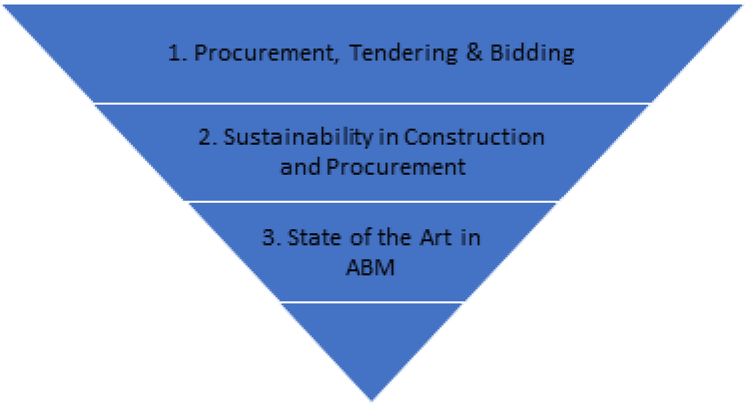


Figure 6: Category Selection

The method used in this review is designed to capture everything relevant to understand and model the bidding environment and sustainability evaluation and selection criteria. It involves a systematic examination of current practices, emerging trends, and ongoing research in construction bidding processes, focusing on identifying challenges and opportunities. Additionally, this is done with an attention to the integration of sustainability criteria. A taxonomical funnel was developed to explore the current body of literature, progressing from broader topics such as Construction Procurement, Tendering, and Bidding Theory and Practice, through Sustainability in these areas, to the specific application of ABMs in these topics. The breadth and depth of the approach ensures comprehensive coverage and balanced insight, where both macro and micro perspectives are considered. This is ideal for developing the ABM in the report's later sections. At the macro level, economic and social patterns influencing procurement and sustainability are examined, while at the micro level, individual agent behaviors are analyzed. This enables effective modelling in later stages of the research. Empirical studies were prioritized in the literature selection process; however, robust qualitative research was also included where quantitative data was limited.

The literature collection utilized key search terms as presented in Table 1. the Primary databases and search engines employed were Google and Google Scholar, chosen for their cross-platform capabilities and access to industry reports, as well as Scopus, which is the largest database of peer-reviewed literature. The search terms were categorized into 5 groups.
The Universal (U) group comprised keywords that could be used in all searches and were combined with terms from all other groups to help find relevant literature across categories.
Group (R), used to narrow down searches to reports and reviews, that help get an overview.
Group 1 contained keywords related to the first category in our funnel: Procurement, Tendering, and Bidding Theory and Practice in general. These terms helped identify literature covering the broad aspects of construction procurement processes and practices.
Group 2 focused on sustainability-related terms in the context of construction and procurement. This group was crucial for identifying literature that addressed environmental and sustainable practices within the industry.
Group 3 included keywords specific to modeling and simulation techniques, with a particular emphasis on Agent-Based Models (ABMs). This group was instrumental in locating studies that employed computational models to analyze construction procurement processes.

Table 1: Key search terms

Group	**Keywords (All Searches *LIMITED TO Construction industry)***
U	(Construct* or Build* or Built* or Contractor*)
R	("Report" or "Review")

1.)	(“Procurement” or “Tender” or “Bidding” or “Auction”) and (“Price” or “Selection” or “Winner” or “Criteria” or “Practices” or “Policies” or “Competition”)
2.)	(“Sustainability” or “Eco” or “Environment” or “Green” or “GPP” or “Circular”)
3.)	(“Agent” or “Agent Based Model” or “ABM”)

By systematically combining terms from these groups into a search query and identifying additional relevant sources through citation-tracking and Google search the initial pool of literature was established. The sources were examined, and exclusion criteria were applied, filtering out articles that were, not written in English, unavailable in full length, or outside the scope of the research.

211 articles were for the first funnel group, using the search query “((U) AND (R) AND (1.) AND NOT (2.)“. After exclusion criteria were applied and the expansion through citation tracking and Google search 37 sources were left.
114 articles were found for the second funnel group, using the search query “((U) AND (R) AND (1.) AND (2.)“. After exclusion criteria were applied and the expansion through citation tracking and Google search 53 sources were left.
52 articles were found for the second funnel group, using the search query “((U) AND (3.)“. After exclusion criteria were applied and the expansion through citation tracking and Google search 15 sources were left.

This taxonomy applied for querying is partially carried through to the review in further chapters, with the distinction that findings are further classified into more topics. Notably, the findings are of the third query is further divided into models that include sustainability aspects and ones which do not.

Literature Review Structure
The literature review in this thesis is strategically divided into two main parts, despite the initial three-pronged search approach. The first part focuses on construction procurement, tendering, and bidding without explicit sustainability considerations. The second part then shifts focus to sustainability in construction, examining how sustainability principles are integrated into procurement, tendering, and bidding processes. By structuring the literature review in this way, we establish a comprehensive foundation of traditional practices before examining how sustainability is reshaping the field. This approach allows us to clearly identify the changes and challenges introduced by sustainability considerations, setting the stage for our model development process which progressively incorporates sustainability elements.

3. STATE OF THE ART OF BIDDING AND PROCUREMENT MODELING

3.1 LITERATURE REVIEW

3.2 MODEL 1

3.3 VERIFICATION AND VALIDATION EXPERIMENTS

3. SUB QUESTION 1

What is the state of the art of modelling bidding and procurement in construction, specifically ABM?

3.1 LITERATURE REVIEW

Overview

A comprehensive overview of procurement in the construction industry can be found in Ruparathna and Hewages' (2015) literature review, which offers a contextual framework for navigating the topic, primarily from the perspective owners. Their work, along with similar reviews, has been instrumental in guiding the selection of literature for this review. They highlight three primary areas of focus within construction procurement research: Processes, methods, and policies and offer an overview of traditional and emerging practices. These focal points are reflective of the broader research trends observed in literature. The body of work found and used in this literature review can also be broadly categorized into three main avenues of research. While two of these closely match the areas of focus presented by Ruparathna and Hewage, this review includes an additional research avenue that considers the contractor's perspective:

Firstly, Procurement systems or methods can often be summarized in the form of contracting, such as Lump Sum Contracting or different forms of Public Private Partnerships, but it includes rules of operation, contractual relations, division of labor, price formation and delivery method.

Secondly, Selection and evaluation criteria for contractors or policy, steer the selection of a winning contractor in support of a given procurement method. The selection method in the private market, even for EU wide public procurement, is often shaped by the values of the owner and can vary widely. Policies and selection techniques for public owners differ in this aspect as they require transparency and tend to be more stringent.

Lastly, contractor bid behavior, including bid/no-bid decisions and markup strategies, represents agent behavior. This research area is central to understanding the decision-making processes of contractors and examines the importance of variables such market conditions or risk-attitude on bidding strategies.

This review aims to present a clear picture of current construction procurement practices while also building a knowledge base for system analysis, model building support and pattern finding as mentioned previously in *section 2.1*.

Procurement systems

When discussing procurement systems, the literature refers to a range of approaches for organizing and managing the acquisition of construction services. Ruparathna and Hewage (2015) provide a comprehensive overview, categorizing procurement models into traditional and emerging methods. Traditional methods include fixed price contracting (lump sum) and involve discrete design, tender, and construction phases, with varying degrees of contractor involvement and risk allocation. New Models of Construction Procurement (NMCP), include Integrated Project Delivery (IPD). These models aim to promote early contractor involvement, collaboration, and shared risk.

While not explicitly linked to contractor bidding, the literature suggests that procurement methods and contracting practices can significantly influence the competitive landscape and contractor bidding behavior in the construction industry (Pasquire et al., 2015; Yu et al., 2013; Loosemore and Richard, 2015). Seen through the lens of auction theory different procurement systems are essentially mechanism designs that use elements such as prequalification, scoring rules or introduction of serial negotiations to influence allocation outcomes. Ruparathna and Hewage (2015) and Sheamar et al. (2023) touch on how different procurement methods can affect competitiveness and the number of participating contractors. For example, in Cost Led Procurement, the client selects several supply chain teams from a pre-established list to collaborate on the project. This approach can limit the number of contractors who are eligible to bid, which might reduce overall competition in the procurement process. Loosemore and Richard (2015) and Pasquire et al. (2015) highlight issues that may particularly affect smaller contractors, such as the industry's adherence to rigid standard forms and traditional contracting methods, which can disadvantage firms with less capacity to absorb risks or engage in protracted disputes. Sheamar et al. (2023) also raise concerns about the fairness of risk-sharing arrangements for smaller subcontractors in new procurement models. These findings suggest that the choice of procurement method can have far-reaching effects on market dynamics, potentially influencing markup strategies, bid participation, and the overall health of the contractor market.

Selection and evaluation of contractors

The selection and evaluation of contractors is a critical process in construction procurement that aims to identify the most suitable contractor for a project. Traditionally, many contracting authorities, especially in the public sector, have relied on the lowest-bid, a price-only bid criterion for contractor selection. The approach promotes competitive prices, transparency and competition. However, research increasingly highlights the limitations of this method.

Many studies of local construction projects reveal a decrease in quality and performance associated with more traditional price-based contractor selection. In Brunei, Olaniran (2015) found that 92% of projects using lowest-bid selection experienced time overruns and 89% faced quality issues. Konno (2018) reported that Japanese projects selected primarily on price experienced 15% more delays and 23% more quality defects compared to those using multi-criteria methods. In Pakistan, Khoso et al. (2021) noted that 62% of modern technology projects failed to meet their objectives when using traditional selection criteria. Similarly, Cheaitou et al. (2019) found that 70% of public construction projects in the UAE exceeded their budgets or timelines when using conventional selection methods.

In response to these challenges, there has been a growing trend towards multi-criteria evaluation methods. Waara & Bröchner (2006) observed a 35% increase in the use of non-price criteria in Swedish public construction contracts between 2001 and 2003, resulting in a 20% reduction in time overruns. Ergonul & Yilmaz (2011) identified seven key non-price factors in Turkish projects that led to a 30% higher stakeholder satisfaction rate.

Khoso et al. (2021) emphasized the importance of adapting selection criteria to modern technology projects, finding that basic criteria were often insufficient for evaluating contractors' capabilities in implementing advanced technologies. The study developed technology-specific criteria that improved alignment between contractor capabilities and project requirements in 80% of pilot projects.

The literature consistently demonstrates the limitations of price-only lowest-bid contractor selection methods. Selecting contractors based solely on cost can lead to decreased profit margins for contractors, delays in project duration, and non-compliance with construction standards (Olaniran 2015). Innovative practices and novel technology are also shown to be disadvantaged under purely economic selection methods. This is where the principle of efficient allocation of auctions often falls short, because valuation and value signals, as are not rigid values in practice and can be traded off for quality or time (Barnes, 2006). This means that in price-only auctions the winner is not only the participant with the highest valuation, or in this case lowest predicted cost, but also the participant most willing to trade quality for price.

The implementation of multi-criteria selection methods, however, presents its own challenges. Bochenek (2014) noted that determining and using non-price factors requires more knowledge and experience, and formulating partial evaluation criteria takes more time and money both in preparing tender documents and during the tender procedure. This complexity can be a barrier to participation resulting in less competition and worse prices for the owner according to bulow-klemperer theorem (Milgrom, 2003). It also hinders adoption, especially in public procurement where transparency and objectivity are important and scoring rules can obscure this. To address these issues, researchers have proposed frameworks, such as the three-stage model developed by Cheaitou et al. (2019), to balance multiple objectives and criteria while maintaining efficiency and transparency.

Contractor bid behavior

The third key aspect of construction procurement research focuses on contractor bid behavior, which can be distinguished into two decision making instances bid/no-bid decisions and markup decision. This area of study is crucial for understanding the contractor agents and how external factors and their environment influence their bidding. If seen through the lens of auction theory, this research essentially breaks down the components of the private and common value signals of the bidders that make up the valuation.

Table 2: Factors for Contractor Bid Behavior

Paper	Decision Type	Factors
Bagies and Fortune (2006) **Literature review**	Bid/No-Bid	Project characteristics (23 factors) Business benefits (3 factors) Client characteristics (8 factors) Contract (10 factors) Project finance (11 factors) Company characteristics/situation (16 factors) Firm's previous experience (4 factors) Bidding situation (7 factors) Economic situation (7 factors) Competition (5 factors)
Shokri-Ghasabeh and Chileshe (2016) **Study Australia**	Bid/No-Bid	Client financial capability (RII = 4.25) Project risk (RII = 4.04) Project future benefits/profitability (RII = 3.97) Number of competitors/bidders (RII = 3.97) Contractor's desire to win (RII = 3.94) Small contractors, the top factor was "client financial capability" (RII = 4.36) Medium contractors, the top factor was "project risk" (RII = 4.17) Large contractors, "client financial capability" and "project risk" were jointly top (RII = 4.40) The study found general agreement in rankings across contractor sizes, with Spearman rank correlations of 0.786 between small-medium, 0.743 between medium-large, and 0.692 between small-large contractors.
Dissanayake et al. (2023) **Study Srilanka**	Bid/No-Bid	Size of the job (RII = 78.8%) Type of the job (RII = 77.3%) Company's strength in the industry (RII = 77.0%) Designer/design quality (RII = 73.1%) Rate of return (RII = 73.1%) Project cash flow (RII = 73.1%)
Li et al. (2021) - Evidential Reasoning Approach	Bid/No-Bid	Rate of returns Revenues Project backlogs Project strategic importance
Ahmed and El-adaway (2024) - Literture Review and Survey	Bid/No-Bid AND Markup	Project-related factors (16 factors) Bidding environment-related factors (8 factors) Economy-related factors (7 factors) Company-related factors (12 factors)
Alsaedi et al. (2019) - Study Saudi Arabia	Bid/No-Bid AND Markup	Size of the job (RII = 78.8%) Type of the job (RII = 77.3%) Company's strength in the industry (RII = 77.0%) Designer/design quality (RII = 73.1%) Rate of return (RII = 73.1%) Project cash flow (RII = 73.1%) Small contractors, the top factor was 'type of the job' (RII = 81.53%) Medium contractors, 'size of the job' and 'rate of return' were jointly top (RII = 82%) Large contractors, "company's strength" was top (RII = 81.94%)
Egemen and Mohamed (2007) - Study Turkey and Norther Cyprus	Bid/No-Bid AND Markup	For bid/no bid decisions, the top 5 factors were: Project size (RII = 0.944) Payment terms (RII = 0.944) Fulfilling tender conditions (RII = 0.915) Current workload (RII = 0.904) Client financial capability (RII = 0.902) For markup decisions, the top 5 factors were: Number of competitors (RII = 0.969) Inflation risk (RII = 0.848) Payment conditions (RII = 0.819)

		Desire of competitors to win (RII = 0.819) Project contribution to firm classification (RII = 0.798) The study found differences between small and medium contractors, with correlations of 0.766 for bid/no bid rankings and 0.831 for markup rankings.
Oo et al. (2023) - Meta analysis	Markup	Competitiveness of other bidders (weighted RII = 0.781) Number of bidders (weighted RII = 0.776) Relationship and past experience with client (weighted RII = 0.768) Experience on similar project (weighted RII = 0.760) Project size (weighted RII = 0.751)
Ye et al. (2014) - Study China	Markup	For public projects, the mean importance scores: Project characteristic: 3.92 Client characteristic: 3.27 Macro condition: 3.59 For private projects, the scores were: Project characteristic: 3.28 Client characteristic: 3.58 Macro condition: 3.64 The study found six common attributes that did not differ significantly between public and private projects, including contract requirements, construction plan, and procurement.

The table above summarizes the key findings from various studies on bid/no-bid and markup decisions. It illustrates the diversity of factors considered by contractors and how their importance can vary across different contexts and studies.

The bid/no-bid decision is the first step in the bidding process, where contractors evaluate whether to pursue a project opportunity or not. From an auction theory perspective, contractors may decide not to bid in several scenarios where expected utility of participating, based on the value signals, is lower than the cost and risks involved. These scenarios can be made up of any combination of the following factors:

- **Low Valuation Relative to Competition**, reducing their likelihood of winning.
- **High Risk Aversion**, risk-averse contractors may avoid projects characterized by high uncertainty or aggressive competition, where the need for bid shading and the risk of financial loss outweigh potential gains.
- **Winner's Curse,** in interdependent or common value settings, the fear of the winner's curse, overestimating the project's value and incurring a loss, may lead to a no-bid decision, especially when reliable information about the project's true value is scarce. This phenomenon is further explained in the following section 3.2.
- **High Participation Costs**, preparing detailed bids or meeting compliance requirements can deter smaller contractors or those with limited resources.

In practice these scenarios can be linked to several factors that consistently emerge as important across studies. Project size is a key factor identified by both Bagies and Fortune (2006) and Egemen and Mohamed (2007). Client financial capability also appears prominently in multiple studies, including Shokri-Ghasabeh and Chileshe (2016) and Egemen and Mohamed (2007). However, the relative importance of these factors varies by region. For instance, while Shokri-Ghasabeh and Chileshe (2016) found client financial capability to be the top factor in Australia, Dissanayake et al. (2023) identified job size as the most critical factor in Sri Lanka.

Once a contractor decides to bid on a project, determining the appropriate markup is a crucial next step. In this step there is a notable consensus on the importance of competition. Oo et al.'s (2023) meta-analysis and Egemen and Mohamed's (2007) study both identify the number of competitors as a top factor. However, there are also significant differences. While Oo et al. (2023) highlight the relationship with the client as a key factor, this doesn't appear in the top factors for Egemen and Mohamed (2007). Instead, they emphasize factors like inflation risk, which isn't prominent in other studies.

Some studies have examined both bid/no-bid and markup decisions together, recognizing that these decisions are interconnected and both closely tied to the value signals and valuation of the contractor. Oo et al. (2023) compared their findings on markup size factors with a previous study on bid/no bid decision factors and found that project size, experience on similar projects, current workload, and availability of other projects were common top factors for both bid/no-bid and markup decisions. This suggests a strong interrelation between these two decision processes. However, Egemen and Mohamed (2007) found that while project size was crucial for bid/no-bid decisions, it didn't appear in the top factors for markup decisions in their study.

The influence of contractor size on bidding behavior is also subject in multiple studies, but with varying results. Shokri-Ghasabeh and Chileshe (2016) found differences in factor importance between contractor sizes in Australia. For small contractors, client financial capability was the top factor, while medium contractors emphasized project risk and large contractors also included client finical capability. Egemen and Mohamed (2007) also observed differences observed differences in decision factors, while Alsaedi et al. (2019) provided more specific insights in the context of Saudi Arabia. They found that small contractors prioritize job type (RII = 81.53%), medium contractors focus on job size and rate of return (both with RII = 82%), while large contractors emphasize company strength (RII = 81.94%).

The findings show that contractor factors for behavior are neither completely different nor exactly the same. Oo et al. (2010) provided further insight into this argument of homogeneity or heterogeneity, more often revered to as asymmetry, by modeling individual contractors' markup behaviors. Their study of Hong Kong and Singapore contractors revealed significant variations in markup preferences and responses to project factors. For Hong Kong contractors, the average markup decreased from about 12% to 7.5% as the number of bidders increased from 4 to 30. Singapore contractors showed even greater sensitivity, with markups decreasing from about 15% to 7.5% under the same conditions. Despite these variations, Oo et al. (2012) found significant correlations in bidding competitiveness ratios across contractor sizes in Hong Kong. Their study revealed correlations of 0.786 between small-medium, 0.743 between medium-large, and 0.692 between small-large contractors. This suggests a complex relationship between firm size and bidding behavior, with both differences and similarities across size categories.

Both market and internal factors play a role in shaping contractor bid behavior. Soo & Oo (2014) conducted an experiment to examine how market factors like construction demand affects bid markup decisions. They found that bidders behaved differently when subjected to varying levels of construction demand. In a "booming" scenario with an increasing number of projects, the average markup was higher (12.68%) compared to a "recession" scenario with decreasing projects (9.29%).
Hartono & Yap (2011) provided insights into the role of internal factors like risk preferences in bidding behavior. Their experiment with 172 experienced construction industry professionals in Singapore revealed that bidders who viewed their companies' past performance as below aspirations tended to engage in more risk-seeking behavior by providing lower bid markups. Conversely, those above aspirations were more risk-averse with higher markups.
Liu et al. (2018) further expanded on this, conducting an experiment with 172 construction professionals to examine how risk preferences impact bid markups. They found that risk preference had a significantly positive effect on bid markups, with more risk-averse bidders tending to have higher markups. Their study also showed that the average markup decreased from 10.22% with 4 bidders to 7.76% with 8 bidders, and 8.75% with an unknown number of bidders. Both Hartono & Yap (2011) and Liu et al. (2018) identified distinct groups of bidders based on their risk preferences and bidding behaviors. Hartono & Yap found that when projects were seen as having high strategic importance, bidders tended to bid more aggressively with lower markups regardless of other factors. Liu et al. identified one group of 16 bidders who consistently bid aggressively with low markups on projects deemed strategically important, and another group of 4 bidders with markups significantly higher than average, even during recession conditions.

Market behavior and Patterns

This review of construction procurement, contractor selection, and bidding behavior literature reveals a complex, interconnected landscape where various elements of the procurement process significantly influence each other. The trend towards multi-criteria evaluation methods (Waara & Bröchner, 2006) represents an attempt to address traditional selection approach limitations such as time overruns, quality and sustainability issues (Olaniran, 2015; Konno, 2018),and opportunistic bid behavior. Lo et al. (2007) and Yan et al. (2007) associated with fostering adversarial relationships and strictness of the owner's project management was found to significantly influence this behavior. New multi-criteria evaluation methods, however, introduce new complexities into the bidding process, requiring contractors to navigate a more nuanced landscape. This evolution in selection criteria may influence contractor bidding behavior. Ahmed and El-adaway's (2024) identifies "bid financial evaluation method," "prequalification requirements," and "type of procurement methods" all as influencing factors. Knowing how contractors and the market will react is difficult as the literature reveals both homogeneity and heterogeneity in contractor bidding behavior and suggests that while broad factors influencing bidding decisions may be similar, their relative importance and specific strategies employed can vary based on contractor characteristics and market position. The review highlights potential unintended consequences of procurement practices. Sheamar et al. (2023) raised concerns about the fairness of risk-sharing arrangements for smaller subcontractors in new procurement models, suggesting that attempts to improve the procurement process can create new challenges for certain market segments.

The literature review revealed multiple trends and practices. However, not all of them are patterns that can be tested within the scope of this research. Still, several consistent patterns across multiple studies were found that are relevant for POM in this research context.

- First, the impact of competition on bidding, with studies by Oo et al. (2010) and Liu et al. (2018) showing that bid markups tend to decrease as the number of competitors increases, for instance dropping from 12-15% with 4 competitors to around 7.5% with 30 competitors.
- Second, Liu et al. (2018) also demonstrated a clear relationship between risk attitude and markup, with more risk-averse bidders typically including higher markups in their bids.
- Third, Khoso et al. (2021) highlighted an economic selection bias, where purely economic selection methods can disadvantage innovative practices and novel technologies, potentially impacting the adoption of sustainable or advanced construction methods.
- Lastly, several studies, including Alsaedi et al. (2019), Egemen and Mohamed (2007), and Shokri-Ghasabeh and Chileshe (2016), found that contractor size significantly influences bid decision factors, with large contractors often prioritizing different factors compared to small and medium-sized contractors when making bidding decisions. These patterns provide a solid foundation for developing and validating the model.

Decision and System Dynamics models

In this section the other two big categories of construction procurement related models are explored. Firstly, contractor decision models focus on individual firm-level choices, such as bid/no-bid decisions and markup determination. For example, Bagies and Fortune (2006) developed a bid/no-bid decision model using parametric solutions, while Cheng et al. (2011) proposed a multicriteria prospect model for both bid/no-bid and markup decisions. Ahmad and Minkarah (1987), Optimum mark-up for bidding: a preference-uncertainty trade off approach. These models often employ techniques like utility theory, neural networks, or fuzzy logic to capture the complexity of decision-making under uncertainty. Contractor ecosystem models or system dynamics models, on the other hand, aim to simulate broader competitive dynamics. Yan (2015) developed a system dynamics model to analyze project-based market competition under different awarding systems, evaluating factors like opportunistic bidding behavior and beyond-contractual rewards. This approach allows for policy experiments through scenario analysis. Dual approaches attempt to bridge individual and market-level dynamics. Mohamed et al. (2022) proposed a mixed qualitative-quantitative approach combining rule-based and fuzzy expert systems to support bid/no-bid decisions while considering market factors. ABM also has the capacity to bridge these two scales by simulating emerging market behavior.

Auction models and ABM in construction

ABM is gaining popularity in construction management research. Liu et al.'s (2024) literature review attributed this increase in studies to it being well-suited due to its ability to simulate complex systems with multiple stakeholders, objectives, and uncertainties. ABM has been applied to various research areas, primarily focusing on safety performance improvement, duration optimization, cost reduction, quality control, risk management, and coordination of multi-party relationships. ABM has also been applied to auctions and the bidding environment in construction. Models have been developed to simulate the behavior of bidders, the impact of different bidding strategies on project outcomes, and the dynamics of the bidding market. The papers relevant to this research are further analyzed in the following.

The number of studies of contractor bidding using agent-based models reflects Liu et al.'s (2024) recorded rise in popularity of the methodology. The following table summarizes the body of work.

Table 3: Summary of Agent-Based Models of Construction Building

Paper	Agent Types	Behaviors	Bid Selection	Research Goal
Awwad et al. (2014)	Contractors, Projects, Owners	Markup (Profit utility theory based on Friedman model) Bid/No Bid, Risk attitude	Lowest Bid	Develop a virtual bidding lab to study impact of risk attitude, project complexity, and market competition on bidding
Asgari et al. (2015)	Contractors, Projects	Markup (multi attribute bidding model), Bid/No Bid, Risk attitude	Lowest bid	Determine optimal risk attitude for contractors to improve financial performance considering competition, risk and need for work
Asgari and Kandil (2016)	Contractors, Projects	Markup (Profit utility theory based on Friedman model)	Lowest bid	Determine optimal risk attitude for contractors to improve long-term financial performance
Ahmed et al. (2016)	Contractors, Projects	Markup (game theory, selective risk neutral Nash equilibrium (SRNNE))	Lowest bid	Analyze winner's curse in single-stage and multi-stage bidding using game theory
Asgari and Shaafat (2016)	Contractors, Projects	Markup (Quantitative models: Friedman, Gates, Fine models)	Lowest bid	Compare effectiveness of different quantitative bidding methods in competitive environments
Farshchian et al. (2017)	Owners, Projects	Budget allocation, Project progress	Lowest bid, multi-attribute	Optimize budget allocation in portfolio of projects considering uncertainties
Farshchian and Heravi (2018)	Owners, Projects	Budget allocation, Cost and time uncertainties, Inflation	Not specified	Probabilistic assessment of cost, time, and revenue in portfolio of projects
Awwad and Ammoury (2019)	Contractors, Owners, Projects	Markup (Profit utility theory based on Friedman model), Bid/No Bid, Bid selection method adoption	Lowest, average, below-average, truncated bids	Study evolution of bid prices under various price-driven bid selection methods from owner's perspective
Elsayegh et al. (2020)	Contractors, Owners, Projects	Markup (model not stated), Learning	Lowest bid	Study competitive construction bidding and the winner's curse
Idrees et al. (2023)	Contractors, Owners, Projects	Markup (exponential weight algorithm	Lowest Qualified Bidder (LQB),	Model impact of changing bid selection method from LQB to

		according to Assad et. al. (2021)), Bid selection method adoption	Below-Average Bidder (BAB)	BAB on market equilibrium and adoption rate

The literature reveals several key themes in agent-based modeling of construction bidding. Most studies model contractors as the primary agents, with many also including owners (Awwad et al., 2015; Farshchian et al., 2017; Awwad and Ammoury, 2019; Idrees et al., 2023) and some incorporating government entities (Elsayegh et al., 2020). Projects are often modeled as passive agents or environmental elements (Farshchian et al., 2017; Idrees et al., 2023). The main behavior modeled for contractors is the markup decision, which is influenced by various factors. The theory basis on which most of these models function is economic utility theory. In which, of the various factors that can influence a markup decision the risk attitude is the key consideration, with some models categorizing it as mild, moderate, or extreme (Asgari et al., 2016) and most other studies being equally vague on the specifics. Need for work is another important factor (Asgari et al., 2016), as is project complexity or risk level (Asgari et al., 2014; Asgari et al., 2016). Some studies also attempt to model the bid/no bid decision (Awwad et al., 2015).

Contractor learning and adaptation are modeled in several studies (Elsayegh et al., 2020; Idrees et al., 2023), with contractors updating their strategies based on past experiences and market conditions. Financial considerations, including the contractor's financial capability and the owner's budget constraints, are explicitly modeled in some studies (Farshchian et al., 2017).

While most models use the lowest bid selection method, some compare multiple methods, including average bidding (Awwad and Ammoury, 2019) and below-average bidding (Idrees et al., 2023). The transition between different bid selection methods and its impact on market equilibrium is a focus of recent research (Idrees et al., 2023).

The research goals vary widely from developing virtual laboratories (Awwad et al., 2015) to studying specific phenomena like the winner's curse (Ahmed et al., 2016; Elsayegh et al., 2020) and optimizing budget allocation (Farshchian et al., 2017). Some studies employ game theory to analyze strategic interactions between contractors and owners (Ahmed et al., 2016; Awwad and Ammoury, 2019).Recent work has also considered the impact of external factors on the bidding process, such as government regulations (Elsayegh et al., 2020), project delays, cost overruns, and inflation (Farshchian and Heravi, 2018). These factors add complexity to the models and help to better represent real-world conditions.

Overall, the literature shows a trend towards increasingly complex and realistic models that incorporate a wide range of factors affecting the construction bidding process. These models provide valuable insights into contractor behavior, market dynamics, and the potential impacts of different bidding policies and strategies.

3.2 MODEL 1

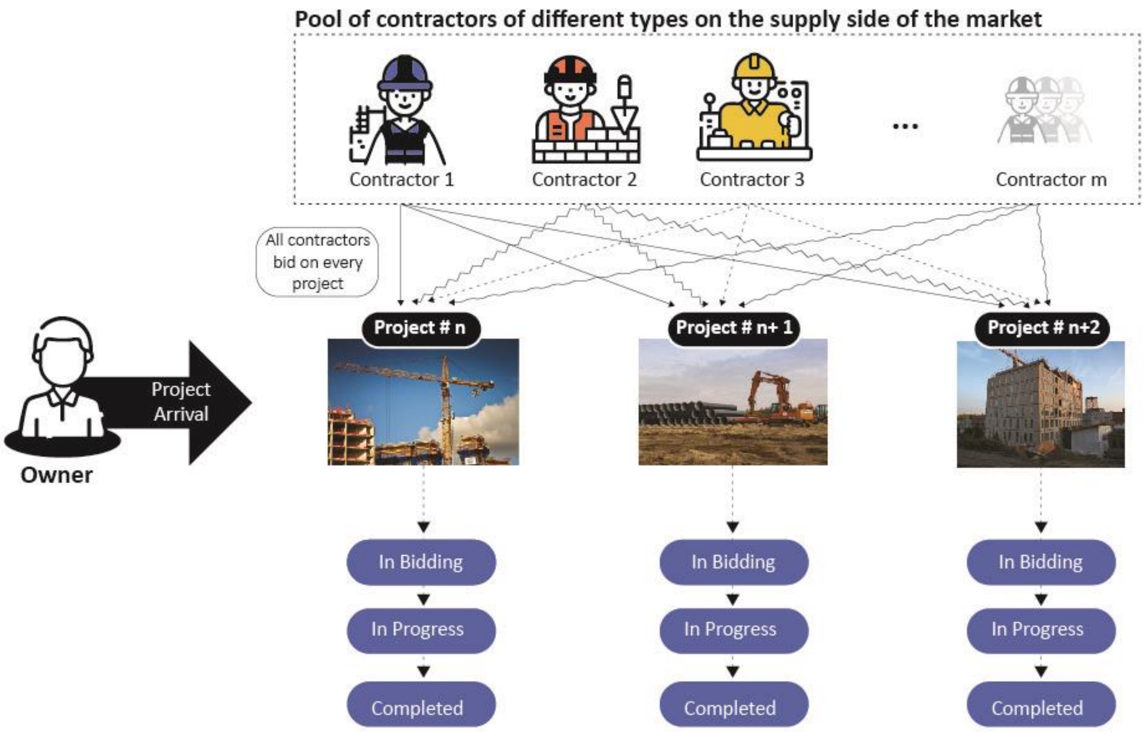


Figure 7: Conceptual Depiction of Model version 1

This model is primarily based on decision analysis and utility theory concepts applied to construction bidding. It draws from several key studies in the construction bidding literature, particularly Friedman's (1956) probabilistic bidding model and subsequent work on incorporating risk attitudes into bidding decisions. This, in combination with Campo's (2012) study forms the basis of this model's common and private value signal logic which is then used in combination with utility theory to create the agent bidding logic. Similar utility theory bidding models have been built in the studies of Awwad et al. (2014) and Awwad and Ammoury (2019). *Figure 7* describes a conceptual model of how the model works, while *Appendix 2* shows the code structure in implementing it. The model describes a bidding environment where projects with different attributes are created and put up for bidding, a pool of contractors with different attributes can then submit their bids whereafter the winning bid is chosen according to some rule, most commonly, LQB. In this section the processes and functions by which the model works are broken down and the operational definitions and key variables are elaborated.

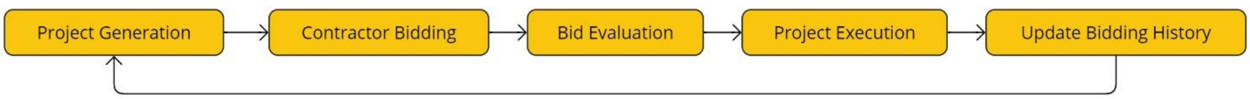


Figure 7: Overall model flow

The model works by simulating the bidding process for multiple contractors competing on a series of projects. As seen in Figure 7, this process is repeated from which and emergent phenomena is produced, the bids and bid prices. These are considered and used as input by contractors for the next round of bidding. The project generation is relatively simple, where either a distribution of projects with: Cost, complexity and duration is generated or, it can be set to a single value.

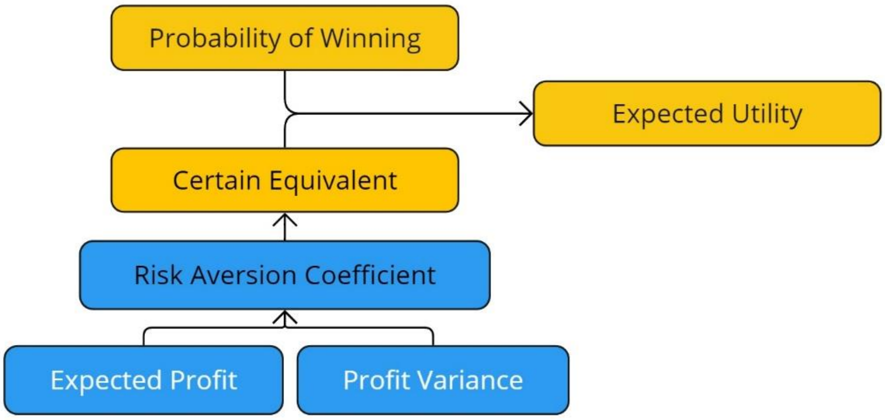


Figure 8: Contractor Bidding Process

The key concept in these auction models is risky bidding. There are two opposing conceptions which constitute this: (1) not winning the contract that is bid on, and (2) winning the contract but earning less profit or potentially incurring a loss.

Table 4: Conceptions of risky bidding

	High Bid Markups	Low Bid Markups
1) Not getting the project	Higher chance (riskier)	Lower chance (less risky)
2) Earning less than aspired to	Lower chance (less risky)	Higher chance (riskier)

The balance for this decision, the markup decision, has a subjective reference point. Some contractors might be willing to bid lower because they are more experienced, or the project is more appealing to them. This balance is influenced by both internal and external factors, collectively represented by the contractor's risk aversion coefficient.
The other two factors, expected profit, calculated from project cost, financial class, estimation accuracy and a given bid markup, and profit variance, calculated from project complexity, are used in the utility function to calculate the contractor's utility for the project.
The probability of winning is estimated by fitting a normal distribution to the competitors' historical bids and calculating the likelihood of submitting the lowest bid.
Each contractor agent possesses a unique risk aversion coefficient and makes decisions that aim to maximize its expected profit utility. The interactions among these key components are illustrated in *Figure 8*. This type of model, based on expected utility, is similarly used in the studies by Awwad et al. (2014) and Awwad and Ammoury (2019), who applied an exponential Constant Absolute Risk Aversion (CARA) utility function. However, empirical findings from Campo's (2021) study on contractor bidding behavior in Los Angeles suggest that observed bidding behaviors are better explained by Constant Relative Risk Aversion (CRRA) utility functions, where risk aversion decreases with increasing contractor experience. Campo (2012) fit a model to bid data that examined financial health and contractor experience as primary sources of bidding asymmetry among contractors, yielding high R-squared values (0.98), indicating minimal unexplained variance. Thus, to base the model on empirical data the contractor CRRA utility function is defined as follows:

$$U(V) = V^{(1-\theta)} \quad (1)$$

Where:
$U(V)$ is the profit utility
V is the profit (value)
$\theta \in [0,1]$ is the (non-normalized) coefficient of relative risk aversion
$(1-\theta)$ is the term describing risk tolerance

The risk tolerance term for contractors is specified by this function as described in Campo (2012) the asymmetry in contractor bidding is here explained by the contractor experience:

(2)

$$\theta = 0.145 + 0.0171 \exp r$$

Where:
$\exp r$ is the experience of a contractor in years.

Table 5: Distributions of contractor firm statistics (Campo 2012)

Variable	Mean	Stdv	Range
Experience	14.50	13.89	0-92
Financial Class	1.70	1.05	1-5

These are the distributions that will be used from here on out in the model to create a representative contractor pool. If simulations require to control these variables they will be set at their mean value.

The function for the second-order Taylor expansion of the certainty equivalent (CE) around the expected value E(V) for risky profit is defined as:

$$CE[V] \approx E[V] - \frac{\theta}{2E[V]} Var[V] \tag{3}$$

Where:
$CE[V]$ is the certainty equivalent or (uncertain) profit value
$Var[V]$ is the variance of profit
$E[V]$ is the expected profit (value)

The $E[V]$ is calculated not only by the markup, meaning the difference between the submitted bid value and the owner appraisal value, but also by the contractor actual cost. In auction theory terms this is the value signal.

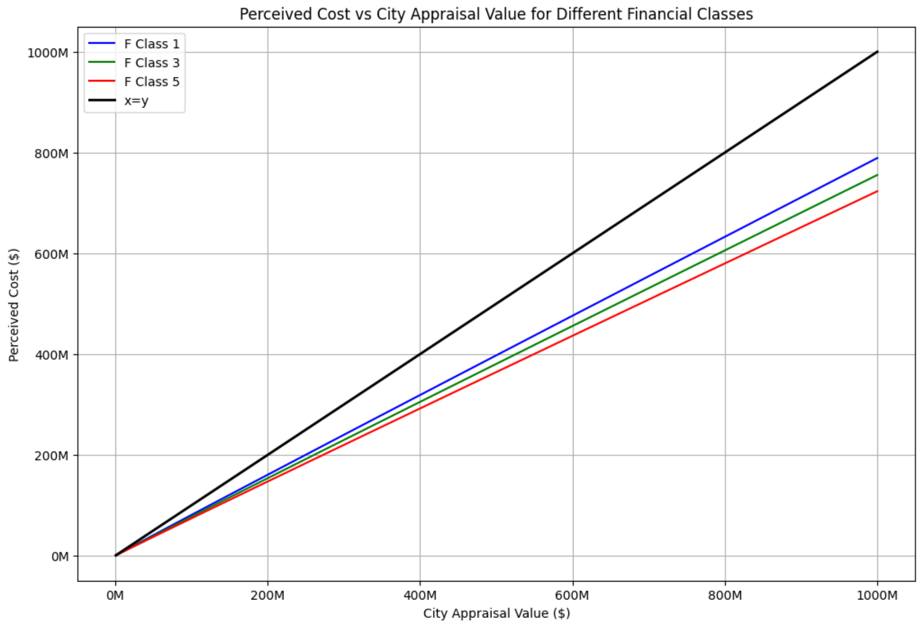


Figure 9: Bid spread and cost estimation based on Campo 2012)

In practice, it is often the case that contractors' actual costs lie slightly below what the owner's side appraises, as they tend to find or have efficiencies in place to reduce prices. The owner side sends a common value signal which the contractors have affiliated values for, in addition to that there is errors and noise. This is why the bid spread is observed to be normally distributed around values lower than the appraisal value. This model as opposed to previous models an interdependent value auction which is much close to what is seen in practice. *Figure 9*, depicts the bidder valuation functions, based on the mean bid empirical data from Campo (2012), this follows a bid spread that is a function of the contractor's financial class. Financial class is defined as a measure of a firm's financial health, ranging from 1 to 5, where a firm with the best financial class has a 0.6% chance of discontinuing operations with loss to creditors, whereas a firm in the worst class has a 15.71% chance. This classification affects firms' cost distribution and bidding behavior, with more financially constrained firms often bidding less competitively due to higher associated production costs and is dictated by this function:

$$\mu_i = 0.0129 + 0.989 \log(am) - 0.0218 * fclass \tag{4}$$

Where:
am is the appraisal value in millions
$fclass$ is the financial class the contractor

The expected utility of a bid as applied in the model is defined by the following function:

$$E[U(V)|x, n] = P[Win|x, n] \times U[CE(V)] \tag{5}$$

$$E[U(V)|x, n] = P[Win|x, n] \times (estimated\ profit - \frac{\theta}{2(estimated\ profit)}(profit\ variance))^{(1-\theta)})$$

Where:
$P[Win|x, n]$ is the probability of winning a bid based on the Friedman method
x is the number of opponents in a bid
n is the markup

To calculate the probability of winning an approximation method was used that is based on Friedmans (1956) probabilistic bidding model.
It is assumed that each opponents markup follows a normal distribution fit to their mark up history of past projects. For each bidder i, where $i \in \{1, 2, \ldots, x\}$.
The probability of a given bid being lower than opponent i's markup is given by:

$$P_i(x) = 1 - \varphi(\frac{x - \mu_i}{\sigma_i}) \tag{6}$$

Where:
φ is the CDF of the normal distribution.
x is the given markup.
μ_i is the mean σ_i is the mean and standard deviation of the markup of each opponent.

The probability of a given bid being the lowest is therefore given by:

$$P_{lowest} = \prod_{i=1}^{n} P_i(x) \tag{7}$$

The approximation of probability of being the i^{th} ranked bidder is given by:

$$P_{i-th\ lowest} = \prod_{i=1}^{i-1} P_{(j)}(x) \times \prod_{k=i}^{n} (1 - P_{(k)}(x)) \tag{8}$$

Where:
The probabilities $P_{(i)}$ are ordered in ascending order.

With this logic multiple price-based awarding systems can be simulated, not only lowest bidder, but also second lowest bidder and below average bidder or even i^{th} lowest bidder. These methods have seen use in parts of the world as discussed in the literature review.
Further model assumptions for this part are that contractors start their first bid at a markup of 1.1, a markup that is considered typical in the industry and a standard deviation of their bid history of 0.005, which is relatively small, this will ensure that the starting point of all simulations is the same.

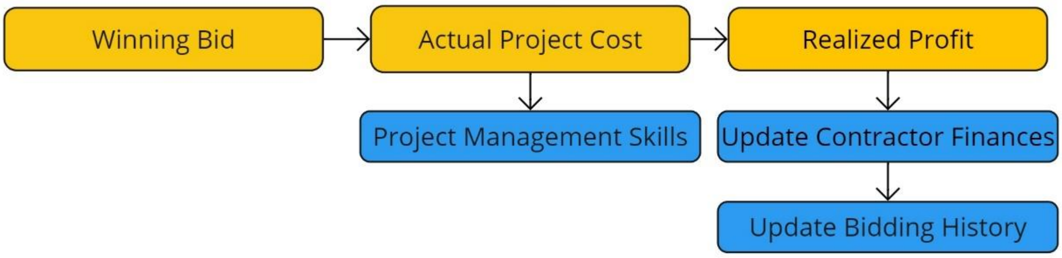


Figure 10: Project Execution and Update

Finally in the last step the winning bid is saved. The contractor executes the winning bid and gets profit which taken from a gumball distribution depending on the project management skill factor. The bidding information that was just generated is saved and will be used in the next round of bidding.

3.3 VERIFICATION AND VALIDATION EXPERIMENTS

Verification

To verify the model and ensure it is working as intended the model integrity is tested by comparing replicability to the results of the existing models of Awwad et al. (2014). Even though the underlying utility functions are different, basic functions were still comparable. In *Appendix 3-6* the results of the study are reproduced, and model behavior corresponds with what is expected for bidders with different risk aversion $\theta \epsilon \{0.1 - 3\}$ that are bidding on the project with the same attributes for 260 steps of the model.

Validation

To further validate the model, the patterns found in the literature review and laid out in the section 'Market Behaviors and Patterns', were developed into experiments as shown in *Table 6* below.

Table 6: Tuning and Validation Patterns and Experiments

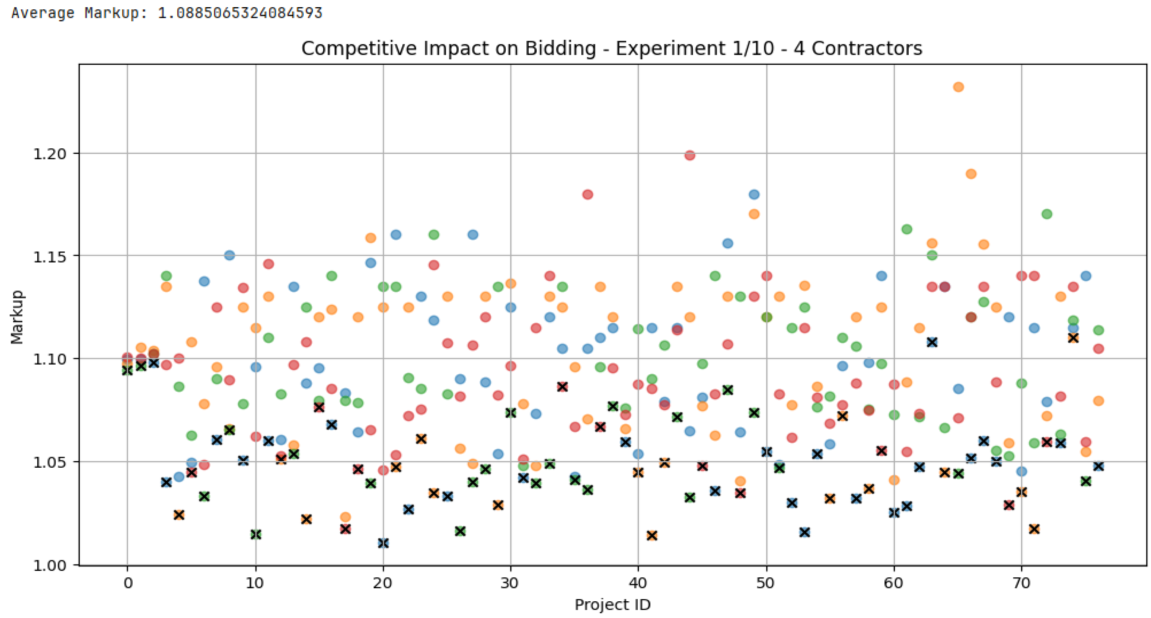
Patterns	Num. Of Bidder	Risk Aversion	Selection Criteria
1) Competition Impact on Bidding Bids decrease as the number of competitors increases (15-12% markup with 4 competitors vs. 7.5% with 30) (20% for 4 and 10% for 8) *(Oo et al., 2010; Liu et al., 2018)*	4-30	Medium	Lowest bid
2) Risk Attitude and Markup Risk-averse bidders tend to include higher markups in their bids *(Liu et al., 2018)*	3	Low Medium High	Lowest bid
3) Contractor size influences bid decision factors Large contractors prioritize different factors compared to small and medium-sized contractors *(Alsaedi et al., 2019; Egemen and Mohamed 2007; Shokri-Ghasabeh and Chileshe, 2016)*	Sensitivity analysis on environmental and internal factors that affect Bid/No-Bid and Markup Features from this model were:(Project size, Risk, Selection criteria, Contractor Size= (Net worth and financial status,)		

1) Competitive Impact on Bidding

The impact of the number of bidders on bidding prices has been observed and recorded in practice in multiple studies, a lower markup usually corresponds with a higher number of bidders and Vica versa. In the model logic the number of bidders is a key input variable in the win probability calculation *(equation 7)* and a higher number of opponents should decrease the probability of winning given a certain markup promoting the contractor agents to bid lower.

This is tested using two model experiments, in the first experiment 4 contractors are bidding for the same project 80 times, each time updating their optimal markups based on how the past bids went.

In the second experiment the same thing is done but with 30 contractors bidding for the same project. Both experiment simulations are run with the same parameters *(Table 5 and 6)*, but different numbers of bidders, they are run 10 times, and the average markup from all projects is calculated and compared.



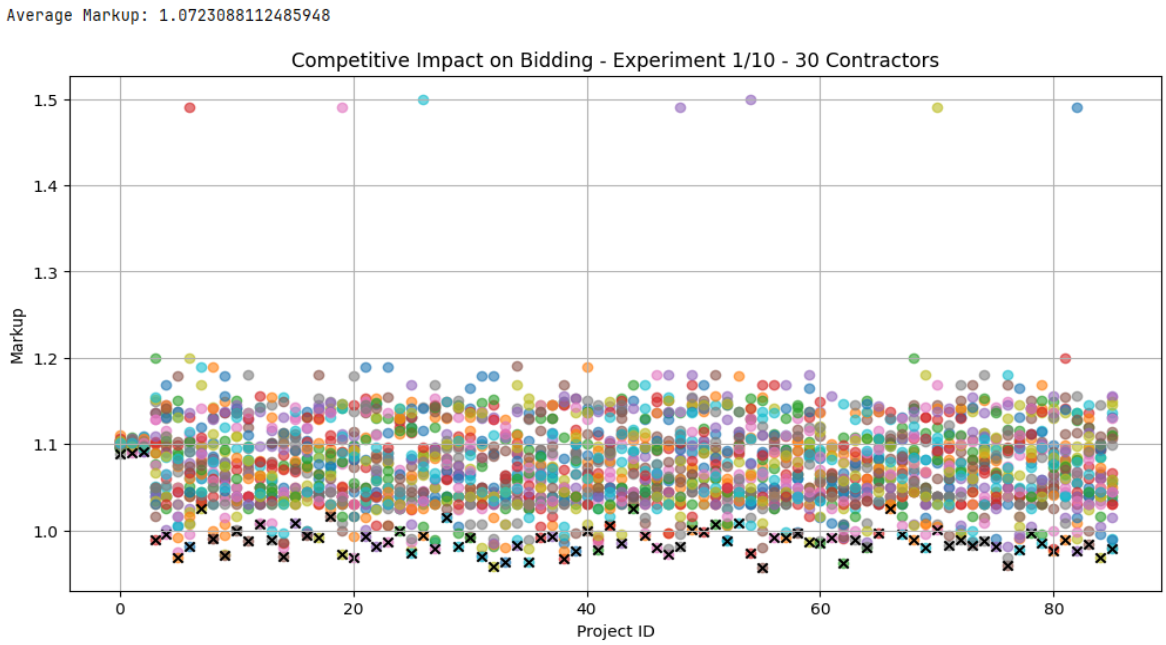


Figure 11 & 12: Experiment: Mark up distribution among 4 and 30 bidders

Seen in *Figure 11 and 12* is the bid distribution of both of the first experiment runs, of both model configurations, first with 4 competing contractors and below with 30. The difference in markup is about 0.016 or 1.6% which is not as high as reported in the studies where it is 6% or 10%(Oo et al., 2010; Liu et al., 2018), but it is still significant. The difference between the model results and the pattern from the literature review can probably be traced back to endogeneity bias. The studies are not studies that researched this effect in in isolation and therefore can give no reliable data on the isolated effect of the competition. It is likely that other factors such as project strategic importance and desirability played a much larger role in the contractor markups as well as the number of bidders. This and the number of other non-economic factors that are not captured or within the scope of this model, can explain this variation. The pattern of the model over all does match what is commonly observed among contractors in the real world and is therefore on the correct path for alignment.

The bid distribution in the lower experiment also has some noticeable outlier bids that submit the highest possible bids for the model, a markup of 1.5, these were filtered out of the average markup calculation. This is because these outliers are signals that the contractor does not want to win the bid.

This happens when, as seen in *equation 5*, the expected utility of a bid grows as the markup increases. This happens under two conditions, when the expected utility of the profit is negative or when the two opposing risk conception's (*Table 4*) and terms within the model, the probability of winning and the expected utility of the profit flip and become dominated by the side of the expected utility. This means considering a markup going from 1.0 to 1.5 the rate of growth for the expected utility is larger than the rate of decay for the probability of winning and even though the expected utility could be positive the contractor will submit a competitive bid anymore and signal a withdrawal from the bid this way. This is an important occurrence in the model that will be seen in subsequent experiments as well.

2) Risk attitude and Markup

The risk attitude on markup is much more studied and also studied in isolation Liu et al. (2018) have observed contractors tend to have a some consistent level of risk aversion across similar bids which affects the markup decision in auctions, more specifically in first price sealed bid auctions, risk averse bidders tend to bid higher than risk tolerant bidders. In the logic of the bidding model the risk aversion is a key variable in the calculation of the certainty equivalent or the (uncertain) profit value for a bidder. The model is set up to run an experiment where contractors with a low, medium and high-risk aversion bid on the same project 36 times the risk aversion is a function of the contractor experience, so the contractors have an experience of 30, 5 and 2 years respectively. Otherwise, the same parameters are used, and the simulation is run 10 times, the average of each contractors' bid across the 10 experiments are taken and plotted.

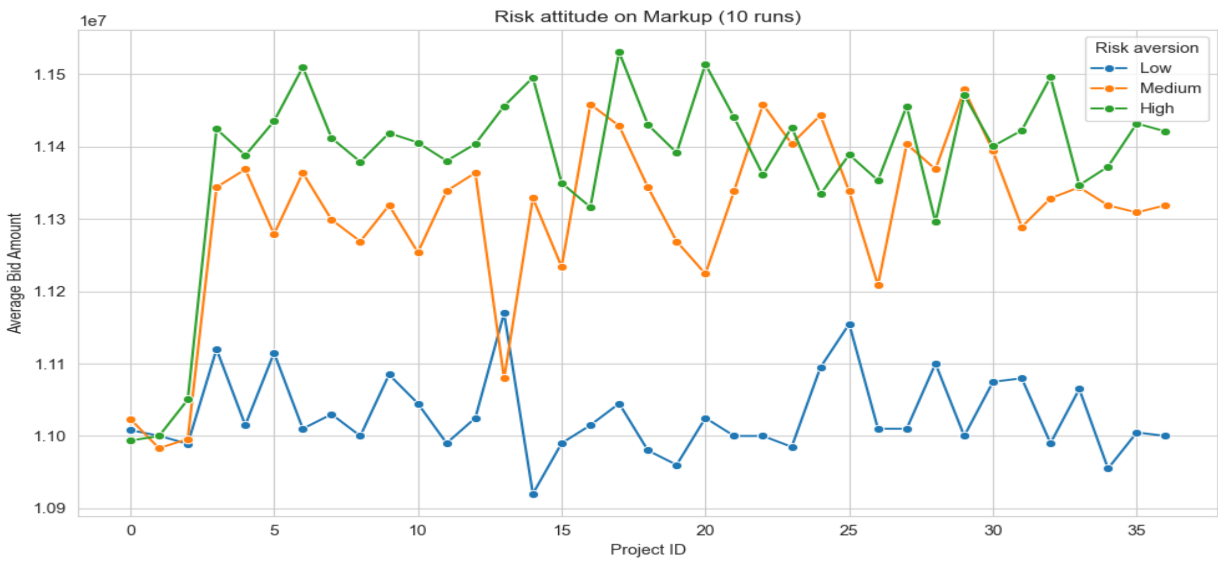


Figure 13: Average bid distribution of 3 contractors with different risk aversion

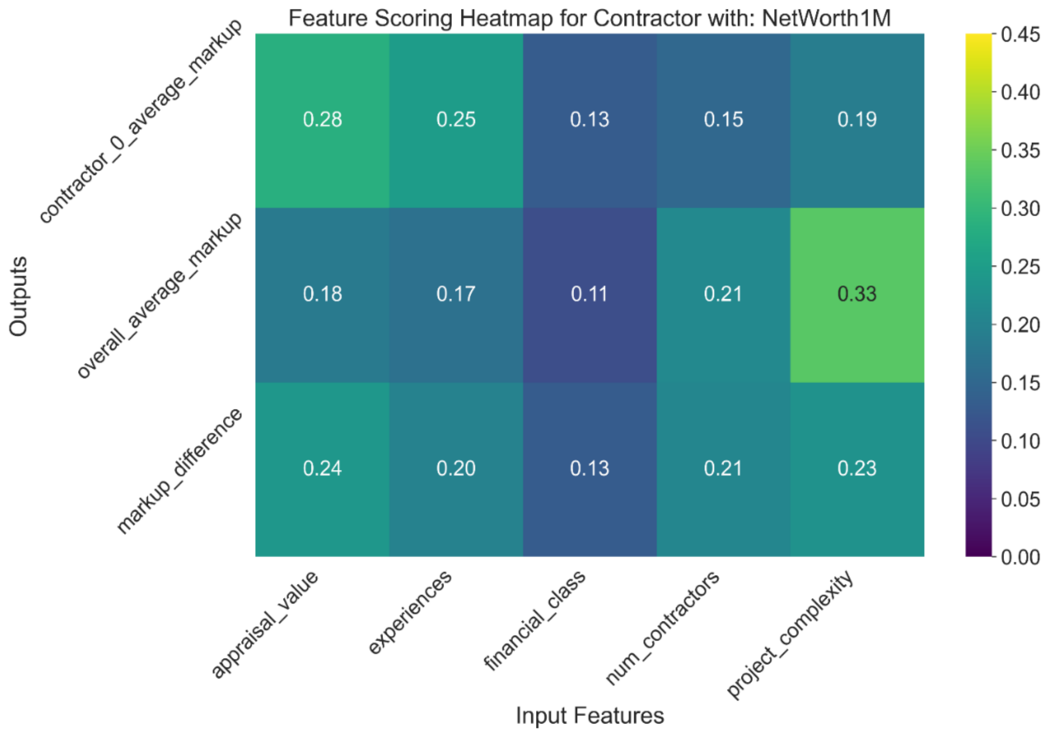
In *Figure 13* shows the clear separation of markup level for the different risk aversion level in contractors risk averse contractors tend to bid higher while risk averse contactors bid lower, in the model the magnitude of this behavior is also dependent on the profit variance as seen in *equation 3* in this model this is variable is called project complexity and is set at 0.2 for this case. The model behavior again follows the pattern observed in practice.

3) Contractor Size influences bid decision factors

This feature scoring and sensitivity analysis was conducted to validate the contractor bidding model using pattern-oriented modeling, examining how various factors influence bid decisions for contractors of different sizes.

Literature, suggests that contractor size impacts bidding priorities, with larger contractors emphasizing different considerations than smaller and medium-sized firms (Alsaedi et al., 2019; Egemen and Mohamed, 2007; Shokri-Ghasabeh and Chileshe, 2016). This analysis empirically tested these assumptions within the model, identifying patterns in factor prioritization linked to contractor size.

To achieve this, a representative pool of contractors was simulated over 1,000 model runs. Contractor 0 was assigned different net worth levels—1M, 50M, and 100M—to assess how contractor wealth alters sensitivity to bidding factors such as financial class, experience, project complexity, and appraisal value. This was measured by Contractor 0's average markup, the overall average markup of all contractors, and the markup difference between the two understand the bidding patterns of the different wealth levels.



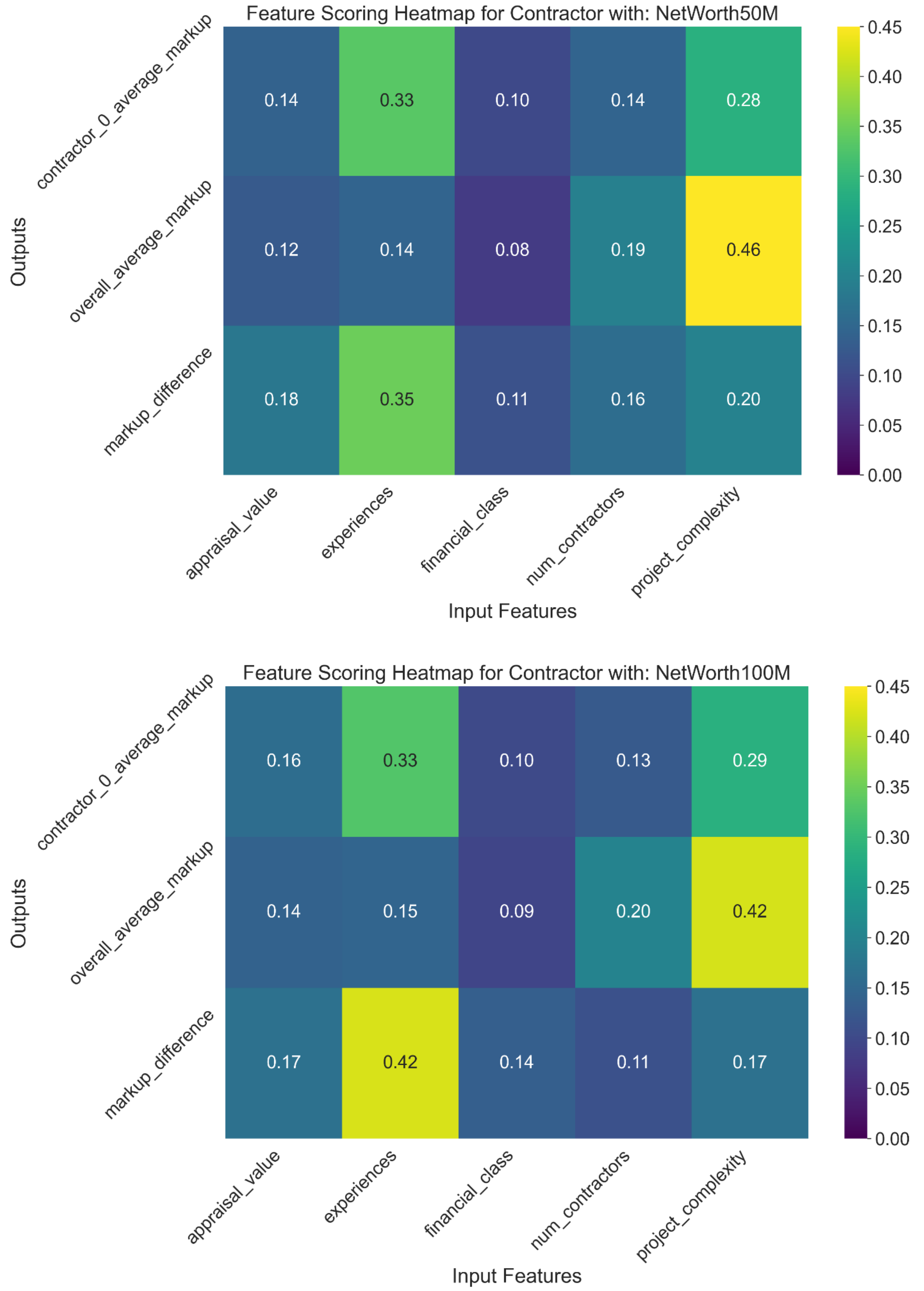


Figure 14-16: Feature scoring sensitivity analysis for contractor with Net-worths of 1M, 50M, 100M

Figures 14 to 16 illustrate that the overall average markup remains consistent across all instances, serving as a reliable control variable. Notably, a significant difference in feature importance can be observed between the smallest contractor and the others. For the smallest contractor, all features are rated more evenly, with project appraisal value becoming much more influential in their bid markup decisions. This contractor tends to deprioritize experience and project complexity, which are weighted more heavily by larger contractors.

In this model, the relative difference between contractor net worth and project appraisal value mainly affects the risk aversion coefficient, simplifying these broader, real-world dynamics. For larger contractors, their higher net worth relative to project values results in lower risk aversion, enabling them to pursue more complex projects. In contrast, smaller contractors exhibit higher risk aversion and focus more on minimizing immediate financial risks. While this aligns with patterns found in the literature (Alsaedi et al., 2019; Egemen and Mohamed, 2007; Shokri-Ghasabeh and Chileshe, 2016), it also highlights the model's limitations in capturing all factors influencing contractor decisions. Conversely a study by Budi Hartono (2010) indicates that contractor size is a factor so dominant that is significantly affects all other considerations, which is not fully reflected in this experiment's results. While the effect of contractor size was measurable, it was not substantial.

Moving forward, contractor size will be de-emphasized in this analysis, with financial class serving as the primary financial indicator. Focusing on contractor size relative to project values introduces complexities that could overshadow other insights. The relationship between contractor size and financial decision-making involves additional considerations such as time value of money, financial strategies (e.g., debt-to-equity ratios), and cash flow management, which collectively shape contractor behavior. Including these interdependencies could lead to endogeneity issues, complicating the isolation of individual factor influences. By focusing on financial class, the model can control contractor size while maintaining clarity in the analysis and grounding it in empirical data from Campo's (2012) study.

4. INTEGRATING AND MODELLING ENVIRONMENTAL SUSTAINABILITY

4.1 LITERATURE REVIEW

4.2 MODEL

4.3 VERIFICATION AND VALIDATION EXPERIMENTS

4.4 EXPERIMENT RESULTS

4. SUB QUESTION 2

How can existing ABM be adapted or extended to incorporate sustainability criteria?

4.1 LITERATURE REVIEW

Overview

Building upon the overview of procurement in the construction, the review now focuses on the intersection of this topic and sustainability. The significant research interest in this topic is reflected in a very comprehensive body of academic literature and industry reports. The volume of research in this field presents both opportunities and challenges for this review.

To navigate this, this review prioritizes comprehensive reviews, aiming to provide a broad understanding of the research. While studies focusing on specific locations or specialized topics are included, they are not the primary focus. This approach allows for the identification of overarching trends and patterns in sustainable construction procurement.

This section focuses on the policies, practices, and trends surrounding sustainable construction procurement. While topics such as procurement methods and systems were covered in the previous section and are found in the literature, this section focuses on contractor selection and evaluation and bidding behavior. This allows for a more focused exploration of sustainability principles in the bidding context of procurement.

Through the literature review, five research areas became apparent. Firstly, research on sustainability criteria and assessment methods investigates how sustainability is measured and evaluated in procurement decisions. Secondly, studies on the sustainability cost premium examine the economic implications of sustainable construction, bridging environmental goals and financeability. Thirdly, studies on public procurement practices explore the integration of sustainability principles in government projects. Lastly, research on contractor behavior examines responses to sustainability measures, offering a view of industry adaptation.

Sustainability Criteria: Measuring impact and integration into procurement

This part of the review examines research on sustainability frameworks, evaluation and criteria in construction, focusing on environmental aspects and how these are integrated into auctions and contractor selection and evaluation. While social and economic criteria are important components of overall sustainability in construction, they are beyond the scope of this review.

Sustainability in construction procurement is evaluated using a diverse range of frameworks and policies that vary in both methodology and implementation. These frameworks aim to assess environmental impacts and guide sustainable practices, often serving as proxies for measuring or setting sustainability goals in construction projects (Kjerulf and Haugbølle, 2021; Zhao et al., 2022; Lima et al., 2021; Desivyana and Farmakis, 2022; Geach, 2016). While frameworks like BREEAM, LEED, and Life Cycle Assessment (LCA) provide widely recognized approaches to evaluating sustainability, their application is not without challenges. These frameworks are not very straightforward, their complexity stems from the difficulty of measuring sustainability, which often leads to trade-offs between criteria, making it challenging to compare environmental aspects across projects (Desivyana and Farmakis, 2022; Zhao et al., 2022).

The challenges of sustainability evaluation are twofold: first, the complexity of the frameworks themselves, and second, the difficulty of integrating these frameworks into procurement processes. In the following, we distinguish between these aspects, with frameworks providing measurement tools and implementation methods integrating these into tendering decisions. However, in practice, these are closely connected, as the effectiveness of frameworks often depends on how seamlessly they are embedded into procurement practices.

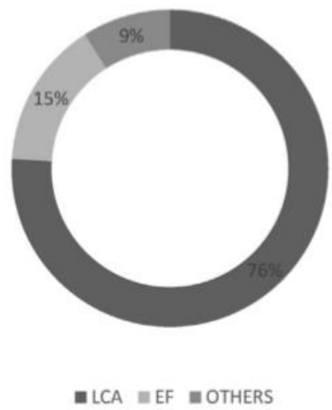


Figure 17: from Lima et al. (2021), Main environmental methodologies found in papers

The construction industry has developed many sustainability frameworks, eco-labels, and evaluation methods to measure environmental impacts. Prominent examples include certification systems such as LEED, BREEAM, DGNB, and Passivhaus, alongside lifecycle-based methodologies like Life Cycle Assessment (LCA) and Environmental Footprint (EF). While the wide range of frameworks might seem fragmented, Lima et al. (2021) identify that these systems can be broadly grouped into three categories: certification systems, lifecycle-based assessments, and environmental footprint methodologies. These categories provide a clearer understanding of how environmental performance is assessed across different contexts.

1. **Certification Systems**: Frameworks like LEED, BREEAM, and DGNB are commonly used in both public and private sectors to rate projects based on factors like energy efficiency, emissions, materials sourcing, and waste management (Lima et al., 2021). These systems often categorize projects into tiers, such as silver, gold, or platinum ratings, and serve as benchmarks for environmental performance.
2. **Lifecycle-Based Assessments**: LCA remains the most widely adopted method in the public sector, providing a comprehensive analysis of environmental impacts throughout a project's lifecycle (Kjerulf & Haugbølle, 2021). LCA focuses on quantifying resource use, emissions, and waste but faces challenges in data quality and standardization, which affect its accuracy and reliability (Desivyana & Farmakis, 2022).
3. **Environmental Footprint (EF)**: EF quantifies natural resource consumption and carbon emissions across a building's lifecycle, focusing on indicators like land use, water usage, and greenhouse gas emissions, highlighting construction's contribution to ecological challenges (Lima et al., 2021).

While sustainability frameworks provide robust tools for evaluating environmental performance, their practical integration into procurement and tendering processes remains a challenge. Translating framework outputs into actionable criteria for contractor evaluation requires careful consideration of the mechanism by which these criteria influence decision-making. This step is essential for bridging the gap between sustainability assessment and procurement implementation.

In practice, several methodologies have been developed to integrate sustainability frameworks into tendering. These different scoring rules range from baseline requirements and specification to more dynamic scoring mechanisms. Three primary approaches have been found to be used in practice:

1. **Continuous Criteria**: These evaluate sustainability performance using measurable metrics, directly linking environmental impacts to tender evaluations. These systems reward incremental improvements, providing contractors with financial incentives or score adjustments proportional to their sustainability achievements. For example, MKI (Netherlands) calculates the environmental costs of materials and processes using LCA, integrating these results into bid evaluations. Similarly, SNAP (Germany) uses quantifiable metrics like CO_2 emissions and energy efficiency to differentiate contractor proposals, encouraging continuous performance improvements.

2. **Discrete Criteria**: These assess sustainability performance by categorizing projects into predefined levels or tiers. These systems offer clear benchmarks and are widely recognized for their simplicity. The CO_2 Prestatieladder (Netherlands) is an example, ranking contractors on levels (1–5) based on their CO_2 reduction efforts. Similarly, certification frameworks like BREEAM, LEED, and DGNB classify projects into tiers such as silver, gold, or platinum, providing recognizable benchmarks for sustainability performance.
3. **Minimum Criteria**: These establish baseline sustainability requirements that all bidders must meet to be eligible. These criteria ensure compliance but do not necessarily encourage performance beyond the baseline. For instance, the EPBD (EU) mandates nearly zero-energy building standards for energy efficiency, while CALGreen (California) enforces minimum thresholds for water conservation and emissions reduction. Both SNAP and MKI also incorporate minimum requirements in some contexts while allowing room for additional performance-based incentives.

In practice, these methodologies are often used in combination to address the diverse goals of sustainable procurement. For example, Rijkswaterstaat integrates minimum criteria (e.g., mandatory compliance with energy standards) with continuous criteria (e.g., MKI score adjustments based on LCA). Similarly, SNAP blends baseline compliance with flexible scoring mechanisms that reward higher sustainability achievements.

Despite the availability and growing sophistication of sustainability frameworks and their integration into procurement, adoption of sustainability frameworks remains uneven due to barriers like cost premiums, technical knowledge gaps, and inconsistent enforcement (Geach, 2016; Prier et al., 2016). Public sector hesitancy and project variability further complicate standardization (Dhliwayo et al., 2024; Desivyana & Farmakis, 2022). It is possible to analyze these challenges by looking at these sustainability criteria as scoring rules for auctions and analyzing them as allocation mechanisms.

Sustainability Cost

As previously mentioned, one of the barriers of entry for more sustainable construction and building practices is cost. There is however very little consensus on how large sustainability cost premiums can be. Proponents argue that initial cost is small and over the lifecycle of the building cost premiums can even be paid back fully. More importantly cost premiums can be caused by different factors and affect different stakeholders. L.N. Dwaikat et. al's (2016) literature review summarized empirical studies measuring the cost premium of green construction buildings, but a pattern or was not found, because the factor influencing the cost, such as location, project type, quality or degree of sustainability are difficult to measure.

In this review more such papers and more recent papers were found, and the following graph was created to visualize the measured sustainability premium across all papers. Even though a precise pattern is still not discernable a range of the sustainability cost premium can be derived.

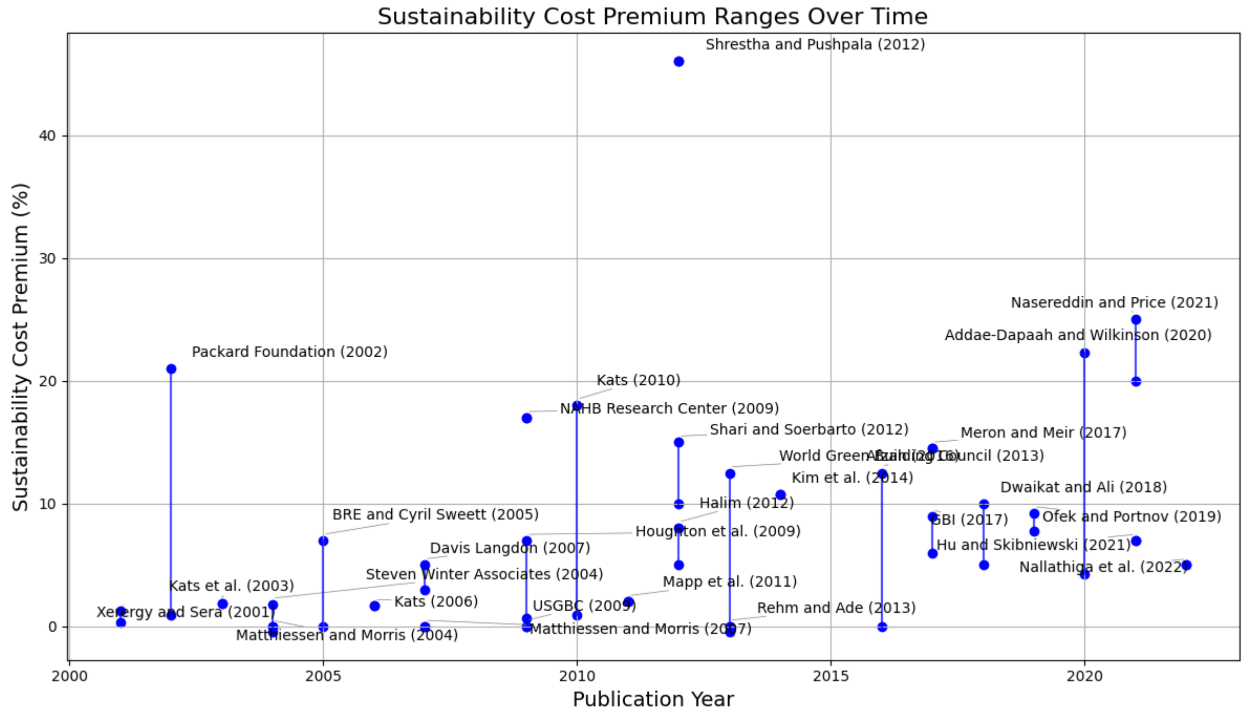


Figure 18: Recorded Sustainability Cost Premium Distribution from Literature

The studies reviewed present a wide range of cost premiums for green buildings, from cost savings to upwards of 40%. The most frequently cited studies are by Kats (2003, 2010), which found that green buildings cost only 1-2% more than conventional buildings. However, these studies have been criticized for potential bias due to their reliance on self-reported data from architects involved in green building projects. Other studies, such as Rehm and Ade (2013), found no statistically significant difference in construction costs between green and conventional office buildings in New Zealand. However, this study only looked at a small sample size of 17 buildings. In contrast, some studies have found that green buildings can cost significantly more than conventional buildings. For example, Shrestha and Pushpala (2012) found that green school buildings in the US cost 46% more than conventional school buildings. However, this study did not specify the level of green certification achieved by the buildings. Overall, the literature suggests that the cost premium for green buildings can vary significantly depending on the location, building type, certification level, and specific green features implemented. A range of cost premium between 2% to 25% can be established with a potential maximum of 46% can be established. All of these findings need to be considered critically though because of the described lack of reliable data.

Sustainability Policy and GPP

Green Public Procurement (GPP) has emerged as a potentially powerful tool for promoting sustainability, but its effectiveness and uptake across the European Union remain inconsistent. Studies indicate significant cross-country variations in GPP adoption, with top performers achieving up to 60% uptake while many member states lag below 20% (Cheng et al., 2018; Rosell, 2021).

GPP implementation has been linked to several economic benefits including driving markets towards sustainable goods and services, reducing environmental impacts, stimulating innovation, and potentially leading to life-cycle cost savings (Pouikli, 2021; Fregonara et al., 2022). This is supported by a case study in Greece (Orfanidou et al., 2023), which found that while green products may have higher upfront costs, their total life cycle cost (LCC) can be lower than non-green alternatives due to reduced energy consumption and maintenance costs. The World Bank (2021) also emphasizes that GPP can lead to long-term cost savings through reduced resource consumption and increased efficiency. Beyond cost savings, GPP can drive market transformation and innovation. Pouikli (2021) argues that GPP incentivizes market development in environmentally friendly solutions, leading to increased competition, innovation, and potentially lower prices for green products and services. The World Bank (2021) echoes this sentiment, highlighting GPP's potential to foster innovation and expand the market for green products and services. This potential for market transformation, as the increased availability and affordability of green products can encourage their adoption in the private sector. GPP implementation has been shown to increase the demand for green products and services. Yu et al. (2020) found a positive correlation between factors like higher contract value, joint procurement, and specific sectors (transport equipment, food) with the adoption of green award criteria in European public procurement contracts. The World Bank (2021) further emphasizes that public procurement of green products can create a "tipping point" where green products become competitively priced and preferred by consumers.

There are, however, also risks associated with GPP such as the risk of substitution. It refers to the possibility that when public authorities increase their demand for green products, private parties may react by increasing their consumption of less environmentally friendly alternatives because of price increases. Especially in construction as the sector is very material and labor heavy. Substitution can potentially offset the positive environmental impact of GPP. Lundberg et al. (2015) highlight this risk, suggesting that the net effect of GPP on the environment depends on the market power of the public sector and the price elasticities of demand for green and brown products. If the increased costs of green procurement led to a decrease in the number of bidders, this could reduce competition and potentially lead to higher prices for the public sector, further exacerbating the risk of substitution.
Lundberg et al. (2015) found empirical evidence suggesting that the risk of substitution is real and can undermine the effectiveness of GPP. In their study of Swedish cleaning service procurements, they found that the use of GPP did not significantly influence suppliers to adopt greener practices. Instead, it primarily attracted suppliers who were already green, indicating a substitution effect where public procurement merely shifted demand from one set of green suppliers to another, without necessarily increasing the overall market share of green products.

However, its impact is limited by several challenges, complexity and heterogeneity of requirements, lack of knowledge and training among procurement officials, financial constraints, insufficient political commitment, and the predominantly voluntary nature of GPP criteria (Cheng et al., 2018; Pouikli, 2021). To enhance GPP's effectiveness, researchers recommend developing mandatory minimum criteria, improving guidance and tools for officials, strengthening political support, promoting joint procurement, and creating standardized methodologies for assessing economic and environmental impacts in tender evaluations (Rosell, 2021; Fregonara et al., 2022). The literature also advocates for the effectiveness of simplifying requirements to lower barrier of entry and complexity, Halonen (2021) and Lundberg et al. (2018) both highlight one such aspect, the importance of harmonized GPP criteria to incentivize companies to develop greener solutions due to consistent demand across the public sector. However, Halonen (2021) also acknowledges the need for flexibility and adaptation in GPP implementation, recognizing that the effectiveness and impact of GPP can vary across different industries and sectors. This suggests that while a unified approach with harmonized criteria is beneficial, it should be balanced with sector-specific considerations to maximize the effectiveness of GPP.

Market behavior and patterns
Implementation of sustainability criteria have noteworthy effects on the market, and bidding behavior particularly on small and medium sized contractors (SMCs) and often present barriers to them.

- Often sustainability criteria come with increased cost and therefore financial burden on SMCs. This stems not only from investment cost and sustainability premium but also the skill and capacity gap that SMCs struggle with. Hwang et al. (2018) found that "extra investment required" was rated as the most significant barrier to meet sustainable construction standards in their qualitative study conducted in Singapore. This was however exacerbated by "slow recovery of investment" and "limited knowledge on sustainable construction,". These challenges are particularly acute in developing regions as Dhliwayo et al. (2024) found to be the case in Namibia, where lack of affordable finance, consistent work opportunities, and necessary skills training play an even larger role in hindering the ability of SMCs to integrate sustainability into their operations.
- Sustainability criteria are also reshaping market dynamics and bidding behavior. Market segmentation is becoming increasingly pronounced as sustainability certifications, such as responsible sourcing standards, become more necessary. Upstill-Goddard et al. (2015) found

that in the UK construction industry, the absence of such certifications can limit business opportunities for firms. Some contractors that don't have the resources may become excluded from certain projects or market segments.

- Another significant impact of sustainability criteria is the short-term productivity decline experienced by firms as they adjust to new environmental regulations. Dechezleprêtre and Sato (2017) conducted a comprehensive review of the literature on this topic, noting that while environmental regulations often lead to an initial decrease in productivity, these effects tend to dissipate over time as firms adapt. Larger firms, with their greater resources and capacity for absorbing compliance costs, are generally better positioned to weather these short-term impacts compared to smaller firms.

In summary, sustainability criteria in the construction industry tend to favor larger firms while presenting significant challenges for small and medium contractors. The impact of these criteria varies depending on many factors, but these findings give pause to think of the unintended consequences of introducing specific sustainability requirements. The ability of firms to adapt to sustainability criteria and policy will be a key determinant of their long-term success and should also be considered in the policy-making process as the effects of this will affect both CAs and contractors.

Sustainability in construction ABMs

The number of studies relevant to this thesis's research focus is limited, but the following focus on the contractor sustainability behavior on a larger scale and are worth mentioning. Liu et al.s (2024) literature review found most application for ABM with regards to sustainability in building and occupancy design, but models have also been developed to simulate the decision-making processes of stakeholders regarding the adoption of green building technologies, the impact of energy efficiency policies on building design and operation, and the environmental impact of construction waste management practices.

Attallah et al. (2013) developed an integrated ABM to evaluate the impact of sustainability policies on construction markets. Their model incorporated modules for policy diffusion, project formation, credit selection, and life cycle assessment to quantify potential environmental impacts. This allowed policymakers to compare different sustainability policy scenarios. Similarly, Hassan et al. (2012) created an ABM framework to simulate the adoption of sustainability practices in the construction industry in response to various policies. Their model considered factors like consultant influence, perceived benefits, and market readiness to predict diffusion patterns.

More recently, Li et al. (2022) applied ABM to explore the evolutionary mechanisms of green development behaviors in construction enterprises. Their model simulated how factors like environmental regulations and industrial clusters influence the adoption of sustainable practices over time. The authors found that sustainable regulations and cluster formation promoted greener behaviors, while short-term policies were less effective. Overall, these studies demonstrate how ABM can provide valuable insights into the complex dynamics of sustainability transitions in construction. Both focus on the contractors as the subject of the model, but neither the bidding nor tendering process is addressed.

4.2 MODEL 2

The key takeaway from the literature review is that incorporating sustainability criteria into a bidding model like this is unprecedented. While there is a consensus that sustainability increases costs in building projects and various studies have explored these cost factors, pinpointing the specific elements that drive up expenses remains challenging. Sustainability and financial considerations often operate on different scales—money is quantifiable, whereas sustainability typically requires developed metrics, such as euros per ton of CO_2, to make it measurable. For this model and research, we adhere to the principles of the KISS methodology (Keep It Simple, Stupid), making necessary assumptions and simplifications to address these complexities.

At the core of incorporating sustainability into the existing bidding model is the sustainability response curve, which is explained in detail in the following sections. This curve is pivotal not only for simulating contractor behavior and how sustainability investments influence bidding strategies, but also important for simulating owners demands with multi-dimensional auction scoring rules.

4.2.1 Sustainability Response Curve

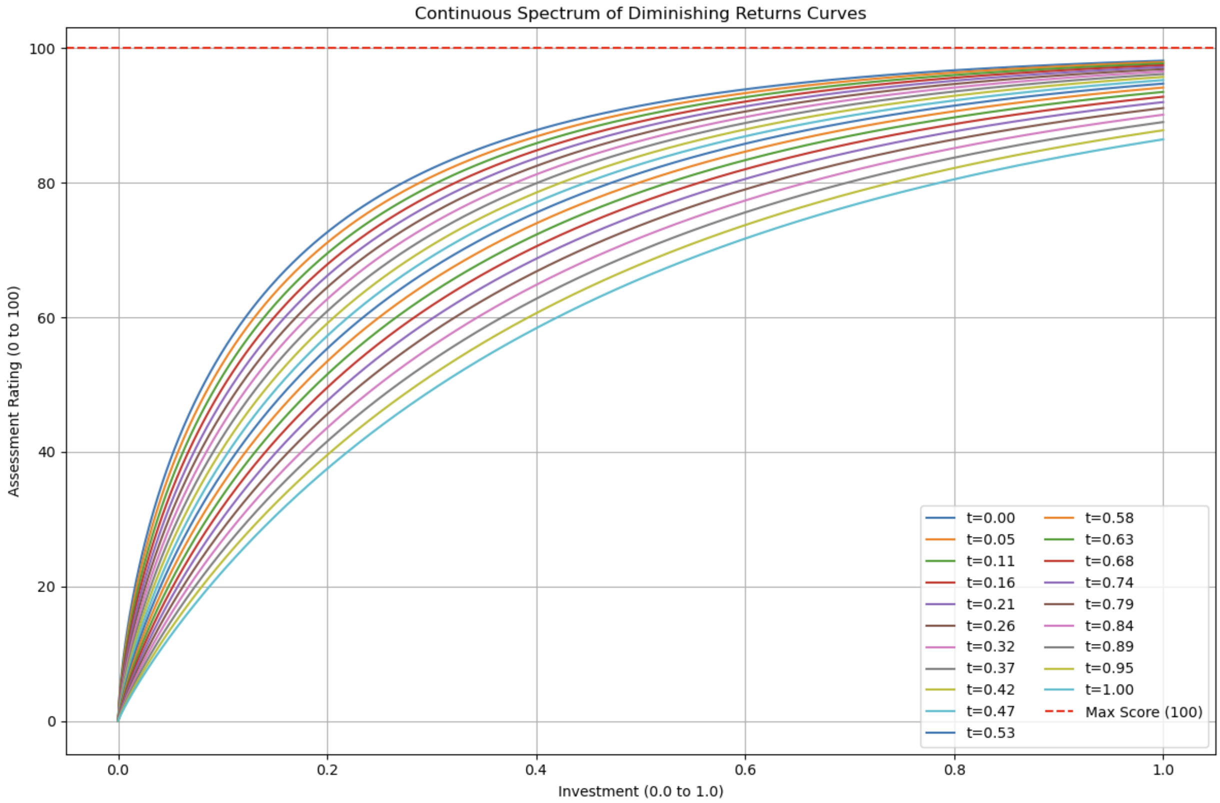


Figure 18: Sustainability Response Curve for simulating sustainability investments in bidding

The custom sustainability response curve represents diminishing returns on sustainability investments. This curve enables assessment of varying levels of sustainability investment, both project specific and upfront investments or sustainability capability in general. For a given project the contractor has the choice to vary their investment level, as shown on the x-axis in *Figure 18*, to receive a sustainability score or (assessment rating) for the project on the y-axis. This depends on the agent's sustainability capability (t - "threshold" factor), which dictates what curve they fall on. The curve is mathematically defined as:

$$Sustainability\ Score = 100 \cdot (1 - e^{-a \cdot x^{b}}) \tag{8}$$

where parameters a and b are determined based on a "threshold" factor, t.

Adjusting t alters the curve's shape, simulating different scenarios for sustainability returns. Lower values of t yield steeper curves with high initial rewards, while higher values result in flatter curves, where substantial investment is required to make incremental improvements.

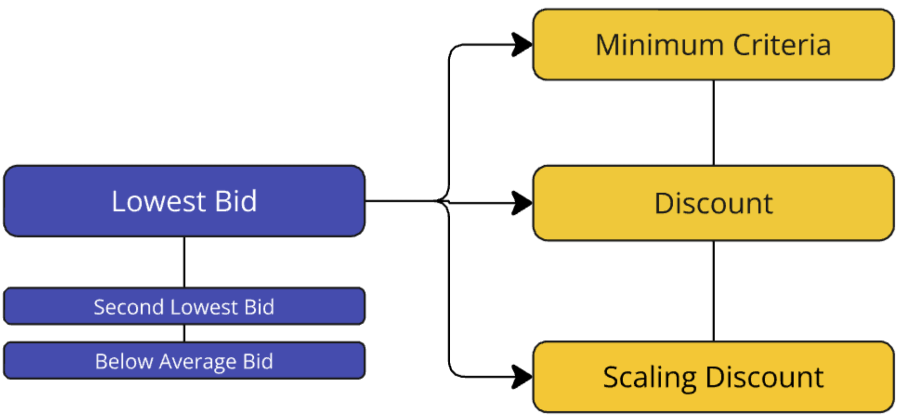
The response curve aligns with multi-objective optimization research in construction, where trade-offs between cost and sustainability are often found along a "Pareto front," enabling contractors to choose options that best suit their financial and environmental objectives (Karatas and El-Rayes, 2015; Abdallah and El-Rayes, 2016). There are some key aspects in sustainable construction that this curve imitates.

1. **Marginal Gains and Diminishing Returns**
   The curve captures the diminishing returns typical in sustainability investments, where early improvements—such as implementing efficient lighting or insulation—yield significant benefits, but additional enhancements bring smaller gains at higher costs. This reflects industry patterns, as shown in studies like Negendahl and Nielsen (2015), which indicate that initial low-cost measures are often the most impactful. Contractors can therefore utilize the curve to strategically allocate their sustainability budgets, optimizing easy investments before diminishing returns set in.

2. **Trade-Off Concentration in the Middle Range**
   Most meaningful trade-offs between cost and sustainability occur in the curve's middle range, where varying the threshold t has the most pronounced effect on outcomes. This reflects empirical findings, such as in Karatas and El-Rayes (2015), where mid-range sustainability levels (around 40-60% impact reduction) show significant variation in cost—up to 50% for similar levels of environmental benefit. By concentrating on this middle range, the model captures the nuanced choices contractors face when balancing cost efficiency with sustainability gains.
3. **Performance Variability Across Contractors**
   The model's flexibility in simulating different response curves also highlights variability in contractors' performance. For example, Abdallah and El-Rayes (2016) found that at similar investment levels, environmental impacts can vary widely—by over 40% in some cases. This aligns with studies showing that contractors with different strategies or experience levels can achieve significantly different results for comparable costs. Evins (2013) discusses similar variances, where energy savings across solutions can range from 10% to 35% depending on approach, underscoring the value of flexible modeling in capturing these differences.
4. **Empirical Basis for Investment Levels**
   The diminishing returns curve is grounded in real-world investment patterns. Abdallah and El-Rayes (2016) found, for example, that upgrading a building for a 70.7% environmental impact reduction required a substantial investment, indicating that major improvements often necessitate high costs. Similarly, Negendahl and Nielsen (2015) documented a near-doubling in cost index to achieve notable energy performance improvements. More examples of this can be found in the literature review of this chapter, conversely there are also many more examples of lower levels of sustainability being reached with very small investments. The shape and scale of the curve is modelled around approximating this reality.

4.2.2 Sustainability Evaluation Methods

The model incorporates three distinct evaluation methods to assess the sustainability aspect of contractor bids: minimum investment, discount, and scaling discount. These methods reflect industry practices discussed in the literature review section, "Current Practices and Policies and Industry Reports," using similar mechanisms to evaluate sustainability in construction procurement to what is used in practice.



The method in the model is based on a sustainability factor that is multiplied with the real submitted bid price, to apply a discount or a penalty, influencing the contractors' change of winning the bid:

$$Evaluated\ bid\ price = Real\ bid\ price * Sustainbility\ Discount\ factor \quad (9)$$

1. **Minimum Criteria Method**

The minimum investment method establishes a baseline threshold for sustainability. Contractors must meet or exceed this threshold to qualify for consideration; otherwise, they are penalized, effectively eliminating them from the bid. This approach mirrors industry practices where minimum sustainability standards are specified as mandatory building requirements or contractor eligibility criteria.

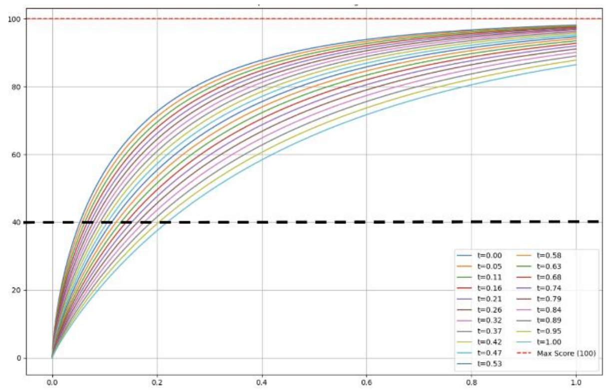


Figure 19: Minimum Criteria Method Represented on Sustainability Response Curve

In *Figure 19,* the minimum criteria are represented by the dashed line on the sustainability response curve. For this example, bids with a sustainability score below 40 are disqualified, with the probability of winning the bid falling to zero. For contractors with different t-values, the required investment to achieve the minimum score of 40 varies between 5–20% of their total sustainability investment. This variation reflects differing levels of sustainability capability or preparedness among contractors, with those on steeper curves achieving the required score with lower investment.

2. **Scaling Discount Method**

The scaling discount method provides contractors with a bid adjustment based on their sustainability score, making their bids more competitive as they invest more in sustainability. This approach ensures that sustainability efforts are rewarded in a proportional and measurable way. It is often finely tuned in practice so that project owners can precisely anticipate the sustainability outcomes and associated costs.

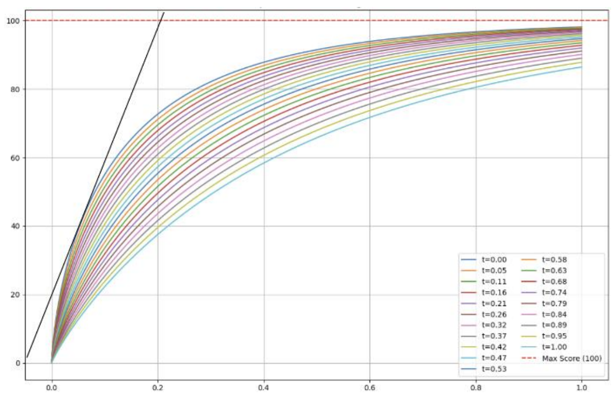


Figure 20: Scaling Discount Method Represented on Sustainability Response Curve

In *Figure 20,* the model implementation of this method is illustrated by a line tangential to the t-value = 0.00 curve at a sustainability score of 40. The t-value of a project represents the stringency of its sustainability requirements. The discount value per sustainability score is calculated by determining the slope of the curve associated with the project's t-value at the desired score. This means that a contractor with a t-curve matching the project’s requirements achieves a breakeven point at the desired sustainability score. Below the breakeven point, contractors reduce their bid price more than the additional costs incurred for sustainability measures, making their bids more competitive. This encourages contractors to strategically optimize their sustainability investments while balancing the financial implications.

3. **Discount Method**

This method is very similar to the scaling discount methods except that a lower cap ensures that small investments do not receive excessive benefits, while the upper cap prevents disproportionately large discounts for extremely high sustainability scores. It is a mix of both previous methods together. For this model the range for the lower to upper bound is set as 10 sustainability score. This approach reflects industry incentives designed to reward sustainable practices up to a point but keeps bidding competitive by capping the rewards. Variations of this are used for example in the MKI used for public procurement in the Netherlands or classified tools like BREEAM.

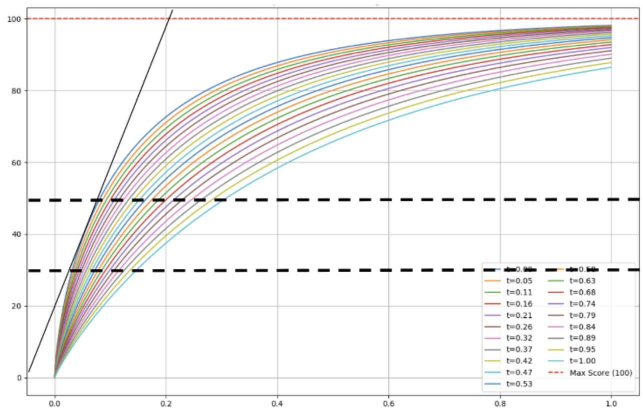


Figure 21: Figure 20: Discount Method Represented on Sustainability Response Curve

The model integrates sustainability investment from the contractor's perspective and evaluation from the owner's side, reflecting key insights from the literature review. The investment component allows contractors to balance their sustainability spending with competitive bidding strategies, while the evaluation methods generalized to cover most common frameworks, simulate how owners assess bids based on sustainability.

4.3 VERIFICATION AND VALIDATION EXPERIMENTS

This model builds on the previous version of the model, incorporating new sustainability evaluation functionalities. Before integrating these new aspects fully, it is essential to verify and validate the model by testing it against known values and patterns. This ensures the model functions as intended and accurately represents behaviors observed in real-world construction practices. The simulation experiments outlined in *Table 7* are based on patterns found in the literature review discussed in the earlier chapter and designed to align with the input parameters used in the model.

Table 7: Sustainability Tuning and Validation Patterns

Patterns	**num. of bidder**	**sustainability experience**	**relative risk aversion**	**selection criteria**	**project landscape**
4) Economic Bias Purely economic selection methods disadvantage innovative practices *(Khoso et al., 2021)*	3	Contractor t-value: 0.3 (High) 1.0 (Low) 1.0 (Low)	Medium	Lowest bid No sustainability	Highly experienced bidder that will always invest in 'innovation', bidding against bidders that don't invest in any 'innovation'.
5) Market Segmentation Contractors without any sustainability experience or certification don't invest to make bids on sustainable projects *(Upstill-Goddard et al., 2015)*	10	t-values: 1.0 – 0.0	distribute d (as described in table 5)	lowest bid sustainability :minium discount scaling discount	Changing selection criteria after 20 steps from no sustainability to sustainability

6) Barriers for entry for Contractors in Sustainability Smaller contractors face challenges participating in projects with significant sustainability criteria and therefore don't enter them *(Hwang et al., 2018)*	30	t-values: 0.9	distribute d (as described in table 5)	lowest bid sustainability :minium class interval continuous	Changing selection criteria after 20 steps from no sustainability to sustainability

4) Economic Selection Bias

When researching the market behavior and patterns in the literature review of the previous chapter indicated there is a bias in construction procurement processes that often disadvantages innovative and sustainability-focused practices and prioritizes purely economic aspects. This leads to a reduced number of successful bids for contractors who prioritize these investments.

To validate this aspect of the model, experiment 4 was conducted, measuring the number of winning bids per contractor. The contractors in this experiment were set up with identical base parameters, but contractor 0 was programmed to always include sustainability investments that ensured a minimum score of 10. Contractors 1 and 2, on the other hand, could submit bids without additional sustainability investments.

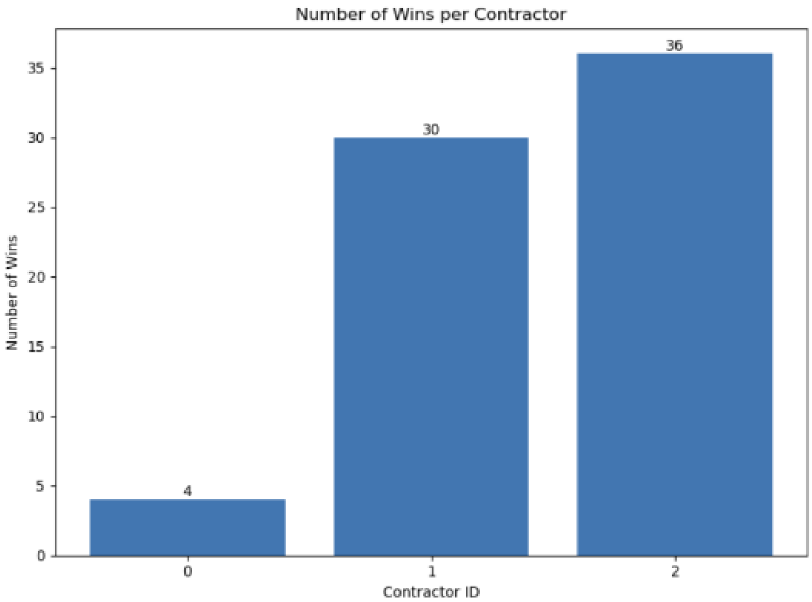


Figure 22: Demonstrating Economic Selection Bias in the Model

Figure 22 illustrates the outcome of this experiment. Contractor 0, despite having the same base parameters as the other contractors, only won 4 out of the 70 available projects. In contrast, contractor 1 secured 30 wins, and contractor 2 won 36 projects. This demonstrates that the purely economically motivated selection criterion in the model favors contractors who do not invest in sustainability, as their bids outperform because of the lower associated costs.

The outcome of this experiment aligns with expectations for the model's behavior and the pattern observed in practice, where sustainability-focused bids can be at a disadvantage when purely cost-driven procurement methods are employed.

5) Market Segmentation

This experiment examines market segmentation, a pattern observed in the construction industry as sustainability requirements become more integrated into procurement processes. The literature review in this chapter discusses how sustainability criteria reshape market dynamics, with studies like Upstill-Goddard et al. (2015) highlighting that the lack of certifications or sustainability investments

can limit opportunities for contractors, effectively segmenting the market. This experiment aims to replicate these market behaviors to verify if the model captures this observed segmentation.
The setup for this experiment involves 10 contractors, all with identical base parameters but with varying levels of sustainability capability, represented by their t-values evenly distributed from 0.0 to 1.0. For the first quarter of the simulation, projects are bid on without any sustainability criteria. After this initial phase, the simulation switches to one of the three sustainability criteria (minimum, discount, or scaling discount) with a desired sustainability score of 30.

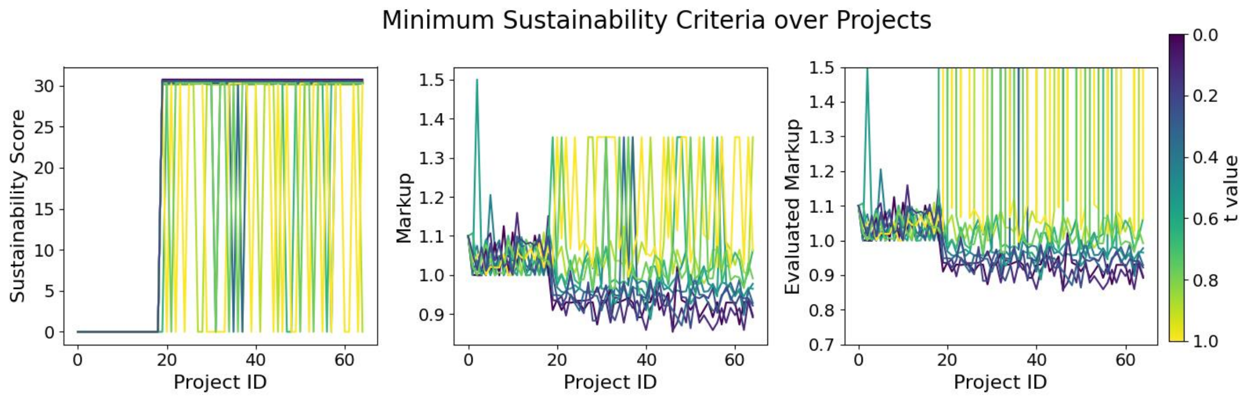


Figure 23: Demonstrating Market Segmentation of Minimum Sustainability Criteria

Figure 23 illustrate the impact of this change in project requirements. The sustainability score, real markup, and evaluated markup for each project are plotted, with the color of each curve representing the sustainability ability of the contractor (a higher t-value indicates a lower sustainability capability). Initially, all contractors are equally competitive, but after project 18, the shift to sustainability requirements changes bidding behavior. Contractors with higher sustainability capabilities maintain competitive bids, even becoming more competitive if their t-value is lower than the owners, while those with poorer capabilities struggle to be competitive, even raising their markups to the maximum allowable level as observed in chapter 3 experiment 1. This signals the risk conceptions flipping, meaning the risk of winning the project and earning less or incurring a loss dominates the desire to win the bid. This effectively signals withdrawal from bid. Occasionally, contractors near or slightly above the owner's t-value also retract from bidding.

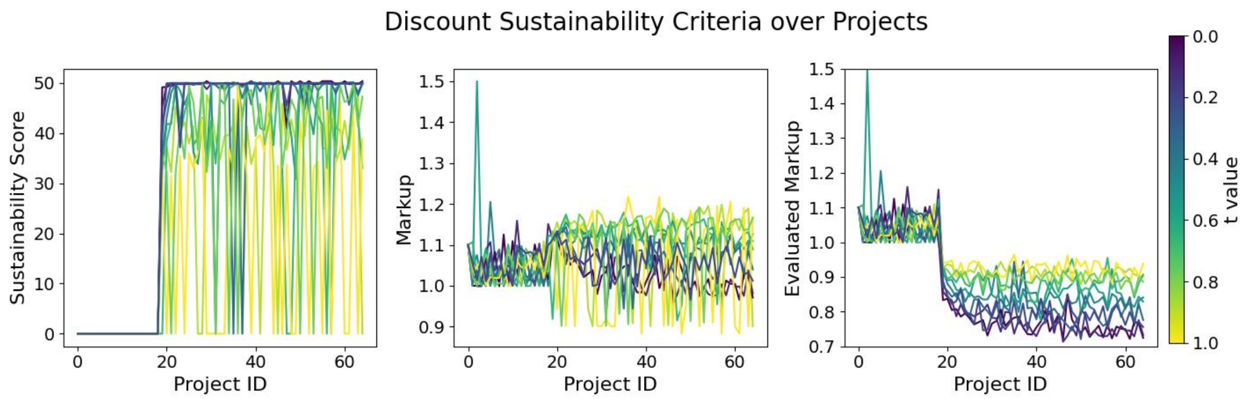


Figure 24: Demonstrating Market Segmentation of Discount Sustainability Criteria

Figure 24 depicts the shift from no sustainability criteria to the discount sustainability criterion. A similar number of bidders with high t-values (lower sustainability capabilities) withdraw from bidding. However, the pattern seen is different, here they opt for the minimum low markup, but this is only due to how the model's optimization calculations works. Notably, the overall sustainability scores among competitive bidders are higher. The discount sustainability method creates more intense competition among the top-performing contractors and rewards them for extra sustainability scores. While the evaluated markup across projects shows a broader spread than the minimum, the upper cap imposed by the discount method ensures that the top three contractors with the best t-values are competing on a relatively level playing field. This pattern demonstrates how the discount sustainability criterion encourages higher sustainability investment at the cost of higher mark ups but also impacts contractor bidding behavior by rewarding sustainability beyond the minimum while still maintaining competitive pressures among top performing contractors.

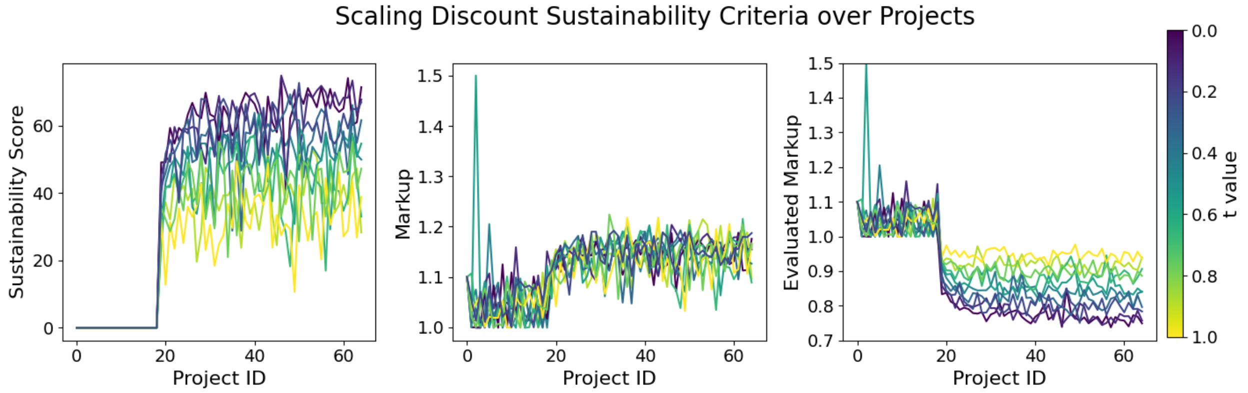


Figure 25: Demonstrating Market Segmentation of Scaling Discount Sustainability Criteria

Figure 25 displays the changes in bidding behavior when switching to the scaling discount criterion. Notably, in this setup, no bidders are seen submitting bids at either the minimum or maximum markup, indicating that none are withdrawing entirely from the bidding. The real markup remains competitive, showing a consistent increase that reflects the added costs associated with sustainability investments. The scaling discount method results in the highest overall sustainability scores, but with the widest spread among contractors out of all selection criteria. This outcome aligns with expectations, as contractors can invest in sustainability to their desired extent until reaching a break-even point differing by contractor and influenced by both contractor and owner t-values. The variability in sustainability scores is mirrored in the evaluated markup also showing a widespread. The contractor with the lowest t-value, demonstrating the strongest sustainability capabilities, consistently secures winning bids. This indicates that the scaling discount method promotes continuous investment in sustainability while maintaining a balanced competitive environment where contractors are rewarded proportionally based on their sustainability investments.

These results verify the model's ability to replicate real-world behavior, capturing how sustainability criteria not only shift competitive dynamics but also contribute to market segmentation by differentiating contractors based on their sustainability capability.

6) Barrier for entry for contractors into Sustainability

This experiment examines the short-term productivity challenges contractors face when adapting to new sustainability requirements. The literature review in this chapter references the findings of Dechezleprêtre and Sato (2017), who highlighted that firms often experience an initial decline in productivity as they adjust to stricter environmental regulations. While larger firms typically manage these adjustments more efficiently due to their resource capacity, smaller firms face more significant obstacles.

This experiment simulation is set up similarly to *experiment 5).* However, the owner sets a sustainability criterion with a desired score of 30 and a t-value of 0.8, which aligns with the sustainability capability of the contractors. However, the financial class of the contractors varies, evenly distributed from 1 to 5. This classification affects a contractor's cost structure and bidding behavior, with firms in higher financial classes facing greater production costs and bidding less competitively. The experiment aims to track contractor behavior under these conditions to observe how sustainability requirements influence their ability to compete and bid effectively.

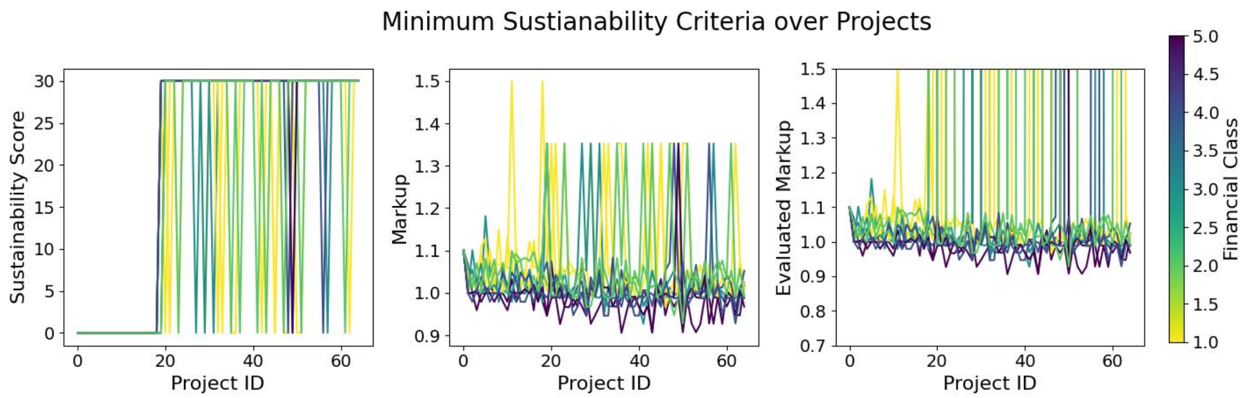


Figure 26: Demonstrating Barriers for Entry of Minimum Sustainability Criteria

Figure 26 again illustrates the shift from no sustainability criteria to the minimum sustainability requirement. The results show that many contractors submit maximum markups, indicating withdrawal from bidding, even though the owner and contractor t-values are aligned. However, there is a greater mix of contractors withdrawing on two occasions, even contractors with the highest financial class, but the overall trend is that the worse financial class will also withdraw more frequently. It shows that sustainability criteria alone are enough to change the contractors' risk perception, and the extra investment cost actually impacts contractors' cross financial classes. This high number of bidding withdrawals even though contractor and owner t-values are aligned can likely be attributed to the added profit variability in project with sustainability goals, its especially high in the minimum criteria because if the sustainability score is not met the contractor cannot win the bid, and the probability of winning falls to 0. The observed spread of bids among the remaining competitive contractors is very tight but the contractors with higher financial class are submitting lower bids and winning a majority of the time.

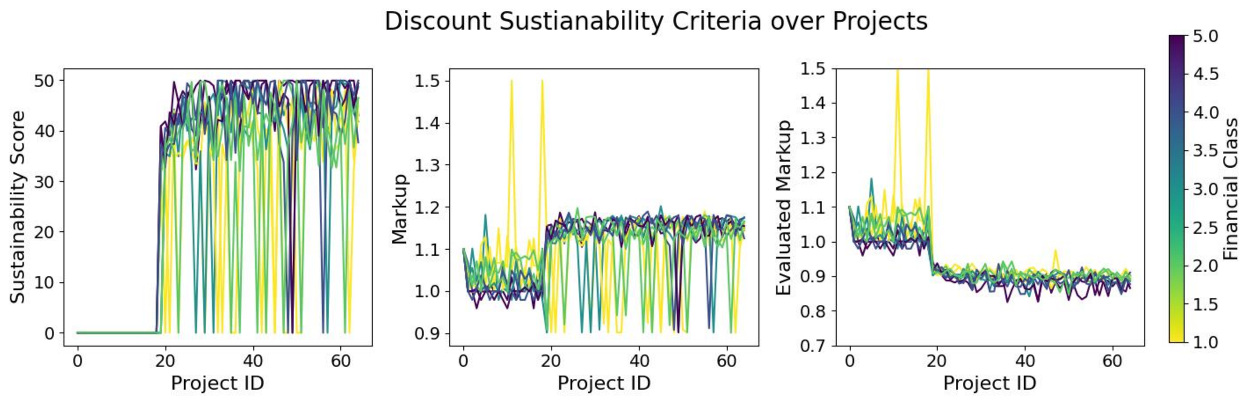


Figure 27: Demonstrating Barriers for Entry of Discount Sustainability Criteria

Figure 27 shows the development of bid prices and sustainability scores for the discount sustainability criteria. The observed behavior mirrors most aspects of the minimum criteria, such as contractors withdrawing. However, a key difference is that both the markup and evaluated markup prices are adjusted to account for the discount and the average sustainability score of the bids submitted is much higher.

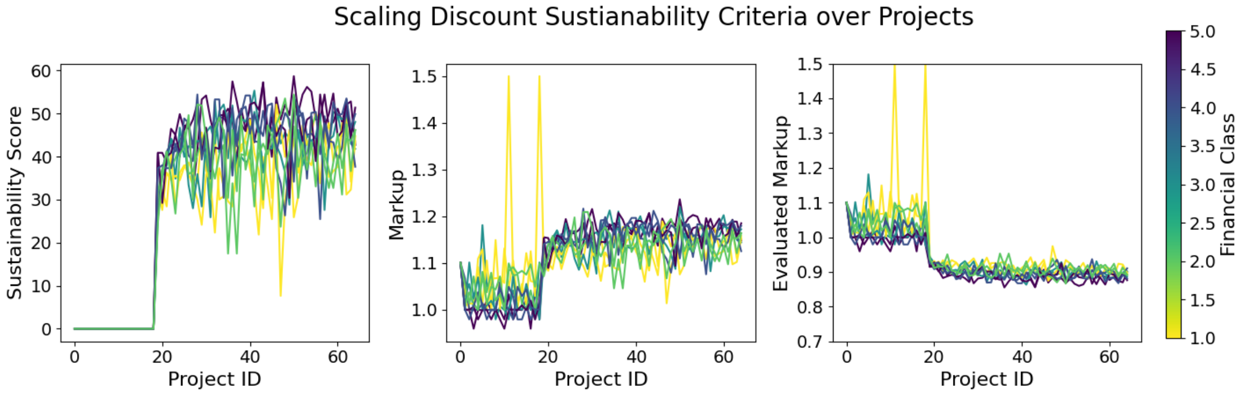


Figure 28: Demonstrating Barriers for Entry of Scaling Discount Sustainability Criteria

Figure 28 shows the transition to the scaling discount sustainability criteria. Similar to experiment 5, the number of withdrawals decreases and eventually drops to zero. This is because the scaling discount criterion provides contractors with a broad range of markup and investment options, allowing them to find their optimal strategy without disadvantage and only rewarding them for sustainability efforts. Interestingly, contractors with higher financial stress classes are observed to submit higher sustainability scores. This behavior suggests that, beyond how their t-curve aligns with the owner's t-curve, they are willing to bid above their sustainability breakeven point as their perceived project costs are lower than those of other contractors. Conversely, contractors with lower financial stress classes tend to gravitate more closely toward their actual breakeven point, which often centers around a sustainability score of 30. Overall, this change in criteria does not drastically alter the competitive landscape. The distribution of bids remains similar to when no sustainability criteria are in place, with the main difference being an increase in mean markup. The variance in evaluated bids is smaller, while the variance in sustainability scores and real markups is higher.

These results confirm the model's ability to replicate real-world dynamics, demonstrating how sustainability criteria create entry barriers and shift contractor behavior. The minimum criterion increases bid withdrawals due to higher risks, while the discount method raises sustainability scores through strategic bid adjustments. The scaling discount effectively reduces withdrawals, promoting balanced competition and rewarding higher sustainability investments without disrupting overall engagement.

4.4 EXPERIMENT RESULTS

This section presents the results and interpretation of all POM experiments conducted. In this section their results specifically the results of previous section are to examined. The first experiment differentiates contractor sustainability capability while the second their financial class, both are the primary performance factors linked to each dimension of the scoring rules. This means that the strength of bidders is only differentiated in each experiment, firstly by their sustainability capability and secondly by their financial class. Analyzing this through the lens of auction theory, a central theorem of efficient auctions needs to be introduced. The Monotonicity theorem states that in auctions, higher valuations lead to higher bids in equilibrium. This is fundamental for ensuring that the auction mechanism is predictable and allocates resources efficiently. In first-price sealed bid auctions this means bidders shade their bids below their true valuations, but higher valuations still correspond to higher bids ensuring that the bidder with the highest valuation wins the auction, achieving allocative efficiency. What is described in the previous section as the bid spread shows the monotonicity of bidding strategies. When looking at the first experiment *(Figure 23-25)* there is no bid spread in the first 20 steps of the simulation, showing that without the sustainability criteria scoring rules the bidders remain at the same strength and value the project the same. When the criteria is switched after step 20 the monotonicity becomes apparent in the bid spread, the stronger sustainable bidders are consistently winning the bids. The second experiment *(Figure 26-28)* shows monotonicity from the start, but only mild bidders with better financial class are winning the bids most of the time, but the spread is not as wide, when the sustainability scoring rules become active after step 20 the monotonicity doesn't change, only the price/mark ups on the project does. This shows that the model is behaving as expected and aligns with the theory.

Other key insights emerge from the experiments about the individual scoring rules or sustainability criteria mechanisms in particular.
The Minimum Criteria approach sets a mandatory threshold for sustainability that contractors must meet to qualify for bidding. The results reveal several notable patterns that seem to foster cost control and fairness among participants but limit overall sustainability outcomes. While efficient for owners, the approach risks excluding less capable contractors, reducing market inclusivity. Following trends can be seen:

- Discouraged Participation: Contractors with lower sustainability capabilities frequently opted out of bidding or submitted throwaway bids. This exclusionary effect highlights the challenges for smaller or less capable contractors in meeting mandatory requirements.
- Even Playing Field: Among participating contractors, evaluated markups tended to converge. The lack of significant variance suggests that the minimum threshold reduced competitive disparities, creating a relatively level playing field.
- Baseline Sustainability Gains: Contractors consistently targeted the minimum sustainability requirement without exceeding it, as there were no incentives to do so.
- Cheapest for the Owner: Price development remained neutral or decreased for some bids. In highly competitive environments, contractors with better sustainability capabilities than expected often underbid the owner’s adjusted budget (t-value) to increase their chances of winning. This reflects cost efficiency for the owner, as the sustainability threshold does not impose additional financial pressure.

The Discount Mechanism introduces sustainability-linked incentives, where contractors benefit from fixed bid price adjustments based on their sustainability scores. This seems to encourage sustainability gains beyond baseline levels while maintaining moderate cost increases. However, it struggles to drive broad participation and achieves only limited reductions in bidding disparities. The following results were observed:

- Moderate Bidding Disengagement: Similar to the Minimum Criteria, the Discount Mechanism led to throwaway bids, particularly among contractors with lower sustainability capabilities, as incentives were insufficient to drive broad participation.
- Top-End Compression: Variance in evaluated markups was noticeably reduced at the upper end of the competition, where capable contractors optimized their sustainability investments to align with the discount structure.
- Higher Sustainability Gains: Contractors frequently exceeded the minimum requirements, indicating a positive response to the sustainability incentives.
- Medium Cost for the Owner: Prices increased moderately as contractors absorbed some sustainability costs. The upward trend in prices remained controlled, with no bids surpassing a markup of 1.2.

The Scaling Discount directly ties incentives to sustainability performance, rewarding higher sustainability investments. It achieves the highest sustainability outcomes but at a significant cost. While it promotes widespread participation, it disproportionately benefits top-tier contractors, creating equity concerns within the market. Key findings include:

- Encouraged Participation: The Scaling Discount significantly reduced throwaway bids, fostering broader contractor participation across varying capability levels.
- High Variance Between Bids: Disparities between evaluated bids were substantial, as contractors with advanced sustainability capabilities consistently dominated the competition. This variance reflects an uneven competitive environment where less capable contractors struggled to compete.
- Maximum Sustainability Gains: Contractors optimized their bids to achieve the highest possible sustainability scores, often far exceeding the owner’s expectations.

- High Cost for the Owner: Sustainability optimization resulted in the steepest increase in markups, as contractors absorbed fewer sustainability costs. This translated to higher overall project costs for the owner.

A critical factor influencing the price and markup development in the experiments is the way the owner agent, project appraisal, and sustainability budgeting are modeled. In the simulation, the project appraisal value is split into two components: a base project cost, representing the value of the project "without sustainability," and an additional sustainability cost that reflects the owner's desired sustainability goals. This separation aligns with how sustainability costs are often budgeted in practice but also introduces specific considerations when interpreting the results.

A number of model parameters influence the sustainability investment ratio and expected outcomes: the owner's sustainability stringency (t-value), the desired sustainability score, and the baseline appraisal value of the project and similarly on the contractor side the sustainability capabilities. Under the Minimum Criteria, competitive pressures created unexpected outcomes. Contractors with advanced sustainability capabilities strategically underbid the owner's expectations, driving markups below 1.0. This behavior, which appears counterintuitive, can be explained by the competitive advantage these contractors hold. As seen in *Figure 23*, the contractors that bid most aggressively, lowering their prices the most, were those with sustainability capabilities exceeding the owner's stringency or desired score. In essence, these contractors leveraged their superior capabilities to optimize their chance of winning projects, even at reduced profit margins. While this benefits the owner financially by reducing project costs, it highlights a key dynamic: sustainability leaders use their advantage to compete on price in a highly competitive environment.

In contrast, the Scaling Discount mechanism shifted contractor strategies toward maximizing sustainability scores rather than minimizing bid prices. Here, the incentive structure drove contractors to prioritize sustainability performance, leading to significant cost escalations for the owner. This outcome underscores the importance of aligning owner ambition (t-value) with appropriate incentive mechanisms. If sustainability stringency is too high without adequate balancing measures, it can drive up project costs as contractors focus on sustainability optimization over cost competitiveness.

5. SCENARIOS FOR EQUITABLE ACCESS TO SUSTAINABLE BUILDING PROJECTS

5.1 MODEL 3

5.2 SCENARIO SIMULATIONS

5.3 VALIDATION

5.1 MODEL 3

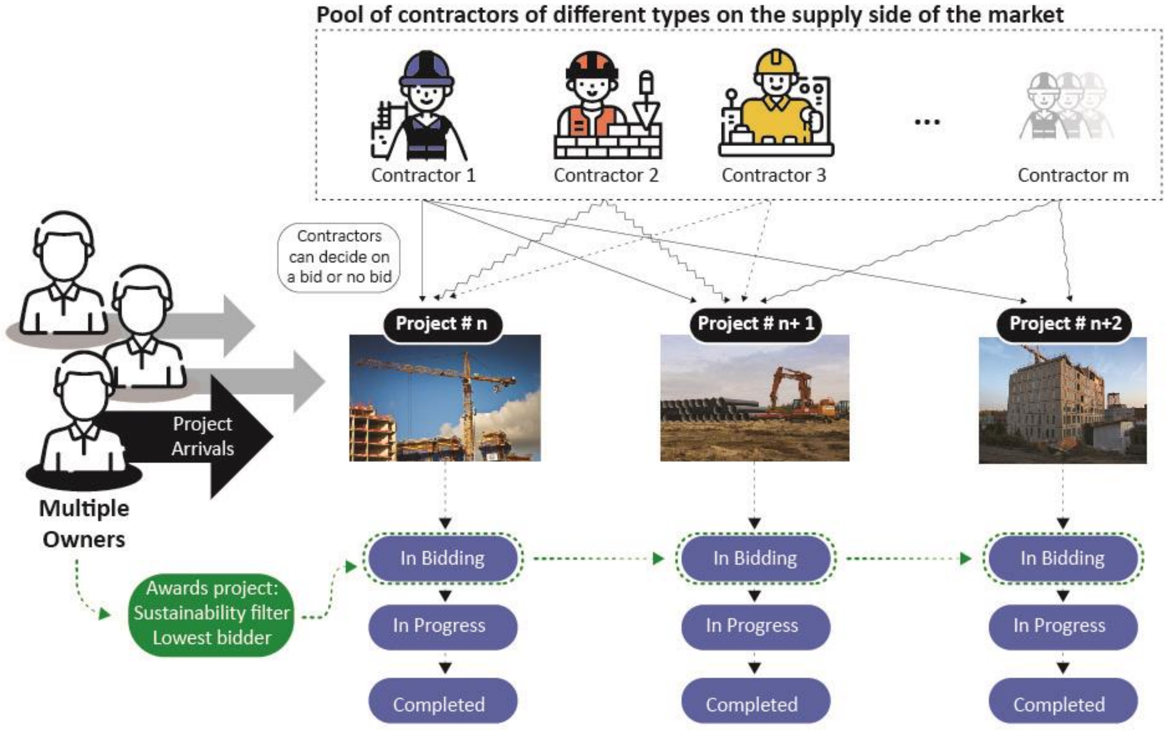


Figure 29: Conceptual Depiction of Model Version 3

In this final version of the model, two significant enhancements have been introduced to better simulate a real-world bidding environment. These additions are depicted in the conceptual model in *Figure 29*. First, the model now allows for multiple owners with different attributes to generate projects simultaneously, reflecting the varied approaches between private sector and public sector procurement criteria. This addition provides a more comprehensive representation of how different ownership types influence project attributes and bid evaluations.

The second key feature is to implement contractor learning, or lasting sustainability investment as reflected by an improvement of their t-value, when they win a contract that has sustainability criteria they improve their t-value the larger the investment the better the improvement this is defined by the following equation:

$$t_{new} = t_{old} - \alpha \times (\frac{I_{project}}{I_{norm}})$$

Where:
t_{new} is the updated t-value after winning and executing the project.
t_{old} is the original contractor t-value
α is the improvement rate
$I_{project}$ is the actual investment made by the contractor
I_{norm} is the desired investment made by the owner

The assumption is if a contractor submits a bid with a certain sustainability value they do not yet necessarily have the means to do it at that quality, but will only for example acquire more sustainability machinery or develop ways of building when they have a guarantee of future cashflow in the form of a project lined up.

The third key feature is the implementation of a bid/no-bid decision mechanism. While earlier simulations indicated contractor withdrawals through the submission of maximum or minimum bids, these submissions distorted the historical bid data that contractors use to calculate their probability of winning. This, in turn, could potentially alter their future bidding behavior. The new bid/no-bid decision functionality refines the model by accurately representing contractors' willingness to engage in a project without affecting the bid history. Analysis of this phenomenon and implementing it as a feature also allows for a closer understanding of contractor behavior in the model, when faced with varying award criteria. The following sections will detail the implementation and impact of the bid/no-bid decision on the model.

Bid/No-Bid simulation and analysis

To comprehensively understand the conditions under which contractors choose to withdraw from bids, the model tested with 2000 scenarios sampled across the following features:

Contractor perceived cost factor (perceived_cost_factor, the difference between the owner estimated cost for the project and the owner appraisal value)
Number of contractors competing in the bidding (num_contractors)
Risk aversion of the contactor (risk_aversion)
Experience (experience, this is directly related to risk aversion in this model)
Financial Class (financial_class)
Award method (award_method_second_lowest, 1 when the second lowest bidder wins 0 when the lowest bidder wins)
Contractor sustainability capability (contractor_t_value)
Owner sustainability criteria stringency (owner_t_value)
Desired sustainability score for the project by the owner (desired_sustainability_score)

To ensure realistic scenarios, the Latin Hypercube sampling method was adjusted using a normal distribution, creating a representative contractor pool consistent with the data from Campo (2012).

The bids from those scenarios were then categorized using a clustering algorithm and manual verification to classify them into "too high" bids, indicating contractor withdrawal, and "acceptable" bids that remained competitive. *Figure 26* below displays the markup distribution of all bids. The data was further divided into four categories based on the sustainability criteria simulated in the model: 'None', 'Minimum', 'Discount', and 'Scaling Discount'. The individual markup distributions *(Appendix 9-12) and Table 8* indicate, similar to findings in *experiments 5 and 6*, that the minimum and discount sustainability criteria result in more bid withdrawals compared to the other two criteria. Notably, the minimum criterion leads to contractor withdrawal in nearly half of the simulated scenarios, suggesting these criteria are more sensitive to triggering contractor exits.

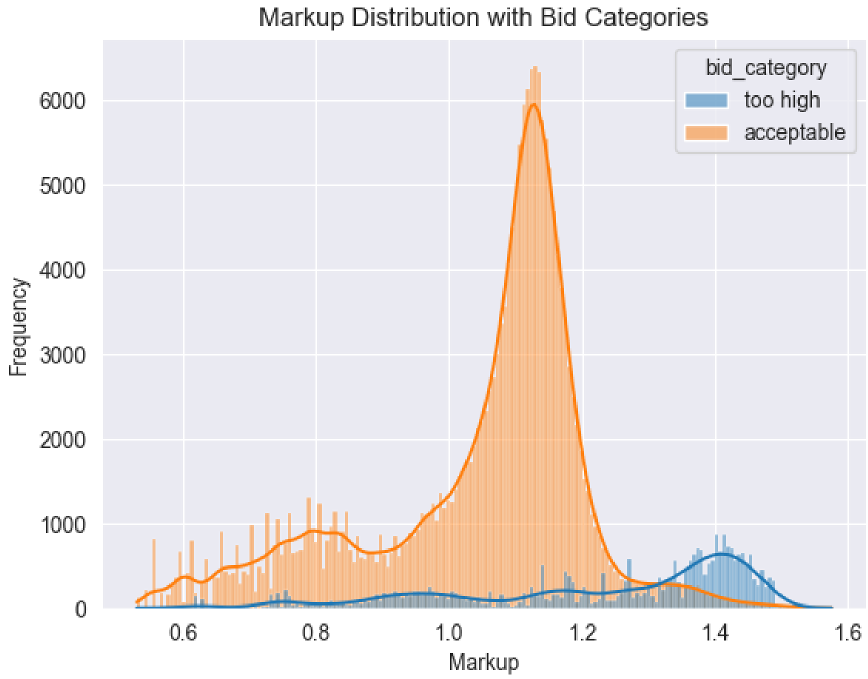


Figure 30: Markup distribution for all scenarios

Table 8: Percentage of bid withdrawals

Sustainability criteria	Percentage of withdrawn bids across all scenarios
'None'	6.29%
'Minimum'	47.44%
'Discount'	20.92%
'Scaling Discount'	9.00%

To deepen the analysis, four random forest models were trained on the data, achieving an accuracy rate of over 91% across all sustainability conditions. This high accuracy demonstrates that the chosen features can reliably predict contractor withdrawal.

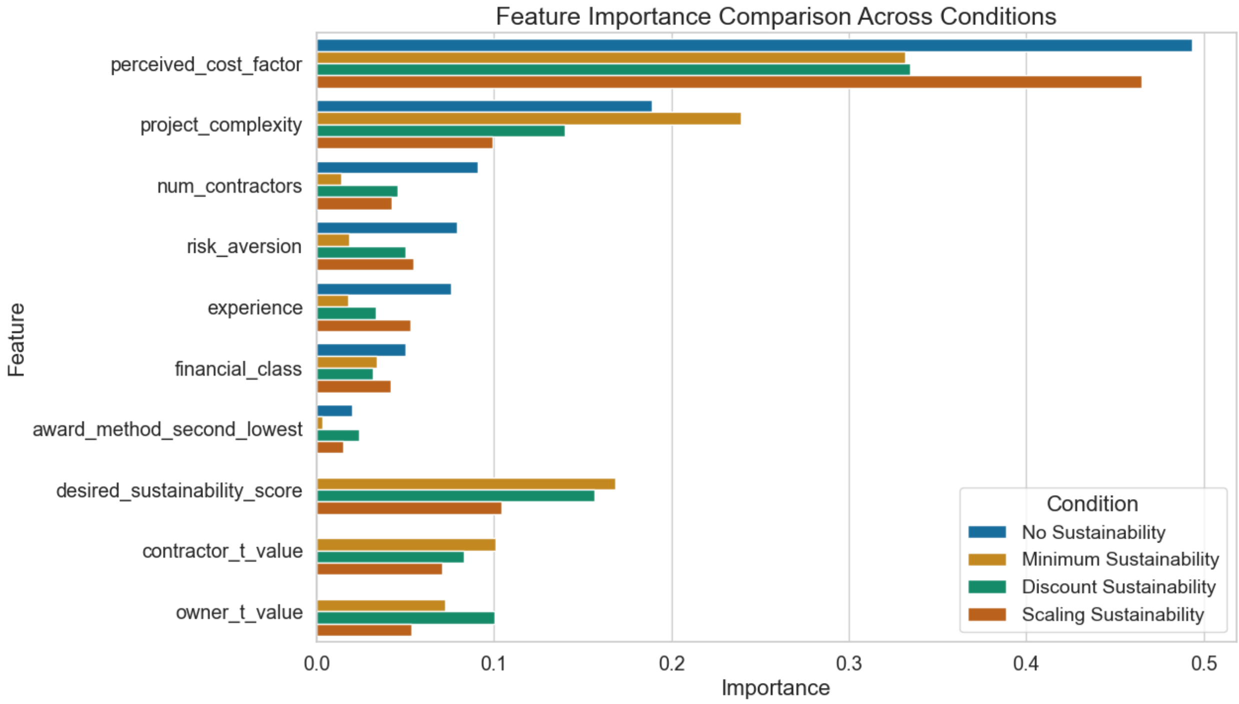


Figure 31: Random Forrest Feature Importance for Bid/ No-Bid decision

Figure 30 highlights that the perceived cost factor is the most significant feature influencing contractor withdrawal, regardless of the sustainability criteria applied. This indicates that contractors heavily weigh the difference between the owner's estimated cost and the project's appraisal value when deciding whether to bid. It also highlights the differences in feature importance across sustainability criteria. The perceived cost factor is consistently the most significant driver of contractor withdrawal across all conditions. Notably, minimum and discount sustainability criteria place a greater emphasis on the owner's desired sustainability score, reflecting stricter constraints that can lead to higher withdrawal rates. In contrast, the scaling discount criterion shows a more balanced distribution of feature importance and less reliance on the owner's sustainability score, offering contractors more flexibility and reducing withdrawal tendencies. The discount criterion stands out for its balanced influence across all features, fostering a more competitive and adaptable environment. As expected, the 'None' condition excludes sustainability-related features, focusing primarily on traditional factors like perceived cost and project complexity. These distinctions emphasize how different criteria shape contractor behavior and withdrawal patterns.

The impact of financial class is more pronounced in the 'Minimum' and 'Discount' sustainability scenarios, aligning with findings that financially constrained contractors are more likely to withdraw under stricter sustainability conditions. Interestingly, award method and the alignment between contractor and owner t-values show relatively lower importance across the board, indicating that while these factors contribute, they do not drive withdrawal decisions as strongly as the perceived cost factor and project complexity do.

With this trained classifier, the model now incorporates a two-step bidding process. In the first step, *shall bid*, the features relevant to the sustainability criteria of the project are input into the random forest classifier. The classifier predicts whether the contractor is likely to withdraw if they choose to bid, essentially determining if the project is worthwhile for the contractor. In the second step, *submit bid*, contractors who decide to proceed calculate their optimal markup and sustainability investment decisions based on the expected competition.

5.2 SCENARIO SIMULATIONS

Scenario setting

To address sub question 3 this section refers back to the literature review, which highlighted the potential benefits of GPP in fostering healthy competition and guiding markets toward sustainability. As discussed, GPP can be a powerful policy tool to align market practices with overarching climate goals, such as achieving a net-zero or circular construction sector by specified target years.

Therefore, this simulation is designed to reflect a scenario in which the construction sector, like the rest of the economy, must significantly cut emissions and enhance sustainability within the next 10 years and continue to progress toward 2050 targets. This aligns with the Dutch government's climate policy, which mandates a 49% reduction in emissions by 2030 and a 95% reduction by 2050. To model this, the simulation setup included two owners: one representing public sector activity, accounting for approximately one-third of the construction market, and the other representing the private sector, responsible for around two-thirds of market activity.

- **Owner 1 (Public Sector)**: Implemented a gradual increase in desired sustainability from 10 to 60 over a 10-year period increasing the desired sustainability score of the projects by 10 every interval i (2 years) , initiating one project every four weeks.
- **Owner 2 (Private Sector)**: Operated without sustainability criteria, releasing one project every two weeks to represent standard market practices.

Four scenarios were designed to evaluate the impact of different sustainability criteria:

1. **Minimum sustainability criteria**.
2. **Discount sustainability criteria**.
3. **Scaling discount criteria**.
4. **Optimized mix of criteria**, grid search was performed in all 243 permutations of the scenario to minimize the mean contractor t-value and maximize the mean number of bidders in the last 2 years.

For each scenario, the owner's t-value (representing the stringency of the sustainability criteria) was kept relatively low to evaluate its impact under practical, moderate conditions. Additionally, contractors have working limits, meaning if they accept 6 projects, they won't have the capacity to bid on any more projects and projects with fewer than three bidders are canceled to reflect real-world practices where insufficient competition leads to project cancellation. The table below summarizes the contractor starting parameters, owner parameters, mean contractor t-value at the end of the simulation, and mean number of bidders during the last interval, providing insights into how different policy approaches influenced contractor sustainability investments and competition levels in the market.

Table 9: Scenario contractor and owner parameters

<table>
<tr><th></th><th>Contractor Starting Parameters</th><th>Owner Parameters</th><th>mean contractor t-value</th><th>Mean number of bidders in last 2 years</th></tr>
<tr><td>1)Minimum</td><td rowspan="4">10 Contractors
t-value: 0.9
Rest of the parameters are set to a representative contractor pool according to Campo (2012)</td><td rowspan="4">2 Owners
Owner 1:
Desired sustainability: S(i)= 10 + i*10
t-value: 0.9
Generating 1/3 of the project
Owner 2:
Desired sustainability: 0</td><td>0.49</td><td>5.05</td></tr>
<tr><td>2)Discount</td><td>0.70</td><td>0.0</td></tr>
<tr><td>3)Scaling Discount</td><td>0.65</td><td>5.85</td></tr>
<tr><td>4)Optimized: S-Criteria(i)= {minimum, minimum, discount,</td><td>0.48</td><td>6.88</td></tr>
</table>

minimum, scaling-discount}		Generating 2/3 of projects		
5)Further Optimized		Owner 1: t-value: {0.71, 0.17, 0.54, 0.29, 0.83}	**0.40**	**8.1**

Results

The sustainability score and bid distributions of the public owner's projects across all scenarios are shown in detail below. The graphs show the development across the scenario described in *Table 9.* Each line represents one contractor's bid for a project from the public owner. As sustainability requirements change over the years, contractor's sustainability capabilities do too. This is signified though the changing colour of the lines.

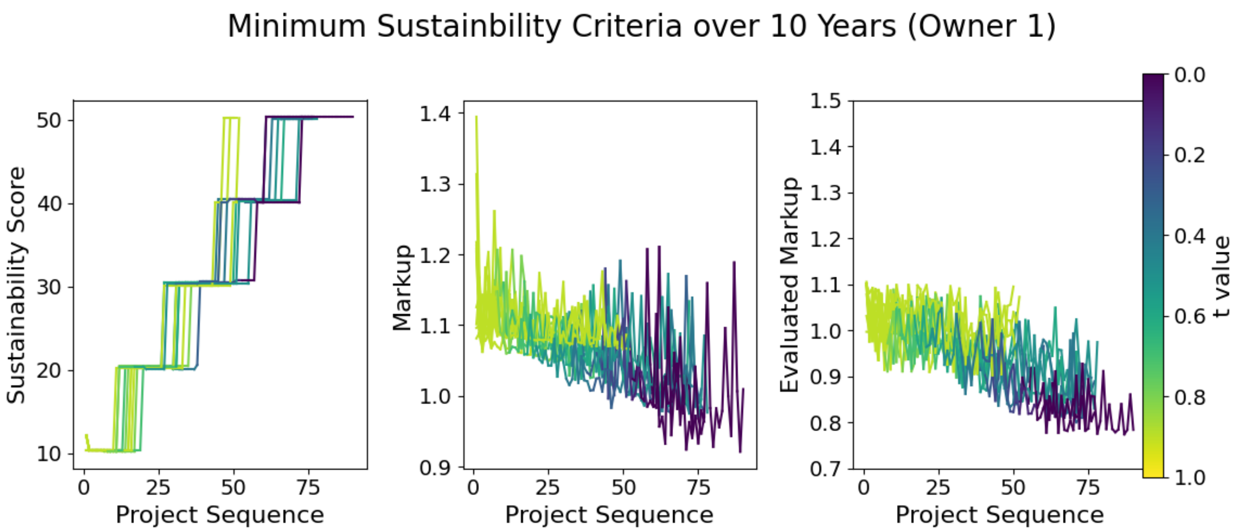


Figure 32: Bid distribution Scenario 1

Figure 32 illustrates scenario 1 the progression of sustainability outcomes when only minimum sustainability criteria are applied to achieve sustainability goals. The observed behavior aligns with previous findings: the minimum criteria lead to the exclusion of many contractors. However, those who do participate, regardless of their sustainability capabilities, submit competitive bids and have a chance to win. By the final two years of the simulation, up to six contractors are consistently submitting competitive bids. This trend is reflected in the metrics shown in *table 9,* where the mean contractor t-value is strong, indicating that a diverse range of contractors secured projects and increased their total sustainability investment. This is also mirrored in the high mean number of bidders during the last two years, demonstrating robust competition. Interestingly, in this scenario, the markup, which signifies the actual cost of the project for the owner decreases over time on average, but price variability increases. This means the contractors themselves are partly absorbing the extra costs for the increased sustainability. This aligns with the results from *section 4.4*, which stipulates that the minimum criteria is cheapest for the owner's side.

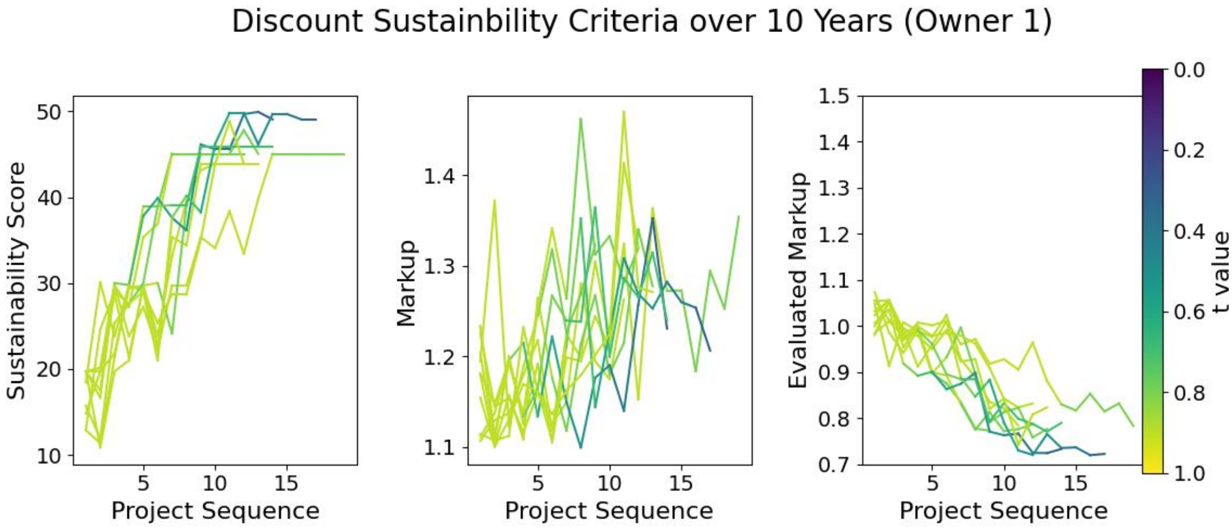


Figure 33: Bid distribution Scenario 2

Figure 33 illustrates the outcome of Scenario 2, where discount criteria are used to achieve sustainability goals. This approach performs poorly compared to other scenarios. It appears to combine the drawbacks of contractor exclusion, similar to what is observed in the minimum criteria, without achieving the benefit of leveling the playing field and encouraging contractor participation. The criteria heavily favor contractors with only marginally better sustainability capabilities, which results in fewer bids being submitted from the start and only a small number of contractors winning projects. As sustainability score requirements increase, the number of bid cancellations rises due to fewer contractors being able to meet the criteria or finding it worthwhile to bid. This leads to a consistently low average contractor sustainability capability, and, by the end of the simulation, no bids being awarded in the final two years. This is reflected in the x-axis (project sequence) not reaching the full 60-100, no bids are being submitted anymore past project 20. There is also a trend toward higher markups meaning it becomes more expensive for the public owner to finance sustainable projects.

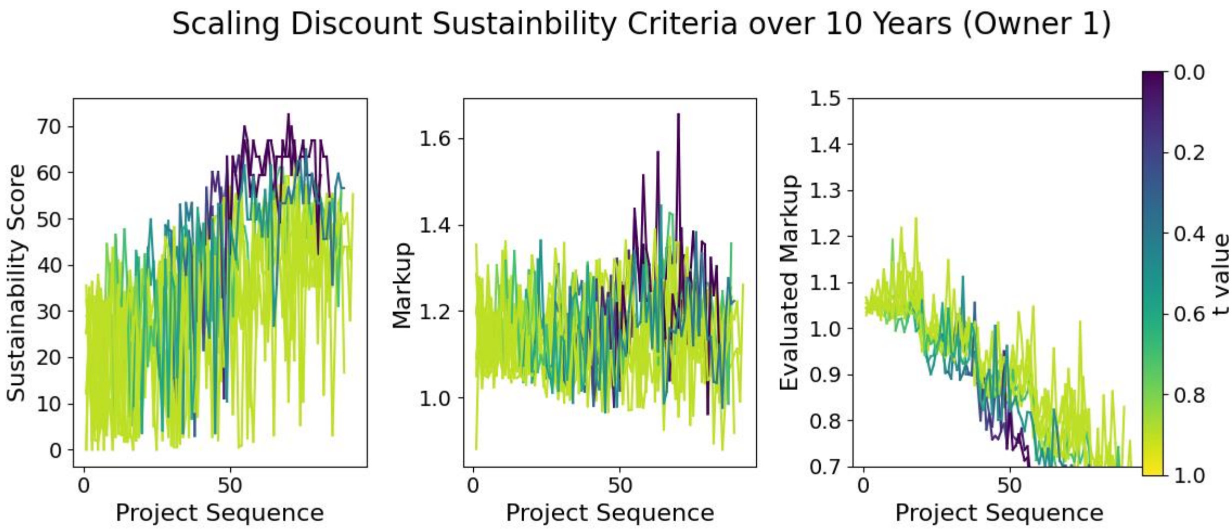


Figure 34: Bid distribution Scenario 3

Figure 34 illustrates the results for Scenario 3, which applies the scaling discount criteria. A key observation is that the number of bidders remains high throughout the entire period, although only a small subset bids competitively and secures project wins. Over time, the gap in competitiveness between contractors widens. The scaling discount criteria effectively attract a large number of bids and maximize project-specific sustainability. However, it does not promote equitable access or provide opportunities for a diverse range of contractors. While participation is encouraged, the benefits are concentrated among a limited group. Only 3 unique contractors are rewarded a project by the public owner. This limits broader contractor engagement and reward distribution. The price development as seen by the markup graph in the middle is relatively neutral, with increasing variance in the later years. It seems that around project 60 the three contractors that always win tried to increase their prices but were pressured by the competition back to relatively normal prices.

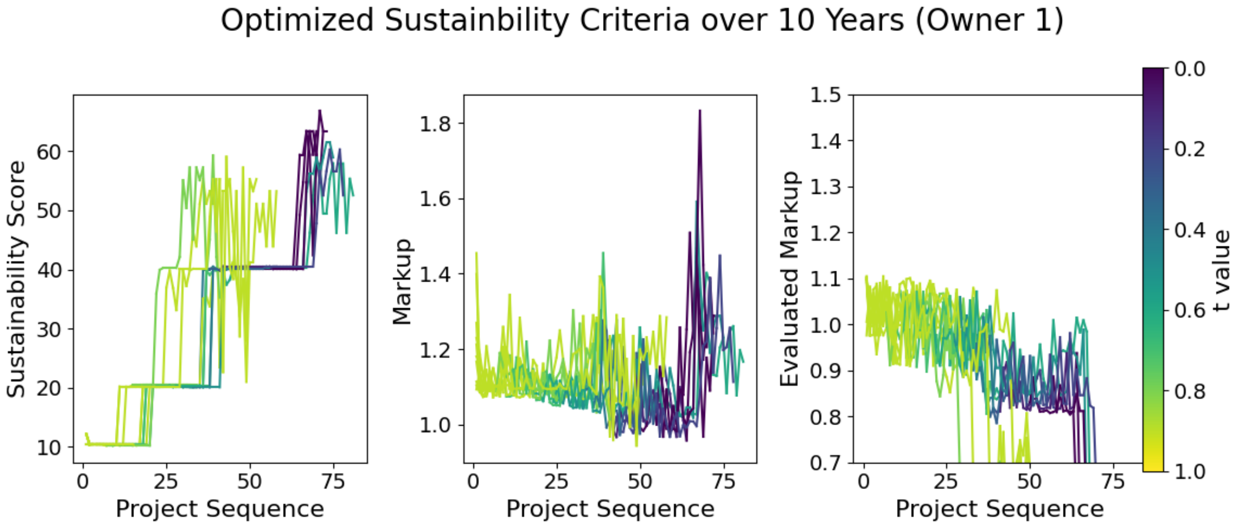


Figure 35: Bid distribution Scenario 4

Figure 35 presents the results of the final scenario, which uses a combination of all sustainability criteria to optimize contractor engagement and sustainability investment. This approach begins with the application of minimum and discount criteria, going back to minimum and transitions to scaling discount criteria in the final phase to maximize bidding participation.

While the underlying mechanism behind its effectiveness is not immediately apparent, it is evident that employing a mix of methods and adapting to market conditions can yield substantial benefits. The strategy appears to initially segment contractors inclined to bid on sustainability projects by starting with the minimum criteria, creating a form of market segmentation. It then broadens the award distribution, creating and maintaining a smaller but competitive pool of contractors as the simulation progresses. This scenario outperforms all others on both key metrics, demonstrating the potential of a flexible and responsive approach to promoting equitable access and sustainability investment. It also shows a very neutral price development, for the first 8 years, as seen in the middle markup graph. When the switch to scaling discount criteria in the last 2 years the 'unrivaled' pool of just a few contractors seems to cause a sudden price explosion, but competitive prices are quickly reestablished though competitive pressures.

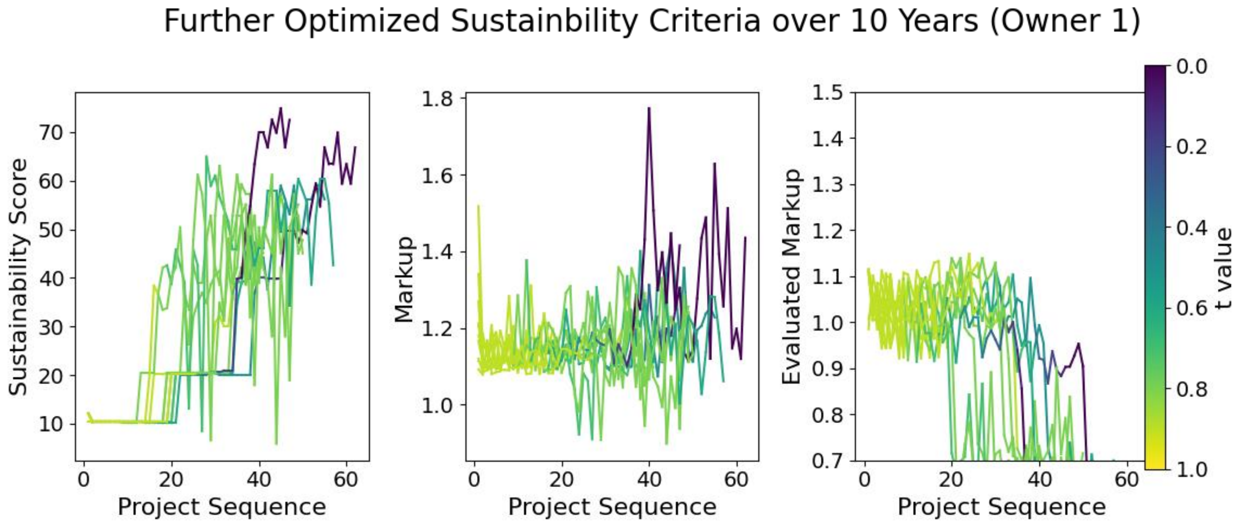


Figure 36: Bid distribution Scenario 5

Figure 36 illustrates the outcomes of the further optimized policy scenario, where the owner t-value (sustainability stringency of the owner) was adjusted over time using a genetic algorithm. This approach enhances both sustainability scores and markup metrics, outperforming all previous scenarios.

Notably, the results show that the optimized owner t-value decreased from the initial 0.9 across all time steps, suggesting that stricter criteria were more effective in this context. This supports the idea that an optimal policy doesn't involve more lenient and forgiving criteria implementation even for the metrics of contractor participation and sustainability investment. The theory of segmenting a smaller, competitive pool of contractors and maintaining it through balanced project awards, seems to be further supported. The findings further highlight that strategic adjustment of sustainability stringency can foster sustained competition and increased sustainability investment among contractors.

Results and Findings

The findings from this section highlight the key trade-offs of different sustainability criteria implementations and their effects on equitable access to sustainable construction opportunities. These results, described in detail across the scenarios, reveal significant patterns in contractor participation, sustainability outcomes, and project costs.

The minimum criteria ensured cost efficiency and fairness but limited sustainability gains, while the discount criteria delivered moderate sustainability improvements with controlled costs but discouraged broader contractor participation. In contrast, the scaling discount achieved the highest sustainability outcomes but concentrated benefits among a small group of top-performing contractors, reducing market inclusivity. The adaptive approach, combining all criteria dynamically over time, emerged as the most effective policy. By segmenting the market initially with minimum criteria and transitioning to scaling discounts, it maintained contractor engagement, promoted sustainability investments, and balanced competition. An additional optimization of the owner's t-value further reinforced the effectiveness of stricter sustainability targets in achieving better outcomes.

While the experiments provided valuable insights, certain aspects remain unexplored. The controlled nature of the model, such as simplified project and contractor attributes, constant bidder numbers, and static market representation, does not fully capture the complexity of real-world procurement markets or the differences between public and private sector dynamics. Additionally, more intricate challenges in Green Public Procurement (GPP), such as substitution risk (Lundberg et al., 2015), where increased public demand for sustainability may lead to unintended market consequences, were beyond the scope of this study. The metrics developed to evaluate contractor behavior, mean contractor t-value (sustainability capability) and mean number of bidders, offered a structured way to assess competition and sustainability outcomes but are inherently subjective and simplified, reflecting the specific needs and assumptions of this research.

5.3 VALIDATION

The external validation process focused on assessing both the overall validity of the model and the outcomes of the simulated policy scenarios. Semi-structured interviews with industry experts were conducted guided by and Interview thread that can be seen in *Appendix 1*, to evaluate whether the model accurately reflects real-world conditions and to gather feedback on the results of the selection criteria scenarios. These interviews were essential in confirming the model's alignment with industry practices and identifying any gaps in its assumptions. The inquiries were divided into two main topics: the validity of various aspects of the model and the applicability of the model in conducting scenario analysis and optimization, as well as potential industry uses for these analyses.

Table 10: Public owner side validation

Category	Model aspect/use		
Model aspects	Bid decision factors	Medium	The owners generally agreed that the factors that decide the contractor agent bid decision are relevant but noted potential gaps. For example, the model does not account for contractors' tendency to submit "false bids" or strategically low bids when they expect limited oversight on their sustainability claims, as well as not considering change orders.
	Sustainability criteria and logic	High	Sustainability was viewed as accurately modeled but noted that in practice, contractors do not always achieve optimal efficiency ("bank for buck"). The feedback also emphasized increased administrative costs for more complicated sustainability tenders and upfront sustainability investments that improve contractor sustainability capability, spanning across many projects. This is different from the 'learning' effect implemented in the current model.
	Estimating markup and win probability	Medium	Owners confirmed that competition strongly affects bidding strategy, yet noted the model doesn't account for contractors' multi-project thinking. Contractors may spread their investment cost onto bid prices across multiple projects to offset the upfront cost of sustainable assets like electric machinery.
	Owner side bidding representation	High	Aligns closely with real-world methods, owners often budget for sustainability (e.g., % set aside) and will accurately tune their sustainability criteria, but the model lacks detail on specific goals or drivers for sustainability value.
Model uses	Simulation results	Medium	The contractor expressed that the up and down sides of the different criteria expressed in the simulation results seem to align with the real world, but the usability is decrease because of the lack of integration of factors such as administrative cost or ease of use of the criteria.
	Real-world use for strategy planning	High	Owner highlights the no simulation of multi-project markets for cost-sharing strategies and strategic bidding adaptations have been done and a model like this might be useful to refine long term strategies to reach sustainability goals.
	Their use of simulation tools	Medium	Owners supported using simulations and expressed some interest in the findings but highlighted that their main use is individual project tenders rather than through broader models. In their experience modeling

			isolated or single-project bidding behavior with sustainability requirements has been effective at optimizing their scoring rules and discount factors

The owner validation underscored several strengths of the model, such as its incorporation of sustainability, the consideration of competitive dynamics in bidding, and the use of a diminishing returns curve for sustainability investments. Owners found that these elements align closely with real-world decision-making processes, suggesting that the model successfully replicates core aspects.

However, certain limitations were also identified. First, owners noted that contractors often submit bids that do not fully account for actual project costs, especially when there is an expectation of limited post-bid oversight. This strategic behavior, often resulting in "false bids," is not currently modeled and may affect the accuracy of simulations where contractor integrity varies. Additionally, while the model represents sustainability investment as a one-time decision per project the multi-project perspective is limited to the sustainability learning mechanism, the owner emphasized that contractors tend to balance sustainability investments across multiple projects. Integrating this feature would allow the model to better reflect cost distribution strategies commonly employed by contractors, particularly for costly assets like electric machinery.

The interviews also revealed areas where the model could be refined for specific purposes. For instance, while the model accurately estimates win probability based on competition, it does not account for the tendency of contractors to adjust bids based on anticipated future projects. In long-term or recurring contract environments, contractors may modify their bidding strategy in response to market trends and ongoing project pipelines. Introducing a market anticipation factor could enhance the model's realism for such scenarios.

Table 11: Contractor side validation

Category	Model aspect/use		
Model aspects	Bid decision factors	High	Their approach to evaluating tenders includes multiple review stages and categorization based on risk exposure. Tenders are assessed through structured criteria (e.g., project size, client, logistics, sustainability alignment) before committing, reflecting a thorough bid/no-bid decision-making process. The model is very accurate in this regard, but many factors that are important on a portfolio level are omitted in this model
	Sustainability criteria and logic	Medium	The contractor emphasizes a strong commitment to sustainability, guided by ambitious targets, such as decarbonization goals by 2030. This means they frequently avoid bids that lack sustainability requirements, suggesting that contractors often self-select projects based on alignment with their sustainability standards. This multi-project thinking is not included in the model and prioritization of sustainable projects only partly.
	Estimating markup and win probability	Medium	Contractors use a multi-stage assessment for bid/no-bid, factoring in project risk, sustainability, and client compatibility, win probability ranks lower in the considerations.
Model use	Simulation results	Medium	Contractor highlights that the prequalification step often contributes much more to a bid/no bid decision than the form of selection criteria. The optimized scenario echoed their sentiment that the best

			solution is flexible and based on contractor owner contractor communication and relationship.
	Real-world use for strategy planning	Medium	The contractor stresses the importance of client collaboration and demand in driving sustainability. They need project owner assurance that upfront sustainability investment will pay off. If a model like this can help owners make that decision they see a use for it.
	Their use of digital tools	Low	Tools like this are not as important as client communication and relationships. Tender specific calculation tools for best scoring are being used.

The interview with contractors provided practical insights into their approach to bidding, sustainability, and client interaction. While the contractor's approach is grounded in structured assessments and extensive client communication, it also reflects challenges and strategies that are not fully captured in the current model. The most common allocation scenario is not an auction but better described as an auction with serial negotiation, a hybrid approach.

Firstly, contractors place significant emphasis on sustainability, integrating it as a core criterion for bid/no-bid decisions. Their commitment to long-term sustainability aligns well with the model's sustainability focus, confirming its importance as a key factor in contractor behavior. However, the contractors utilize a multi-stage decision process that considers portfolio alignment, evaluating how each project fits into broader business objectives and resource distribution. This aspect suggests that the model could be enhanced to include more dynamic bid/no-bid decisions that incorporate portfolio-level thinking. They also emphasize that pre-qualifications are often more important than the selection criteria themselves, as contractors highlighted that passing the pre-qualification phase often dictates whether they will continue to bid.

The contractor's feedback also emphasized the cost challenges associated with sustainability investments, such as high upfront costs for equipment like electrified machinery. Although the model accounts for sustainability investment, it could better capture the financial burdens contractors face during the early stages, especially in markets lacking supportive infrastructure. Reflecting gradual sustainability transitions and the distribution of costs across multiple projects could make the model more realistic in these contexts.

Adaptability to client-driven project modifications is another area for potential improvement. Contractors frequently collaborate with clients to adjust project specifications and include sustainable features. The current model assumes fixed bid requirements, which limits its application in scenarios where sustainability objectives evolve through client interaction. Merging client interaction insights with these findings could enhance the model's representation of collaborative, flexible project adaptations. Real-world flexibility was a recurring theme in the interviews. Processes aren't as rigid as the model may suggest, with contractors often needing to navigate changes and communicate effectively with clients to adapt to evolving project requirements.

The validation process through interviews with both public owners and contractors has highlighted that while the model effectively simulates key aspects of contractor bidding behavior and sustainability integration, there are areas for refinement. The model's strengths lie in its realistic representation of bid decision factors, sustainability logic, and competitive dynamics. However, it could benefit from enhancements to better reflect multi-project strategies, the significance of prequalification stages, and the adaptability required for client-driven project modifications.

Crucially, the simulation results were supported by industry feedback, emphasizing that flexibility in applying selection criteria and maintaining a competitive pool of contractors are key to effective procurement strategies. The concept of market segmentation was positively echoed by contractors, who noted that sustainable capabilities can be subcontracted or shared through partnerships, making specialization and niche investment highly advantageous.

7. DISCUSSION

7.1 DISCUSSION

7.1 DISCUSSION

This research set out to address key gaps in the literature by examining how the integration of sustainability criteria affects contractor behavior in construction procurement, using a novel bidding model as its foundation. To provide a comprehensive discussion, the research is broken down into several interconnected components: (i) literature search and data collection, (ii) model conceptualization and implementation, and (iii) simulation experiments, results analysis, and recommendations. Each of these elements will be analyzed through the lens of the study's outcomes to highlight their contributions and implications.

Literature research and Data collection

This discussion begins by reflecting on the process of literature research and data collection. While literature research is often seen as a foundational step that provides context for the subsequent research part, in this case, it played a much more iterative role. The literature search not only set the stage for identifying the research gap but also served as a guiding and validation instrument throughout the entire research process.

Sustainable procurement is a multidimensional and interdisciplinary topic. This translates into many key-works for a comprehensive search of the topics. As the study progressed, additional keywords were incorporated into the search process to ensure a more detailed understanding of the literature. A citation-based approach proved particularly invaluable in bridging gaps and uncovering overlooked studies with empirical data, such as Campo (2012). The inclusion of such foundational data was very important to this research, providing the empirical basis often absent in other studies applying auction theory to construction procurement models such as Idrees et al. (2023). Campo's dataset, while foundational to this research, does have limitations. It is dated and focused exclusively on contractors in Los Angeles participating in government contracts, which may introduce bias. Despite this, the utility curves extracted from the data align with economic intuition and were validated through contractor feedback, demonstrating their relevance to real-world contexts.

Challenges arose when seeking empirical evidence for contractor behavior patterns under sustainability-driven criteria, particularly for POM. Many existing studies rely on qualitative observations, with few providing isolated or measurable effects validated by empirical data. Aggregation of data to support findings in studies often resulted in broad patterns rather than fine-grained insights applicable to specific contexts, that could have been replicated in more detail to validate the models more robustly. This was also the case for studies and data used to build the model, the sustainability aspect of the model used patterns found in related studies such as sustainability cost premium studies or sustainability optimization studies to imitate the identified common trends.

This approach makes the model more generalizable and adaptable, especially for exploring diverse procurement scenarios. However, it also introduces a trade-off, as it limits the model's ability to capture the nuanced, context-specific dynamics of projects. However, for ABM methods, this balance between generality and specificity is very important, as will be explored in the next section.

Model Conceptualization and Implementation

This section reflects on the modeling decisions made throughout the study, addressing the choices, trade-offs, and their implications for the research outcomes. While detailed descriptions of models are provided in earlier chapters, this discussion focuses on the rationale behind key decisions and their consequences for the study's theoretical and practical contributions.

A variety of modeling approaches were considered, including utility theory, game theory, and behavioral models, all of which draw upon previous studies on markup strategies and bid/no-bid decision-making. However, no single framework was found to provide bid predictions that aligned consistently with all contractor behavior. Among the options, utility theory emerged as the most promising, not only for its widespread use but also for its alignment with basic economic principles that drive contractor decision-making. As an extension of utility theory, prospect theory was also considered, but utility theory was favored due to its simplicity and adaptability to the bidding environment simulated in this research.

An important aspect of the model to highlight is the treatment of budgeting and desired sustainability. The model assumes that a project has a baseline appraisal value, the common value signal for bid participants, essentially a project without any sustainability. The sustainability goals are budgeted and accounted for separately in a second separate common value signal. This separation, briefly explained in *Section 4.4*, reflects the current mindset in procurement practices, where sustainability goals are often considered an additional cost layered onto traditional project budgets. While this approach aligns well with how procurement systems currently function, it is inherently reductive. In reality, no project is truly "without sustainability," as every decision throughout a project's lifecycle (design, material selection, and construction methods) has environmental implications. This detail cannot be fully captured in the current model, the current implementation has implication on how the simulation results should interpreted as reflected in *Section 4.4.*

One of the most challenging aspects of the modeling process was incorporating the bid/no-bid decision. Existing studies often rely on highly detailed data about project and contractor attributes, which were not available for this purely economic auction model. A simplified approach was adopted, where "throwaway bids" observed in simulations were used as a proxy for no-bid decisions. This adjustment reflects behavior seen in practice and discussed in the literature, allowing the model to capture key dynamics without adding unnecessary complexity.

Given the general-purpose nature of the model built for this research, simplifications were necessary to incorporate assumptions and behavioral patterns from the literature into the model. This approach worked well, as evidenced by validation feedback, which showed agreement from industry experts. However, the breadth of this study also introduced limitations. A more focused approach tailored to a specific project type, such as roadworks, could have enabled the use of more detailed datasets, simplifying the modeling process and improving specificity. Feedback during the validation phase echoed this sentiment, suggesting that narrowing the scope could improve the model's applicability to real-world contexts.

This research not only explored the integration of sustainability criteria into construction procurement but also addressed a critical gap identified in the literature review: the limited applicability of classical auction theory to construction bidding models. However, there are many deviations from traditional auction theory in construction that are highlighted in *section 1.4.* Drew (2010) highlights a fundamental issue, that is also echoed in validation interviews. The misalignment stems from the complex and context-dependent nature of construction procurement and the value theory – the worth of a project to a contractor, which is difficult to capture in traditional auction models. He questions the feasibility of directly applying auction theory to construction, given its assumptions about bidder behavior and market dynamics, which may differ significantly from how contractors actually bid or submit tenders in practice.

By incorporating utility theory and sustainability criteria into the bidding model, this study extends auction theory beyond its conventional boundaries, providing a highly theoretical lens for understanding construction procurement. While uncertainties remain regarding the representativeness of all procurement nuances in construction, the model effectively captures key economic principles. Modern applications of auction theory, as highlighted in the research gap (e.g., FCC spectrum auctions and carbon trading schemes), demonstrate high context dependence are not always necessary to yield meaningful insights.

In this study, the agents behave according to established economic theories that align with real-world company behavior, maximizing utility within the given parameters. By adding a layer of sustainability complexity, the model reveals how utility-maximizing agents would respond to different auction setups that use multi-dimensional scoring rules instead of price-only bid selection. This provides valuable insights into the strengths and limitations of various sustainability criteria implementation.

The adaptability of the model developed in this study represents one of its key strengths. By incorporating behavioral factors such as risk aversion and sustainability preferences, the model bridges theoretical frameworks with practical considerations, offering insights applicable across various contexts. However, a common challenge with Agent-Based Models (ABMs) is that increasing complexity can introduce uncertainty, where results may become artifacts of the model's intricate design rather than genuine reflections of real-world behavior. This is an inherent limitation of bottom-up modeling approaches, emphasizing the need to strike a balance between simplicity and complexity. As discussed in the Methodology chapter, this research adhered to the KIDS and KISS principle, ensuring the model remained robust and interpretable while still capturing meaningful patterns and behaviors. Despite these challenges, the study contributes significantly to the literature by integrating auction theory and sustainability criteria into construction procurement, providing a foundation for future research to build upon and refine.

Simulation Experiments, Analyzing Results and Deriving Recommendations
The simulation experiments in this study served a dual purpose: to validate the model using POM (Model 1 and Model 2) and to explore the effects of integrating sustainability criteria into contractor bidding environments (Model 2 and Model 3). While the experiments were relatively simple in design, this was partly dictated by the straightforward nature of the validation patterns due to the limited literature and empirical data available, as discussed earlier. Nevertheless, the experiments effectively captured key dynamics and patterns within procurement scenarios, that were also partly validated by traditional auction theory like the monotonicity theorem. The analysis of simple bid patterns and scenarios already provided foundational insights into contractor behavior under different sustainability criteria.

In particular, Model 2 demonstrated significant variations in contractor responses to continuous, discrete, and minimum sustainability criteria. These findings align with speculations in the literature that procurement methods and selection criteria can influence contractors' bidding strategies and participation decisions. As pointed out in *section 3.1* Ruparathna and Hewage (2015) and Sheamar et al. (2023) highlight how different procurement practices can shape the competitive landscape, affecting not only the number of contractors willing to bid but also their markup strategies and overall bidding behavior. The model shows that this is also true for sustainability criteria implementation in this research.

The final simulation experiment adopted a simplified design to isolate the effects of sustainability integration within the bidding environment. Key features included a sustainability learning mechanism for contractors, as well as controlled project and contractor attributes, ensuring clarity in interpreting results. Although larger and more realistic simulations were possible, the focus on simplicity enabled a more direct examination of the dynamics at play. The results revealed that maximal adoption and investment in sustainability were most effectively driven by a smaller subset of contractors. This challenges prevailing assumptions in the literature suggesting that market segmentation, often viewed as a drawback, can actually foster a concentrated, competitive pool of contractors willing to invest in sustainable technologies and practices and can do so without going against efficient allocation of contracts. These findings align with concerns raised in the literature review, which highlighted how sustainability criteria often favor larger, more capable contractors while excluding smaller firms (Hwang et al., 2018; Upstill-Goddard et al., 2015). However, the results here suggest that strategic segmentation, combined with balanced rewards, can actually have positive consequences when it comes to achieving sustainability goals without compromising competition.

In general, it could be said that the developed theoretical framework seems to be quite effective for explaining and predicting bid mark-up decisions. As for the effectiveness of the model, some considerations are noteworthy, as follows:

- **Effectiveness in Capturing Bid Dynamics**
  The framework's utility-based foundation successfully modeled bid pricing in first-price blind auctions, aligning well with established economic theories. This alignment provides confidence in the model's ability to replicate core contractor behaviors under varied procurement conditions. However, one notable limitation is the underrepresentation of

prequalification stages. Validation feedback emphasized the importance of prequalification as a decisive factor in contractor decision-making, often preceding considerations of bid pricing or sustainability. Incorporating structured prequalification mechanisms in future iterations could enhance the model's realism and predictive power.

- **Challenges in Representing Sustainability Nuances**
  While the sustainability component introduced innovation to contractor bidding simulations, it relied heavily on aggregated patterns from literature. This approach, while practical, limits the ability to capture the nuances of real-world contractor practices, such as region-specific sustainability strategies or market-specific dynamics. Moreover, the policy scenario simulations revealed the importance of tailoring sustainability criteria to encourage meaningful contractor participation. Simulations showed that mixing and adapting sustainability criteria fosters a more competitive bidding environment while maintaining stringent sustainability demands, underscoring the need for flexible and context-aware criteria implementation.
- **Market Segmentation and Competitiveness**
  The findings from the final simulation challenge the conventional view in literature that market segmentation hinders sustainability progress. Instead, the results suggest that concentrating sustainability efforts among a smaller group of contractors can drive innovation without compromising competitive pressures. This was further supported by insights from policy scenario evaluations, which demonstrated that early market segmentation—if managed strategically—can lead to effective sustainability investments while preserving competition. Such segmentation rewards niche capabilities and promotes specialization, offering a pathway to achieve sustainability objectives without diluting market competitiveness.
- **Balancing Model Simplicity and Realism**
  A recurring theme in validation feedback was the trade-off between simplicity and realism. While the simplified design of the simulations facilitated clear insights, it also highlighted the limitations of a general-purpose approach. For instance, the static nature of bid requirements in the model does not reflect the adaptability required in real-world procurement, where client-driven project adjustments are common. Additionally, the absence of multi-project strategic planning limited the model's ability to capture economies of scale, which contractors often leverage to offset sustainability investment costs. Future iterations of the model could address these aspects by incorporating adaptive bid requirements and multi-project strategies, thereby enhancing its relevance and applicability to diverse procurement scenarios.

Limitations, Representativeness and Biases

While this study makes meaningful contributions to the theoretical development and application of bidding models in sustainability-driven construction procurement, several limitations warrant discussion. These limitations relate to the model's scope, the representativeness of the data, and potential biases that influence the findings and their applicability.

This research presents an initial model that captures the integration of sustainability criteria into construction procurement, supporting a subset of common bid scenarios. While the findings offer significant theoretical insights into bid mark-up decisions and sustainability trade-offs, the model does not aim to cover the full complexity of real-world procurement contexts. The use of simplified assumptions constrains the model's ability to simulate dynamic, multi-project bidding environments. As such, while the study provides valuable starting points, it does not claim comprehensive coverage of all scenarios. The while the limitations of the approaches and methods were already mentioned in the corresponding chapters and sections, the following are limitations inherent to the model and the and the experiment designs:

- **Small-Scale Experiments:** The experiments were constrained to simplified, small-scale scenarios that controlled many variables. While this allowed for clearer identification of the effects of sustainability criteria, it limits the model's applicability to large-scale, dynamic procurement environments. For instance, real-world bidding often involves fluctuating competition levels and project-specific complexities that could not be fully captured here.
- **Static Project Attributes:** The model assumes fixed project attributes across simulations, omitting factors such as location, contract duration, and risk levels, which are frequently cited

in literature as critical determinants of contractor behavior. Egemen & Mohamed (2007) emphasize the strategic importance of certain projects, where factors like market expansion or classification improvement influence bid/no-bid decisions. These attributes were not modeled, restricting the ability to simulate varied strategic behaviors.

- **Limited Contractor Heterogeneity:** Contractor diversity in terms of size, risk appetite, and resource availability was simplified, which fails to capture market heterogeneity. Shokri-Ghasabeh & Chileshe (2016) illustrate that small, medium, and large contractors approach bids differently, prioritizing client capability, project risk, or long-term growth strategies, respectively. While the financial class modeler provides some differentiation, other factors—such as operational capabilities or experience—were not explicitly modeled.
- **Assumption of Full Bid Information:** The model assumes that contractors have access to complete bid histories to calculate their win probabilities using Friedman's method. While this simplifies the decision-making process, it does not reflect real-world conditions, where imperfect information and strategic ambiguity influence bidding behavior. Empirical studies like Drew (2010) highlight the gap between theoretical auction assumptions and the realities of construction bidding, where information asymmetry is common.
- **Single-Project Focus:** The model simulates contractor behavior for isolated projects, ignoring portfolio-level strategies where contractors distribute sustainability investments across multiple projects to optimize long-term returns. As noted in Shokri-Ghasabeh & Chileshe (2016), larger contractors often balance short-term financial goals with strategic priorities, an aspect that would require multi-project dynamics to capture effectively.
- **Simplified Auction Assumptions (Common Value Models):** The model assumes a common value auction framework, where contractors derive bid values based on shared cost estimates. However, Drew (2010) argues that the assumptions of Independent Private Value (IPV) and Common Value (CV) auction theories are often contested in construction procurement due to the inherent uncertainty and strategic differences between contractors. The model does not address these complexities, limiting its alignment with real-world bidding conditions.

Additionally, from an academic standpoint, this study highlights the need for further empirical validation of the model across different procurement scenarios. While the current research successfully integrates utility theory and sustainability considerations, its empirical grounding relies heavily on limited datasets and generalized patterns from the literature. A broader and more diverse dataset, particularly one encompassing different regions and project types, would enhance the robustness of the findings. Moreover, integrating multi-project dynamics and adaptive contractor strategies into the model could address key gaps in understanding how sustainability investments are distributed over time and across portfolios.

However, from a practical standpoint, the model still demonstrates several strengths. Its qualitative predictions offer owners actionable insights into how different sustainability criteria can be implemented to balance environmental goals with competitive pricing. By illustrating the trade-offs between continuous, discrete, and minimum sustainability criteria, the model equips policymakers and procurement officials with tools to assess which approaches align best with their goals. Furthermore, the model's flexibility in simulating diverse contractor behaviors ensures relevance across a variety of procurement contexts.

Certain drawbacks were particular to practice identified. The reliance on aggregated data and simplified bidding dynamics limits the model's precision. For instance, the static bid requirements used in simulations do not fully capture the iterative nature of real-world procurement, where client feedback often shapes contractor decisions and change orders play a big part in the day to day between owners and contractors. Additionally, the exclusion of administrative costs—such as the overhead of sustainability reporting or prequalification compliance—may underestimate the full economic impact of sustainability-driven procurement policies. Addressing these aspects in future research could improve the model's accuracy and practical relevance.

Linking Findings to Procurement Trends

The findings of this research directly align with key themes and challenges highlighted in the literature and industry practices concerning sustainable construction procurement. As discussed in the introduction, the construction sector is under significant pressure to balance cost efficiency, market competitiveness, and sustainability goals. This tension drives the need for innovative procurement models that can integrate these competing priorities effectively.

The study contributes to ongoing trends in procurement by demonstrating how sustainability criteria can influence contractor behavior and bid strategies. The insights derived from the final simulations show that carefully designed sustainability incentives—such as continuous criteria and controlled segmentation—can promote environmental investments without compromising competition. This aligns with recent shifts in procurement operations that increasingly prioritize value-based approaches, where sustainability and long-term environmental impact are considered alongside financial performance.

Governments worldwide are advancing initiatives to integrate sustainability into public procurement. For example, in May 2024, Germany's Federal Ministry for Economic Affairs and Climate Action launched its Green Public Procurement Initiative, targeting carbon neutrality by 2045. Among other measures, the initiative aims to drive demand for low-carbon materials in key sectors such as construction by developing clear definitions and labeling systems. However, these labels need to be integrated into the incentive structure and the procurement processes. This directly aligns with this research's emphasis on sustainability criteria as a mechanism to influence market dynamics and contractor behavior.

Ongoing efforts, such as Rijkswaterstaat's MKI system in the Netherlands and Germany's SNAP methodology, further demonstrate the evolving landscape of procurement, highlighting the need for flexible and context-specific strategies. Both approaches emphasize mixed methodologies, incorporating minimum, continuous, and capped criteria to balance sustainability goals with competitive bidding environments.

Effective procurement strategies, grounded in long-term sustainability objectives, are essential for transitioning to a more environmentally responsible construction industry. By influencing contractor behavior through well-designed incentives, public procurement can serve as a powerful tool to align market dynamics with global climate goals. This research provides valuable insights into how these strategies can be modeled and tested, offering a foundation for developing more effective and sustainable procurement practices.

8. CONCLUSION

8.1 CONCLUSION

This research sets out to integrate sustainability criteria into construction procurement through an ABM, focusing on economic outcomes, contractor behavior, and equitable access under various policy scenarios. The analysis provided key insights into how sustainability-driven procurement strategies impact market dynamics and contractor engagement.
To conclude this research, we address the sub questions and the main research question.

- **Sub-question 1:** What is the state of the art of modelling bidding and procurement in construction specifically ABM?

The use of ABMs in construction procurement remains a contested area of research. While many studies have sought to model contractor bidding behavior, there is a level of skepticism for the practical relevance of these efforts, highlighting a disconnect between theoretical models and the complex realities of construction tendering (Drew, 2010). Despite these concerns, studies demonstrate that contractor bid patterns can be effectively interpreted and explained using utility theory models, which align with economic principles and observed behaviors (Awwad et al., 2014; Asgari & Kandil, 2016; Awwad & Ammoury, 2019; Elsayegh et al., 2020).
The review also revealed that existing models, while insightful, often lack empirical grounding. By integrating empirical data from Campo (2012), this research enhanced the ABM's realism, particularly regarding financial health and risk aversion among contractors. This approach bridged a significant gap by connecting bidding behavior with auction theory, a connection absent in most prior studies. The study also contributed to advancing ABMs in construction procurement by validating model behavior against patterns observed in practice.

- **Sub-question 2:** How can existing ABMs be adapted or extended to incorporate sustainability criteria?

This research represents one of the first attempts to extend ABMs and auction models to include sustainability criteria in construction procurement. While no prior models explicitly addressed this challenge even in traditional auction theory scoring rule auctions with multi-dimensional bid evaluation are rarely subject of research (Milgrom 2003). This study confronted key issues, such as the inherent difficulty of reconciling sustainability goals with the lowest-bid winner logic of procurement processes. The difficulty in measuring sustainability outcomes not only poses challenges in practice, for which many sustainability frameworks have been developed, but also posed significant modeling obstacles. The second challenge is the lack of clear commensurability between financial and sustainability metrics, which is further complicated by the difficulty of embedding sustainability into incentive structures and procurement processes for contractors. To address these challenges, this research identified and modeled three commonly used mechanisms minimum criteria, discounts and scaling discounts.

Despite these challenges, the study successfully developed an ABM that incorporates sustainability considerations. By introducing mechanisms such as sustainability response curves and evaluation methods, the model was able to simulate nuanced contractor decision-making. This approach offered insights into how contractors balance sustainability investments with competitive pressures. However, the model's qualitative nature reflects both the limited availability of empirical data and the deliberate methodological choice to balance simplicity and realism. This balance was key to maintaining interpretability and ensuring the model's applicability across diverse procurement contexts, even if it meant sacrificing the precision of highly specific, quantitative simulations."

While the model proved effective in demonstrating important dynamics, the study identified opportunities for improvement. For example, future adaptations could incorporate portfolio-wide sustainability investments to simulate contractors' longer-term strategies more accurately. This would provide a more comprehensive view of how contractors balance sustainability goals across multiple projects, aligning the model more closely with real-world practices.

- **Sub-question 3:** What policy scenarios are most effective in promoting equitable access to sustainable construction opportunities?

The simulation experiments in this study offered valuable insights into the effects of different sustainability criteria on contractor behavior, competition, and sustainability outcomes. While the experiment design was small scale and controlled many variables of the experiments, limiting the representativeness and realism of the model, the findings point to key dynamics that can inform policy designs.

The optimized mixed-policy scenario emerged as the most effective strategy. By combining all implementation methods over time, this adaptive approach fostered contractor engagement, improved sustainability capabilities, and maintained healthy competition. The scenario demonstrated that a dynamic policy design can balance sustainability goals with market inclusivity, illustrating the potential for nuanced, multi-stage strategies to address the challenges inherent in sustainable procurement.

While the experiments cannot provide definitive guidance for all situations, these findings highlight the importance of context-specific and flexible policy approaches. They emphasize the value of adaptive strategies that evolve alongside market conditions and contractor capabilities, ensuring that both sustainability and equity objectives are addressed effectively.

- **Main research question**: What are the effects of different sustainability criteria implementations on contractor bid behavior in construction procurement?

The findings of this research confirmed that the implementation of sustainability criteria significantly impacts contractor behavior, competition, and economic outcomes in construction procurement. By focusing on commonly applied criteria—minimum, discount, and scaling discount—the study highlighted the advantages and limitations of each approach, shedding light on their effects within a lump sum bidding environment.

Minimum Criteria: These promoted fairness among participants by establishing a baseline requirement, ensuring that only contractors meeting sustainability thresholds could compete. However, this approach reduced competition and resulted in moderate sustainability gains, illustrating the trade-offs between inclusivity and environmental impact.

Discount Method: By providing incentives to all contractors based on their sustainability performance, this method maintained broader participation but failed to drive significant improvements in sustainability outcomes, underscoring its limited potential for achieving ambitious environmental goals.

Scaling Discount: This approach encouraged higher sustainability investments, maximizing project-specific sustainability outcomes. However, it disproportionately benefited more capable contractors, raising concerns about equity and access for smaller or less experienced firms.

The optimized mixed-policy scenario emerged as the most effective strategy, demonstrating how an adaptive combination of minimum criteria and scaling discounts can balance sustainability objectives with competitive inclusivity. By starting with minimum thresholds and transitioning to more incentive-driven mechanisms over time, this approach fostered contractor learning, enhanced sustainability capabilities, and maintained healthy market dynamics.

While the research focused on these commonly found criteria implementations, it acknowledges that they represent only a subset of possible strategies. The results suggest that targeted and adaptive policy adjustments can align contractor behavior with sustainability goals while preserving competition. However, further research is needed to explore additional criteria implementations and their applicability across diverse project types and procurement models.

In conclusion, this study highlights the potential of empirically informed ABMs to provide meaningful insights into the interplay between sustainability criteria and contractor behavior. The findings emphasize the importance of strategic, context-aware policy design to achieve a balanced and competitive procurement environment that encourages sustainable practices in the construction industry.

8.2 FURTHER RESEARCH

This study contributes to the growing body of knowledge on integrating sustainability into construction procurement through agent-based modeling. However, it also highlights several areas for further exploration, which can be divided into two categories: complementary research, addressing gaps and challenges encountered during this research process, and further research, extending the scope of this study to develop more targeted and impactful strategies.

Complementary research focuses on refining models and addressing gaps identified throughout this study to enhance their practical applicability.

- Empirical Data for Sustainability Metrics in Construction Procurement: A significant obstacle is the scarcity of comprehensive data, particularly concerning sustainability metrics, response curves, and cost premiums. The lack of standardized data hampers the development of accurate models and informed decision-making. Future research should prioritize the collection and standardization of sustainability-related data to enhance model precision and applicability.
- Auction Theory in Construction Procurement: Understanding contractor behavior in auction settings is crucial for designing effective procurement strategies. Existing theories, such as the Independent Private Values (IPV) and Common Value (CV) models, offer frameworks for analysis. However, empirical studies, like those by Drew (2010), question their applicability in real-world construction auctions. Further empirical research is needed to ascertain which theoretical models accurately reflect contractor behavior, both at individual project levels and across portfolios.

Further research builds on this study's findings to advance sustainable construction procurement in more specific contexts.

- Multi-Project Strategy Modeling: Investigating how contractors allocate sustainability investments across multiple projects can provide insights into long-term planning and resource optimization. Modeling these strategies would reflect real-world scenarios where contractors manage portfolios rather than isolated projects.
- Project-Type Specific Implementations: Tailoring models to specific types of construction projects, such as roadworks or residential buildings, can enhance relevance and accuracy. Different project types have unique sustainability challenges and opportunities; thus, specialized models can better inform procurement strategies.
- Economic Implications of Sustainability Investments: Analyzing the financial impacts of incorporating sustainability into procurement, including potential cost savings and return on investment, can provide a compelling case for stakeholders. Understanding the economic benefits is crucial for widespread adoption of sustainable practices.

Addressing these research areas will contribute to a more comprehensive understanding of sustainable procurement in construction.

8.3 SUMMARY

This research examined how the integration of sustainability criteria influences contractor behavior and pricing outcomes in construction procurement, utilizing an ABM as its foundation. The study aimed to address gaps in the literature on bidding and procurement by extending traditional auction theory and incorporating sustainability-driven mechanisms. The research not only contributes to the theoretical understanding of contractor bidding behavior under sustainability criteria but also provides practical insights for designing more effective procurement policies.

The research involved developing a novel ABM to simulate contractor behavior under various sustainability criteria implementations, such as minimum investment, discount, and scaling discount. Empirical insights from studies like Campo (2012) were integrated into the model to enhance its realism, focusing on key variables such as financial health, risk aversion, and sustainability investment behavior. The study relied on a comprehensive literature review to identify existing gaps and validate its approach, emphasizing the need for data on sustainability cost premiums and response curves in construction.

Through a series of simulation experiments, this research explored contractor decision-making and the implications of sustainability-driven procurement strategies. The findings highlight how different criteria implementations impact market competition, contractor engagement, and sustainability outcomes. Notably, the optimized mixed-policy scenario demonstrated the potential to balance sustainability goals with market inclusivity, fostering both contractor learning and environmental investments over time.

This study also revealed key challenges and limitations, such as the scarcity of standardized sustainability data and the difficulty of modeling portfolio-wide contractor strategies. However, the general-purpose nature of the model allows it to be adapted for various project types, offering a foundation for future studies to refine and expand upon.

In conclusion, this research highlights the importance of strategic, adaptive policy design in public procurement, showcasing how sustainability criteria can be leveraged to align contractor behavior with broader environmental goals. By bridging theoretical insights with practical considerations, the study lays the groundwork for future exploration into sustainable construction procurement, offering tools and frameworks to guide both academic inquiry and policy development.

APPENDIX

Introduction to the Model

Our model simulates how contractors make decisions in the bidding process for construction projects. Key features include:

- **Decision to Bid:** Contractors decide whether to bid on a project based on factors such as their current workload, project size, complexity, and expected competition.
- **Bid Calculation:** Contractors estimate their costs and add a markup to determine their bid amount. They may also decide how much to invest in sustainability measures, especially if the project requires certain sustainability standards. From this they can estimate the profit margin.
- **Win Probability Estimation:** The model calculates the likelihood of winning a bid using statistical methods, considering the number of competitors and their expected bidding strategies. Trying to balance profit maximization and win probability.
- **Sustainability Considerations:** Contractors evaluate the benefits and costs of investing in sustainability features, affecting both their bid amounts and perceived chances of winning.

We aim to replicate real-world decision-making processes to understand and predict contractor behavior in procurement auctions. Your feedback will help us validate and improve the model.

Section 1: Model Bidding Behavior

1. **Alignment with Real Practices**
   - **Question:** Does the model's depiction of how contractors decide whether to bid on a project reflect your experience?
   - **Grade (1-5):** Please rate the alignment (1 - Not at all, 5 - Completely aligned).
   - **Comments:** Are there any important factors or steps that the model misses?
2. **Factors Influencing Bid Decisions**
   - **Question:** The model considers workload, project characteristics, and competition when deciding to bid. Are these the main factors you consider?
   - **Grade (1-5):** Rate the importance of these factors in your decision-making (1 - Not important, 5 - Very important).
   - **Comments:** What other factors influence your decision to bid?

Section 2: Sustainability Logic/Considerations

1. **Impact of Sustainability Requirements**
   - **Question:** Does the model accurately represent how sustainability requirements affect your bidding process and decision-making?
   - **Grade (1-5):** Rate the accuracy (1 - Not accurate, 5 - Very accurate).
   - **Comments:** How do sustainability requirements influence your bids in practice?
2. **Deciding on Sustainability Investments**
   - **Question:** In the model, contractors decide how much to invest in sustainability measures based on project demands and potential benefits. Is this consistent with your approach?
   - **Grade (1-5):** Rate the consistency (1 - Not consistent, 5 - Very consistent).
   - **Comments:** How do you determine the level of investment in sustainability for a project?

Section 3: Estimating Win Probability

1. **Methods of Estimating Chances**
   - **Question:** The model uses statistical methods to estimate the chance of winning based on the number of competitors. Does this reflect how you estimate your chances?
   - **Grade (1-5):** Rate the reflection of your practice (1 - Not at all, 5 - Very much so).
   - **Comments:** How do you estimate your chances of winning a bid?
2. **Influence of Competitors**
   - **Question:** Does the number of competitors significantly influence your bidding strategy, as represented in the model?
   - **Grade (1-5):** Rate the influence (1 - No influence, 5 - Strong influence).

- **Comments:** How does the presence of competitors affect your bidding decisions?

Section 4: Simulation Method and Digital Tools

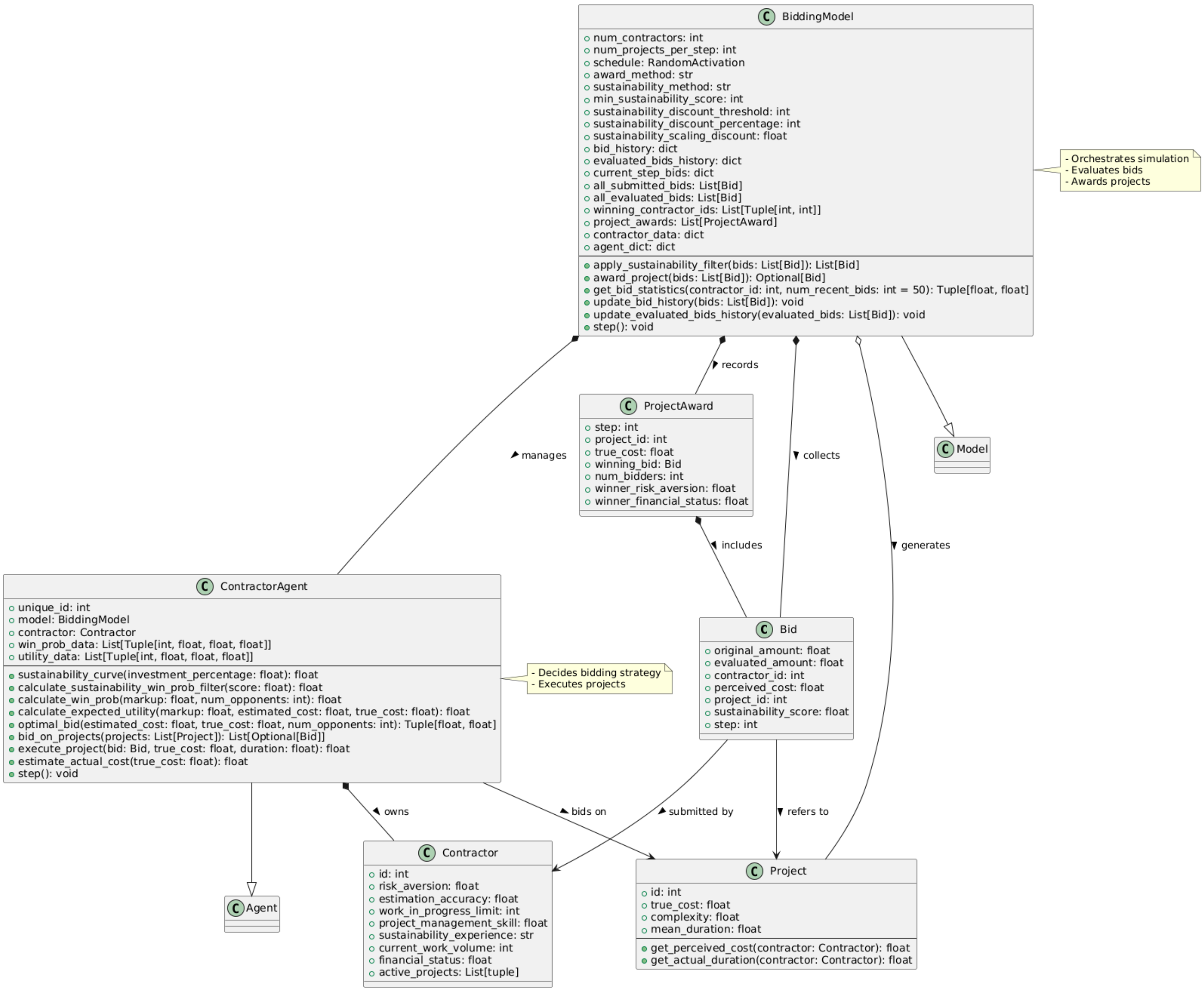
1. **Appropriateness of Simulation Approach**
    - **Question:** The model simulates contractor behavior using statistical and computational methods. Do you think this is an appropriate way to analyze bidding behavior?
    - **Grade (1-5):** Rate the appropriateness (1 - Not appropriate, 5 - Very appropriate).
    - **Comments:** Do you think simulation models can capture the complexities of real-world bidding?
2. **Use of Digital Tools in Bidding**
    - **Question:** Do you use digital tools or software to assist in your bidding process?
    - **Grade (Yes/No):** Please specify.
    - **Comments:** How do these tools influence your bidding strategy?

Section 5: Simulation Results and Real-World Representation

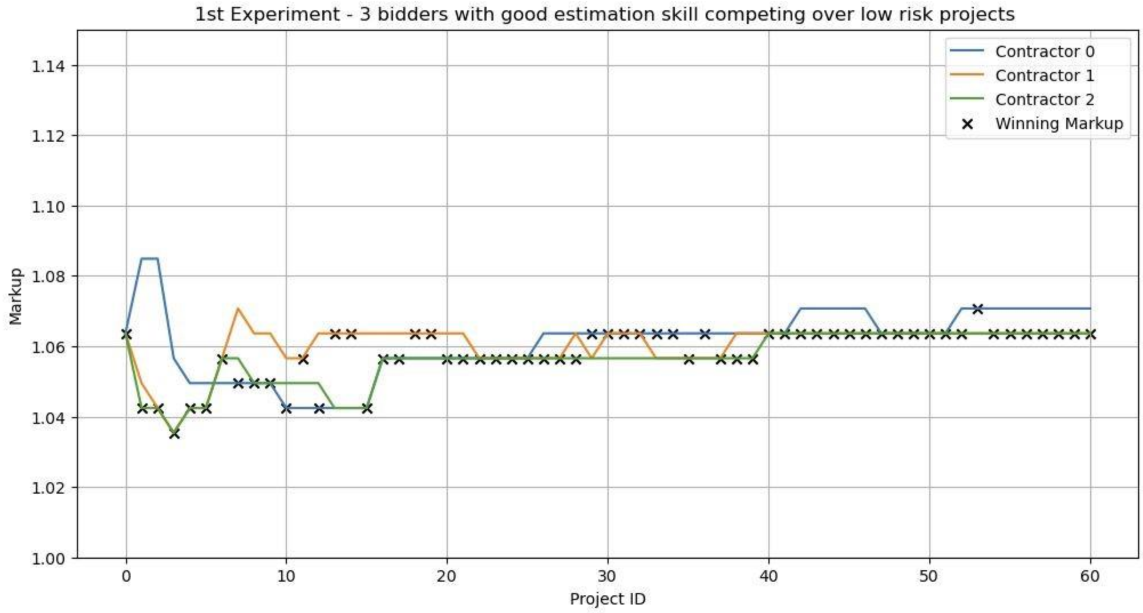
1. **Realism of Model Outcomes**
    - **Question:** The model suggests that contractors adjust their bids based on competition and sustainability requirements. Does this reflect real-world behavior?
    - **Grade (1-5):** Rate the realism (1 - Not realistic, 5 - Very realistic).
    - **Comments:** Are there any discrepancies between the model's results and actual industry practices?
2. **Applicability of Model Insights**
    - **Question:** Do you find the insights from the model applicable to your bidding strategies?
    - **Grade (1-5):** Rate the applicability (1 - Not applicable, 5 - Highly applicable).

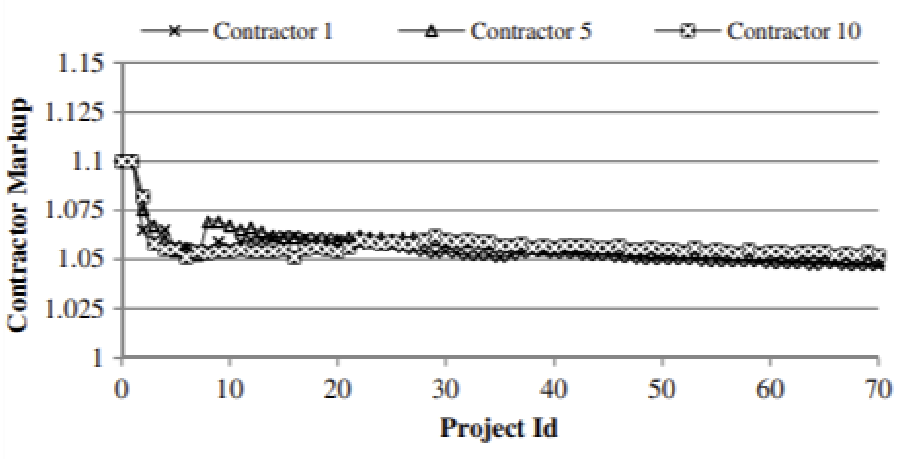
Comments: How could the model's insights be useful or improved?

APPENDIX 1: Interview Outline

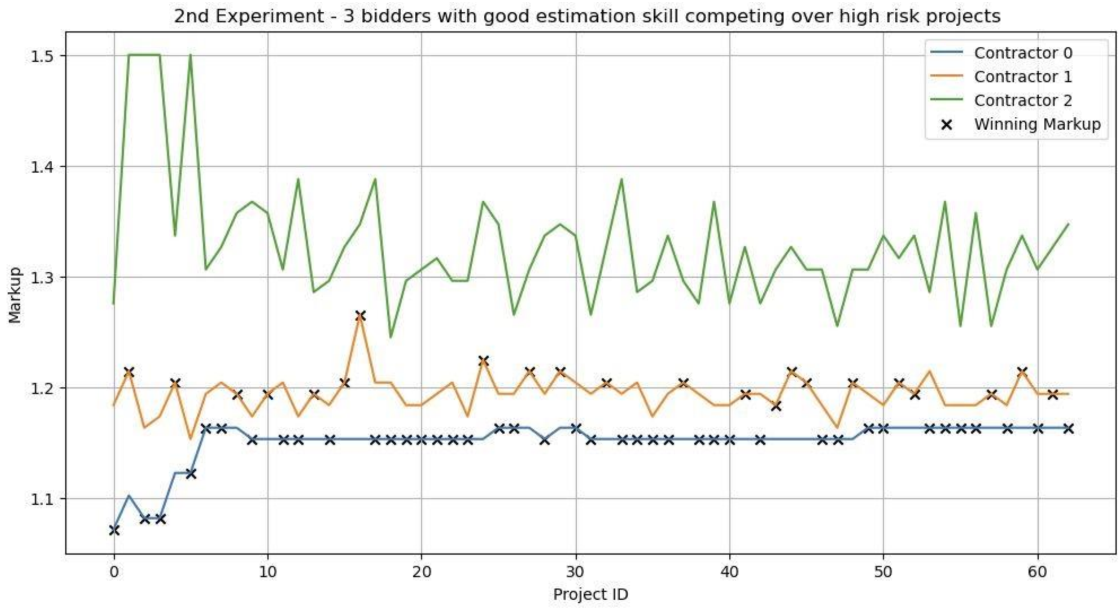


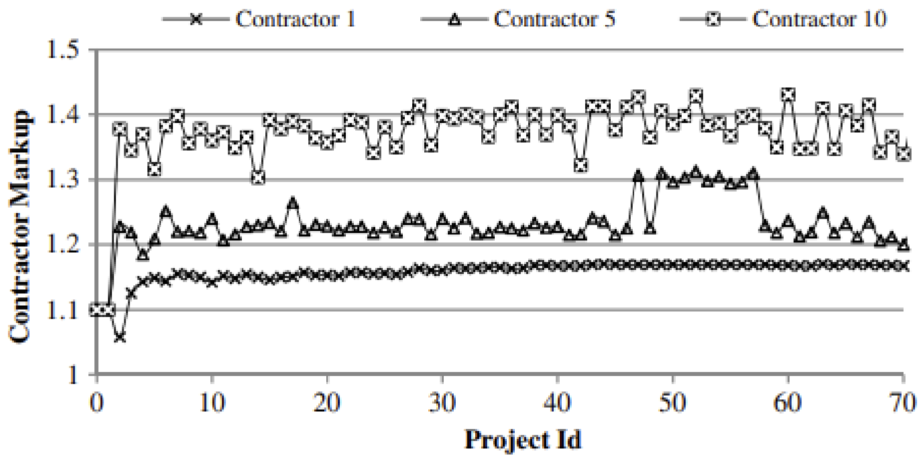
APPENDIX 2: Model 2 UML



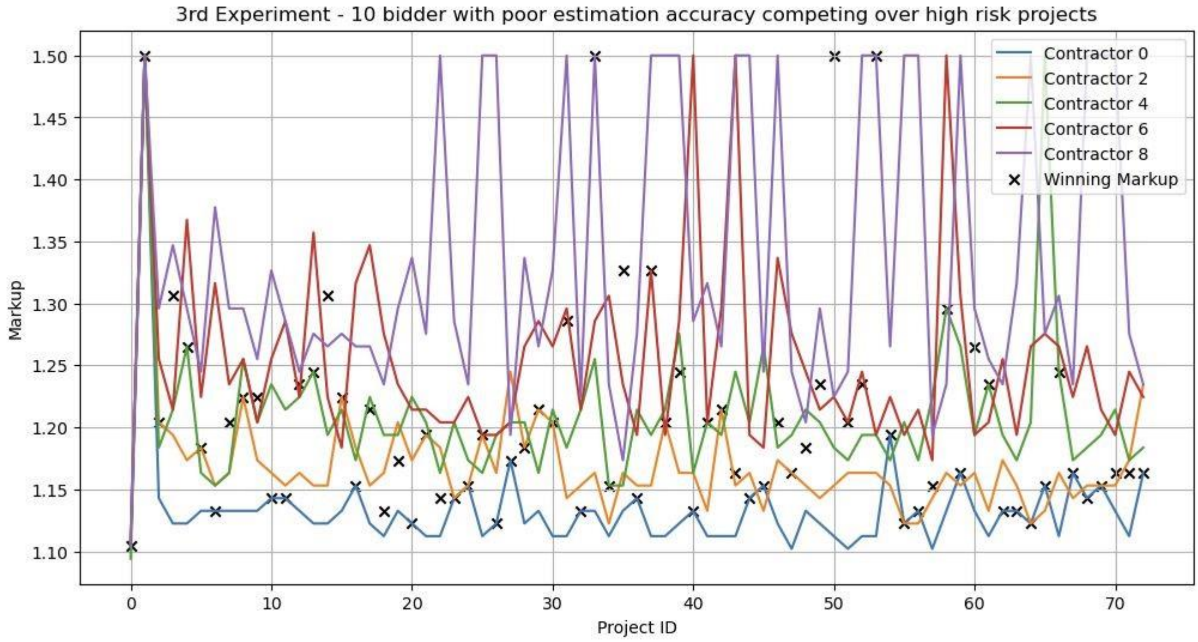


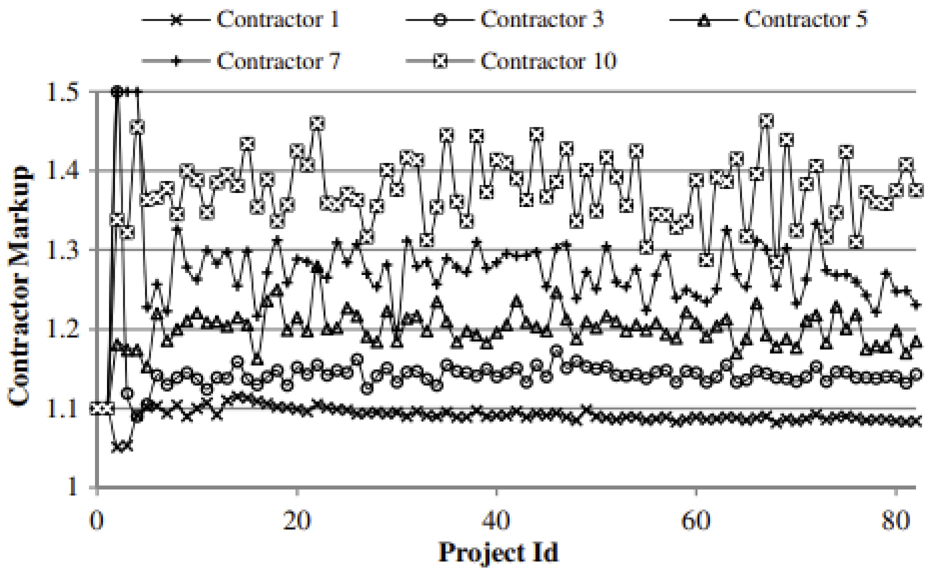
APPENDIX 3: Recreating Study findings from Awwad et al. (2015)



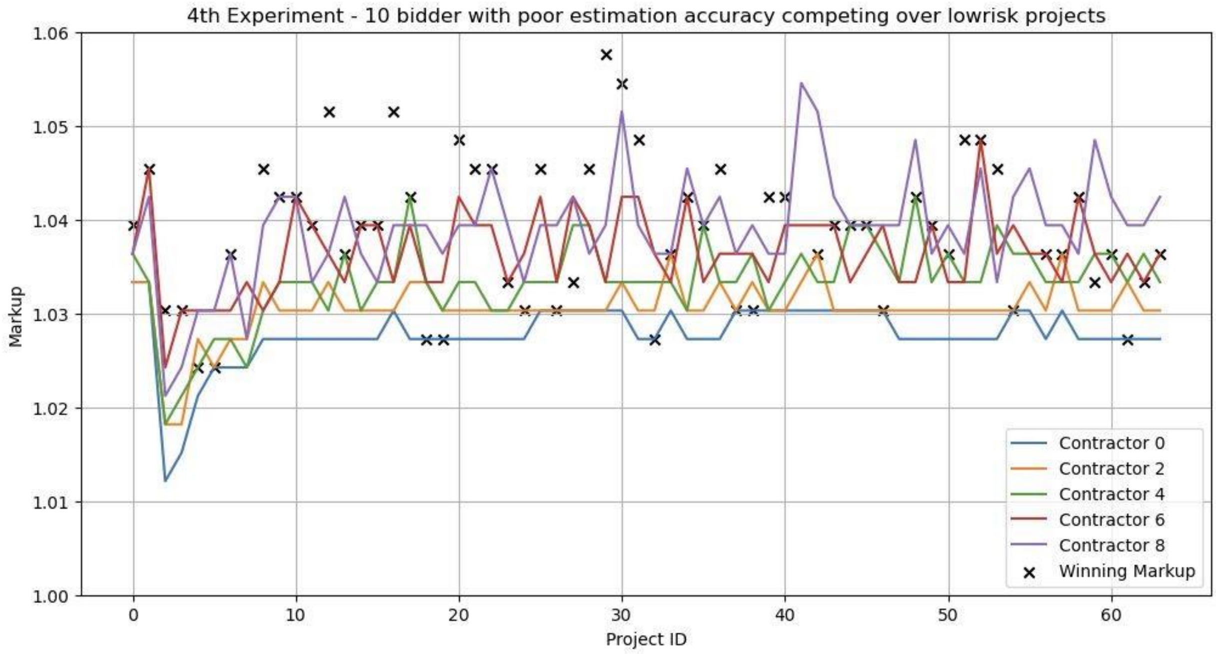


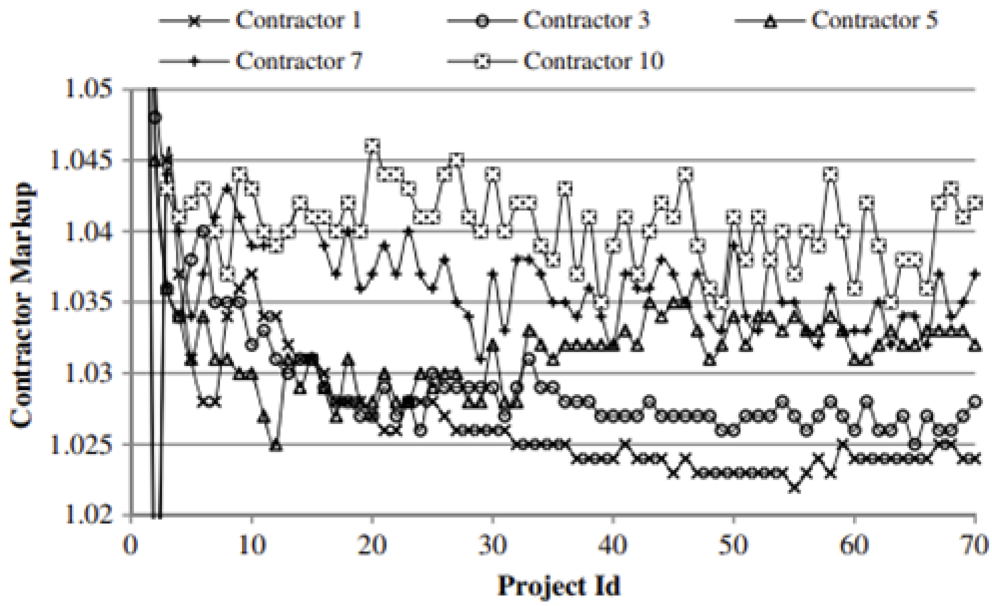
APPENDIX 4: Recreating Study findings from Awwad et al. (2015)



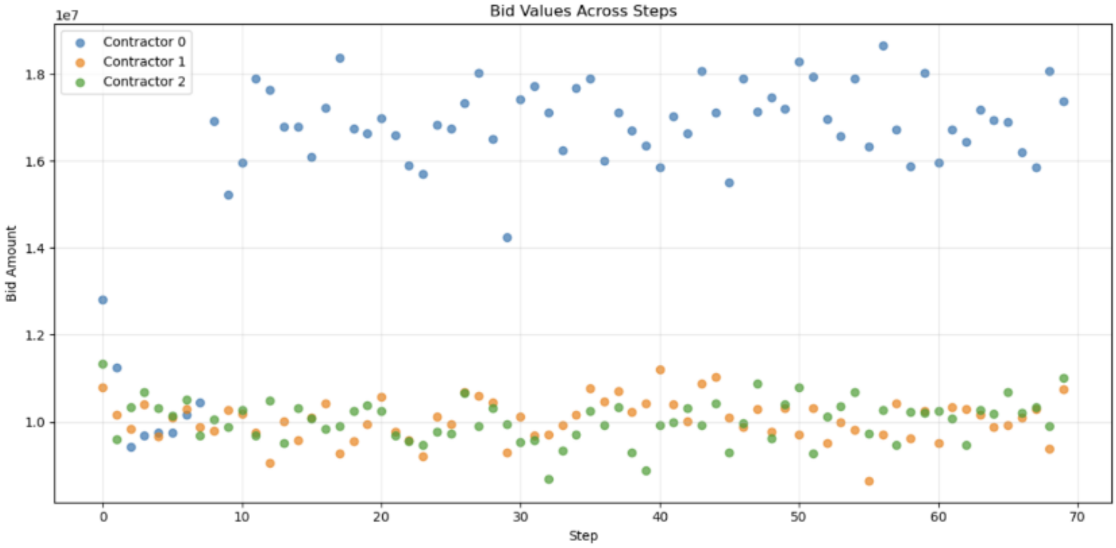


APPENDIX 5: Recreating Study findings from Awwad et al. (2015)

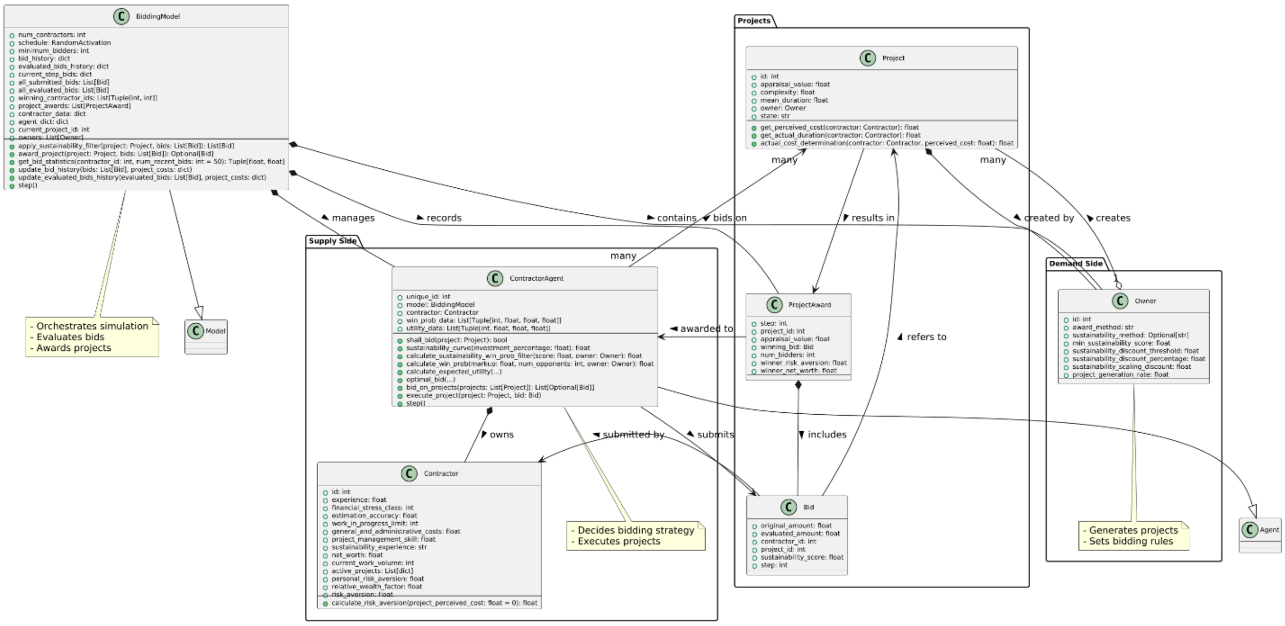




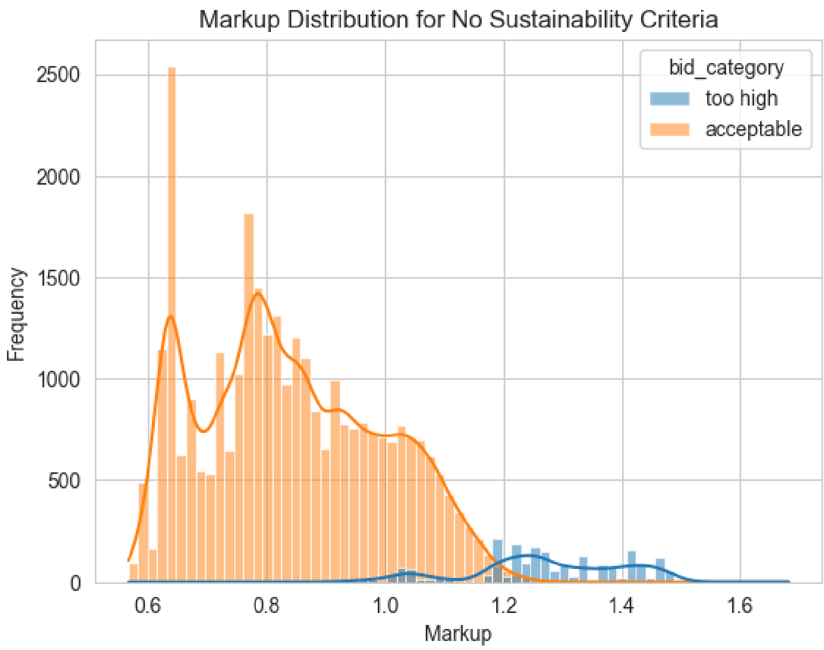
APPENDIX 6: Recreating Study findings from Awwad et al. (2015)



APPENDIX 7: Bid distribution of Experiment 4



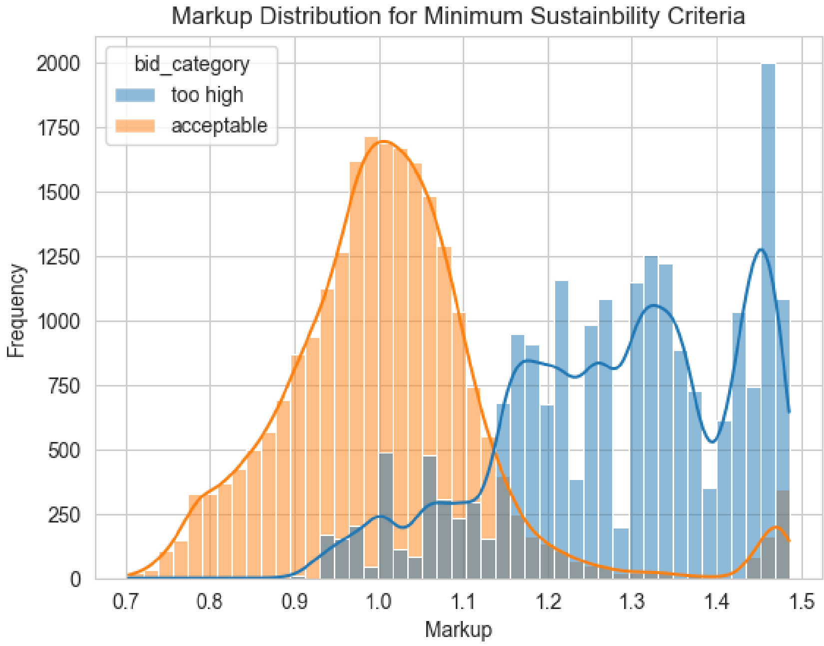
APPENDIX 8: UML of Model 3



Classification Report:

	precision	recall	f1-score	support
0	0.54	0.49	0.51	413
1	0.97	0.97	0.97	6158
accuracy			0.94	6571
macro avg	0.75	0.73	0.74	6571
weighted avg	0.94	0.94	0.94	6571

APPENDIX 9: Bid/No-Bid Classification Report for Projects with No Sustainability Criteria

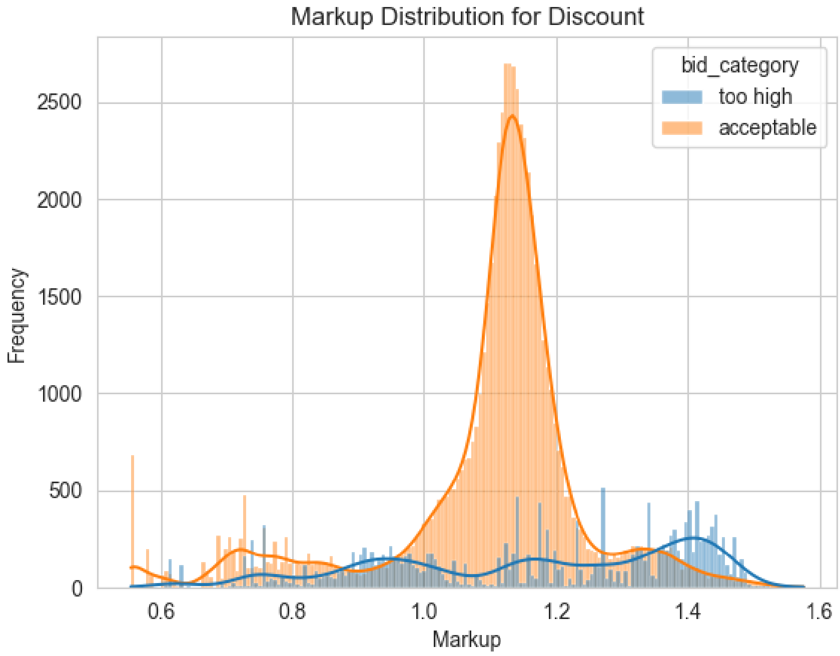



```
Classification Report:
              precision    recall  f1-score   support

           0       0.90      0.91      0.90      4165
           1       0.92      0.91      0.91      4614

    accuracy                           0.91      8779
   macro avg       0.91      0.91      0.91      8779
weighted avg       0.91      0.91      0.91      8779
```

APPENDIX 10: Bid/No-Bid Classification Report for Projects with Minimum Sustainability Criteria

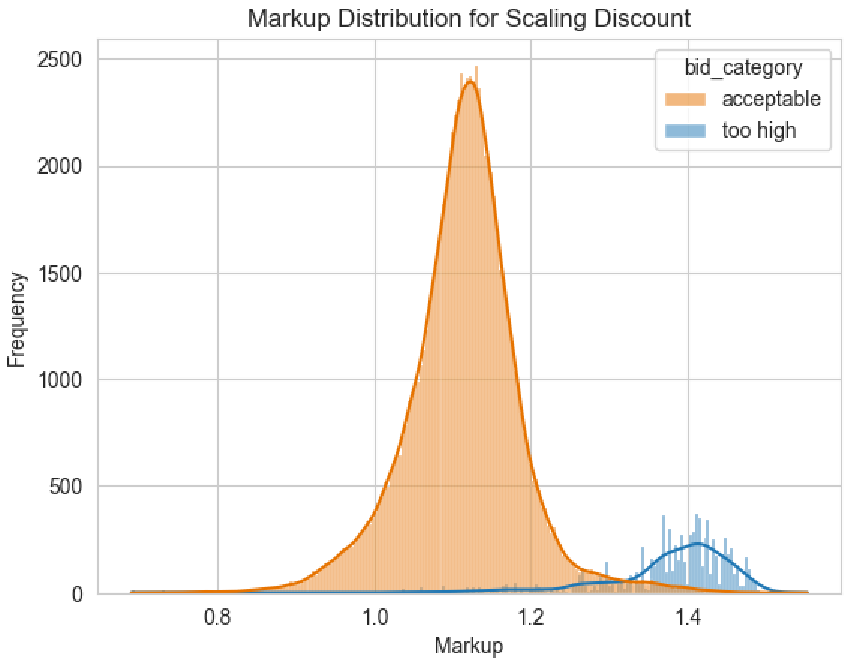



```
Classification Report:
              precision    recall  f1-score   support

           0       0.83      0.80      0.82      3466
           1       0.95      0.96      0.95     13102

    accuracy                           0.92     16568
   macro avg       0.89      0.88      0.88     16568
weighted avg       0.92      0.92      0.92     16568
```

APPENDIX 12: Bid/No-Bid Classification Report for Projects with Discount Sustainability Criteria



Classification Report:

	precision	recall	f1-score	support
0	0.59	0.45	0.51	1699
1	0.95	0.97	0.96	17182
accuracy			0.92	18881
macro avg	0.77	0.71	0.73	18881
weighted avg	0.91	0.92	0.92	18881

APPENDIX 13: Bid/No-Bid Classification Report for Projects with Scaling Discount Sustainability Criteria

BIBLIOGRAPHY

Abdallah, M., & El-Rayes, K. (2016). Multiobjective Optimization Model for Maximizing Sustainability of Existing Buildings. *Journal of Management in Engineering*, *32*(4). https://doi.org/10.1061/(asce)me.1943-5479.0000425

Addae-Dapaah, K., & Wilkinson, J. (2020). Green Premium: What is the Implied Prognosis for Sustainability? *Journal of Sustainable Real Estate*, *12*(1), 16–33. https://doi.org/10.1080/19498276.2021.1915663

Ahmad, T., Shaheen, N., & Ali, M. (2023). *A Review of Sustainability Indicators for Small-Scale Construction Projects by Private Contractors*. *6*(2), 32–41. https://doi.org/10.26392/SSM.2023.06.02.032

Ahmed, M. O., & El-Adaway, I. H. (2024). Exploring the Influences on Construction Bidding Decisions: Insights from Literature and Industry Experts. *Construction Research Congress 2024, CRC 2024*, *3*, 350–360. https://doi.org/10.1061/9780784485286.036

Ahmed, M. O., El-adaway, I. H., & Caldwell, A. (2024). Comprehensive Understanding of Factors Impacting Competitive Construction Bidding. *Journal of Construction Engineering and Management*, *150*(4). https://doi.org/10.1061/jcemd4.coeng-14090

Almohassen, A. S., Alfozan, M., Alshamrani, O. S., & Shaawat, M. E. (2023). Evaluating construction contractors in the pre-tendering stage through an integrated based model. *Alexandria Engineering Journal*, *82*, 437–445. https://doi.org/10.1016/j.aej.2023.09.069

Alsaedi, M., Assaf, S., Hassanain, M. A., & Abdallah, A. (2019). Factors affecting contractors' bidding decisions for construction projects in Saudi Arabia. *Buildings*, *9*(2). https://doi.org/10.3390/buildings9020033

Antipova, E., Boer, D., Guillén-Gosálbez, G., Cabeza, L. F., & Jiménez, L. (2014). Multi-objective optimization coupled with life cycle assessment for retrofitting buildings. *Energy and Buildings*, *82*, 92–99. https://doi.org/10.1016/j.enbuild.2014.07.001

Asadi, E., da Silva, M. G., Antunes, C. H., & Dias, L. (2012). A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. *Building and Environment*, *56*, 370–378. https://doi.org/10.1016/j.buildenv.2012.04.005

Asgari, S. (2020). Comparative analysis of quantitative bidding methods using agent-based modelling. *Civil Engineering and Environmental Systems*, *37*(3), 81–99. https://doi.org/10.1080/10286608.2020.1821670

Asgari, S., Awwad, R., Kandil, A., & Odeh, I. (2016). Impact of considering need for work and risk on performance of construction contractors: An agent-based approach. *Automation in Construction*, *65*, 9–20. https://doi.org/10.1016/j.autcon.2016.01.004

Asgari, S., & Shafaat, A. (2016). *Simulating Construction Bidding Using Agent-Based Modeling*.

Awwad, R., Asgari, S., & Kandil, A. (2015). Developing a Virtual Laboratory for Construction Bidding Environment Using Agent-Based Modeling. *Journal of Computing in Civil Engineering*, *29*(6). https://doi.org/10.1061/(asce)cp.1943-5487.0000440

Bagies, A., & Fortune, C. (2006). Bid/ No-bid decision modelling for construction projects. *Association of Researchers in Construction Management*, 511–521.

Barnes, M. (2006). *HOW IT ALL BEGAN*. www.pmworldlibrary.net

Benachio, G. L. F., Freitas, M. do C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. In *Journal of Cleaner Production* (Vol. 260). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.121046

Berglind, N., Hjerpe, M., Sjödin, E., & Staun, J. (2018). Building across borders: The state of internationalisation in European public construction tenders. *McKinsey & Company*.

Bidin, Z. A., Bohari, A. A. M., Rais, S. L. A., & Saferi, M. M. (2018). Green related practices for construction procurement. *IOP Conference Series: Earth and Environmental Science*, *140*(1). https://doi.org/10.1088/1755-1315/140/1/012099

Binshakir, O., AlGhanim, L., Fathaq, A., AlHarith, A. M., Ahmed, S., & El-Sayegh, S. (2023). Factors Affecting the Bidding Decision in Sustainable Construction. *Sustainability (Switzerland)*, *15*(19). https://doi.org/10.3390/su151914225

Blanco, J. L., Engel, H., Imhorst, F., Ribeirinho, M. J., & Sjödin, E. (2021). Call for action: Seizing the decarbonization opportunity in construction. *McKinsey & Company: New York*, 1–12.

Bohari, A. A. M., Ikau, R. A., Budin, H., Hadi, N. A., & Chan, V. S. L. (2021). The Key Criteria in Deciding to Tender for Construction Projects. *International Journal of Integrated Engineering*, *13*(3), 229–235. https://doi.org/10.30880/ijie.2021.13.03.028

Bohari, A. A. M., Skitmore, M., Xia, B., & Teo, M. (2017). Green oriented procurement for building projects: Preliminary findings from Malaysia. *Journal of Cleaner Production*, *148*, 690–700. https://doi.org/10.1016/j.jclepro.2017.01.141

Bohari, A. A. M., Skitmore, M., Xia, B., Teo, M., & Khalil, N. (2020). Key stakeholder values in encouraging green orientation of construction procurement. *Journal of Cleaner Production*, *270*. https://doi.org/10.1016/j.jclepro.2020.122246

Caimi, V., & Sansonetti, S. (2023). *The social impact of public procurement. Can the EU do more?*

Chersan, I. C., Dumitru, V. F., Gorgan, C., & Gorgan, V. (2020). Green public procurement in the academic literature. *Amfiteatru Economic*, *22*(53), 83–102. https://doi.org/10.24818/EA/2019/53/82

Çimen, Ö. (2021). Construction and built environment in circular economy: A comprehensive literature review. In *Journal of Cleaner Production* (Vol. 305). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2021.127180

Cox, James C., Vernon L. Smith, & James M. Walker. (1988). Theory and Individual Behaviour of First-Price Auctions. *Journal of Risk and Uncertainty*, 61–99.

Dechezleprêtre, A., & Sato, M. (2017). The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy*, *11*(2), 183–206. https://doi.org/10.1093/reep/rex013

Derek S. Drew. (2010). *Modern Construction Economics, Competing in construction auctions: A theoretical perspective* (1st ed.).

Desivyana, N. M. N., Farmakis, O., Cusumano, L., & Rempling, R. (2023). Challenges in the adoption of sustainable criteria in the Swedish. *Procedia Computer Science*, *219*, 1752–1759. https://doi.org/10.1016/j.procs.2023.01.470

Dhliwayo, T., Musonda, I., Gumbo, T., & Kaisara, G. (2024). Critical success factors framework for enhancing the sustainability of small and medium-sized contractors in Namibia. *Acta Structilia*, *31*(1). https://doi.org/10.38140/as.v31i1.7889

Diakaki, C., Grigoroudis, E., & Kolokotsa, D. (2008). Towards a multi-objective optimization approach for improving energy efficiency in buildings. *Energy and Buildings*, *40*(9), 1747–1754. https://doi.org/10.1016/j.enbuild.2008.03.002

Dissanayake, K. M. P. B. G., Perera, P. L., & Gimhani, K. D. M. (2023). Critical Selection Factors for Contractors to Make Bid/No-Bid Decision in Construction Projects in Sri Lanka. *Lecture Notes in Civil Engineering*, *362 LNCE*, 191–203. https://doi.org/10.1007/978-981-99-3471-3_14

Dwaikat, L. N., & Ali, K. N. (2016). Green buildings cost premium: A review of empirical evidence. In *Energy and Buildings* (Vol. 110, pp. 396–403). Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2015.11.021

Dyer, D., & Kagel, J. H. (1996). Bidding in common value auctions: How the commercial construction industry corrects for the winner's curse. *Management Science*, *42*(10), 1463–1475. https://doi.org/10.1287/mnsc.42.10.1463

Egemen, M., & Mohamed, A. N. (2007). A framework for contractors to reach strategically correct bid/no bid and mark-up size decisions. *Building and Environment*, *42*(3), 1373–1385. https://doi.org/10.1016/j.buildenv.2005.11.016

Evins, R. (2013). A review of computational optimisation methods applied to sustainable building design. In *Renewable and Sustainable Energy Reviews* (Vol. 22, pp. 230–245). https://doi.org/10.1016/j.rser.2013.02.004

Fay, M., Lee, H. Il, Mastruzzi, M., Han, S., & Cho, M. (2019). *Hitting the Trillion Mark A Look at How Much Countries Are Spending on Infrastructure*. http://www.worldbank.org/

Fregonara, E., Ferrando, D. G., & Tulliani, J. M. (2022). Sustainable Public Procurement in the Building Construction Sector. *Sustainability (Switzerland)*, *14*(18). https://doi.org/10.3390/su141811616

Geach, I. (2016a). *Investigating the Role of Sustainability in Contractor Selection and Evaluation*.

Geach, I. (2016b). *Investigating the Role of Sustainability in Contractor Selection and Evaluation*.

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207

Goddard, J. U., Glass, J., Dainty, A., & Nicholson, I. (2016). Implementing sustainability in small and medium-sized construction firms the role of absorptive capacity. *Engineering, Construction and Architectural Management*, *23*(4), 407–427. https://doi.org/10.1108/ECAM-01-2015-0015

Goh, C. S., Chong, H. Y., Jack, L., & Mohd Faris, A. F. (2020). Revisiting triple bottom line within the context of sustainable construction: A systematic review. In *Journal of Cleaner Production* (Vol. 252). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.119884

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., Thulke, H.-H., Weiner, J., Wiegand, T., & Deangelis, D. L. (2024). *Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology*. https://www.science.org

Halonen, K. M. (2021). Is public procurement fit for reaching sustainability goals? A law and economics approach to green public procurement. *Maastricht Journal of European and Comparative Law*, *28*(4), 535–555. https://doi.org/10.1177/1023263X211016756

Hartono, B. (2010). *INVESTIGATING RISKY DECISIONS OF CONSTRUCTION CONTRACTORS IN COMPETITIVE BID MARK-UPS INVESTIGATING RISKY DECISIONS OF CONSTRUCTION CONTRACTORS IN COMPETITIVE BID MARK-UPS*.

Hartono, B., & Yap, C. M. (2011). Understanding risky bidding: A prospect-contingent perspective. *Construction Management and Economics*, *29*(6), 579–593. https://doi.org/10.1080/01446193.2011.569733

Hu, M., & Skibniewski, M. (2021). Green Building Construction Cost Surcharge: An Overview. *Journal of Architectural Engineering*, *27*(4). https://doi.org/10.1061/(asce)ae.1943-5568.0000506

Huang, H., Zhou, C., & Deng, H. (2024). A DEA Game Cross-Efficiency Model with Loss Aversion for Contractor Selection. *Mathematics*, *12*(10). https://doi.org/10.3390/math12101519

Hwang, B. G., Shan, M., & Lye, J. M. (2018). Adoption of sustainable construction for small contractors: major barriers and best solutions. *Clean Technologies and Environmental Policy*, *20*(10), 2223–2237. https://doi.org/10.1007/s10098-018-1598-z

International Energy Agency. (2013). *Technology Solutions and Policy Instruments for the Transition*.

Kapote, M. M., Wagh, A. A., & Pimplikar, S. S. (2023). Contractor Selection Approaches and Pre-qualification Criteria on Construction Projects: A Review. *Lecture Notes in Civil Engineering*, *346 LNCE*, 27–40. https://doi.org/10.1007/978-981-99-2552-0_3

Karatas, A., & El-Rayes, K. (2015). Optimizing tradeoffs among housing sustainability objectives. *Automation in Construction*, *53*, 83–94. https://doi.org/10.1016/j.autcon.2015.02.010

Kjerulf, L., & Haugbølle, K. (2021). Circular Prequalification and Bidding Practices at Contractor Firms. *THIRTY-Seventh ANNUAL CONFERENCE*, 684–693.

Kwerel, E. R., & Rosston, G. L. (2000). An Insiders' View of FCC Spectrum Auctions. In *Journal of Regulatory Economics* (Vol. 17, Issue 3, pp. 253–289). Springer Netherlands. https://doi.org/10.1023/A:1008126116011

Laryea, S., & Hughes, W. (2009). Commercial reviews in the tender process of contractors. *Engineering, Construction and Architectural Management*, *16*(6), 558–572. https://doi.org/10.1108/09699980911002575

Lauermann, S., & Speit, A. (2023). Bidding in Common-Value Auctions With an Unknown Number of Competitors. *Econometrica*, *91*(2), 493–527. https://doi.org/10.3982/ecta17793

Liu, J., Cui, Z., Yang, X., & Skitmore, M. (2018). Experimental Investigation of the Impact of Risk Preference on Construction Bid Markups. *Journal of Management in Engineering*, *34*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000596

Liu, S., Meng, X., & Tam, C. (2015). Building information modeling based building design optimization for sustainability. *Energy and Buildings*, *105*, 139–153. https://doi.org/10.1016/j.enbuild.2015.06.037

Lo, W., Lin, ; C L, & Yan, M. R. (2007). Contractor's Opportunistic Bidding Behavior and Equilibrium Price Level in the Construction Market. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/ASCE0733-93642007133:6409

Lo, W., & Yan, M.-R. (2009). Evaluating Qualification-Based Selection System: A Simulation Approach. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/ASCECO.1943-7862.0000013

Longo, S., Montana, F., & Riva Sanseverino, E. (2019). A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. In *Sustainable Cities and Society* (Vol. 45, pp. 87–104). Elsevier Ltd. https://doi.org/10.1016/j.scs.2018.11.027

Loosemore, M., & Richard, J. (2015). Valuing innovation in construction and infrastructure: Getting clients past a lowest price mentality. In *Engineering, Construction and Architectural Management* (Vol. 22, Issue 1, pp. 38–53). Emerald Group Publishing Ltd. https://doi.org/10.1108/ECAM-02-2014-0031

Luu, D. T., Ng, S. T., Chen, S. E., & Jefferies, M. (2006). A strategy for evaluating a fuzzy case-based construction procurement selection system. *Advances in Engineering Software*, *37*(3), 159–171. https://doi.org/10.1016/j.advengsoft.2005.05.004

Marques F, Ribeiro G, & Sjödin E. (2023). The strategic era of procurement in construction. *McKinsey & Company*.

Marques Francisco, Ribeiro Goncalo, & Sjodin Erik. (2023). The strategic era of procurement in construction. *McKinsey & Company NY*.

Mergawy, R. T., Hosny, H. E., & Abdelazeem, A. S. (2023). Decision Support Model for Contractor Selection. *The Open Civil Engineering Journal*, *17*(1). https://doi.org/10.2174/18741495-v17-e230215-2022-51

Milgrom, P., & Kwerel, E. (2003). *Putting Auction Theory to Work*.

Mohamed, E., Jafari, P., & Hammad, A. (2022). Mixed qualitative–quantitative approach for bidding decisions in construction. *Engineering, Construction and Architectural Management*, *29*(6), 2328–2357. https://doi.org/10.1108/ECAM-12-2020-1060

Nallathiga, R., Raipure, A., Ate, P., & Singh, A. (2022). Green Buildings, Sustainability and Value Premium: An Empirical Study of Pune. *Atlantis Highlights in Social Sciences, Education and Humanities*.

Nasereddin, M., & Price, A. (2021). Addressing the capital cost barrier to sustainable construction. *Developments in the Built Environment*, *7*. https://doi.org/10.1016/j.dibe.2021.100049

Negendahl, K., & Nielsen, T. R. (2015). Building energy optimization in the early design stages: A simplified method. *Energy and Buildings*, *105*, 88–99. https://doi.org/10.1016/j.enbuild.2015.06.087

Obwegeser, N., & Müller, S. D. (2018). Innovation and public procurement: Terminology, concepts, and applications. *Technovation*, *74–75*, 1–17. https://doi.org/10.1016/j.technovation.2018.02.015

OECD. (2023). Assessing green public procurement. In *Government at a Glance*. OECD. https://doi.org/10.1787/8d90f627-en

Oo, B. L., Lim, B. T. H., & Runeson, G. (2023). Mark-up on construction projects: what have we learnt in the last 20 years? *Engineering, Construction and Architectural Management*, *30*(9), 4319–4338. https://doi.org/10.1108/ECAM-01-2022-0070

Oo, B. L., Lo, H. P., & Lim, B. T. H. (2012). The effect of bidding success in construction bidding. *Engineering, Construction and Architectural Management*, *19*(1), 25–39. https://doi.org/10.1108/09699981211192553

Oo, B.-L., Drew, D. S., & Lo, H.-P. (2010). Modeling the Heterogeneity in Contractors' Mark-Up Behavior. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/ASCECO.1943-7862.0000186

Oz, B. (2024). A non-price-based tender evaluation methodology considering tenderers' self-confidence with partial value functions and time decay analysis. *Expert Systems with Applications*, *252*. https://doi.org/10.1016/j.eswa.2024.124186

Pasquire, C., Sarhan, S., & King, A. (2015). A Critical Review Of The Safeguarding Problem In Construction Procurement: Unpicking The Coherent Current Model. *Proceedings of the IGLC*. https://doi.org/10.13140/RG.2.1.1461.2328

Peleckis, K. (2022). Determining the Level of Market Concentration in the Construction Sector—Case of Application of the HHI Index. *Sustainability (Switzerland)* , *14*(2). https://doi.org/10.3390/su14020779

Pham, V. H. S., & Phan, K. A. (2021). Bid compensation effectiveness analysis based on owner and contractor perspective using game theory approach. *Asian Journal of Civil Engineering*, *22*(7), 1269–1279. https://doi.org/10.1007/s42107-021-00380-1

Pouikli, K. (2021). Towards mandatory Green Public Procurement (GPP) requirements under the EU Green Deal: reconsidering the role of public procurement as an environmental policy tool. *ERA Forum*, *21*(4), 699–721. https://doi.org/10.1007/s12027-020-00635-5

Prier, E., Schwerin, E., & Mccue, C. P. (2016). Implementation of sustainable public procurement practices and policies: a sorting framework. *Journal of Public Procurement*, *16*, 312–346.

Puri, D., & Tiwari, S. (2014). Evaluating The Criteria for Contractors' Selection and Bid Evaluation. *International Journal of Engineering Science Invention*, *3*, 44–48. www.ijesi.org44|

Ribeirinho, M. J., Mischke, J., Biörck, J., & Strube, G. (2020). The next normal in construction. *McKinsey & Company*, 2–3. https://www.mckinsey.com/~/media/McKinsey/Industries/Capital%20Projects%20and%20Infrastructure/Our%20Insights/The%20next%20normal%20in%20construction/The-next-normal-in-construction.pdf

Rosell, J. (2021). Getting the green light on green public procurement: Macro and meso determinants. *Journal of Cleaner Production*, *279*. https://doi.org/10.1016/j.jclepro.2020.123710

Ruparathna, R., & Hewage, K. (2015a). Review of Contemporary Construction Procurement Practices. *Journal of Management in Engineering*, *31*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000279

Ruparathna, R., & Hewage, K. (2015b). Sustainable procurement in the Canadian construction industry: Current practices, drivers and opportunities. *Journal of Cleaner Production*, *109*, 305–314. https://doi.org/10.1016/j.jclepro.2015.07.007

Russ, N. M., Hanid, M., & Ye, K. M. (2018). Literature review on green cost premium elements of sustainable building construction. *International Journal of Technology*, *9*(8), 1715–1725. https://doi.org/10.14716/ijtech.v9i8.2762

Rwelamila, P. D., Talukhaba, A. A., & Ngowi, A. B. (2000). Project procurement systems in the attainment of sustainable construction. *Sustainable Development Sust. Dev*, *8*, 39–50.

Sajid, Z. W., Aftab, U., & Ullah, F. (2024). Barriers to adopting circular procurement in the construction industry: The way forward. In *Sustainable Futures* (Vol. 8). Elsevier Ltd. https://doi.org/10.1016/j.sftr.2024.100244

Säynäjoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? In *Environmental Research Letters* (Vol. 12, Issue 1). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/aa54ee

Schmalensee, R., & Stavins, R. N. (2017). The design of environmental markets: What have we learned from experience with cap and trade? *Oxford Review of Economic Policy*, *33*(4), 572–588. https://doi.org/10.1093/oxrep/grx040

Semaan, N., & Salem, M. (2017). A deterministic contractor selection decision support system for competitive bidding. *Engineering, Construction and Architectural Management*, *24*(1), 61–77. https://doi.org/10.1108/ECAM-06-2015-0094

Shan, M., Liu, W. Q., Hwang, B. G., & Lye, J. M. (2020). Critical success factors for small contractors to conduct green building construction projects in Singapore: identification and comparison with large contractors. *Environmental Science and Pollution Research*, *27*(8), 8310–8322. https://doi.org/10.1007/s11356-019-06646-1

Sheamar, S., Wedawatta, G., Tennakoon, M., Palliyaguru, R., & Antwi-Afari, M. F. (2024). The potential of new models of construction procurement to counter cost overruns in construction projects: an exploratory study from a contractors' perspective. *Journal of Financial Management of Property and Construction*, *29*(2), 211–228. https://doi.org/10.1108/JFMPC-08-2022-0035

Shokri-Ghasabeh, M., & Chileshe, N. (2016). Critical factors influencing the bid/no bid decision in the Australian construction industry. *Construction Innovation*, *16*(2), 127–157. https://doi.org/10.1108/CI-04-2015-0021

Soo, A., & Oo, B. L. (2014). The effect of construction demand on contract auctions: An experiment. *Engineering, Construction and Architectural Management*, *21*(3), 276–290. https://doi.org/10.1108/ECAM-01-2013-0010

Sourani, A., & Sohail, M. (2011). Barriers to addressing sustainable construction in public procurement strategies. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, *164*(4), 229–237. https://doi.org/10.1680/ensu.2011.164.4.229

The Economist. (2017, August 19). *Efficiency eludes the construction industry*. The Economist. https://www.economist.com/business/2017/08/19/efficiency-eludes-the-construction-industry

The Economist. (2022, June 18). *The construction industry remains horribly climate-unfriendly*. The Economist, . https://www.economist.com/finance-and-economics/2022/06/15/the-construction-industry-remains-horribly-climate-unfriendly

Toyibah Masyhur, R., Hizami Alias, A., Azam Haron, N., & Zulkafli, Z. (2024). A systematic review on green practices in the Malaysian construction industry: Status, challenges, key motivations, rating systems and technology evolution. *Energy and Buildings*, 114550. https://doi.org/10.1016/j.enbuild.2024.114550

Venkatachalam, R. (Ed.). (2023). *Artificial Intelligence, Learning and Computation in Economics and Finance*.

Wang, C., & Guo, P. (2017). Behavioral models for first-price sealed-bid auctions with the one-shot decision theory. *European Journal of Operational Research*, *261*(3), 994–1000. https://doi.org/10.1016/j.ejor.2017.03.024

Wiik, M. K., Flyen, C., Fufa, S. M., & Venås, C. (2020). Lessons learnt from green public procurement in the Norwegian construction sector. *IOP Conference Series: Earth and Environmental Science*, *588*(2). https://doi.org/10.1088/1755-1315/588/2/022017

World Bank. (2021). *Green Public Procurement: An Overview of Green Reforms in Country Procurement Systems*. www.worldbank.org

World Green Building Council. (2013). *The Business Case for Green Building. A Review of the Costs and Benefits for Developers, Investors and Occupants.* www.worldgbc.org

World Green Building Council. (2022). *EU Policy whole life carbon roadmap*. www.worldgbc.com

World Green Building Council. (2023). *Global Policy Principles for a Sustainable built environment*. www.worldgbc.org

World Green Building Council. (2024). *European Manifesto for a sustainable built environment. How sustainable buildings can be at the heart of a prosperous and equitable future for Europe.*

Yan, M. R. (2015). Project-based market competition and policy implications for sustainable developments in building and construction sectors. *Sustainability (Switzerland)*, *7*(11), 15423–15448. https://doi.org/10.3390/su71115423

Ye, K., Shen, L., Xia, B., & Li, B. (2014). Key attributes underpinning different markup decision between public and private projects: A China study. *International Journal of Project Management*, *32*(3), 461–472. https://doi.org/10.1016/j.ijproman.2013.06.001

Yu, A. T. W., & Shen, G. Q. P. (2013). Problems and solutions of requirements management for construction projects under the traditional procurement systems. In *Facilities* (Vol. 31, Issue 5, pp. 223–237). https://doi.org/10.1108/02632771311307098

Zhang, Y., Tai, S., Zhang, D., & Wu, L. (2023). How to promote the diffusion of green behavior among contractors? Analysis and simulation using the SIR model. *Journal of Environmental Management*, *335*. https://doi.org/10.1016/j.jenvman.2023.117555

Zhang, Z., & Liao, H. (2022). A stochastic cross-efficiency DEA approach based on the prospect theory and its application in winner determination in public procurement tenders. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04539-0

Zuo, J., Zillante, G., Wilson, L., Davidson, K., & Pullen, S. (2012). Sustainability policy of construction contractors: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 6, pp. 3910–3916). https://doi.org/10.1016/j.rser.2012.03.011