Encouraging Circular Wood-Based Building Practises in Amsterdam

An Agent-Based Modelling Approach

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A map is not the territory it represents, but, if correct, it has a similar structure to the territory, which accounts for its usefulness.

Alfred Korzybski, Science and Sanity, 1933

Summary

The aim of this thesis project is to understand how policy instruments influence the adoption of wood-based building practices and to examine the effect of increased wood-based construction on circular practices. This study identifies key actors in the built environment, including housing associations, private owners, construction and demolition companies, and material suppliers. The behavior and relationships of these actors are analyzed. An agent-based model is developed to explore the impact of various policy instruments, such as carbon taxation, demolition notification, and knowledge sharing.

The study revealed several findings. First, there is significant inertia among construction companies and building owners towards adopting wood-based construction, primarily due to high initial investments and lack of familiarity. This results in a hefty premium being paid for wood-based construction before it becomes well established. It was discovered that a substantial subsidy on mass timber is essential. Additionally, significant taxation on reinforced concrete, such as through carbon taxation, helps overcome the inertia in the system. Another effective instrument is the sharing of wood-based construction knowledge among construction companies. Once wood-based construction is established, it becomes cost-competitive, reducing the need for continuous stimulation through policy instruments. With the establishment of wood-based construction, several effects on the circularity in the built environment and material usage have been identified. Despite a shift to wood-based construction, the demand for concrete remains significant. This underscores the importance of concrete recycling practices. The increase in wood content in construction requires enhanced mass-timber recycling practices. This study highlights the role of temporary material storage in facilitating circularity. It suggests the need for strategies to match material streams from demolition to construction.

In summary, this thesis project demonstrates that a combination of policy instruments, especially carbon taxation and knowledge sharing, is crucial in transitioning to wood-based construction. The study highlights the need for continued attention to concrete use and recycling, especially when wood-based practices gain traction.

Preface

This thesis is the product of the graduation phase of the master's thesis for the master's program in Engineering and Policy Analysis at TU Delft. The primary objective was to explore policy tools that promote the adoption of wood-based construction practices in Amsterdam's built environment, particularly examining their impact on circularity. To achieve this, the study employed an agent-based modeling approach.

During this thesis project, I had the pleasure of having the support of a diverse and very knowledgeable supervisory team. First and foremost, I want to thank Felipe for his unconditional support throughout the thesis project. Our weekly meetings were of the utmost importance, and I couldn't have finished this thesis without him. I also want to thank Neil, Amineh, and Gijsbert for their fruitful comments and helpful assistance during this thesis. Although we didn't meet on a weekly basis, your comments have significantly contributed to this work.

Assistance from the Municipality of Amsterdam, the Circulaw team, the AMS Institute, and Smith and Wallworks has been very beneficial to the thesis work. I want to thank everyone who contributed to this work while working at these organizations.

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Acronyms

BAG Basisregistratie Adressen en Gebouwen - Basic Registration Addresses and Buildings. 26

CBS Centraal Bureau voor de Statistiek - Statistics Netherlands. 24–26

CE Circular Economy. 14, 51

EPA Engineering and Policy Analysis. 10

GIS Geographic Information System. 25

ODD Overview, Design concepts and Details. 35

UN United Nations. 4, 16

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1 Introduction

1.1 Problem background

The increasing concentration of carbon dioxide in the atmosphere caused by human activities can have a detrimental impact on our way of living. The effect of climate change on our planet already makes human life increasingly more difficult, especially for the least well off (Hallegatte and Rozenberg, 2017). Among scientists there is consensus that the main cause for global warming is induced by human activity (Masson-Delmotte et al., 2021). The United Nations developed 17 Sustainable Development Goals, one of which aims to promote sustainability in human settlements and cities (United Nations, 2015). To mitigate our environmental impact, a range of measures must be taken, including the adaptation of the built environment. Cities are responsible for 70% of global greenhouse gas emissions, and this is expected to increase due to the growing urban population (Dasgupta et al., 2022). The built environment in cities is crucial in promoting environmental sustainability. The environmental impact of buildings needs to be taken into account, including their construction and demolition, not just their operational costs. This presents a challenge for individuals, organizations, and governmental bodies to redefine the built environment in a way that reduces carbon emissions, promotes sustainability, and caters to the needs of the inhabitants. Such changes must be implemented at both a societal and behavioural level.

Numerous cities across the world have integrated circular build environment strategies into their vision for the future (Bucci Ancapi et al., 2022). These strategies, which include sectorial policies and roadmaps, must establish the foundation for sustainable practices in the built environment, accounting for resources used during construction and maintenance. The city of Amsterdam leads the way in promoting circular practices, with the municipality aiming for a 50% reduction in primary resource usage by 2030 and full circularity by 2050 (Gemeente Amsterdam, 2020). Such an ambitious goal is not only drastic but also complex in nature. Implementing circular practices in the built environment requires stakeholder involvement and societal participation, as it is not merely a technical fix (Naustdalslid, 2014). Societal systems are intricate and nonlinear, which can lead to indirect, unforeseen consequences when policies are put into effect (Skeldon et al., 2018). The municipal strategies will induce systemic changes, resulting in behavioural patterns that are difficult to anticipate. Therefore, it is critical that the policy interventions needed to achieve these goals be meticulously designed and tested before being implemented.

In the literature, considerable research has been conducted on alternative building materials, with a particular focus on transitioning away from traditional masonry materials towards an increased usage of wood (Churkina et al., 2020). Buchanan and Bry Levine seminal work on the use of wood as a building material reveals that "an analysis of typical forms of building construction shows that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminum, steel and concrete." (Buchanan and Bry Levine). Wood and wood-based materials offer a range of technical and ecological advantages, such as carbon storage and favorable processing characteristics. Because of these attributes, wood is well-suited for use in the circular built environment.

Modelling techniques can provide valuable insights into the effects of policy instruments on complex dynamic systems. By allowing for the experimentation and visualization of complex interactions and their aggregated behaviour, models can serve as effective tools for understanding such systems. A transparent modelling approach can enable non-academic stakeholders to comprehend the workings of the system under consideration. While the municipality of Amsterdam has a solid understanding of the potential actions and levers that could facilitate the transition to a more circular built environment, it has yet to determine how these policies should be implemented to achieve the optimal outcome. Thus, we contend that a modelling approach is appropriate for addressing this problem.

1.2 Motivation for thesis

This research study is being conducted by a graduate student enrolled in the Master of Engineering and Policy Analysis (EPA) program at Delft University of Technology (TU Delft). The EPA program is an interdisciplinary master's program that emphasizes policy processes, analytics, modelling, and simulation in a social-political context (TU Delft, 2022). Given the need for a modelling approach in this research topic and the resulting policy advice that will be generated, it is well-suited for an EPA master's thesis.

The motivation for conducting this thesis research is two-fold.

As previously stated, there is an urgent need for more sustainable construction practices, including the use of materials with lower-carbon emissions, such as wood. Although it is feasible to construct buildings from wood in Amsterdam, this is not yet a common practice, and the majority of newly built buildings are made from masonry materials (MRA, 2020a). Developing a better understanding of the built environment and identifying policies that could potentially encourage wood-based building practices would be of great value in promoting more sustainable construction practices. The model building process itself represents an opportunity to gain insight into the built environment.

Secondly, this thesis research reflects a personal interest in the intersection of multiple fields. The author's educational background in Electrical Engineering focused on deterministic systems, which the author found inadequate for addressing problems in everyday social-technical systems. Pursuing a master's degree in Engineering and Policy Analysis provided the author with a more suitable toolkit for understanding ambiguous systems. Building social-technical models is a creative endeavor that combines art and science, which is of great interest to the author. Additionally, the author's close proximity to the built environment in the center of The Hague, as well as personal experiences with construction processes, have sparked an interest in gaining a deeper understanding of the relevant processes in the built environment.

1.3 Knowledge gap

The literature on policies to encourage the usage of circularity by wood-based building is present. However, these policies are merely qualitative suggestions and have not been tested with the use of a (quantitative) modelling approach. A model that provides the city of Amsterdam with a better understanding of the system at hand, and further policy analyses is therefore deemed desirable. In order to fill this gap, the main research question for this thesis is defined as follows: *How do policy instruments influence the adoption of circular wood-based building practices in Amsterdam, and what influence do they have on the city's built environment?*.

The goal of this thesis research is twofold. Firstly, we aim to investigate the potential impact of policy instruments on promoting wood-based building practices. Secondly, we aim to examine the broader implications of such policies on the built environment. This separation is necessary because while our overall objective is to encourage wood-based building practices, the model results may indicate that effective policy instruments could have negative consequences for the built environment. In order for the research to be valuable for the practice of decision making, it is necessary to consider these effects. Therefore, both aspects of the main research question must be addressed in order to provide a comprehensive analysis.

1.4 Research questions

The main question is defined as: *How do policy instruments influence the adoption of circular wood-based building practices in Amsterdam, and what influence do they have on the city's built environment?* This question is broken up into four sub-questions, namely:

1. Which agents and environmental factors shape Amsterdam's built environment?
2. How do the key actors interrelate and influence each other's behaviours?
3. In what ways do municipal policy instruments promote or hinder wood-based building practices?
4. How does the increased use of wood-based building materials influence circularity?

The first sub-question: *Which agents and environmental factors shape Amsterdam's built environment?* is important during the system analysis phase of the model building process. Academic literature suggests a variety of potential policy instruments to encourage wood-based building in the Amsterdam built environment. Since this research solely focuses on the situation in the city of Amsterdam, not all of the policy instruments mentioned in academic literature are suitable. Therefore, it is necessary to converse with (municipal) policy makers, active in the city of Amsterdam, to understand what policy instruments are within the limits of the law. Knowledge institutes and public servants can offer insights into policy integration and potential implementation challenges.

The second sub-question: *How do the key actors interrelate and influence each other's behaviours?* belongs to *system analysis phase* of the model building process. When there is a good understanding of the relevant actor's in the system at hand, the relation between the actors needs to be established and implemented. Both the literature and conversations that brought forward the actors, likely provides relations and interdependencies too. Further literature research and interviews will yield a better understanding of the actors environment when this is deemed necessary.

The third sub-question is formulated as: *In what ways do municipal policy instruments promote or hinder circular wood-based building practices?* This sub-question provides insight into the various policies that one can implement and the respective behaviour over time. The model will give insight into the built environment behaviour over time.

To get an understanding of the influence of enhancing wood-based building practices on masonry building materials, this sub-question was defined: *How does the increased use of wood-based building materials influence circularity?* Policy advice requires taking into account multiple facets than solely the results after the modelling process, the policy instrument that performs the best for encouraging wood-based construction practices is not necessarily the right policy instrument to be implemented. Policy advice requires to take into account multiple facets of the advice including the consequences for present conditions on circularity.

1.5 Research outline

In order to visualize the process, a research-flow-diagram was made (see Figure 1). This diagram includes the approach used for the research for this thesis, how the phases of the research approach relate to the content within the thesis, and in what chapter this content and the research questions will be answered. The diagram should be read horizontally from left to right. The items that are vertically aligned belong to each other. The modelling process is part of the whole thesis process and is demarcated by a box. The System Analysis, Model Design, Detailed design, Software Implementation and Model Evaluation phases follow directly on one another in the diagram. Research questions sometimes fall under more than one modelling step each. In such cases, these questions are aligned with the modelling step to which they are most closely related.

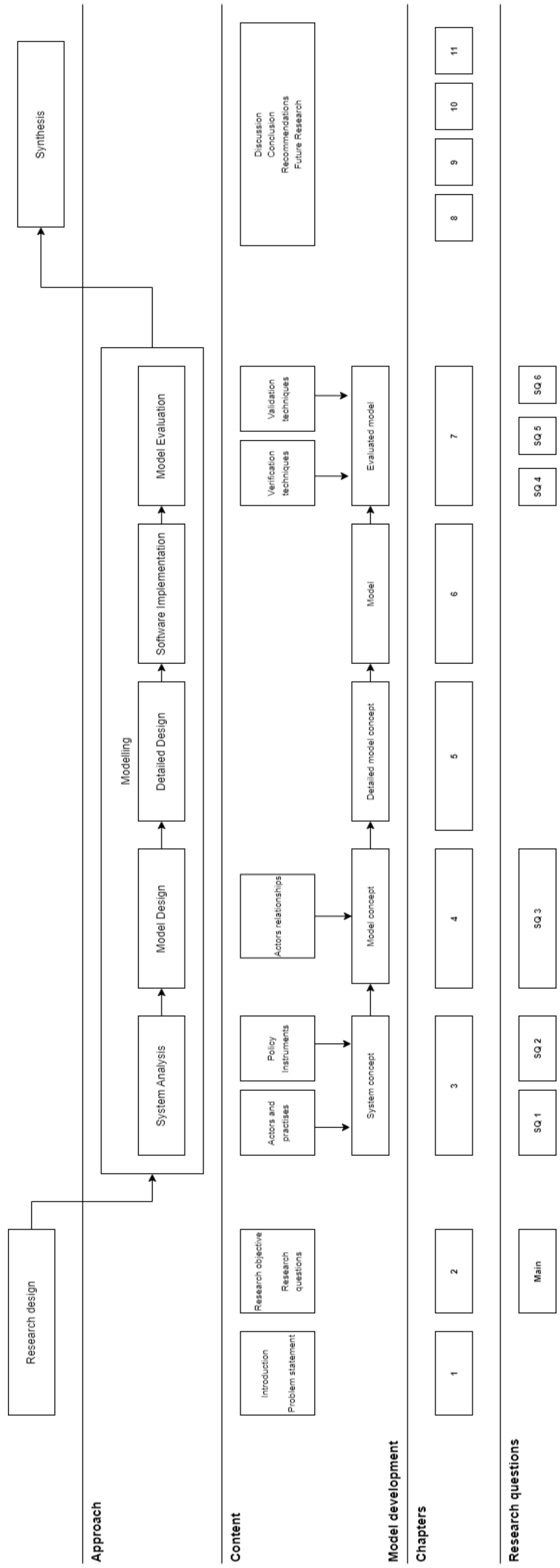


Figure 1: *Research flow diagram*

2 Case background

The aim of this chapter is to provide the theoretical basis for this study. Scholars have studied various aspects of the built environment that are relevant for the development of this model. This chapter will explore the general concepts of a circular city, examine policy instruments for encouraging wood-based building practices, and explain how the city of Amsterdam is approaching circularity.

2.1 Circular economy

A Circular Economy (CE) is defined as an economy "that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times." (Hart et al., 2019). A CE focuses on the redesign of processes and the cycling of materials within commerce and industry. This involves reusing materials, durables and energy (Williams, 2019). Within academia, scholars have intensified their efforts to understand circularity in cities (Hart et al., 2019). A closed-loop CE was first mentioned in the work of Boulding (1966). Boulding separates an open-loop system from a closed-loop system, where in an open-loop system the outputs are used as inputs. He argues that for a long time, humanity assumed resources to be unlimited. There was always a resource or place humans could address when they were deprived of their necessities. Resources can be drawn and waste disposed without facing the negative consequences from both practices. Although these practices are, and always have been unsustainable in the long run, humans have difficulty acknowledging this. Boulding (1966) recognises that especially economists have trouble with the notion of a closed-world system. He makes the distinction between a cowboy-economy, where both production and consumption are seen as desirable, and a spacemen economy, where we measure in terms of throughput, and throughput is seen as something to be minimized. Even though this paper was written in 1966, it is still relevant today. The idea of infinite growth in our economies is still present. However, an increasing amount of research related to circularity in economies is undertaken. Geissdoerfer et al. (2017), in his paper The Circular Economy: 'a new sustainability paradigm', mentioned that he sees an exponential growth in the amount of publications on circular economies. Geissdoerfer mentioned that this surge started after the implementation of regulatory controls in China and then spread to Europe. Since, in the face of climate change, sustainability gets more attention nowadays, Geissdoerfer et al. concludes that within literature, a circular economy is seen as a condition for sustainability and therefore also receives more attention.

2.2 Circular built environment

From the notion of a CE, we move to the notion of a circular built environment. A circular built environment consists of 'circular buildings'. The term 'circular building' defines a building that is designed, planned, built, operated, maintained, and deconstructed according to the principles of a circular economy (Pomponi and Moncaster, 2017). Pomponi and Moncaster argue however that principles which apply to short-lived products, the main focus when one thinks of a circular economy do not fully apply to buildings. Buildings are constructed from standard manufacturing products that together form a complex ever-transforming entity. When one would take principles from short-lived products and apply them to buildings, a whole range of already existing buildings would not be taken into account. However, due to the long lifespan of buildings, these buildings need to be taken into consideration too. Not solely the long lifespan of a building in the built environment is important to take into account when moving to circularity, but also the numerous stakeholders, components and materials that interact need to be accounted for (Hart et al., 2019). Hart describes the barriers and drivers of circularity of the built environment. He identifies barriers and enablers from literature namely: cultural, regulatory, financial, and sectoral. This thesis research will mainly focus on the regulatory barriers and enablers. Under regulatory barriers, Hart lists the following ones: lack of consistent regulatory framework, obstructing laws and regulations, and Lack of incentives for CE. Under enablers Hart puts: policy support & public procurement, regulatory reform, fiscal support and producer responsibility. Especially policy support in fiscal and regulatory form seem to be lacking.

2.3 Wood-based construction practices

There is a wide variety of literature to be found on the intensification of wood in the built environment. A comprehensive assessment of wood as an alternative building material requires a holistic view of all the processes that surround its usage. This entails the full lifecycle of wooden building components including the extraction, processing, installation and demolishment. Intermediate stages like transport also need to be incorporated. A comparison between wooden building components with their masonry equivalent was done by multiple scholars (Buchanan and Bry Levine, 1999; Gustavsson and Sathre, 2006; Pajchrowski et al., 2013). They all concluded that using wood as an alternative building material reduces CO_2 emissions during the whole life-cycle. Pajchrowski et al., 2013 sums up a variety of non-ecological qualities that make wood an interesting building material. Wood is both light and mechanically strong, which is beneficial during design, construction and transport. Wood can easily be worked on mechanically and is therefore inexpensive to modify and reuse. Wood has a good thermal conductivity coefficient, it deadens noise, is resistant against the effect of chemical substances and regulates humidity which creates a pleasant living environment. These benefits make wood attractive to work with in the built environment.

Even though there seems to be consensus among scholars about the environmental and technological benefits of the usage of wood within buildings, the adoption of wood has been slow (Franzini et al., 2018). A study on the motivations and barriers of using wood in multistory and non-residential construction projects sums up potential barriers for this slow adoption, namely, higher building cost, missing expertise, the durability of the material, the culture of the industry and the availability of the material (Franzini et al., 2018). The study by Franzini et al. mainly focuses on actors within the construction industry and therefore excludes other stakeholders including governmental bodies and homeowners. Stakeholders will be accounted for in this thesis project.

2.4 Wood-based construction in the Amsterdam

The city of Amsterdam aims to increase the use of wood-based building practices in its built environment. The main driver for the shift towards wood-based construction practices is to induce a reduction in CO2 emissions, since the building sector worldwide is responsible for nearly 40% of the overall carbon emissions. However, other incentives are a reduction in noise pollution, a cutback on waste, accelerating housing construction, and creating employment opportunities. All with the aim of creating a healthier and more sustainable built environment. The city's ambition is to have 20% of the housing construction executed with wood as a primary material by 2025 (MRA, 2020a). However, there are significant challenges that need to be addressed. Amsterdam identified a lack of knowledge and experience with wood as a construction method, regulatory challenges like the need to update building regulations, and a lack of understanding on how to stimulate wood as a construction practice. The city of Amsterdam aims to actively promote innovation in the building sector by sharing knowledge about construction methods and regulations. Within the city, Amsterdam wants to identify suitable location for wood-based construction projects and identify the spatial and financial requirements. To understand the challenges present and to support solutions, the municipality aims to collaborate with private landowners and other stakeholders. The efforts of knowledge institutions and public entities are outlined in the Green Deal Covenant (MRA, 2020b).

2.5 Policy for enhancing wood-based construction practices

Various organizations have addressed policy directions and instruments in order to enhance wood-based building practices. To get an understanding of the policy environment currently present, two organizations and their respective policy proposals are described. First, an organization named Circulaw, that advises on various policy instruments on a municipal level. The United Nations also proposed a comprehensive list of key insights on various governance levels. The model for this thesis research is based upon various insights that originate from both organizations.

2.5.1 Circulaw

Circulaw is a knowledge platform that aims to speed up the transition towards a circular economy. Circulaw does this by informing policymakers, project leaders, and buyers how they can leverage existing policy. They state that policy instruments can be used to effectively promote a circular economy. Circulaw covers various themes like promoting wood-based construction, circular wind turbines, and circular mattress chains. For every topic a set of policy instruments is proposed with explanation, potential effectiveness, and legal feasibility. For enhancing wood-based practices, Circulaw has identified 37 relevant policy instruments (CircuLaw, n.d.). The most important policy instruments for this thesis research as proposed by Circulaw are listed down below:

- Giving timber construction a place in the municipal environmental vision.
- MPG as a sub-selection criterion for land allocation.
- Demolition notification.

This thesis will further elaborate on the last instrument due to its ability to translate it into a model environment. Although not explicitly modelled, the model is still able to identify the importance of the two other instrument mentioned on the Circular website through the use of a proxy.

2.5.2 United Nations (UN) report

The United Nations published a report with the intention to provide insights, recommendations and strategies that relate to the impact of building materials on the climate (United Nations, 2023). It provides guidance on how to transition towards more environmental friendly building practices. Wood-based materials take a prominent place in the document. However, the recommendations are not restricted to only wood-based practices and also cover other construction materials. The report mentions some key points in relation to wood and timber. The most pertinent ones to this thesis are listed below. However, this list is far from complete.

- Promotion of material efficiency: The development of structural standards for renewable material.
- Regulation and certification: Incorporation of certified products in the building code.
- Training and upskilling: Training construction actors in the use of building materials.
- Promotion and Incentivization: Incentivization of the use of structural mass timber in building structures.
- Improving manufacturing and processing: Reducing the loss during timber processing.

Although the document does not provide us with concrete policy instruments that can readily be used in the built environment, it does offer a comprehensive overview of potential incentives to reduce the environmental impact of building practices.

3 Research methodology

In order to understand the system at hand and the influence of the respective policy instruments, an agent based model will be developed and tested. The outcome of the model analysis enables us to answer the main research question: "How do policy instruments influence the adoption of circular wood-based building practices in Amsterdam, and what influence do they have on the city's built environment?" This section elaborates on the process to design, develop, verify and analyze the ABM model. It starts off with an explanation of the method used for model development. Then we will elaborate on ABM modelling as a modelling technique. The gathering of data will also be touched upon. Methods of validation and how to analyze the model will be briefly explained.

3.1 Model design

The model design has been carried out in accordance with model design method proposed by (Dam et al., 2013). This method involves a ten-step process to design and implement an agent-based model. Although the process of modelling is not a linear but iterative process, this method helps to improve our understanding of where we are in the modelling process and what to do next. The flowchart is visible in Figure 2.

1. Problem Formulation and Actor Identification: In order to assess the system at hand, we want to get a better understanding of the actors in the built environment and the environment itself. The key actors are identified by literature on the built environment and talks with knowledge organizations and the municipality of Amsterdam. This step will also answer the sub-question: Which agents and environmental factors shape Amsterdam's built environment?

2. System Identification and Decomposition: The built environment of Amsterdam is a complex socio technical system. This step decomposes the system into the relevant components. In the case of the built environment of Amsterdam, mainly types of buildings and material types.

3. Concept Formalisation: In this step the concept is formalized and the key steps relevant to the model are defined.

4. Model Formalization: The model development is based on the concepts identified. During this step we decide on the rules and interactions of the model which will form a basis of how the actors act in the model.

5. Software Implementation: In this step the concept model will be translated into code. For the built environment model we will use Netlogo.

6. Model Verification: The model will be verified during this step. Here we will identify if the model behaves as we expect and that no coding errors are present in the model. A sensitivity analysis is conducted to verify how input parameters affect the outcomes of the model.

7. Experimentation: During the experimentation phase, the model will be run for various iterations under different policies and scenarios. These experiments provide insight into how various policy instruments effect the adoption of wood-based construction practices.

8. Data analysis: The data that originates from the experimentation phase will be analyzed and conclusions are drawn.

9. Model validation: The model will be validated based on real world data and expert opinions.
10. Model Use: The model will be used to answer the main question and therefore support the decision making process.

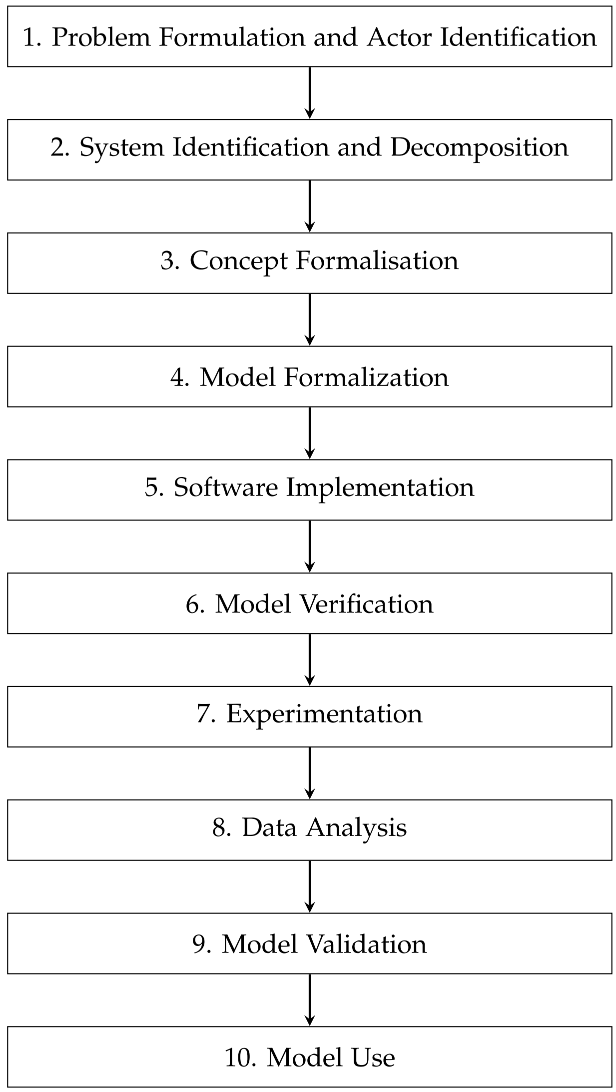


Figure 2: *Flowchart of the Model Design Process*

3.2 Agent-based modelling

Agent-based modelling is a modelling paradigm that studies social interaction, collaboration, group behaviour, and the emergence of higher order social structures (Macal and North, 2005). ABM finds its origin in modelling human social behavior and decision making (Bonabeau, 2002). This simulation method is used to assess the effects of agent behaviour on the system as a whole. Agents make decisions based on decision-making rules, one another and the environment. This modelling technique is becoming more and more popular. In a tutorial on ABM, Macal and North state three reasons for this development. First, traditional modelling tools are not suitable anymore for the complexity of the systems we need to study. For example, Macal and North discuss the use of models in the increasingly deregulated electric power industry. The increasing amount of interdependencies makes traditional modelling techniques ineffective. Secondly, Macal and North argue that some systems have always been too complex to model by traditional modelling techniques. The models that existed consisted of assumptions necessary to be computationally tractable. This resulted in oversimplifications that could not capture the reality at a desired level. Agent-based modelling partially resolves this problem. Thirdly, nowadays low-level data is available that creates a (quantitative) understanding of the behavior of actors. Finally, Macal and North argue that due to the increased computer power, simulating agent-based models is less computationally expensive.

An agent-based model consists of the following four components:

- Agents: Entities in the model that can interact with one another.
- Properties: The properties of the agents, depending on the model.
- Environment: The world where agents interact.
- Rules: What happens when agents interact with each other or the environment.

Computer agents typically have the following properties (Wooldridge and Jennings, 1995):

- Autonomy: Agents can operate autonomously.
- Social ability: Agents can interact with other agents.
- Reactivity: Agents have a perception of the environment and respond to it.
- Proactivity: Agents can take initiative and engage in goal-directed behavior.

Agent-based modelling is well suites for the problem at hand. A variety of properties of an agent-base model and how this aligns with the problem at hand is listed down below.

- Heterogeneity among agents: The Amsterdam built environment consists of multiple different agents that interact with one another. Their decisions shape the built environment. An agent-based model enables us to model different agents and investigate how their behavior effects the environment. Policy instruments act differently upon different actors which requires the use an agent-based approach.
- Interaction effect: Actors in the environment influence one another through their interaction. It could be that these interaction effects have a significant importance and therefore needs to be taken into account. Agent-based models enable us to incorporate and simulate interaction effects.
- Adaptation and learning: Actors learn and adapt over time. The built environment has multiple actors that specify in a certain material type. An agent-based modelling approach is well suited to incorporate learning and adaptability in the model.
- Emergent behaviour: through agent interaction, the built environment changes. We are especially interested in the emergence of the model. In relation to the built environment, we are interested in the ratio of wood-based building compared to all buildings. The aim is to end up with a high ratio of wood-based buildings.
- Flexible and modular design: Agent-based models are modular in design and can therefore be updated and modified. The model can function as an instrument in the toolbox of policy makers for the use of wood-based policy instruments. However, it could also be useful for policy instruments in the built environment. This will likely require model updates.

Additionally, it may well be required be to update the model when new research is conducted or new data is collected.

3.3 Modelling software

The modeling software used is NetLogo 6.3 (Wilensky, 1999). Optimized for creating agent-based models, NetLogo is well-suited for this application. Its user interface allows for interaction with the model through various input methods, including sliders and buttons that modify the model's operations. Live graphs visualize the model's workings, and an informative 'info' tab in NetLogo explains these workings in more detail, enhancing its utility for this application.

Although NetLogo is an accessible tool for interacting with the model, it has limitations during the model development phase. This is particularly evident when validating the model, which requires running the model numerous times. Therefore, the programming language Python will be employed for this purpose. The package 'Pynetlogo' provides an interface between the Python programming language and the NetLogo model (Jaxa-Rozen and Kwakkel, 2018). This integration enables the modeler to feed and extract data from the model, facilitating further processing of outcomes from multiple model runs.

3.4 Data gathering

Data will be gathered from multiple sources. For this thesis project we're in close contact with the municipality of Amsterdam. They have a rich body of knowledge on the built environment and the various actors involved. We will also gather information from the AMS Institute in Amsterdam. They work on the topic of wood-based building practices in the Amsterdam built environment. Quantitative data will be gathered from literature and various databanks. CBS data, in particular, is important for quantifying the Amsterdam built environment. GIS data will be used for more specific data.

3.5 Validation

To ensure the model's credibility and the reliability of the policy findings, it is vital to confirm that the model's behavior aligns with its intended design. Therefore, we will conduct a model verification. This verification will consist of several steps:

1. Aligning the model description with the actual model.
2. Conducting a code review and testing the model's boundaries.
3. Performing a consistency check.
4. Undertaking a step-by-step analysis.
5. Executing a global sensitivity test.

4 System analysis

This chapter aims to understand the different actors and factors active in the built environment system. Therefore, it tries to answer the first two sub-questions, namely:

1. Which agents and environmental factors shape Amsterdam's built environment?

2. How do the key actors interrelate and influence each other's behaviours?

For the clarity of this chapter, table 1 lists the data sources used for defining the model.

Data	Source
Material intensities wood	Smith and Wallwork Engineers, 2023
Material intensities concrete	Sprecher et al., 2021
Distribution SFH, MFH, utility buildings	CBS, 2023
Weibull distribution parameters	Deetman et al., 2020; Yang, Hu, Zhang, et al., 2022
Floor surface residential buildings	CBS, 2023
Floor surface utility buildings	CBS, 2023; Kadaster, 2023
Recycling rates	Zhang et al., 2020
Distribution ownership	CBS, 2023

Table 1: *Data sources for material intensities, building distributions, and other building-related parameters.*

4.1 Built environment system

The built environment system encompasses actors and processes that alter the built environment. The objective of this chapter is to gain a deeper understanding of the actors involved and their respective behaviours. This knowledge can then be leveraged to determine which actors should be included or excluded from a model. The information was gathered through a combination of interviews and further literature review.

The built environment is a complex system with many actors and factors at play. Actors range from municipal and governmental bodies to the construction industry, developers, residents, and financial and legal organizations. Although a ideal model would incorporate all actors in the environment, such models do not exist. Keeping the model understandable is one of the main aims of the model building process. Since the model is developed with understandability and simplicity in mind, the actors that are incorporated in the model are also deemed most influential in the built environment. In the understanding of the author, the behavior of the actors could move building practices from masonry to wood-based.

Construction companies
Construction companies are of primary importance in the built environment for a variety of reasons. Construction companies are responsible for determining construction methods before the construction project. In close cooperation with architects and engineering firms, construction companies have a major influence on what material is used in buildings. The interaction between construction companies, architects and engineering firms, is complex but influential. However, modelling the decision process between these agents is very complex in nature and solely focuses on another level of decision making than that of the model's interest. The model's purpose is to identify aggregated patterns on a city level as well as financial incentives. Therefore, the model

focuses on solely construction companies and their expertise with wood-based practices. The model incorporates the expertise and adaptability of architects and engineering firms into the overall behavior of the construction companies.

Demolition companies
As previously mentioned, one of the benefits of wood-based constructions is the ability to effectively reuse the material components after demolition. Demolition companies play a primary role in modeling circularity, specifically through looping actions, in the built environment. One of the promising policies for encouraging wood-based building practices identified by Circulaw is the demolition notification as mentioned in section 2.5. This policy encourages demolition companies to monitor and recycle materials that are released during demolition. The model therefore takes into account the role of demolition companies and how they influence the built environment.

Material supplier
In line with demolition companies, the material supplier is important for modeling looping material flows in the built environment. The material supplier acts as a more passive agent in the model. The material supplier accepts secondary material and supplies primary material. The material supplier has a capacity for secondary material which enables them to convert demolished material into material that is suitable for primary use. With policy instruments, one is able to alter the behavior of the material supplier. Investment in better recycling practices can increase the amount of material that can be recycled. More storage also enables the material supplier to accept more material from demolition companies, increasing the circular capacity of the environment. Both instruments can be influenced on a municipal level. Temporary storage of materials is an important subject for the municipality of Amsterdam, and some exploratory research for Amsterdam has already been done Loeber and Snoek, 2018. Therefore, the ability to influence these parameters is paramount.

Owners
Owners are the primary decision-makers, when it comes to the selection of construction materials and methods. There is a diverse range of owners, including private individuals, housing associations, and real estate developers. Their preferences have an impact on the built environment. Their familiarity with and trust in specific materials can influence their decisions regarding those materials. Owners are also economic actors, basing decisions on budget and investment potential. Within the model, the role of owners is paramount.

Actors left out of the model
Several actors have been left out of the model that are active in the built environment. This section will briefly discuss which actors have been left out and why they are left out. Engineers and architects were left out of the model. Their behaviours are incorporated into the behaviours of the construction companies. The reason for this simplification is that modelling the interaction between architects, engineers, and construction companies would make the model overly complex and add limited content to the model. Therefore these interactions have already been researched (Knoeri, 2015).

4.2 Physical built environment

To effectively populate the model with the current building stock, it is necessary to quantify physical parameters of the built environment. The physical built environment in this model encompasses all residential and commercial buildings in the city of Amsterdam. While the model does not utilize a one-to-one spatial representation of the city, a simplified representation is used. To achieve this, an assessment of the current Amsterdam building stock was conducted, encompassing multiple relevant parameters necessary for the model. In order to generate a model representation of the current physical built environment of Amsterdam, it is necessary to accurately quantify the distribution of buildings that the city consists of and their relevant properties.

4.2.1 Amsterdam building stock

The model represents the built environment of Amsterdam and utilizes multiple data sources to simulate material flows. Understanding the amount of material present in the building stock is crucial for accurately measuring material flows, especially when changes are made to the stock. The physical built environment model serves as the foundation for actor interactions. Although each data source has its limitations, combining them results in a detailed and comprehensive model environment.

The Netlogo model is composed of patches with each patch representing a building, classified as either residential or utility. Residential buildings include apartments, single-family houses, and row houses, while utility buildings encompass commercial (shops), and offices. Dividing buildings into subcategories allows for more precise information about their construction years, floor surface values, and material intensities.

Table 2: *Quantity per building type in the city of Amsterdam (CBS, 2023)*

Type - function	Building quantity
Rowhouse	975
Single Family House	1211
Apartment	1259
Office	1066
Commercial	1139
Other	1185

Figure 3 and Figure 4 show the number of buildings per construction year interval together with the average floor surface for these buildings. These data originate from CBS. This data is used to populate the model of the built environment.

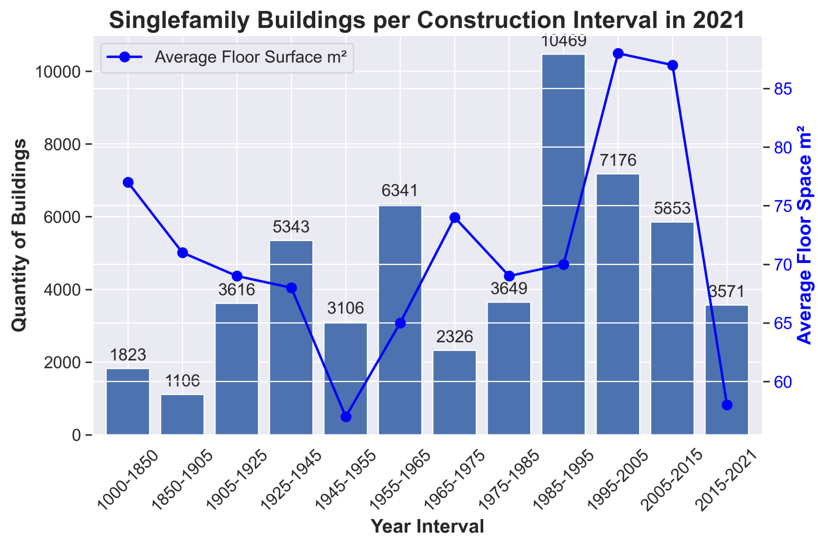


Figure 3: *Singlefamily Buildings per Construction Interval in 2021 (CBS, 2023)*

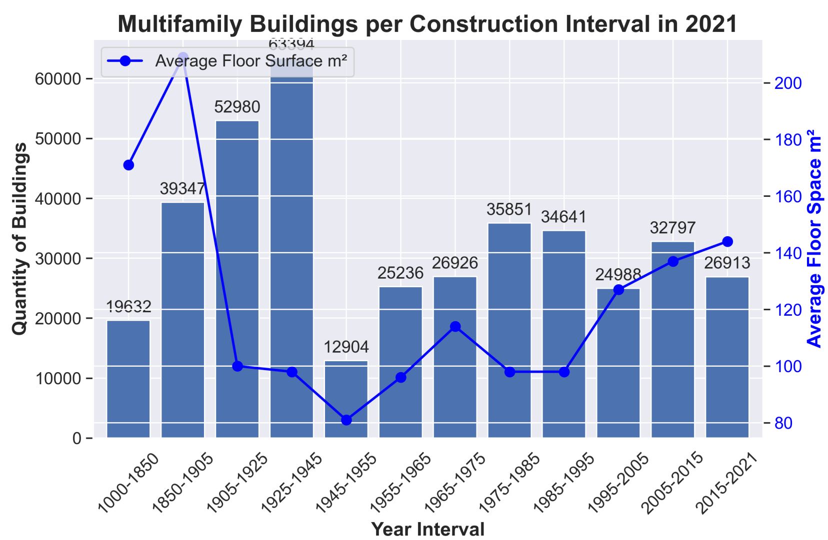


Figure 4: *Multifamily Buildings per Construction Interval in 2021 (CBS, 2023)*

The CBS (Centraal Bureau voor de Statistiek - Statistics Netherlands) and GIS (Geographic Information System) data are crucial to the built environment model, providing essential information for simulating material flows. The GIS data are used for modelling the floor surface and construction year of utility buildings. CBS data are used for modelling floor surface and construction year of residential buildings, but also for the distribution of ownership. The data provided by both sources in combination with material intensities enables the model to predict material stock in the built environment and potential material flows. High resolution is especially necessary when it comes to utility buildings. In comparison to residential building, utility buildings vary greatly in floor size which makes it hard to evaluate their material content. Therefore we have specified a wide range of utility building types.

4.2.2 Building lifespan

The data on the lifespan of buildings in Amsterdam's built environment is limited and there is no specific data on the lifespan of buildings in Amsterdam. Although BAG data provides the construction year of all buildings in Amsterdam and CBS data provides the amount of buildings demolished in this region, it is impossible to calculate the lifespan of these buildings in order to extrapolate this for the remaining building stock. Therefore the model uses a distribution for estimating the lifespan of buildings. Multiple distributions are used in literature, including normal, Weibull, log-normal distributions (Miatto et al., 2017). However, this model uses the Weibull distribution which is well suited for this purpose due to its accurate performance in material flow analysis. The parameters are summarised by Deetman et al., 2020 and also found to be effective for the model by Yang, Hu, Tukker, et al., 2022; Yang, Hu, Zhang, et al., 2022. This model uses values similar to those used in a material flow model in Leiden (Yang, Hu, Tukker, et al., 2022), as this data closely approximates the material intensities found in the Netherlands.

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

where:

- $f(x;\lambda,k)$ is the probability density function of the Weibull distribution.
- x is the random variable.
- λ (lambda) is the scale parameter of the distribution.
- k is the shape parameter of the distribution.
- e is the base of the natural logarithm.

Table 3: *Weibull distribution parameters for the Western World (Deetman et al., 2020)*

Region	Shape	Scale	Mean lt (yr)
Western Europe	2.95	70,82	63

4.2.3 Material intensity

Material intensities play a crucial role in the model as they help estimate the amount of material used in individual buildings in the Amsterdam built environment, and the potential for reusing these materials after demolition. Since there is no available data on the precise amount of material used, material intensities are used instead. The model uses a bottom up approach to estimate the material flows similar to what was done by Wiedenhofer et al. (2015). This means that the material flows are estimated from a estimation of material content after a building is demolished, instead of estimated on a municipal level. These intensities indicate the amount of material per square meter of floor surface. By multiplying the material intensities with the floor surface of each building, we can get an approximation of the amount of material used in a building.

Table 4 displays the material intensities used for masonry building types, which were derived from research conducted in Leiden (Sprecher et al., 2021). For the purposes of this model, we assume that all buildings in the Amsterdam built environment are constructed using masonry materials upon initialization. The current number of wood-based buildings is limited (MRA, 2020a), assuming all building types to be masonry is unlikely to significantly affect the accuracy of the model's representation of the current built environment stock.

The material intensities for mansonry-based building archetypes in kg/m^2 for both concrete and wood are shown in Table 4 for relevant building archetypes.

Table 4: *Masonry material intensities kg/m^2 for concrete, steel and timber (Sprecher et al., 2021)*

Material	Row	Single	Apartment	Office	Commercial	Other
Concrete	353	974	883	615	573	564
Steel	12	34	31	22	21	20
Timber	39	216	19	22	48	35

To provide insight into the weight difference between concrete and wood in masonry-based construction, Figure 5 displays the material intensities for all building archetypes. We notice that for every archetype, the weight of concrete is an order of magnitude larger.

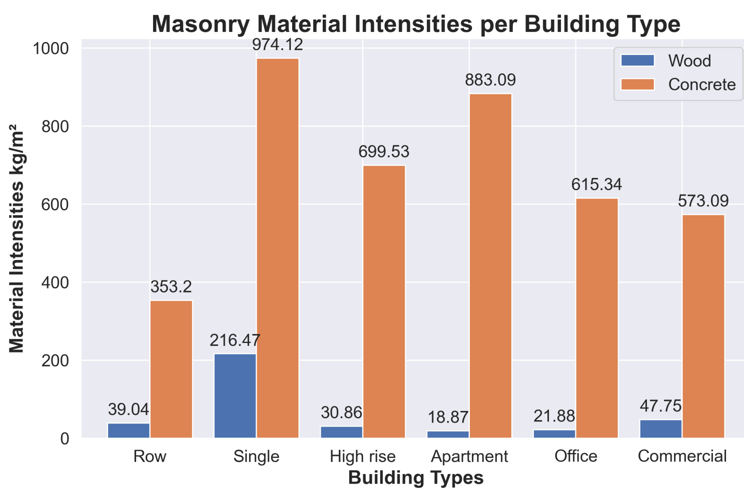


Figure 5: *Masonry material intensities per building type (Sprecher et al., 2021)*

As one can observe, concrete is more commonly used in masonry-type buildings than wood. Apartments, high rise buildings and single family homes have a relative high amount of concrete compared to row houses and utility buildings. However, the weight of concrete per m^2 relative to wood in figure 5 is slightly distorted due to concrete being 4.62 times (MASEA, 2023) heavier than wood.

The data on mass-timber constructions are limited since these buildings are novel in the built environment. However data was acquired with the help of an engineering company specialized in wood-based constructions. The material intensities for wood-based buildings are derived from their project dataset (Smith and Wallwork Engineers, 2023). Smith and Wallwork Engineers provided a list of construction projects with corresponding parameters. We have selected comparable projects for each building archetype, using the material intensities from these construction projects in the model. The material intensities for wood-based building archetypes in kg/m^2 for both concrete and wood are shown in Table 5. The reference projects can be found Table 25 in the appendix.

Table 5: *Wood-based material intensities kg/m^2 for concrete, steel and timber (Smith and Wallwork Engineers, 2023)*

Material	Row	Single	Apartement	Office	Other
Concrete	374	677	157	272	370
Steel	41	19	8	16	21
Timber	150	75	144	200	142

4.2.4 Material reusage

In the Netherlands, 95% of the building demolition waste is recycled. However, most of the waste is recycled for low value applications like road construction (for the case of concrete) that originate from building demolition (Schut et al., 2016). The use of secondary materials in construction of buildings is found to be less than 3% (Hu et al., 2017). The potential for upcycling materials is much higher.

The collection rate and the recycled content potential for both concrete and wood are shown in Table 6. The recycled content potential as defined by Verhagen et al. is the amount of primary material that can be replaced by upcycling demolition waste.

Table 6: *Collection rate and Recycled Content Potential (Verhagen et al., 2021)*

Material	EOL Collection Rate (%)	Recycled Content Potential (%)
Concrete	85%	50%
Wood	95%	90%
Steel	95%	85%

From all construction and demolition waste, concrete and masonry materials account for 64% and wood accounts for 6% (Zhang et al., 2020). The waste processes for both wood and concrete are shown in Table 7. Here we see that only a small portion of the concrete is upcycled for the concrete industry. The majority of the concrete is downcycled for site elevation or used as road base material. As indicated by Table 6, the recycled content potential for concrete is much higher (50%). For wood the majority of waste product is used for energy recovery by incineration (76%). Only 13% is used for chipboard. Although the primary use of wood waste product is for energy recovery, it has a recycled content potential of 90%. This means that a far higher percentage of the wood can be reused for construction. Reusing wood is favourable over energy recovery in terms of carbon emission mitigation (Niu et al., 2021).

Table 7: *Waste processes for concrete and wood Zhang et al., 2020*

Material	Waste process	% of fraction
Concrete	Recycling for concrete industry	3
	Downcycling for site elevation	19
	Downcycling as road base material	78
Wood	Unknown	11
	Recycling for chipboard	13
	Incineration	76

4.2.5 Selective deconstruction

Selective deconstruction is an approach towards disassembly to maximize the recovery of materials after demolition. This practice, also known as 'construction in reverse', is used to dismantle buildings for reuse, repurposing, recycling and waste management. Selective deconstruction differs from conventional demolition methods since more attention is given to separation of materials. Selective deconstruction plays a key role in advancing a circular economy within the built environment sector. It promotes the recycling of building components and waste materials. This reduces waste materials that would otherwise be landfilled or downcycled. Avoiding construction and demolition waste greatly reduces emission (Keena et al., 2022).
Another approach is to look at the ability to reuse building materials and components after the lifetime is expired. When architects and engineers incorporate reusability into their designs, building components can be effectively reused. Computer-aided design can help to streamline the demolition process and improve the reusability of materials (United Nations, 2023).
There are various policy instruments that enhance selective deconstruction practices. Governments can adapt the demolition process by obliging demolition companies to administrate the material that is released during demolition and where the material is disposed of (Circulaw, 2023). In addition to obligatory measures, governments can support education and research on necessary practices for conducting selective deconstruction. Promoting markets for reused products and incentivizing reuse centers and specialized contractors can be beneficial to promote a circular economy (United Nations, 2023).

4.2.6 Construction cost price

The construction cost price for masonry-based buildings is not the same as for wood-based buildings. However, the model requires a set of input variables in order to calculate the construction cost price. This section goes into the calculation of the construction cost price for both building types.

Construction cost differences
Lets first asses the construction cost differences between wood-based buildings and masonry-based buildings. The difference between the construction cost for a wood-based building it's masonry variant differed much throughout literature. Some estimations for cost differences are listed in Table 8.

Table 8: *Construction cost differences masonry and wood*

Building archetype	Construction type	Cost difference	Nation	Source
Apartment	Mass timber	+16% to +29%	US	Fanella, 2018
Row house	Mass timber	+35%	NL	Beijers, 2021
Row house	Wooden frame	-2%	NL	Stichting Hout, 2021
	Mass timber	+27%	NL	Stichting Hout, 2021
Apartment	Wooden frame	-21%	NL	Stichting Hout, 2021
	Mass timber	+14%	NL	Stichting Hout, 2021
Various	Wooden frame	+4.3%	CR	Hrdlicka et al., 2022
Row house	Wooden frame	-1.1%	UK	Dacre, 2018

Table 8 highlights the cost differences between masonry building types and wood-based buildings. As one can observe in Table 8, mass timber buildings are more expensive relative to wooden frame building types. Wooden frame building types are more common over the world, especially in nations where wood is readily available. However, in this study we focus on buildings constructed from mass timber since it seems more promising for dense areas such as the city of Amsterdam.

Centrum Hout mentions in its report that it is likely that the higher construction cost for mass timber is caused by the pilot status and additional ambitions for these buildings (Stichting Hout, 2021). In the Netherlands, there is a lot of experience with masonry-based building and less experience with other material types, therefore making wood-based buildings more expansive to construct.

Beijers Beijers (2021) conducted a comparative analysis of construction costs. He assessed the costs for two row houses with similar dimensions and functionality, one constructed out of wood and the other out of masonry materials. Both houses had a floor surface of $243\,m^2$ with a volume of $334\,m^3$. The masonry row house was estimated at €130,691.81, resulting in a unit cost of €913.93 per square meter. The wooden row house was estimated at €198,463.78, resulting in a unit cost of €1,387.86 per square meter. As shown in Table 8, there is a significant cost increase for buildings constructed out of mass timber.

Becoming more familiar with wood-based construction practices is likely to result in cost reductions, as seen in nations where these practices are already well established. However, in the Netherlands, wood-based building practices are novel, and the numbers calculated by Beijers Beijers, 2021 are likely representative of the starting situation in the country.

Labour-cost price

The construction cost of a building is comprised of material cost and other costs, primarily labour cost. From now on we will refer to all the cost next to the material cost as labour-cost. When the cost of material is altered, this will influence the construction cost price and the same goes for the labour cost. It can be difficult to estimate both parts of the construction cost price since these value change over time (see Figure 6). However, Figure 6 also shows that the increase of material cost goes conjointly with wages and construction cost. Therefore we assume that the ratio between labour cost and construction cost remains the same for masonry based buildings in The Netherlands (Ceteris paribus). This forms the basis of the material and labour cost calculation.

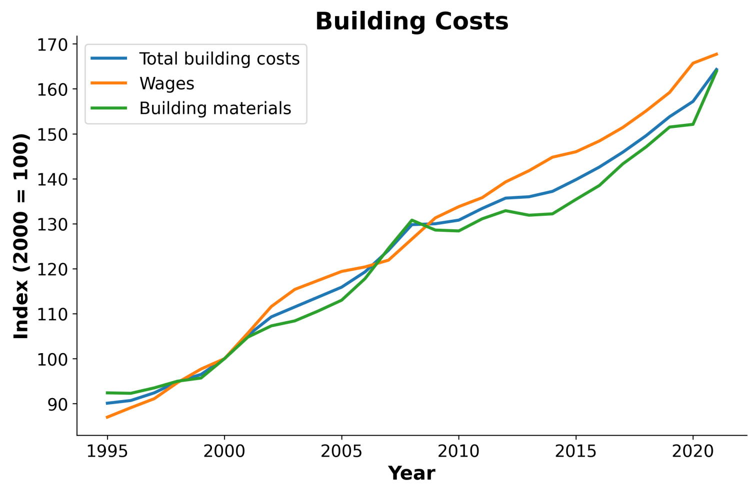


Figure 6: *Building cost indices CBS, 2023*

We will first asses the ratio between material cost and labour cost. Table 9 shows the material cost as a percentage of total construction cost. The values range between 50% and 65%. For the model we assume the material cost per masonry-based building to be around 55% of the total construction cost. This is in line with the literature as presented in Table 9.

Table 9: *Material cost as a percentage of total construction cost*

Estimated material cost in % of total construction cost	Author
55% to 60%	Shet and Narwade, 2016
50% to 60%	V P* and Shabeen S*, 2019
65%	Somerville, 1999

Table 10 shows the construction cost for various masonry-based building archetypes in The Netherlands. These values originate from data provided by the Dutch government (Overheid.nl, 2021). Although the model incorporates all archetypes, the labour cost calculation will use the average construction cost per square meter of all archetypes

Table 10: *Masonry construction cost values for residential and commercial buildings Overheid.nl, 2021*

Archetype	Price €/m^2
Rowhouse	975
Single Family House	1211
Apartment	1259
Commercial	1066
Office	1139
Other	1185

It is assumed that as a construction company specializes in a particular material type, construction costs change accordingly. Greater experience in masonry-based construction can lead to reduced costs for masonry buildings. It is believed that short-term price shifts due to specialization result from decreased labour-costs, stemming from more efficient building methods. The reduction in labour costs, whether from increased or decreased specialization, can be estimated using Wright's Law or the Learning Curve Effect. This model applies the mathematical principle to determine labour costs. Essentially, Wright's Law states that for every doubling of units produced, costs reduce by a consistent percentage. This is represented in equation 2. The learning rate for the construction industry is estimated around 0.9 (Mályusz and Varga, 2017).

$$C(N) = C_1 N^{-\beta} \tag{2}$$

where:

- $C(N)$ is the cost of producing the N-th unit.
- C_1 is the cost of the first unit.
- N is the cumulative number of units produced.
- β is the learning coefficient.

Based on the average construction cost per square meter and the ratio of material cost as a percentage of total construction cost, we can now estimate the labour cost per square meter for a construction company at full specialization. Full specialization is empirically determined at 20 units produced based on equation 2 and the values in Table 8. Figure 7 shows how the labour cost per square meter reduces with more buildings constructed.

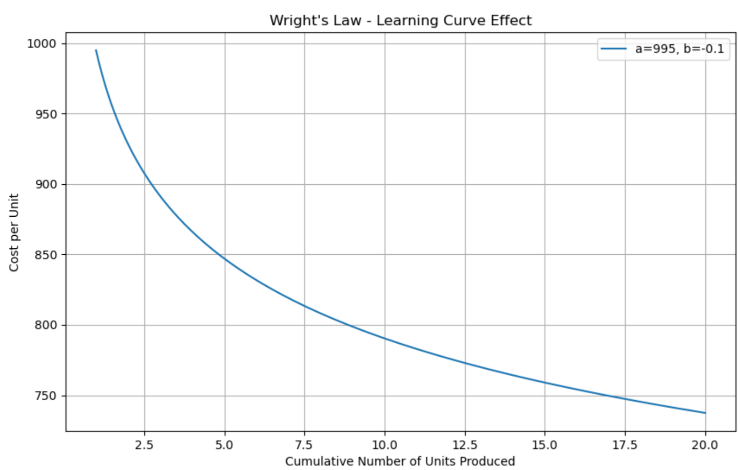


Figure 7: *Wrights Law Curve for construction companies*

Material cost price

Material cost price estimates were gathered from various sources. The model requires material prices for mass-timber beams, reinforced concrete, and steel beams. To obtain accurate and up-to-date material cost estimates, these values were gathered from various construction sites. Table 11 shows the material cost values per square meter for mass-timber, reinforced concrete, and steel beams, along with the respective sources.

Material	Price per kg (€)	Source
Reinforced Concrete	0.34	Livios, 2023
Steel Beams	1.2	Twentse Staalhandel, 2023
Mass Timber	1.277	Thunder Said Energy, 2023

Table 11: *Material cost price for various construction materials*

4.3 Policy instruments

The purpose of this model is to evaluate the effectiveness of policy instruments in promoting wood-based building practices. These instruments were based on work from Circulaw and the UN as descibed in Section 2.5. The following section lists the identified policy instruments, which will be explained in more detail.

The following policy instruments have been identified and selected for further analysis through modelling:

- Carbon tax
- Demolition notification

4.3.1 Carbon tax

Carbon taxation is an instrument primarily aimed at reducing carbon emissions. The aim of this tax is to reduce carbon emissions produced when burning fossil fuels. By adding a financial cost to these emissions, carbon taxation incentivizes industries and consumers to reduce their fossil fuel usage. This can be done by shifting from fossil fuels to renewables.

Carbon taxation applies to fossil fuels but can also serve as a mechanism to reduce the use of carbon-intensive materials in the construction sector, such as concrete. Studies on building material competitiveness and economic instruments for mitigating climate change indicate that higher energy and carbon taxation leads to increased competitiveness of wood construction materials (Sathre and Gustavsson, 2007). By increasing the cost of concrete, other less carbon-intensive and more sustainable materials like mass timber become more competitive. Another advantage of a higher price for primary concrete is that it likely encourages reusing and upcycling practices. Materials already in the built environment that can be reused emit fewer emissions compared to materials sourced from primary sources.

The model will imply a carbon tax through a proxy. The model increases the cost of concrete and reduces the cost of mass timber to mimic the effects of a carbon tax. This will influence the likelihood that owners will decide to construct wood-based instead of masonry-based.

4.3.2 Demolition notification

A demolition notification is a mandatory notification that initiators of demolition activities must submit to the Environmental Permitting Counter. The initiators of demolition need to give an estimate of the amount of material that is released during demolition and where the material is disposed of. This notification enables the municipality to test if the demolition is carried out safely and whether responsible handling of residual materials and waste separation takes place. Another advantage is that municipalities can gain insight into which materials become available and the extent to which their circular policy matches material flows in the city through demolition notifications. A demolition notification promotes two circular aspects: regulating the demand and supply of residual streams. This can be done by using a platform that connects demolition parties with material users. Another benefit for circularity is keeping track of how circular policy influences material flow.

A demolition notification enables municipalities to impose stricter requirements on initiators of demolition activities called "maatwerkvoorschriften" (customization regulations). Among other things, this regulation can determine that the initiator of the demolition needs to report the actual material stream during demolition. They can also be asked to demolish additional fractions. Fractions are specified as groups of material streams such as concrete floors, insulation material and wood. This enables these materials to be sold off easily.

The demolition notification must be submitted at least four weeks before the start of the demolition activities and is mandatory when asbestos is removed or the estimated amount of demolition waste is more than 10 m^3.

Circulaw estimates this policy instrument as potentially having an average influence with a high legal feasibility.

Circulaw has specified what a demolition notification involves (Circulaw, 2023)

Table 26 in the appendix contains all policy instruments proposed by Circulaw for the use of enhancing wood-based construction practises. The list was compiled on 27-11-2023.

5 Model description

The model description was created following the Overview, Design concepts and Details (ODD) protocol for describing individual-based and agent-based models, as suggested by Grimm et al. in 2006. The purpose of this protocol is to establish a standardized format for describing agent-based models in detail, with the primary goal of improving reproducibility. The description is structured into seven elements and is presented visually in Figure 8.

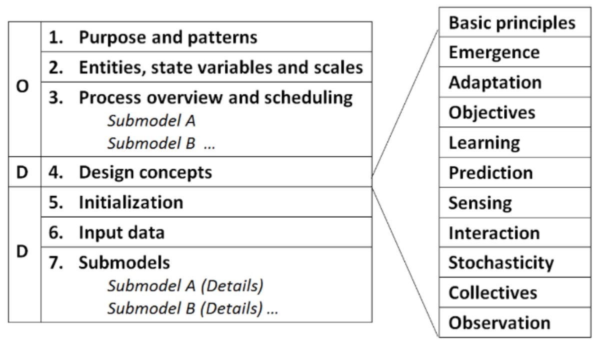


Figure 8: *Structure of model descriptions following the ODD protocol (Grimm et al., 2020)*

5.1 Purpose

As described in the main research question, to what extent do policy instruments impact circular wood-based building practices in Amsterdam, and to what extent does that influence the built environment? The purpose of the model is to shed light on the various policy instruments that can be implemented to encourage wood-based building practices in Amsterdam. The chosen policy instruments for further investigation are as follows: carbon tax and demolition notification. It is assumed that these policy instruments are most influential when it comes to enhancing wood-based construction.

As described in the chapter on Related Work, there are models with similar objectives; however, these models primarily focus on different aspects of the decision-making process and model a distinct built environment (Knoeri, 2015).

5.2 Entities, state variables and scales

The model consists of the following entities: private households, companies, housing associations, and houses (residential and utility), material suppliers, demolition companies, and construction companies. The physical built environment consists of buildings (patches in the model) that are continuously manipulated through demolition and construction carried out by construction and demolition companies. Although households, companies, and housing associations play an active role in shaping the built environment and choose to change their buildings based on their preferences.

Although the model uses data from actual buildings in the built environment, the location of the actual building is not taken into account. The model is not a literal spatial representation of the built environment in the city of Amsterdam. The model visualizes the different entities on a 2D grid, but their initial location on this plane has no influence on the model dynamics. Distances between buildings are also not relevant for the behavior of the model.

The size of the 2D grid does not represent the spatial layout of the built environment. Buildings are randomly placed on the grid during the setup of the model. Consequently, the size of a cell in the grid does not correspond to the physical world's size. Apartments are not assigned to specific apartment buildings but have their own place on the grid.

The scale of the model is adjustable. This means that you can choose to model the built environment of Amsterdam on a smaller scale than in real life. This reduces computational expenses but also decreases the resolution of the built environment, resulting in fewer buildings being modeled. Due to the way the model selects utility buildings, this can lead to some buildings being overrepresented in terms of their material contribution. Therefore, higher resolutions yield more accurate results.

Every house is connected to either a private owner, a company, or a housing corporation. The ownership of the buildings does not change over the duration of the simulation for the reasons that ownership mutation wouldn't be of importance when focused on aggregated behavior. However, private owners, companies, and housing associations base their decision for a wood-based or masonry construction on different variables and therefore have different state variables.

The model consists of three housing associations, three construction companies, a demolition company, and a material supplier. It was chosen to only model one demolition company because of its limited importance in the decision for wood-based practices. Although demolition companies have the ability to decide on recycling more materials, which could be beneficial for the adoption of wood-based practices, there is no added benefit in modeling differences between demolition companies as with construction companies. The same goes for material suppliers, which, although they have some decisive freedom, are mainly passive agents.

Tables 12 to 20 list the state variables for the observer, construction company, demolition company, housing associations, material supplier, owners, and buildings. The last column mentions where the variable originates from. 'Endogenous' means that the value is determined in the model. 'Experimental' means that the value is determined by experimentation. To get a more comprehensive overview of all data sources used, see Table 1.

Table 12: *State variables of the observer*

State variable	Description	Source
months	The amount of ticks (months) since the start of the simulation.	Endogenous
buildings_constructed	The amount of buildings constructed over the course of the simulation.	Endogenous
buildings_demolished	The amount of buildings demolished over the course of the simulation.	Endogenous
masonry_based_buildings	The amount of buildings primarily constructed of masonry-based material.	Endogenous
wood_based_buildings	The amount of buildings primarily constructed of wood-based material.	Endogenous
[material]_landfilled	The quantity of material landfilled over the course of the simulation.	Endogenous
[material]_requested	The quantity of material requested over the course of the simulation.	Endogenous
primary_[material]	The quantity of material sourced from a primary source over the course of the simulation.	Endogenous
[material]_demolished	The quantity of material demolished over the course of the simulation.	Endogenous

Table 13: *State variables of the construction company*

State variable	Description	Source
project_capacity	The construction capacity in m^2.	Experimental
specialization	The specialization in wood-based or masonry practices.	Endogenous
projects	The projects currently under construction by the construction company.	Endogenous

Table 14: *State variables of the demolition company*

State variable	Description	Source
projects	The projects currently being demolished by the demolition company.	Endogenous

Table 15: *State variables of the housing associations*

State variable	Description	Source
assets	The buildings that belong to the housing associations.	Endogenous
material_preference	The preference for either wood-based or masonry-based buildings.	Experimental

Table 16: *State variables of the material supplier*

State variable	Description	Source
stock_steel	The amount of in steel stock in kg.	Endogenous
stock_wood	The amount of in wood stock in kg.	Endogenous
stock_concrete	The amount of in concrete stock in kg.	Endogenous

Table 17: *State variables of the private, company, and other owners*

State variable	Description	Source
assets	The building that belongs to the owner.	Endogenous
material_preference	The preference for either a wood-based or masonry-based building.	Endogenous

Table 18: *State variables of the buildings*

State variable	Description	Source
status	The current status of the building.	Endogenous
time_empty	The time the plot has been empty. When there was no building constructed on the plot.	Endogenous
building_type	The type of building; apartment, single_family, row, office and shop	Endogenous
building_construction_year	The year in which the building is constructed.	CBS, 2023; Kadaster, 2023
building_floor_surface	The floor surface of the building when constructed in m^2.	CBS, 2023; Kadaster, 2023
remaining_lifespan	The remaining lifespan of the building when constructed in months.	Endogenous
owner	The owner of the building, either private, company or housing association.	CBS, 2023; Kadaster, 2023
kg_concrete	The amount of concrete in the building when constructed in kg.	Smith and Wallwork Engineers, 2023; Sprecher et al., 2021
kg_wood	The amount of wood in the building when constructed in kg.	Smith and Wallwork Engineers, 2023; Sprecher et al., 2021
kg_steel	The amount of steel in de building when constructed in kg.	Smith and Wallwork Engineers, 2023; Sprecher et al., 2021
material_type	The material type of the building either wood-based or masonry.	Endogenous

Table 19: *State variables of the material supplier*

State variable	Description	Source
stock_steel	The amount of in steel stock in kg.	Endogenous
stock_wood	The amount of in wood stock in kg.	Endogenous
stock_concrete	The amount of in concrete stock in kg.	Endogenous

Table 20: *State variables of the private, company, and other owners*

State variable	Description	Source
assets	The building that belongs to the owner.	Endogenous
material_preference	The preference for either a wood-based or masonry-based building.	Endogenous

5.3 Process overview and scheduling

The following schedule is repeated with every model step. The general flowchart is displayed in Figure: 9. The individual flowcharts are displayed in Figures 23 to 29 in the appendix.

1. All owners (private_owners, company_owners, and housing associations) are asked to evaluate their building stock.
   (a) Demolition requests are placed in the outbox.
   (b) Construction cost requests are placed in the outbox.
2. All owners (private_owners, company_owners, and housing associations) are asked to check their inbox.
   (a) Construction project estimates are evaluated based on a set of criteria.
   (b) Construction commissions are placed in the outbox for the construction companies.
3. All construction companies are asked to check their inboxes.
   (a) Material cost requests are placed in the outbox for the material supplier.
   (b) Projects are added to the project list.
   (c) Construction cost estimates are placed in the outbox for the owners.
4. All construction companies are asked to check their projects.
   (a) Construction time is updated for every construction project.
   (b) Building parameters are updated.
   (c) The project is removed from the project list.
   (d) The construction counter is updated.
   (e) Specialization parameter is adapted
5. The demolition company is asked to check its inbox.
   (a) Projects are added to the project list.
   (b) Secondary material is sent to the material supplier.

6. The demolition company is asked to check its projects.
   (a) The demolition time is updated for every demolition project.
   (b) The plot parameters are updated.
   (c) The projects are removed from the project list.
   (d) The demolition counter is updated.
7. The demolition company is asked to clear its material stock.
   (a) Secondary material request is sent to the material supplier.
8. The material supplier is asked to check its inbox.
   - The material costs are calculated for buildings.
   - Primary material response messages are placed in the outbox for the respective construction companies.
   - Secondary material response messages are placed in the outbox for the demolition company.
   - The material stock is updated.
9. The model checks if there are any messages in any of the outboxes.
10. All messages are sent out from the respective outbox of the sender to the respective inbox of the receiver.

The steps above are repeated until no messages are send anymore, resulting in that there are no messages in any of the outboxes. When this is the case, the following steps are executed:

11. The remaining lifespan is reduced by one month for every building.
12. One month is added to the simulation runtime counter.

The model operates through a messaging system. Each actor has both an inbox and an outbox used for receiving and sending messages. Based on its state, the state of its assets, or an incoming message, the actors initiate actions or send out messages. After initialization, all buildings are placed in the environment and allocated to owners.

The first model step starts with asking all owners, whether they are private owners, company owners, or housing associations, to evaluate their assets. Assets can encompass buildings and plots, and ownership remains unchanged over the course of the model runtime. Whenever a building has reached the end of its operational life, registered by the model as a remaining lifetime of zero months, the owner sends out a request message to the demolition company for demolishing the asset. The demolition request is then added to the outbox of the owner.

Whenever a plot is vacant, the owner takes action to construct a building. At first, a building type is determined by the owner. This is done based on a distribution of building types in the city of Amsterdam and can differ from what was historically present on the vacant plot. Determining the properties of a new building is a stochastic action. Subsequently, depending on the building type, a floor surface is selected. The owner verifies if there is sufficient project capacity among the construction companies to fulfill the construction order, and if this is the case, a request is generated and placed in the owner's outbox. Whenever the project capacity is not sufficient for constructing

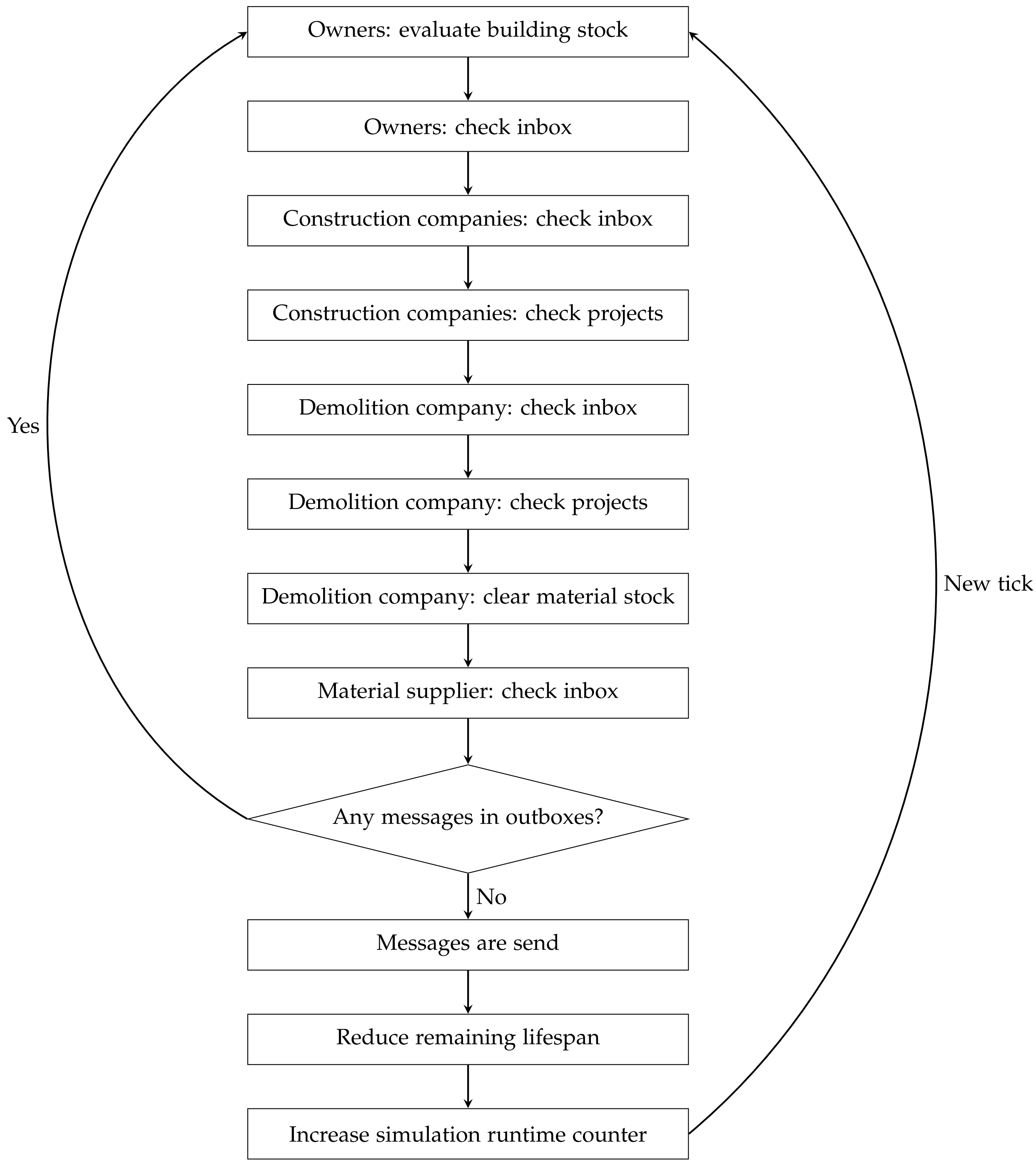


Figure 9: *Flowchart of the model schedule*

the building, no request is sent. After a request is sent, the status of the building (patch) is changed. After a construction cost request, the status is changed to *waiting_for_construction_cost_estimate*. After a demolition request, the status is changed to *waiting_for_demolition_company*. The patch color is altered based on the status of the building.

The second model step is to ask all owners to review their inboxes. When an owner receives a construction cost estimate from a construction agent, the construction project is added to an evaluation list. All construction cost estimates are grouped per building patch, and for every patch, the lowest cost option for wood-type buildings and the lowest cost option for masonry-type buildings is calculated. An owner prefers a wood-based or masonry-based building based on the price in the construction cost estimate, but also on other characteristics. Housing associations take into consideration their familiarity with both material types. The more familiar they are with wood-based buildings, the more likely they are to choose to construct their new building with wood as a basis. Familiarity is modeled by evaluating their current assets and checking how many buildings are constructed with mass timber as a basis, and how many buildings are constructed with masonry materials. Private and company owners are influenced by their surroundings. Whenever the building patch is surrounded by masonry buildings, the owner is more likely to choose a masonry-based building, and vice versa. The personal preference is expressed as a preceived extra cost and added to the construction price. The lowest perceived construction cost estimate is then placed in the outbox as a *construction_commission_request* for the respective construction company agent.

The third model step is to ask all construction companies to review their inboxes. When a construction company receives a construction cost request, the material quantities for wood, steel, and concrete are calculated for both a wood-based building and a masonry-based building. In order to get an estimation for the total materials cost, a material cost request is generated and put in the outbox to be sent to the material supplier.

Whenever a construction commission is received, first, the remaining project capacity is updated. The construction company verifies if it has enough capacity to construct the building. If the construction company lacks the required project capacity, the project is canceled, and the status of the patch is set to 'empty' again. Whenever the project capacity is sufficient, the project is added to the project list together with a project duration. Masonry buildings have a different construction time relative to wood-based structures. The status of the patch is then changed to 'under_construction.'

When a construction company receives a 'primary_material_response' from the material supplier, this indicates that the material supplier has calculated the material cost for a building project. The construction company then calculates the cost for both a masonry-based building and a wood-based building depending on the material cost, building type, specialization component, and the material type. The construction cost estimates are put back in the outbox in the form of a message to be sent back to the owner.

The fourth model step is to ask the construction companies to review their construction projects. The construction time depends on the material type and the building floor surface area. With each step, the remaining construction time is reduced by a month. Whenever the remaining construction time is zero, the construction project is completed. The parameters of the building are assigned to the corresponding patch, and the project is removed from the project list. The construction company adjusts its specialization component based on the building's material type. Finally, the building construction counter is updated.

The fifth step of the model is to ask the demolition company to review its inbox. When the demolition company receives a demolition request from an owner, the demolition project is added to the project list. The demolition company has no capacity constraints and therefore accepts all demolition projects. The demolition project is added to the demolition projects list together with a demolition time component.

Whenever the demolition company receives a *secondary_material_response* from the material supplier, it will reduce its material stock by the amount of concrete, steel, or wood as indicated by the material supplier. Material that cannot be recycled due to capacity limitations on the side of the material supplier is then landfilled.

In the sixth step, the demolition company is asked to review its projects. Every month, the remaining demolition time of each project is reduced by one. When the remaining demolition time is zero, the building is completely demolished. The extracted building material, including wood, concrete, and steel, is added to the material stockpile of the demolition company. The parameters of the building patch are then set, and the demolition counter is updated.

In the seventh step, the demolition company is asked to clear its material stock. Every month, the demolition company gathers all the material from all demolition activities in its stock. This material can either be landfilled or recycled. The demolition company will try to recycle as much of the material stock as possible. Therefore, the demolition company puts a message in its outbox to the material supplier, with the amount of material currently in stock. The material that can be recycled will go to the material supplier; the other material is landfilled.

In the eighth step, the material supplier is asked to review its inbox. When the material supplier receives a material request, it calculates the material cost for the construction project. The material cost is based on the quantity of concrete, wood, and steel. The *material_cost_response* is put in the outbox to be sent to the construction company.

When the material supplier receives a *secondary_material_request*, the amount of secondary material that can be handled by the material supplier is reviewed, and a message with this quantity is sent back to the demolition company.

The next step is to check if there are any messages in one or multiple agents' outboxes. If there are messages present, the messages are sent from the respective outbox of the sender to the respective inbox of the receiver. The model then starts again at the first step and iterates until no messages are being sent anymore, and all outboxes are empty. Once this condition is met, the remaining lifespan of the buildings is reduced by one month, and a month is added to the simulation runtime counter.

5.4 Design concepts

5.4.1 Emergence

The model shows emergent behavior on a city's built environment scale. Different types of agents, including owners, construction companies, demolition companies, and material suppliers, interact with each other and make decisions that alter the composition of the built environment. The system-level phenomena that emerge from these individual actions are categorized as follows:

Built environment development
Over time, the composition of the built environment changes due to the actions of individual agents. Owners try to optimize the resources they have for constructing a new building, therefore limiting construction expenses and making decisions in accordance with their knowledge of building practices. As described in Chapter 4, the built environment is quite conservative in nature when it comes to construction techniques. This rigidity is partially caused by the choice of owners to optimize for cost and familiarity, and it can be seen as an emergent property of the system. Similarly, construction companies also have an influence on the development of the built environment. Their familiarity with certain construction practices influences the development of the built environment. Whenever a construction company is more familiar with, for example, wood-based construction practices, this influences the construction price in favor of wood-based buildings. This, in itself, has an indirect influence on the composition of the built environment, as described above.

The time span upon which the built environment is developed is also influenced by the interaction between actors and the influence of their preferences for a certain building practice. The construction time for wood-based buildings is shorter than that of masonry-based buildings. This causes the on-site construction time to be reduced, thereby increasing the development of the environment. Although the construction time is a relatively short period in the lifetime of a building, there is a small difference between building primarily with wood-based materials compared to masonry-based materials.

One emergent property of the built environment in the model is the clustering of the same material-type buildings. Owning agents have a certain familiarity with a building material. For private owners, this familiarity is derived from their surroundings. The more neighboring buildings are from a certain material type, the more likely the owner is to choose that material type. For housing associations, their familiarity with a material type is derived from the composition of their assets. Relatively more assets from a certain material type will shift their preference toward this material type. When private owners are surrounded by masonry buildings, they are more likely to construct a masonry building themselves, causing neighboring owners to do the same after the lifetime of their building has expired. Housing associations have a similar influence on the city as a whole. This can potentially cause clusters.

Efficiency and specialization clustering
The model emulates three construction companies which can specialize in a certain construction technique. All construction companies have the ability to build wood-based and masonry-based structures. However, by building with a certain material type, they increase their specialization with this material, therefore increasing their efficiency. This leads to their ability to build a similar building for a lower construction cost. Emerging from this behavior, we see that companies that start building with a novel building material generate an advantage relative to other construction companies for this material but a disadvantage for the other material type. Specializing in one material type reduces the specialization in the other material. When owners decide to solely want to build wood-based, for example due to the influence of stimulating instruments like subsidies, this then causes the most efficient construction company in wood-based building practices to be able to offer the lowest construction cost, which results in attracting most owners and further enhancing their expertise. Capacity limitations, however, prevent a monopoly by one construction

company.

Material Recycling and Circularity
The model replicates material streams in wood, concrete, and steel. After a building is demolished, the material is either upcycled and used for a new building or landfilled/downcycled. This creates a stream of material looping through the model and influences the amount of primary material 'brought' into the model. Material upcycling and downcycling are emergent properties since these streams are altered by the agents' decisions to build wood-based or masonry-based structures. Both material types require different quantities of wood, concrete, and steel. A constructed building will eventually be demolished after the lifespan of the building has expired. A built environment consisting of primarily wood-based buildings will, therefore, have a different material composition and subsequently a different material metabolism compared to a built environment consisting primarily of masonry-type buildings. This is also influenced by policy instruments to stimulate material recycling.

5.4.2 Adaption

The actors in the model adapt to their surroundings, their assets, and limitations imposed on them by other actors and the observer. Over the course of the simulation, they increase their fitness in the environment. The most notable form of adaptation is present in the behavior of construction companies. Construction agents adapt their specialization based on the construction commissions they receive from owners. When a construction company constructs a building from a certain material type, the company becomes more specialized in that material type, therefore reducing the construction cost price. This enables the construction company to adapt to the needs of owners and increase their fitness in the environment. Owners adapt to the properties of their assets, the construction cost price, and their surroundings. Whenever the lifespan of a building has expired, the owner is forced to demolish the building and request a construction company for a new building. Capacity limitations at construction companies can cause the owner of the building to change their preference based on available capacity. When the environment is primarily composed of wood-based buildings, and therefore the construction companies that specialize in wood-based building attract most construction commissions, construction companies that specialize in masonry-based practices offer higher prices for wood-based construction projects, therefore the owners adapt their preference to masonry-based construction practices based on aggregated system properties. The same is true for how owners adapt to their environment. Social influences cause an owner to base their decision for a material type on its direct neighbors. This causes local changes in the environment.

5.4.3 Sensing

What an actor can sense differs per actor. Owners have complete knowledge of the properties of their assets. These properties consist of the remaining lifetime, construction year, building archetype, material type, and quantity of materials present in the building. Owners also have knowledge of their direct surroundings when it comes to the material types of neighboring buildings. Construction prices are gathered by sending out messages to construction companies. Owners know all construction and demolition companies and can send out messages when deemed necessary. Owners also have knowledge of the capacity limits of construction companies.

Construction companies have access to their own state variables at all times, including the projects they are working on and their specialization component. Construction companies have limited knowledge of the built environment as it is. They are contacted by owners through the messaging system and adapt through project handling. When a construction cost request is sent, the construction company is notified of the location (patch), owner, building archetype, and the required floor area of the building to be constructed. The material cost is then requested from the material supplier. Whenever a construction company accepts a construction commission, all the properties of the building are available to this actor. If the project is completed and removed from the project list, the construction company loses all access to the properties of the building.

Demolition companies have access to their own state variables at all times, including their projects and their material stock. Similar to construction companies, demolition companies have limited access to knowledge of the built environment. Whenever a demolition project is proposed by an owner, the demolition company has access to the building properties provided in the message, including owner and location. When the demolition company accepts the demolition project, the company gains access to all building properties. If the project is completed and removed from the project list, the demolition company loses all access to the properties of the plot. For recycling materials, the demolition company sends a message to the material supplier and consequently obtains information on how much material can be recycled.

The material suppliers have access to their own state variables at all times, including their material stock. The information related to primary and secondary material flows is presented to them through the messaging system. Material suppliers have no access to information on the composition of the built environment.

5.4.4 Interaction

Agents communicate with each other through a dedicated asynchronous messaging system. These messages contain information related to construction and demolition activities, such as invoices, demolition instructions, and construction instructions. The messaging system makes it possible to intercept messages and enable further development of the model. All agents have both an inbox and an outbox. The agent systematically processes the messages from the inbox and takes action accordingly. Messages requiring transmission are then moved to the outbox. The outbox is cleared, and the messages are dispatched into the inboxes of the relevant agents. This iterative process continues throughout the simulation. Advanced messaging functions like delivery confirmation and messaging cancellation are not implemented in the model. Table 21 shows a list of messages sent by actors in the model. Figure 10 illustrates the pattern of communication between actors.

Table 21: *Messages messaging system*

From	To	Message type
Owners	Demolition company	Demolition Request
	Construction company	Construction cost request
	Construction company	Construction Commission
Construction company	Owner	Construction Cost Estimate
	Material supplier	Primary Material Request
Demolition company	Material supplier	Secondary Material Request
Material supplier	Construction company	Primary Material Response
	Demolition company	Secondary Material Response

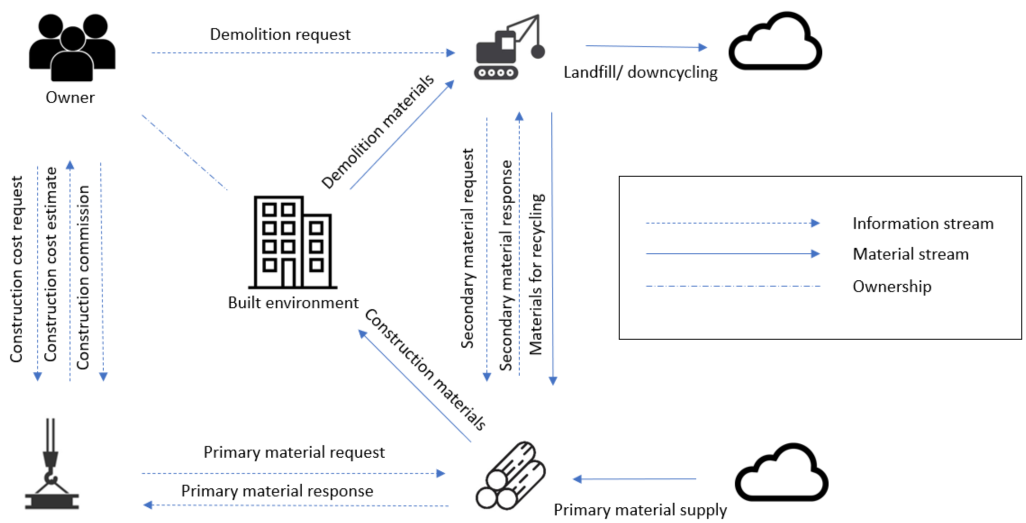


Figure 10: *Information and material flows in the model's built environment*

5.4.5 Stochasticity

Stochasticicity is present in the model during initialization and runtime. During initialization, the model creates a representation of the built environment based on the city of Amsterdam. The distribution of various building archetypes is extracted from CBS and GIS data. For computational reasons, and since the model is not a spatial representation of the built environment, less buildings are present in the model environment compared to the actual environment. The model uses these distribution to create a small scale model built environment. Every patch is assigned a building archetype with a random function that uses weights based on this distribution. For example, apartments have a higher weight than single family houses since they are present in higher quantities relative than the latter. During runtime, upon constructing a new building, the type of the building is again determined in a similar function. Not solely the building archetype is determined in this manner, but also ownership, floor surface, and construction year. All distributions are derived from data from the Amsterdam built environment.

Another form of stochasticity is used for determining the lifespan of a building. This is done with the help of a Weibull distribution. The input parameters for the Weibull distribution are sourced from literature. When during runtime a new building is constructed, its lifetime is determined in a similar fashion.

There is stochasticity involved in the decision making process of owners. The preference of an owner to go for either a wood-based or masonry-based building depends on the construction cost and its surroundings. Both influences are quantified and converted to a score for wood-based and masonry-based constructions. These scores are weighted and used in a random function to determine the decision of the owner. The reason for using a random function is that some influences for this decision are not known or quantified. Especially when scores are close to each other, the random function can give more diversity in the decisions which is assumed to be more realistic.

5.5 Initialization

The initialization of the model consists of setting up all actors, structuring, and populating the built environment. As mentioned in the previous chapter, the model is not a one-to-one spatial representation of the built environment of Amsterdam. Instead, the model only represents a small portion of the buildings present in the environment, however, with a similar distribution to the city. Based on the size of the actual built environment, the model calculates a model-to-real-world ratio. The user is able to scale up or scale down the number of modeled buildings by changing the resolution of the grid. Upon initialization, the model loads the following data:

- Distribution of the built environment: The amount of buildings per building archetype (apartments, single-family houses, row houses, offices and shops).
- Construction cost for building archetypes: The normalized cost values for different building archetypes.
- Material intensities for wood-based buildings: The material intensities for steel, concrete, and wood, per square meter for wood-based buildings.
- Material intensities for masonry-based buildings: The material intensities for steel, concrete, and wood, per square meter for masonry-based buildings.
- Weibull parameters: The Weibull parameters used for estimating the lifespan of a building.
- Collection and recycling rates: Rates for wood, concrete, and steel for collection and recycling after a building is demolished.
- Ownership distribution of houses: The distribution of house ownership in the city of Amsterdam for private owners, housing associations, and other types of owners.
- Distribution of multifamily housing: The distribution of apartments based on construction year and floor surface.
- Distribution of single-family houses: The distribution of row houses and single-family houses based on construction year and floor area.
- Material cost index: An index of the material cost for wood, concrete, and steel.
- Amsterdam utility file: A subset of utility buildings categorized by building archetype.

When all data are loaded into the model, the model will set up the actors and buildings in the model environment. Initially, the model allocates a subset of patches to buildings. The remaining patches are for the construction companies, the housing associations, the demolition company, and the material supplier. Some empty plots in the built environment belong to the municipality and are randomly distributed over the environment using a random function. The other patches contain masonry-based buildings. The building archetype is selected based on the above-mentioned distribution of building archetypes in Amsterdam. Based on this building archetype, a construction year and floor surface are assigned to all houses. The lifetime of a house is estimated with a Weibull distribution. If, according to the estimated lifetime and the construction year, the house should have already been demolished, a new lifetime is generated. Based on the material type, building archetype, and the floor surface, the material quantities are then calculated and assigned. The ownership of houses is randomly selected based on the distribution as mentioned above. When the owner of the house is a private entity, a new owner agent is created. When the owner of the house is a housing association, the house is allocated to one of the housing associations.

When it comes to utility buildings, the process of selecting a floor surface and a construction year is done by randomly selecting a building from a subset of the respective building archetype. This list is compiled from GIS data of the city of Amsterdam. Since the properties of the utility buildings are not as homogeneously distributed as the properties of houses, this is assumed to be the most suitable way of representing an accurate environment. In the model, ownership for utility buildings always belongs to private entities.

5.6 Input

The model uses various sources of input data to construct the built environment. Table 22 provides an overview of the used data sources their origin.

Data	Source
Material intensities wood	Smith and Wallwork Engineers, 2023
Material intensities concrete	Sprecher et al., 2021
Distribution SFH, MFH, utility buildings	CBS, 2023
Weibull distribution parameters	Deetman et al., 2020; Yang, Hu, Zhang, et al., 2022
Floor surface residential buildings	CBS, 2023
Floor surface utility buildings	CBS, 2023; Kadaster, 2023
Recycling rates	Zhang et al., 2020
Distribution ownership	CBS, 2023

Table 22: *Data sources for material intensities, building distributions, and other building-related parameters.*

6 Model evaluation

In order to evaluate the model, a model verification and validation was conducted. Both are described in the following sections.

6.1 Model verification

To ensure the credibility of the model and the reliability of the policy findings, it is essential to identify if the model's behavior is in line with what the model was designed for. Therefore, a model verification was conducted. The model was verified along a number of steps.

First, the model description was aligned with the model. All agents, interactions, and rules were reconsidered based on coherence, understandability, and authenticity. The complexity of the model was reduced when this was deemed beneficial for the model's understandability.

After this step, a code review was conducted. The model was written in NetLogo version 6.3.0, an agent-based modeling environment. In order to reduce mistakes, the code was fully evaluated, and some parts were rewritten and corrected when this was deemed necessary. All parts of the model were tested in a testbench, which made it easier to understand where certain behaviors originated from.

After this step, the boundaries of the model were tested. Unpredictable behavior that originated from actors and anomalies in agent interaction were identified, and the cause of this behavior was traced back. A variety of changes have been made based on these findings. The messaging system proved to be very handy in the verification process. It enabled the modeler to trace back the interaction between the actors and subsequently where mistakes were required to be corrected. The boundary testing was also helpful in order to get a sense of the bounds of the variable inputs and the overall limitations of the model.

Then a consistency check was conducted, not solely for the boundaries of the model but also for the general operation of the model. When similar agents in the model behaved differently, the reason for this behavior was identified. Unexpected outcomes were traced back to their origin, and the mistakes were corrected accordingly.

At that point, a step-by-step analysis was conducted. At every non-repetitive step, the behavior and interaction around agents were evaluated. Although this was already partially done in the previous steps, this test was a more comprehensive evaluation test.

Then, a global sensitivity test was conducted. The input bounds for 17 parameters had been determined. The values for these 17 parameters were understood to be uncertain or important for policy analysis. 18,432 samples (an explanation of how I came up with this number will be added) were generated for a Sobol analysis. The parameters that were tested are listed in Table 23. The output parameters are listed in Table 24. The model was adjusted accordingly, and the samples were rerun. After this run, the model behaved as expected, and no anomalies were identified. The results of the global sensitivity analysis are shown in the appendix.

Table 23: *Base, upper and lower values for sensitivity input variables.*

Variable name	Base value	Lower bound	Upper bound
capacity_wood_stock_material_supplier	15000.00	0.00	25000.00
capacity_concrete_stock_material_supplier	50000.00	0.00	100000.00
capacity_steel_stock_material_supplier	15000.00	0.00	25000.00
labour_cost_per_m2	922.00	461.00	1383.00
project_capacity_construction_companies	500.00	250.00	1000.00
preference_bias	0.10	0.00	0.20
material_cost_concrete	0.34	0.17	0.51
material_cost_wood	1.28	0.64	1.91
material_cost_steel	1.20	0.60	1.80
collection_rate_concrete	0.85	0.00	0.85
collection_rate_wood	0.95	0.00	0.95
collection_rate_steel	0.95	0.00	0.95
recycling_rate_concrete	0.03	0.00	0.85
recycling_rate_wood	0.24	0.00	0.90
recycling_rate_steel	0.85	0.00	0.85
learning_speed	1.00	0.00	2.00

Table 24: *Reporter variables with Netlogo notation*

Variable name	Netlogo code
ratio_wood_based_buildings	count patches with [material_type = wood_type] / (count patches with [status = occupied]),
ratio_concrete_primary_requested	primary_concrete / concrete_requested,
ratio_wood_primary_requested	primary_wood / wood_requested,
ratio_steel_primary_requested	primary_steel / steel_requested,
ratio_concrete_landfilled_demolished	concrete_landfilled / concrete_demolished,
ratio_wood_landfilled_demolished	wood_landfilled / wood_demolished,
ratio_steel_landfilled_demolished	steel_landfilled / steel_demolished

6.2 Model validation

The model validation was done with the help of expert opinions at the municipality of Amsterdam on 17-10-2023. The actors were part of the Circular Economy (CE) team from the municipality of Amsterdam with the function of gathering municipal actors from all areas of intervention for a CE in Amsterdam. A brief presentation was held, and the experts were able to comment and ask questions. The presentation gave a general overview of the actors incorporated in the model and the interaction between these actors. The results were also presented. Various questions were asked in relation to the data the model was based on. One comment was made in relation to the model. The first critique was that it does not account for renovation practices even though this generates significant material streams and prolongs the lifetime of a building. This valid point is discussed in the limitations section. However, the model was not significantly altered based on these insights. Another validation session was held on November 1, 2023, with a policy expert from the municipality of Amsterdam. The limitations that were discovered were in line with the ones already established. Some suggestions were given to make the model more attractive for policymakers, such as a more elaborate explanation of the model principles present in the environment and a discussion on how the model results can be validated in the future.

7 Results

This chapter presents the findings and key results derived from the analysis of this study. It is divided into two sections: the results for enhancing wood-based construction practices, and the results for wood-based construction and circular practices.

7.1 Results for enhancing wood-based construction

Tax on reinforced concrete

As described in Section 4.3.1, carbon taxation is simulated in the model by increasing the price of reinforced concrete. Reinforced concrete is significantly more present in masonry-based construction compared to wood-based construction. An increase in the price of concrete will therefore raise the cost of masonry-based construction relative to wood-based construction. The results of the sensitivity analysis, displayed in Figure 11, show the ratio of wood-based buildings. We can observe that there are policy combinations/situations where the ratio of wood-based construction increases based on the price of concrete. However, the relationship is not significant, and even the upper bound value of a price increase in concrete will not always result in an increase in wood-based constructions.

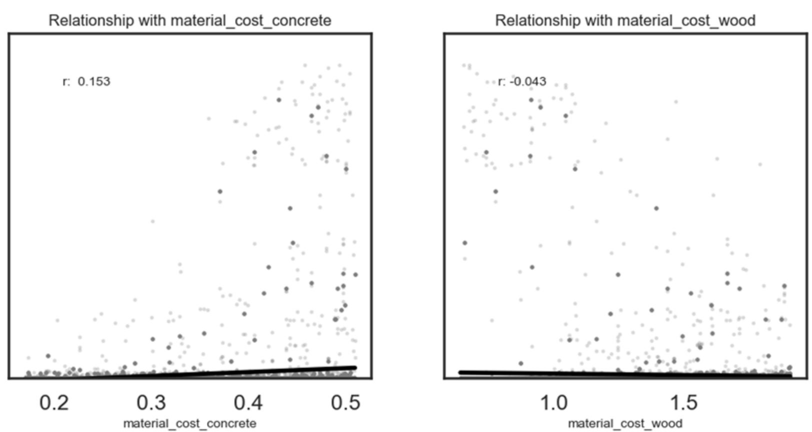


Figure 11: *Sensitivity analysis - relationship between the ratio wood-based building and reinforced concrete (left) and mass timber (right)*

Subsidy on mass timber

Another policy instrument is the reduction of the price of mass timber in the form of a subsidy. Mass timber is present in higher quantities in wood-based construction relative to masonry-based construction. Therefore, a reduction in mass timber will also reduce the relative price of wood-based buildings. Figure 11 illustrates the relationship between the price of mass timber and the ratio of wood-based construction. Similar to how price changes in concrete affect construction, a reduction in the price of mass timber can sometimes lead to an increase in wood-based construction.

Policy combination: tax on reinforced concrete and a subsidy on mass timber.

The model allows us to explore a combination of a tax on reinforced concrete and a subsidy on mass timber. Figure 12 depicts multiple runs where the price of reinforced concrete is increased by 10%, and the price of mass timber is reduced by 10%. During each run, we notice that wood-based buildings are being constructed as the ratio of wood-based construction increases. The relative price of wood-based construction is lower than that of masonry-based construction. Increased demand for wood-based buildings leads to a shift in specialization within construction companies towards wood-based practices. This also results in greater familiarity with wood-based construction among owners. Both mechanisms will reduce the absolute and perceived price of wood-based construction.

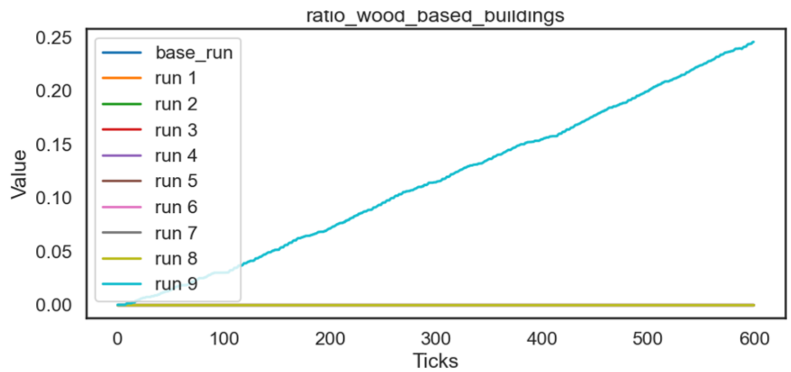


Figure 12: *Ratio wood-based buildings for nine runs*

Figure 13 depicts 177 combinations of a subsidy on mass timber and a taxation on reinforced concrete. Whenever a combination results in a wood-based building ratio higher than zero, the dot in the figure is colored green. We notice that all green dots are located in the bottom right corner with a high material cost for concrete and low material cost for wood. This marks the area where the combination of policies is effective.

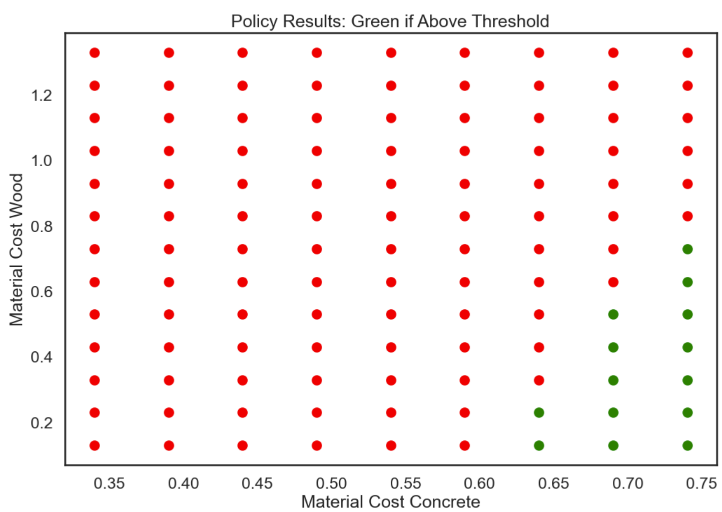


Figure 13: *Combination of a subsidy on mass timber and a taxation on reinforced concrete. Green means that the final wood-based building ratio is non-zero.)*

Figure 14 shows the specialization components for all construction companies for run 9 (with an increase in the price of reinforced concrete by 90% and a reduction in price for mass timber by 90%). Figure 14 shows that wood-based specialization stabilizes.

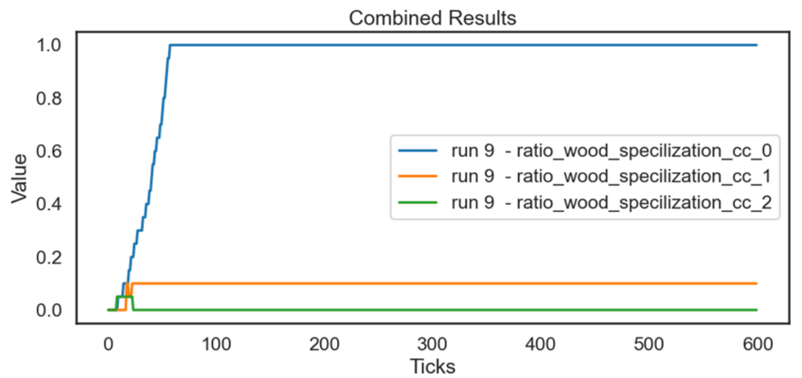


Figure 14: *Specialization component for all construction companies (run 9)*

Considering the specialization of construction companies in wood-based construction practices can have a significant impact on the construction cost of wood-based projects. It may prove beneficial to explore the effects of altering the upfront specialization of construction companies, which the municipality can achieve through knowledge-sharing initiatives, for instance. To test this intervention, we modified the specialization component of all construction companies, ranging from 5 to 15. In this scale, 5 represents the familiarity component with wood-based construction, while 15 indicates the familiarity component of masonry-based construction. This adjustment was deemed reasonable.

Figure 15 illustrates the same results as Figure 12, demonstrating the significant impact of an upfront increase in specialization for wood-based construction. The implementation of a subsidy for mass timber materials and a tax on reinforced concrete can expedite the adoption of wood-based construction methods.

Furthermore, Figure 16 once again highlights the specialization trends among all construction companies. After a certain threshold is reached, the rate of specialization accelerates. Various factors influence this threshold, with the production capacity of construction companies playing a particularly significant role in determining the speed at which companies specialize and the volume of wood-based buildings they construct.

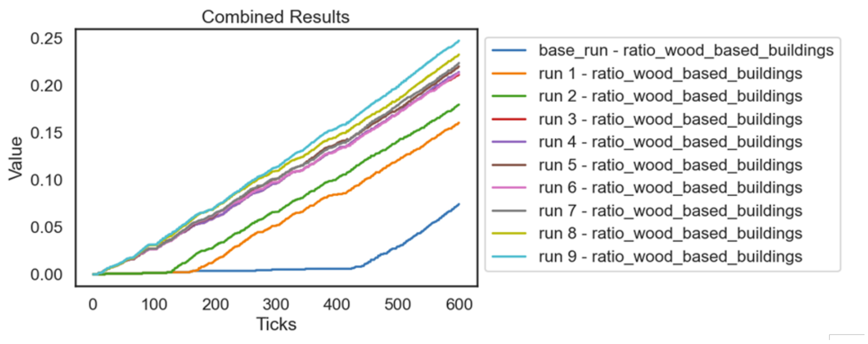


Figure 15: *Ratio wood-based buildings for nine runs*

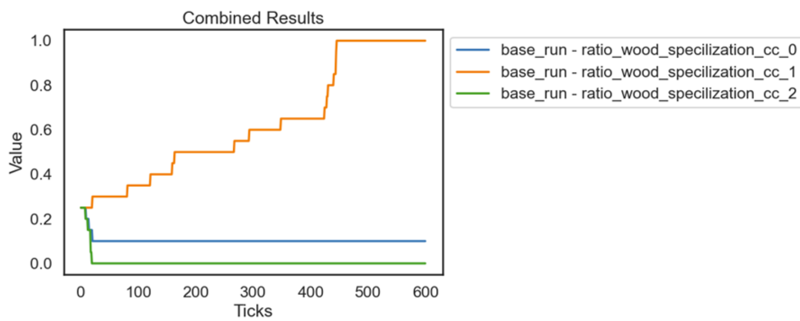
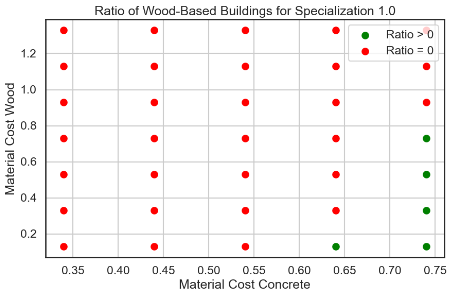
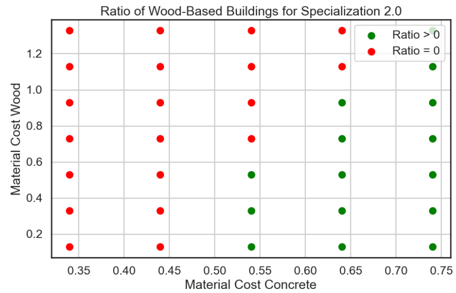


Figure 16: *Specialization component for all construction companies with increased wood-based specialization (base run)*

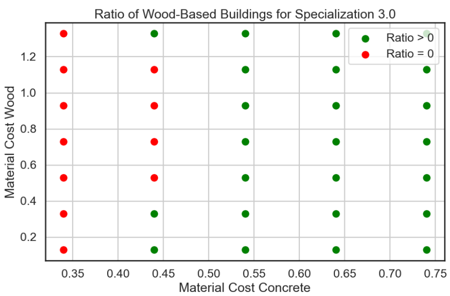
Figure 17 illustrates the combinations of a subsidy on mass timber and a taxation on reinforced concrete for multiple wood-based specialization values. A specialization value of 5 means that a construction company has a similar expertise in wood-based as well as masonry-based construction.



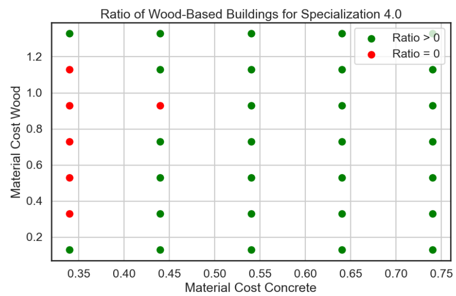
(a) *Specialization value: 1*



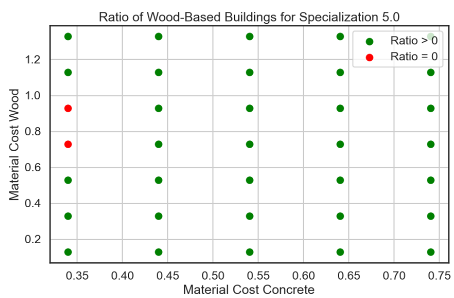
(b) *Specialization value: 2*



(c) *Specialization value: 3*



(d) *Specialization value: 4*



(e) *Specialization value: 5*

Figure 17: *Combination of a subsidy on mass timber and a taxation on reinforced concrete by Specialization. Green means that the final wood-based building ratio is non-zero.*

7.2 Wood-based construction and circular practices

The model enables us to explore circularity and the effect of the built environment, and vice versa. Figure 18 visualizes the influence of various parameters that affect the amount of concrete landfilled as a ratio of the amount of concrete demolished. Figure 19 visualizes the amount of concrete primarily acquired as a ratio of the amount of concrete requested. A lower value for the *ratio_concrete_primary_requested* means that more material is recycled. The same is true for a lower value of *ratio_concrete_landfilled_demolished*. Whenever the built environment becomes more circular, both ratios go down. A lower value for both parameters is thus desired.

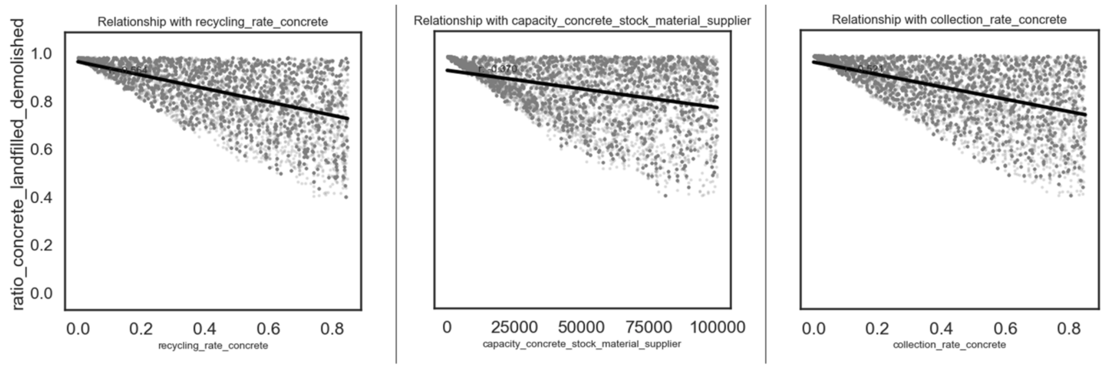


Figure 18: *Influential input variables for ratio concrete landfilled*

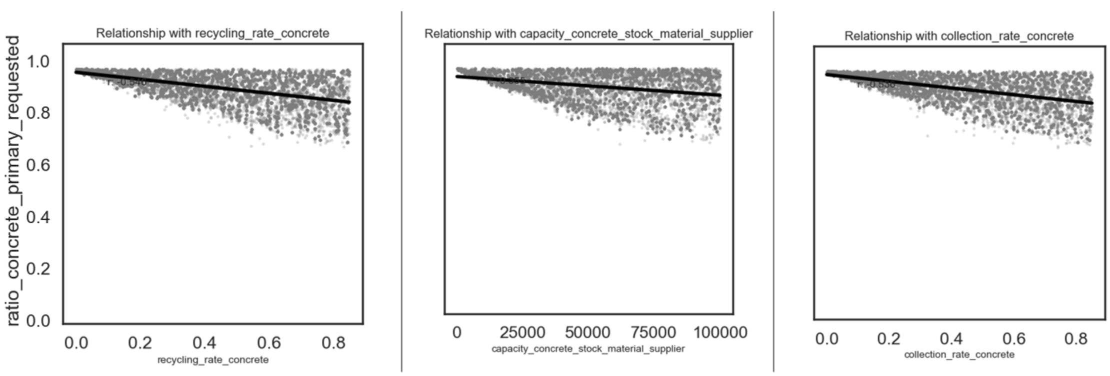


Figure 19: *Influential input variables for the ratio of concrete requested*

Both figures show that there is a significant relationship between the (collection rate of concrete, the recycling rate of concrete, the capacity of the concrete stock at the material supplier) and the (amount of concrete landfilled, the amount of primary concrete requested). The same goes for steel and wood when we regard the collection rate and the recycling rate. However, the influence of the stock capacity for wood and steel is less significant than the relationship between the capacity of the materials stock for concrete.

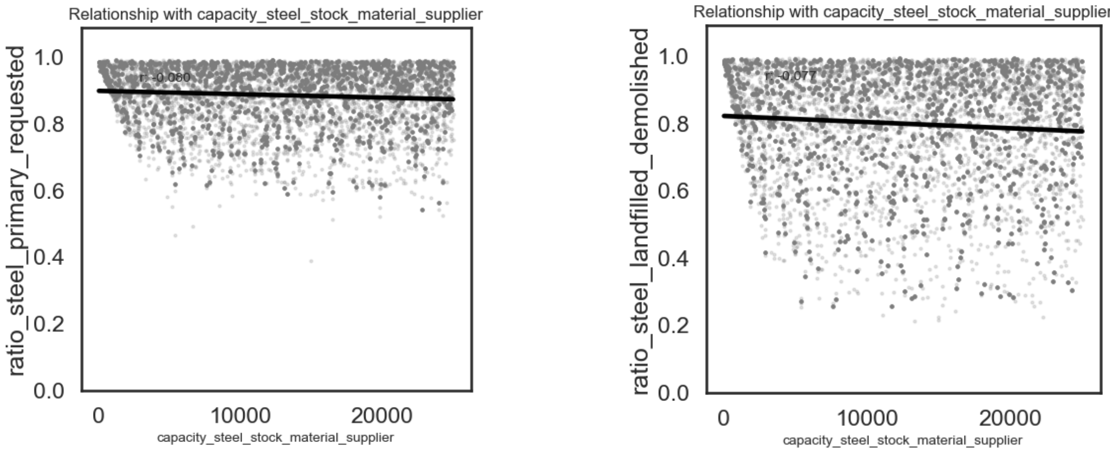


Figure 20: *Influence of the stock capacity on steel primary requested and landfilled.*

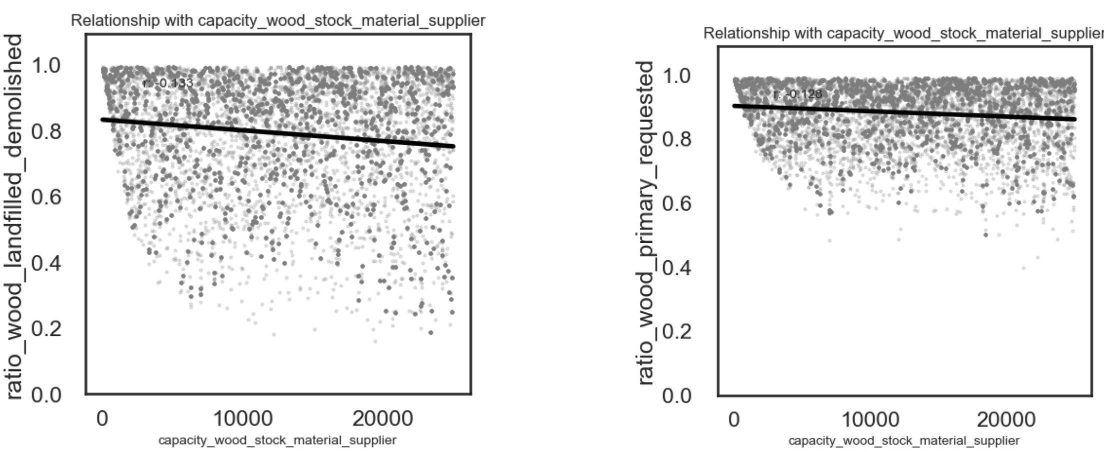


Figure 21: *Influence of the stock capacity on wood primary requested and landfilled.*

The model fails to accurately reflect the price differences between primary and secondary materials, which makes it unlikely that the number of wood-based buildings will be affected by a higher recycling rate for these materials. Nevertheless, we anticipate a correlation between increased wood-based construction and the quantity of concrete landfilled. As a result, any instruments influencing the amount of wood-based construction would also affect how much concrete is landfilled. However, this expected relationship appears to be absent. Another anticipated relationship is between the instruments that influence wood-based construction and the demand for primary wood material. Masonry-based construction uses less wood compared to wood-based construction. Let us examine further how wood-based construction affects the circularity of wood and concrete materials.

Figure 22 illustrates a base run without any policy intervention, and run 1 with policy interventions. In run 1, we notice the ratio of wood-based buildings rising in the built environment. We also see that only the recycling of wood differs over time. It is important to note that these values, except for the wood-based building ratio, are aggregated. This means that a value at a higher tick incorporates all values before that tick. Therefore, we notice some artifacts in the first 50 ticks since small influences have a larger impact on the reported value. The reason for using an aggregated reporter is that material demand and demolition waste fluctuates heavily. Since the buildings that were demolished are not the same in archetype and size to the buildings that are constructed, material demand and material secondary material supply vary heavily with every time step. The timeline in which materials are released and new materials are required also differ. When examining the ratios at each tick, one would only see spikes. Aggregated values are more insightful.

This highlights another point: material released during demolition is not always matched with the material required. When the material stock is full, recycling is not possible, and the excess is landfilled. A shift towards wood-based construction will require more mass timber. As these buildings are demolished, more wood is released, reaching capacity limitations sooner. Therefore, a higher recovery and recycling rate, as well as a larger material stock, become more important when wood-based materials are used more extensively. This is also visible in Figure 22: over time, more wooden material is landfilled because more wood is released during demolition in the built environment. We don't see this with concrete material. This is likely due to the significant amount of concrete still required in wood-based construction. What changes however is the content of wood in the built environment whenever many wood-based buildings are present in the environment.

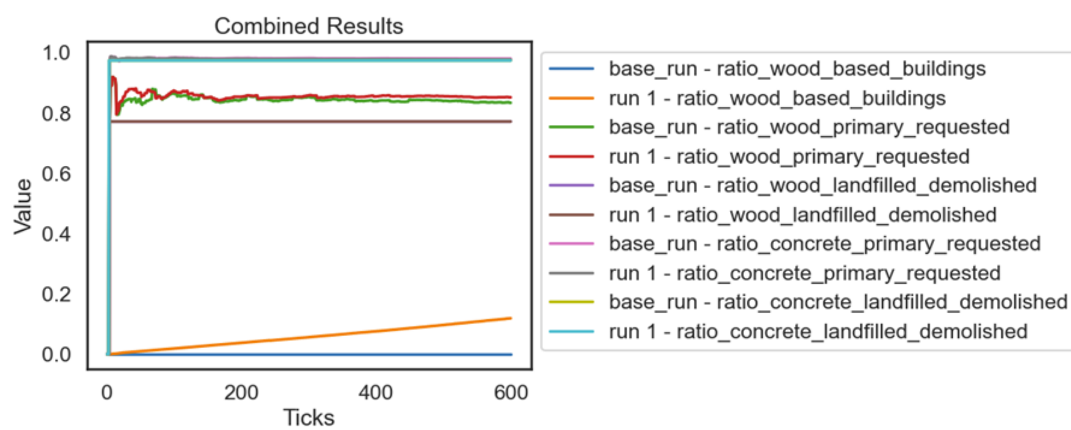


Figure 22: *Base run and run with wood-based construction*

8 Discussion and conclusion

8.1 Summary of evidence

It was observed that solely raising the price of reinforced concrete or lowering the price of mass timber has no robust outcome. This is caused by the inertia of construction companies and building owners. Upon initialization of the model, all construction companies are fully specialized in masonry-based construction. This results in a hefty premium paid when one wants to build with wood-based materials. The price perceived by agents is also higher due to their unfamiliarity with the material. This applies to both private owners and housing associations. Solely changing the material cost of reinforced concrete requires a concrete unit price that is far above the reasonable upper bound material unit cost. However, the relationship does not always hold, meaning that there are policy combinations and situations where taxation of reinforced concrete and a subsidy on mass timber is effective, but also a whole range where a decrease in the price of mass timber does not yield the desired effect. Solely changing the material price within reasonable bounds has no consistent effect and will therefore not be robust. Both policy instruments individually are deemed insufficient for overcoming the inertia in the system.

It is evident that there is a relationship between a tax on reinforced concrete and the ratio of wood-based buildings, as well as a subsidy on mass timber and the ratio of wood-based buildings. However, the relationship is not sufficiently robust. A combination of both policies yields more promising results. Nevertheless, it necessitates a significant reduction in the price of mass timber and an increase in the price of reinforced concrete.

A more promising policy instrument was identified during the analysis of the model. One can alter the initial familiarity of construction companies with wood-based material practices. Potentially, the municipality of Amsterdam is able to promote knowledge sharing of wood-based construction practices. A significant portion of the premium paid for wood-based construction originates from construction companies; their familiarity greatly impacts the construction cost price. By disseminating knowledge among construction agents and their supply chain, the initial familiarity gap between wood-based and masonry-based construction can be reduced. Therefore, a reduction in price is accomplished.

When focusing on the specialization component of construction companies, it was identified that the specialization of construction companies stabilizes after a while. This stabilization is likely due to dependency paths of the construction companies. Whenever a construction company specializes in a particular construction practice, it can then lower its price for that construction practice relative to other companies. This price advantage causes the construction company to further specialize and become a market leader in wood-based construction. One of the other companies that did not specialize in wood-based construction will continue to lead and receive a larger portion of the market for masonry-based construction. Making wood-based construction cost competitive leads to divergent specializations among construction companies. The reason not every construction company starts building wood-based structures is that there will be buildings where the masonry-based variant is more cost-effective than the wood-based variant, even when a subsidy is applied. This happens due to the inherent characteristics of the building. It is important to take into account that specialization will lead to divergence, and masonry-based construction will remain important for certain construction projects. Policy instruments are important to overcome the inertia in the system to increase specialization and familiarity. However, in the long term, these instruments will strain masonry-based construction. Therefore, it is recommended to phase out the incentivization of wood-based practices after wood-based construction is cost competitive.

Another recommendation is to give special attention to the use of intermittent material storage and their relative capacity. The release of materials during demolition does not align with the use of materials during construction. The model highlights the importance of having sufficient storage so this material can be used instead of being landfilled. One could decide to alter the size of these material storages in order to accommodate material that is not yet required. It can be difficult to make space for more capacity inside the city environment due to space limitations and permits. Actors in the environment also need to experience sufficient benefit from reusing materials instead of utilizing primary materials. One could also argue for a better information system that enables construction and demolition actors in the environment to align their material flows. This could have a significant impact on the city's ability to reuse materials. We recommend devoting special attention to reusing concrete materials since virtually all (97%) of the material is currently downcycled. It is also important to highlight that the material remains important due to its significant presence in wood-based construction.

The importance of housing associations is highlighted by the model. Housing associations own a large part of the built environment. When housing associations decide to construct a larger part of their assets using wood-based materials, this will result in a shift in specialization among construction companies and a greater familiarity with wood-based construction among other property owners. The municipality could decide to increase the familiarity of housing associations through information campaigns or design incentives that promote the use of mass timber, such as subsidies.

The model proves that one effective way of reducing primary material use and lowering landfilled material is to extend the lifetime of a building. The UN report mentioned a similar outcome where they state that an increase in building lifetime reduces carbon emissions (United Nations, 2023). However, extending the building lifetime requires an investment up front and renovation during the lifetime of the building. The model does not connect the construction cost price and lifetime. It also does not incorporate renovation practices. It would be interesting to get a better understanding of how both influence material streams and carbon emissions.

8.2 Limitations

The model has a variety of limitations that are deemed necessary to be mentioned. This chapter highlights dome of these limitations.

The use of an Agent-based model introduces certain limitations. An agent-based model is well-suited for understanding the emergent behaviors that result from agent interactions. However, agent interactions in the built environment are very complex and heterogeneous in nature. Projects involve many different interactions where it is not always clear which interaction caused a particular outcome. The model simplifies interactions and uses input data to facilitate decision-making processes within the model. This reliance on data is significant. However, since data on wood-based construction is relatively novel and scarce, it could be beneficial to use a modeling technique that is less dependent on low-level data sources and instead utilizes more aggregated sources for modeling policy instruments.

Secondly, there are some limitations in respect to the representation of buildings in the model. The model only accommodates buildings constructed after 1900. Buildings constructed before 1900 remain unchanged in the model's simulation due to the limited data on these structures. The buildings that were constructed before 1900 belong to the outliers in the Weibull distribution that was used. It is, therefore, difficult to estimate when these buildings will be demolished. It could very well be that the remaining lifetime of these buildings is determined by completely different factors compared to the majority of the building stock. Further research is required to understand if the lifetime can be estimated and, if so, how this can be done accurately.

In terms of wood-based construction, the model solely focuses on mass timber buildings. However, there is a range of wood-based buildings that do not use mass timber components, such as framed buildings, which are commonly found in Scandinavian nations (Anttonen, 2015). The main reason for omitting these buildings is that mass timber construction is more suited to the building archetypes commonly used in our environment, compared to other wood-based construction types like framing. Although they are considered less suitable, there are cases where this form of wood-based construction can be beneficial. Therefore, incorporating these non-mass timber buildings could provide us with new insights due to their different material composition and construction cost.

The model treats individual apartments as separate buildings. This results in each individual apartment having its own lifespan and being demolished individually. The model is limited to a small subset of Amsterdam's built environment and does not take into account the significant material streams generated when demolishing entire apartment blocks. Since the lifespan is determined by a distribution, demolition becomes a stochastic event that could lead to undesired and unrealistic data spikes when this small subset of Amsterdam combines apartments into apartment blocks. It would be more realistic to group apartments into apartment blocks and demolish these blocks collectively when simulating a larger part of the built environment.

As with the building archetype distributions, material intensities remain unchanged throughout the simulation. However, building practices change over time, altering the material composition of buildings. This could have an impact on material streams. The model assumes that labor cost increases and reductions due to specialization are the same for wood-based and masonry-based construction. However, there may be differences in how specialization affects labor costs between these two material types. Further research is needed to determine the relevant parameters.

Currently, the model does not account for transportation. The spatial location of buildings in the model is assigned randomly. Accounting for transportation and spatial location could provide insight into how location affects the feasibility of reusing and recycling materials (components). One could then better understand how distance affects the economic feasibility and how material storage hubs in the city can be located and utilized in an effective way. This will likely result in a model that simulates the entire city of Amsterdam.

The distribution of building archetypes remains constant throughout the simulation since it is difficult to estimate how these distributions change over time. However, in the real built environment, the distribution of building archetypes is subject to change. This alters the material composition of the built environment, thereby changing material flows. Modeling various scenarios with different archetype distributions would ensure a more thorough insight. This would also enhance the robustness of the modeled policy instruments. However, in order to estimate potential changes in archetype distributions, a better understanding of the development of the built environment is required.

The model does not take into account the renovation of buildings. Renovation is an important practice to increase the lifetime of a building. It also generates a significant amount of material waste and requires a large quantity of construction material. However, the data on renovation is limited relative to the data on demolition and construction, since renovation practices are hard to track due to the inability of municipal bodies to track and record renovation practices. Another problem is that renovation practices differ significantly from project to project, therefore it is harder to estimate how much material is released and required for renovating a certain building. Further research is required for the effects of renovation on the lifetime of a building and the generated material streams.
The model is limited and does not incorporate factors outside of the built environment. However, it is also important to take these factors into account. It is assumed that there are no supply limitations for both wood and concrete. However, one can imagine that rapid establishment of wood-based construction would require a significant quantity of wood to be sourced from outside of the environment. This has an impact on the wood stock, particularly outside of the Netherlands, because most wood domestically used is currently sourced from outside of the Netherlands (**??**. This will have an effect on the supply chain and alter material pricing. The effects of long-distance transportation and deforestation need to be taken into account when Amsterdam wants to reduce its carbon footprint. This is especially important when the built environment is not yet circular and therefore requires a large amount of primary wood products.

8.3 Conclusion

The aim of this thesis project was to create a better understanding of how policy instruments influence the adoption of circular, wood-based building practices in Amsterdam, and what impact they have on the city's built environment. Particular focus was given to circularity since the wish for more wood-based construction is driven by Amsterdam's goal to increase circularity in the city's built environment. To answer this question, it was decided to construct an agent-based model of the built environment of Amsterdam. Multiple sub-questions were defined, with the first one being: *Which agents and environmental factors shape Amsterdam's built environment?* Data was gathered on actors and environmental factors through a literature search, and communication with various instances in Amsterdam. The most important actors were identified, namely: housing associations, private owners, construction companies, demolition companies, and material suppliers. The second sub-question was defined as: *How do the key actors interrelate and influence each other's behaviours?* In a similar fashion as the first question, data was gathered through literature search and communication with stakeholders in the environment. The development of the agent-based model required a quantitative definition of the environment. The following parameters were defined for the built environment: material intensities for wood-based and masonry-based construction, building archetype distribution in Amsterdam, floor surface values, recovery and recycling rates, and ownership distributions. Data originates from public as well as private sources. The interactions among the actors were identified, and their respective behaviours was incorporated into an agent-based model. The model was verified and validated. Validation happened through two sessions with circular policy advisers of the municipality of Amsterdam. The following sub-question was then addressed: *In what ways do municipal policy instruments promote or hinder wood-based building practices?* The model enabled the exploration of various policy instruments, namely: carbon taxation, demolition notification, and knowledge sharing. Carbon taxation was tested through a proxy by altering the cost of reinforced concrete and mass timber. Demolition notification was tested through the adjustment of material extraction rates in the model. We identified inertia at construction companies and among building owners. The adaptation of construction practices requires large investments, which takes time and effort. This results in a premium paid for wood-based construction. Owners' unfamiliarity with wood-based construction reduces their likelihood of adopting it. It was identified that significant carbon taxation is required to overcome the inertia in the system, especially the inertia that is created by construction companies. A combination of carbon taxation and knowledge sharing among construction companies is deemed more effective. The need for stimulation of wood-based construction decreases once such practices are well-established in the environment, since wood-based construction becomes cost-competitive after being incentivized. The following question was defined for the circularity part of the main research question: *How does the increased use of wood-based building materials influence circularity?* In relation to circularity, it was found that multiple factors need to be accounted for when wood-based construction increases. Although one would expect a significant reduction in concrete use, this is likely not the case. Wood-based construction still requires a significant amount of concrete; therefore, the importance of concrete demolition and recycling practices remains crucial. However, with the increased wood content in the environment, mass timber recycling practices become more important. The model also identified the importance of temporary material storage to benefit circularity. The size of the storage limits the amount of material that can be recycled. Although the model does not represent spatial properties of the built environment, it argues for either temporary material storage or otherwise matching material streams from demolition sites to construction sites.

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9 Appendices

9.1 Reference buildings wood-based construction

Building Archetype	Name	MI Concrete/m^2	MI Steel/m^2	MI Timber/m^2
Apartments	Yoker Residential	157.14	7.75	143.77
Row Housing	Robert Pearce House	374.36	41.03	149.74
Single Family House	Marsh Hill House	677.12	18.81	75.24
Office	Barkarby School	271.67	15.65	199.87
Other	NaN	370.07	20.81	142.16

Table 25: *Reference buildings for wood-based material intensities (Smith and Wallwork Engineers, 2023)*

9.2 Flowcharts model schedule

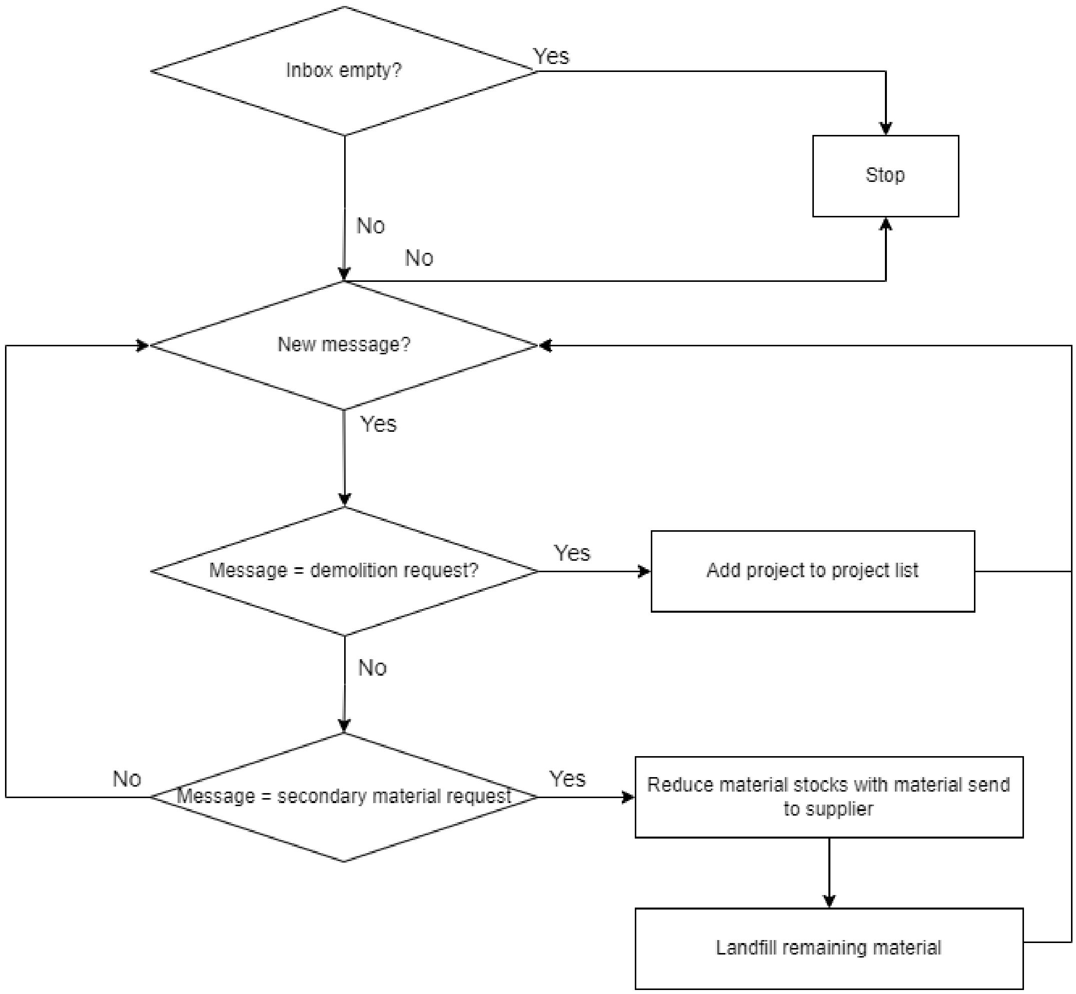

Figure 23: *Flowchart of a demolition company's inbox checking process.*

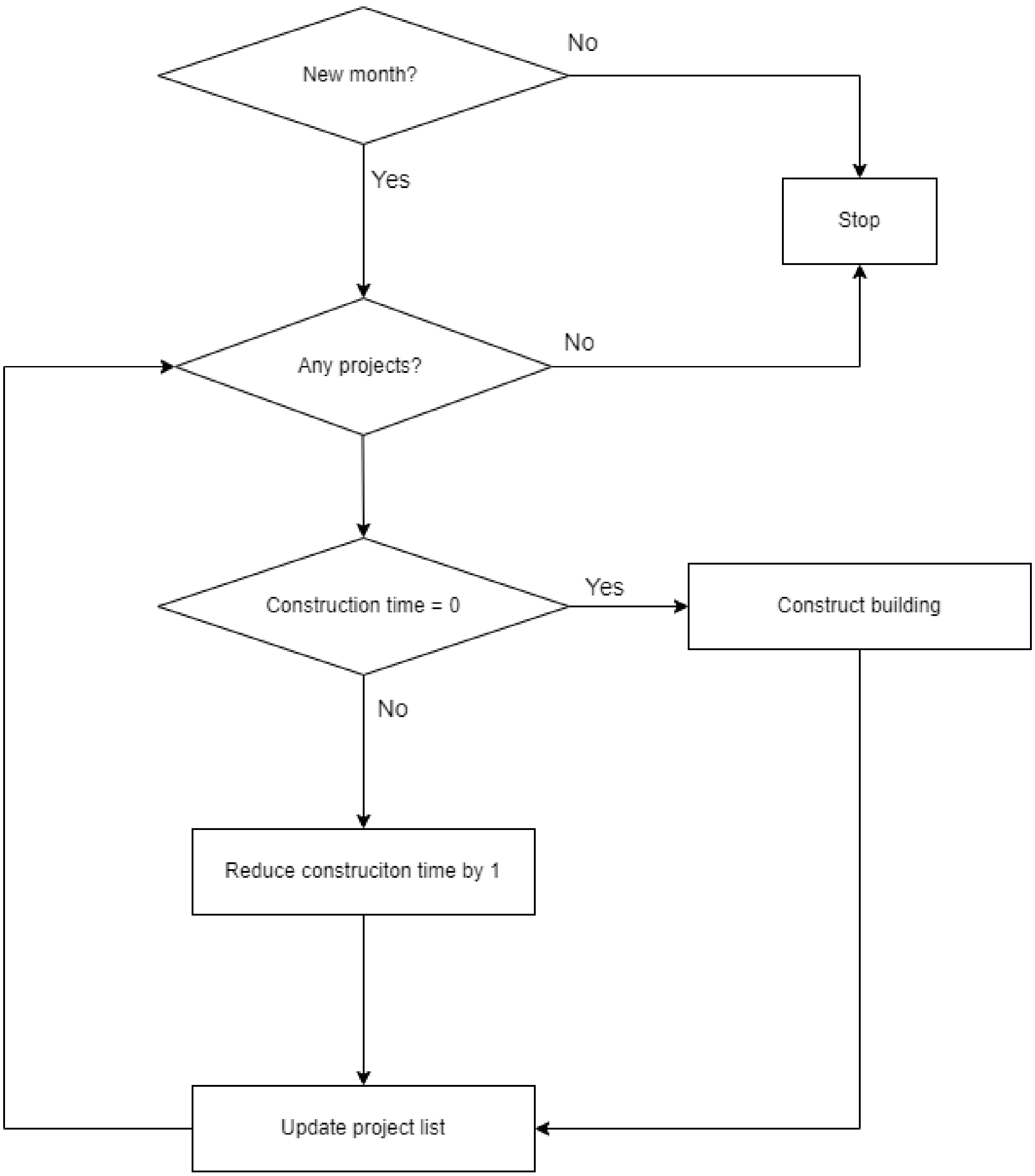

Figure 24: *Flowchart of construction companies' project checking routine.*

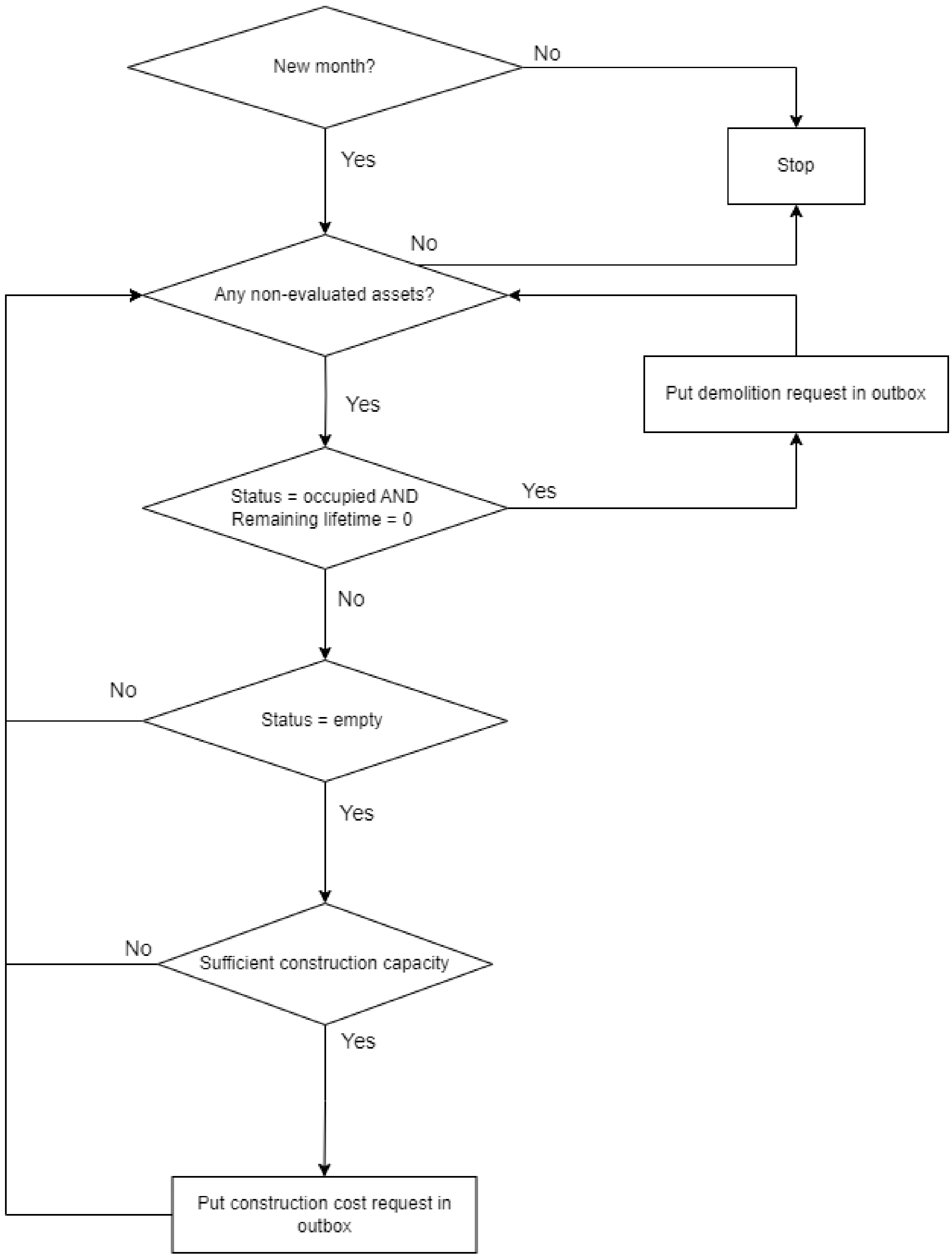

Figure 25: *Flowchart detailing the inbox processing for construction companies.*

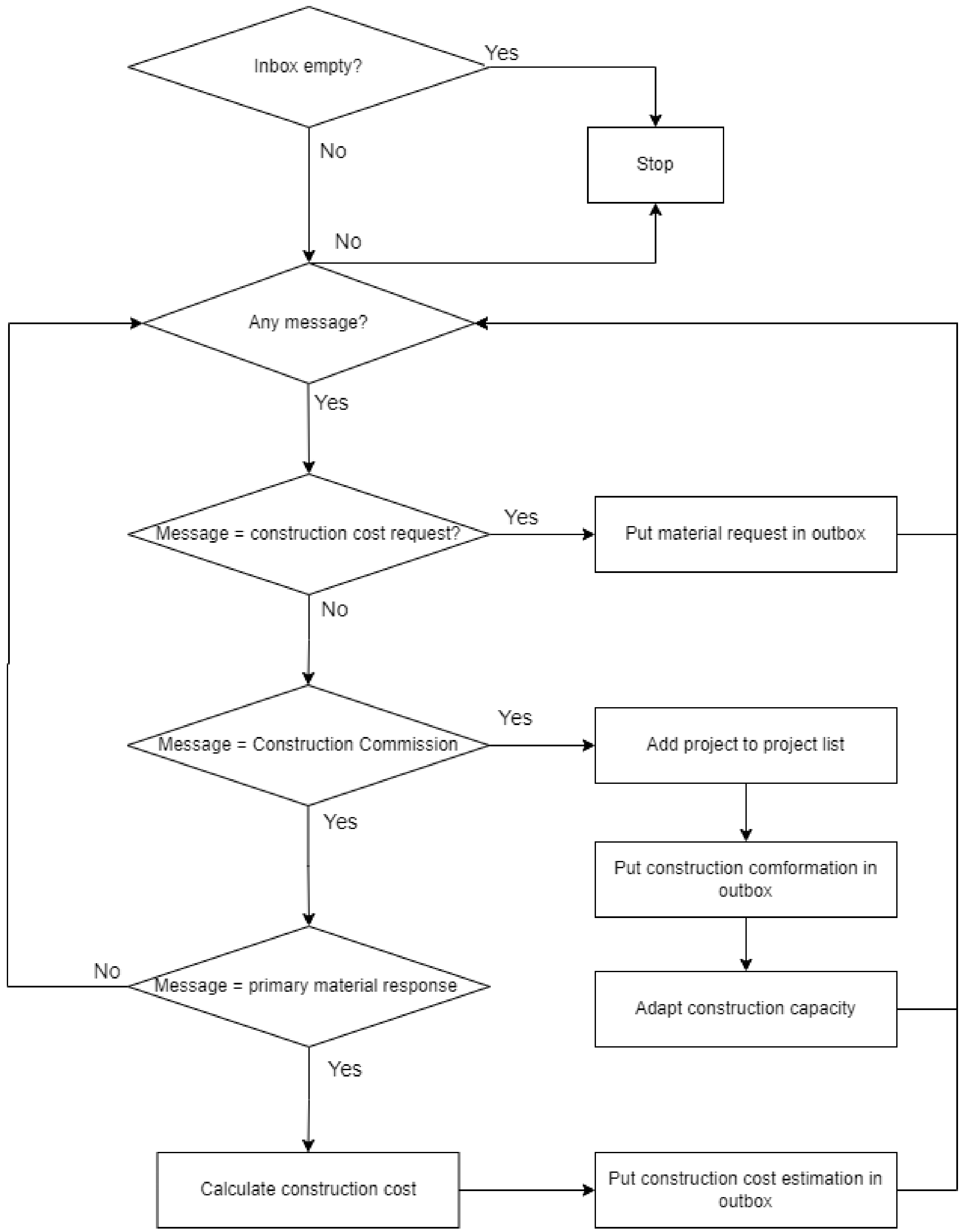

Figure 26: *Process for evaluating construction project ownership.*

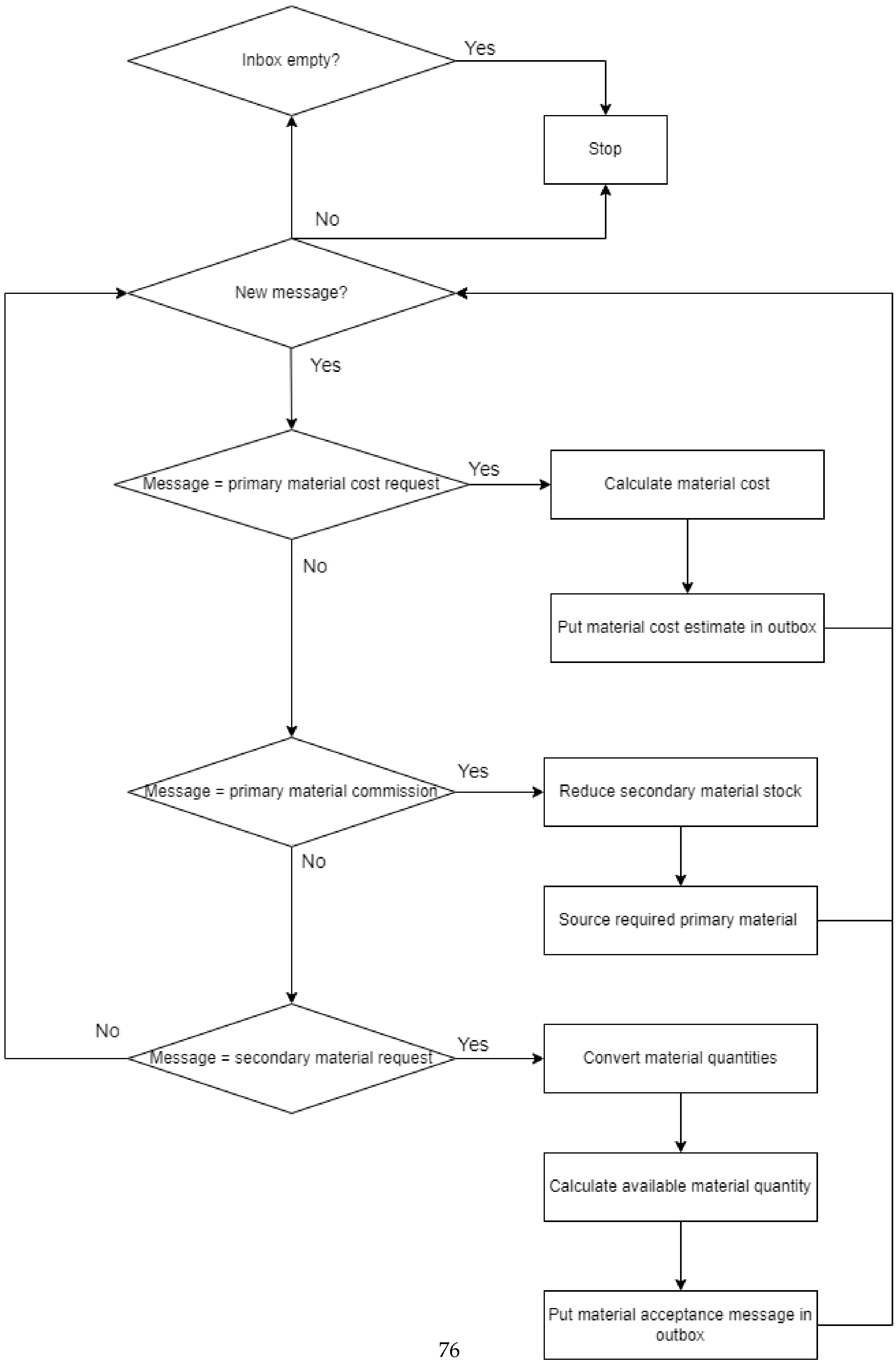

Figure 27: *Material supplier's inbox review flowchart.*

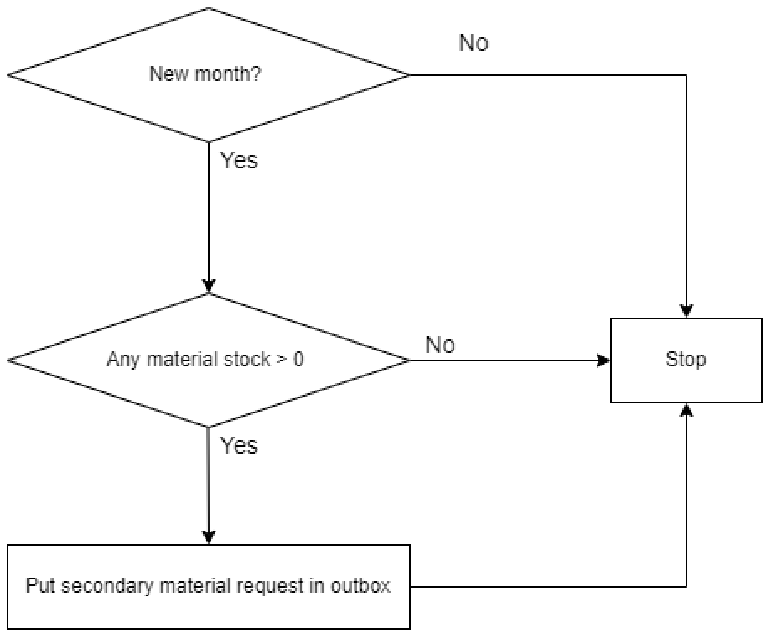

Figure 28: *Procedure for clearing material stock in a demolition company.*

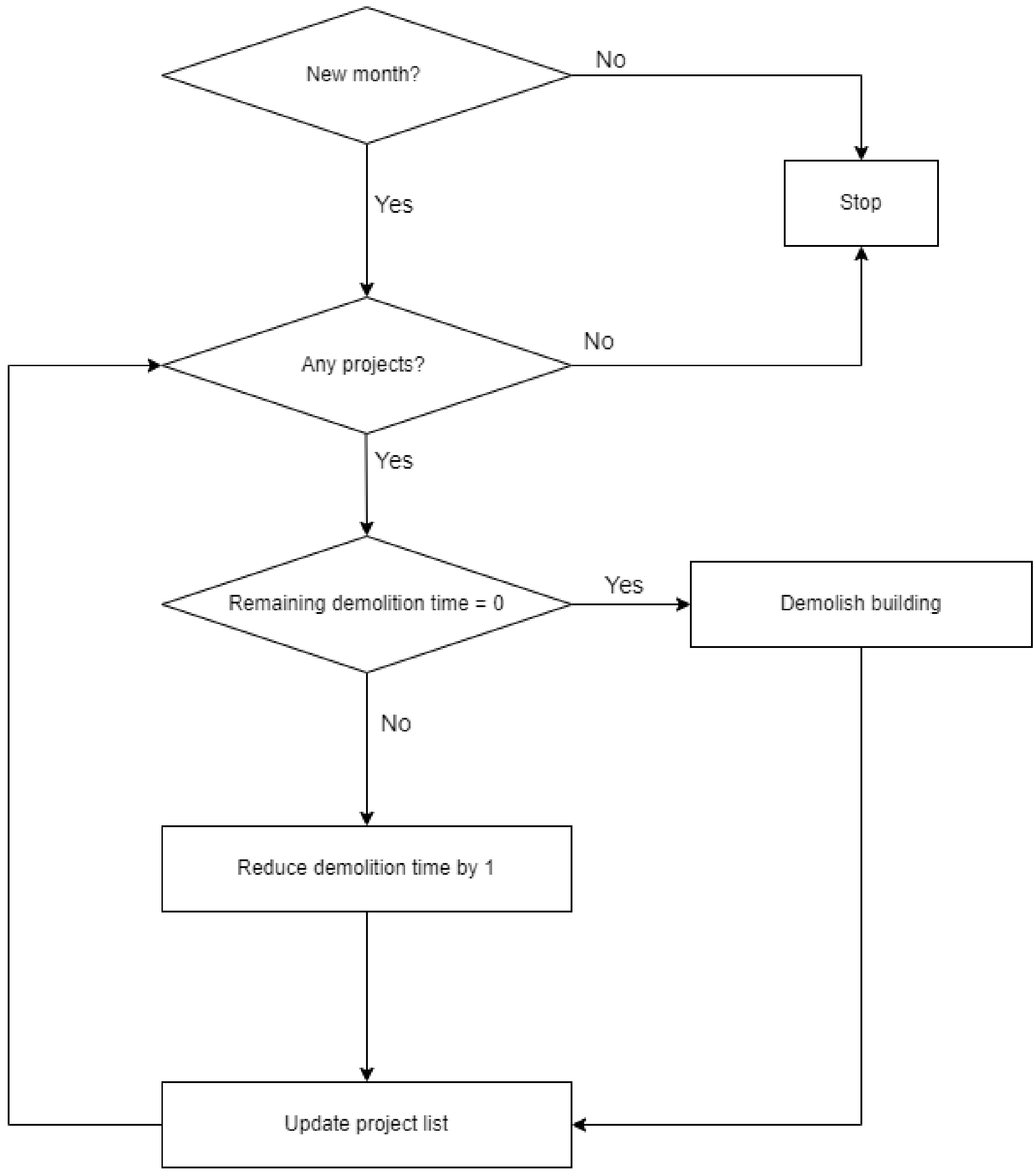

Figure 29: *Flowchart showing the demolition company's project tracking system.*

9.3 Policy instruments Circulaw

Instruments Circulaw	Legal Feasibility	Influence
Tendering under the European thresholds	High	Average
Making agreements on wood construction in a covenant	Average	Average
Deviating from the Bbl based on equivalence	Average	High
Use the equivalence provision in a permit application	Average	Limited
Land issuance by other authorities than municipalities	High	Average
Apply green fees for permit applications	High	High
Stimulate wood construction with aesthetic criteria	Average	High
Long-term collaboration for own real estate development	High	High
Include bio-based and circular construction in measures for the environmental impact assessment (EIA)	Average	Average
Include experience with wood construction as a suitability requirement	High	Average
Incorporate wood construction in the municipal environmental vision	High	High
Incorporate wood construction in the national environmental vision	High	Average
Incorporate wood construction in the environmental ordinance	Average	Average
Incorporate wood construction in the provincial environmental vision	Average	Average
Incorporate wood construction in the environmental plan	Average	Average
Incorporate wood construction in the environmental program	High	Average
Include MPG as a sub-award criterion in land issuance	High	High
Include technical specifications of wood construction in tender for land issuance	Average	Average
Develop tender policy	High	Average
Apply competitive dialogue in tendering	Average	Average
Apply innovation partnership in tendering	Average	Average
Apply competitive procedure with negotiation in tendering	Average	Average
Apply expropriation	Average	Limited
Prescribe wood construction in an environmental permit	Average	Average
Include selection criteria for land issuance in tenders	Average	Average
Establish a visual quality plan for area developments	High	Average
Set custom regulations for existing construction	Average	Average
Set custom regulations for demolition	Average	Average
Make notification of wood waste offer mandatory	High	Average
Make demolition notification mandatory	High	Average
Establish a preferential right on a building	Average	Average
Add a quality mark to a tender	High	Average
Request special implementation conditions in the tendering	High	Average
Request lifecycle costs as a sub-award criterion in tendering or tender	High	Average
Request sub-award criteria in tendering	High	Average
Change the land policy	High	Average
Employ the experimental provision	Average	Average

Table 26: *Wood Construction Instruments CircuLaw, n.d.*

9.4 Figures sensitivity analysis

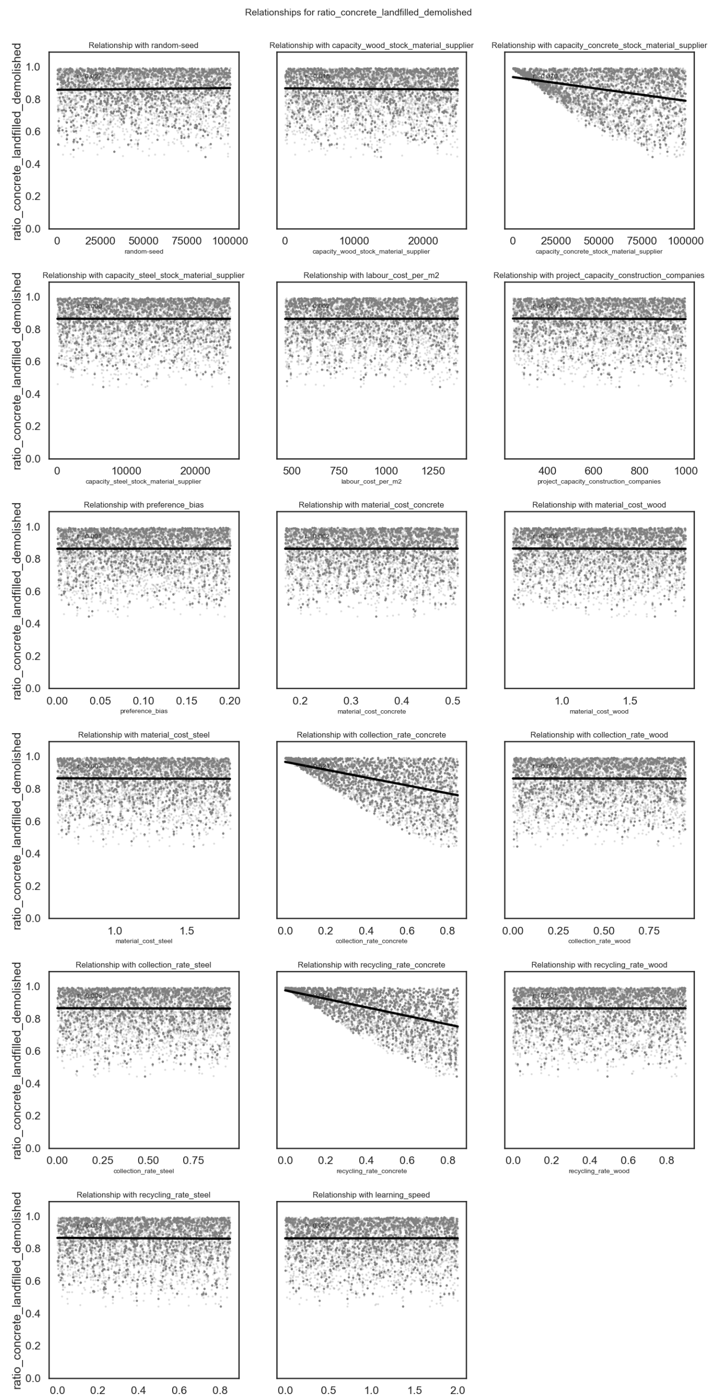

Figure 30: *Bivariate scatter plot for ratio_concrete_landfilled_demolished_relationships.*

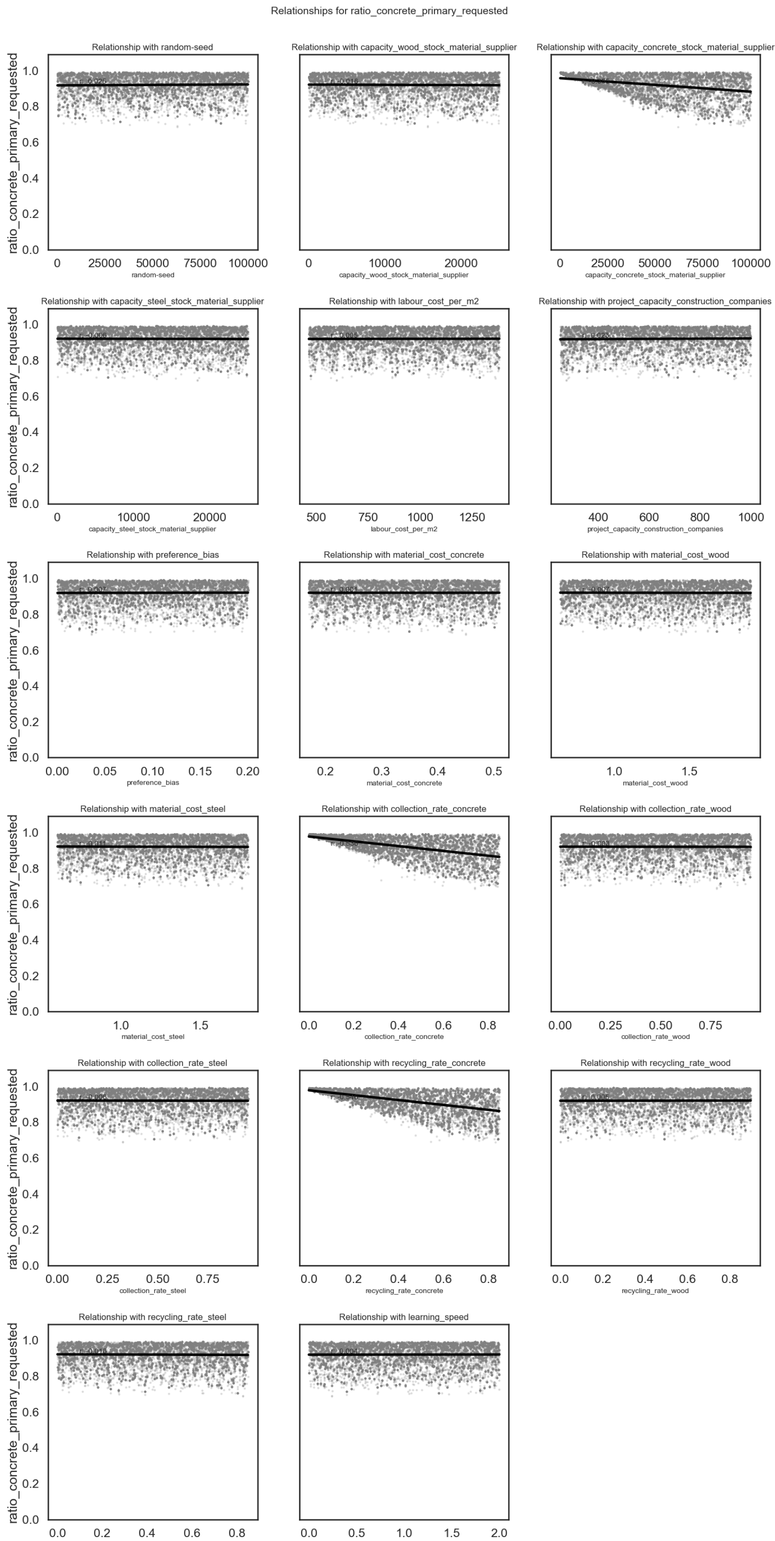

Figure 31: *Bivariate scatter plot for ratio_concrete_primary_requested_relationships.*

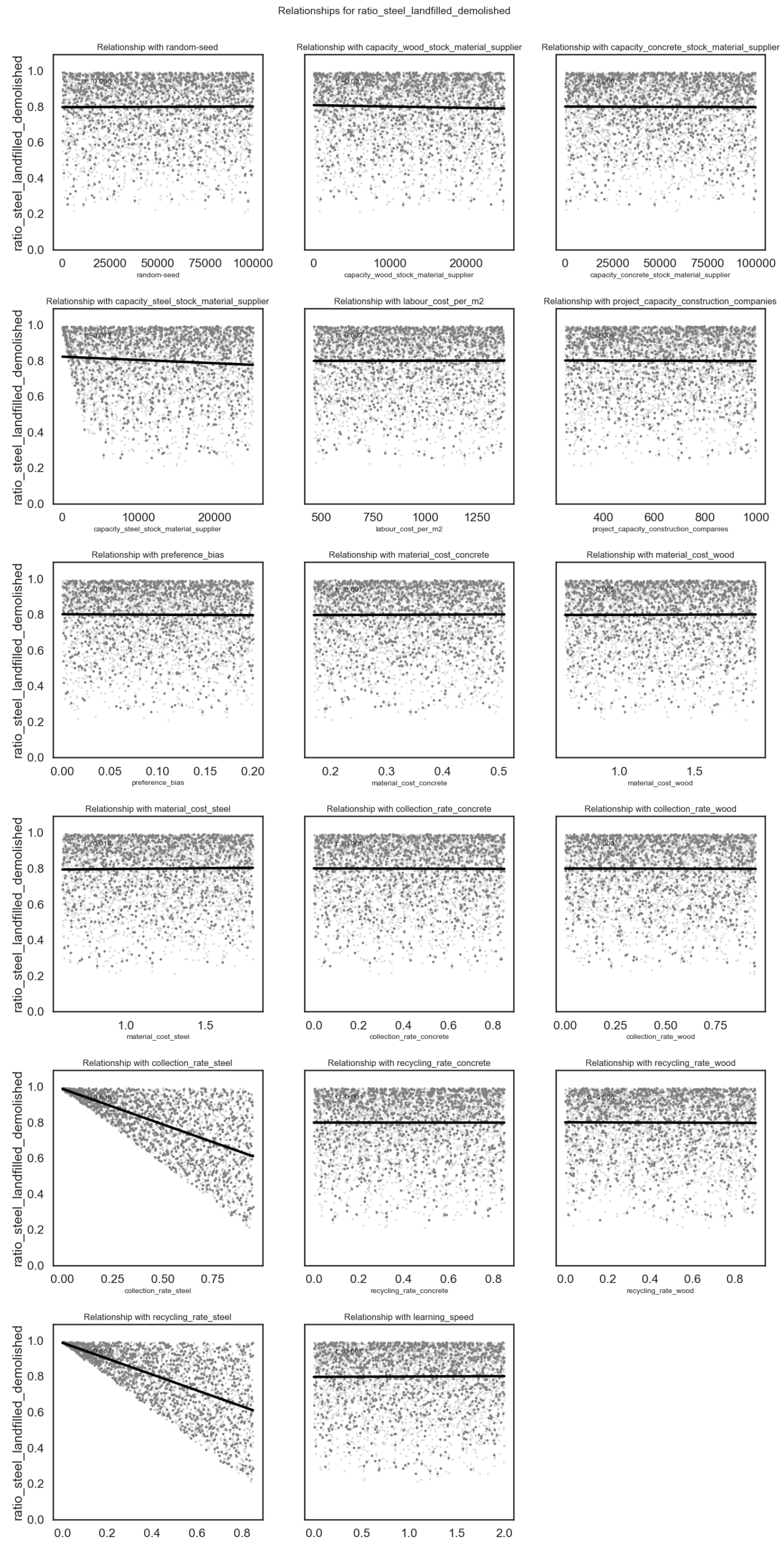

Figure 32: *Bivariate scatter plot for ratio_steel_landfilled_demolished_relationships.*

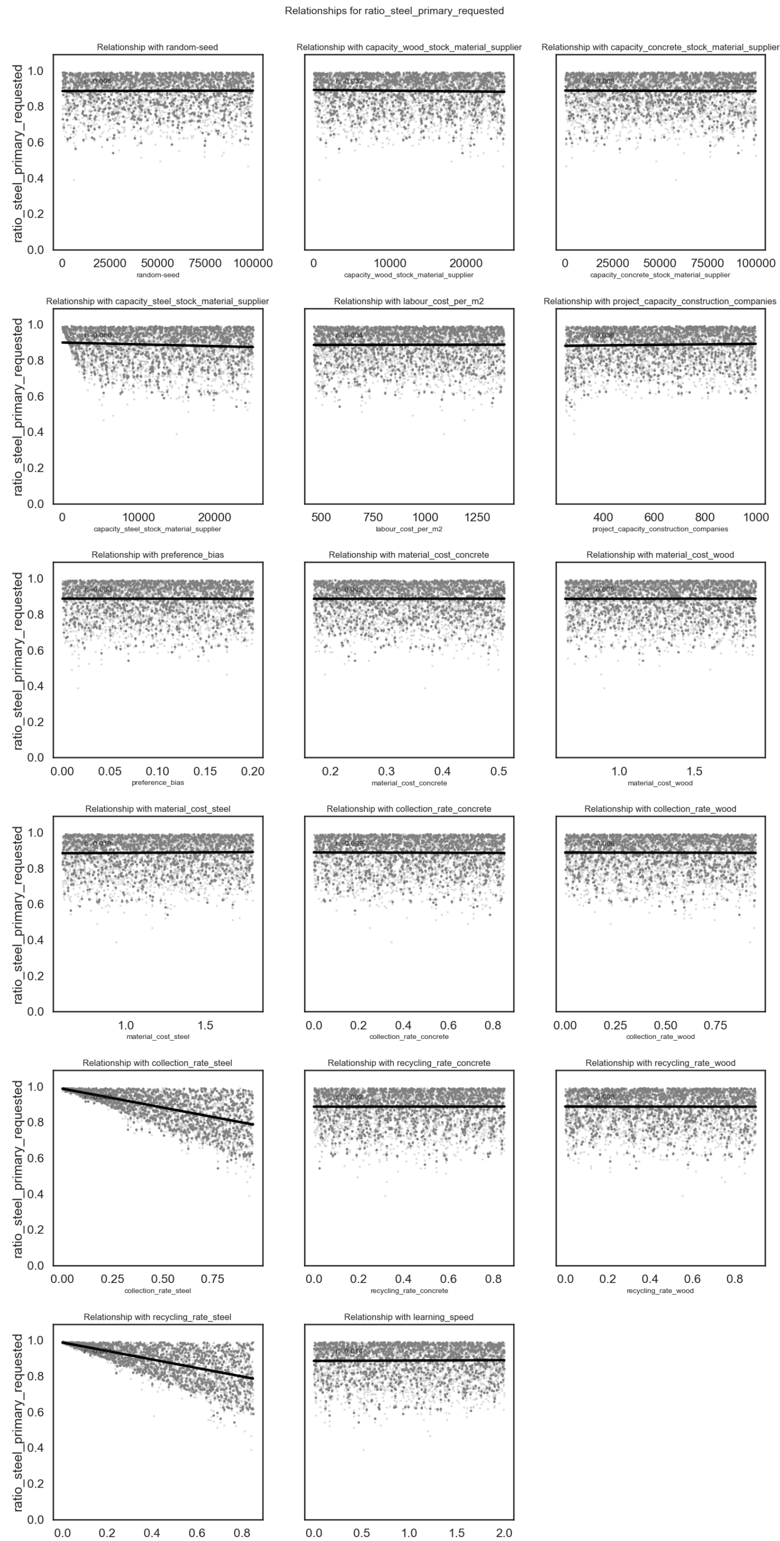

Figure 33: *Bivariate scatter plot for ratio_steel_primary_requested_relationships.*

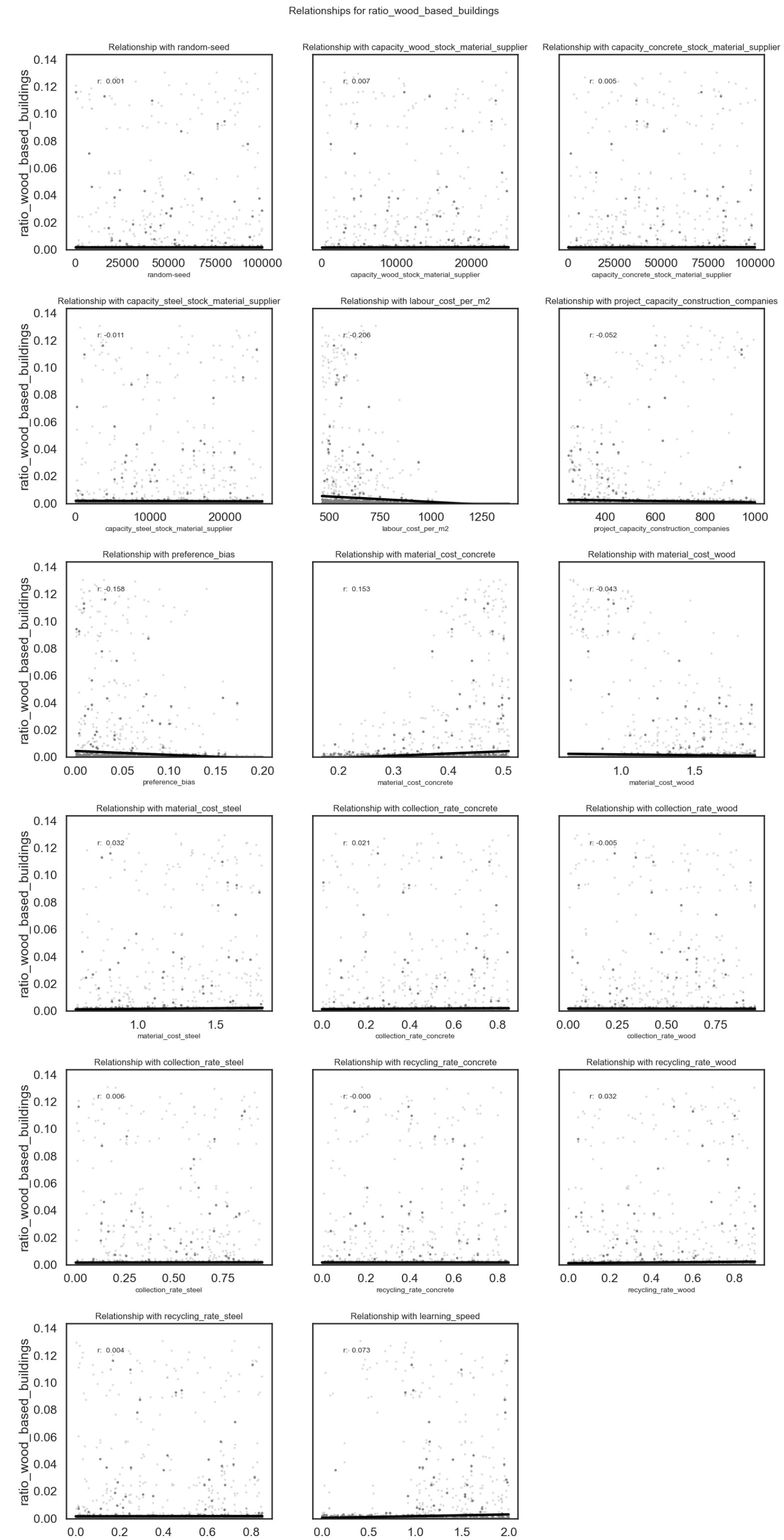

Figure 34: *Bivariate scatter plot for ratio_wood_based_buildings_relationships.*

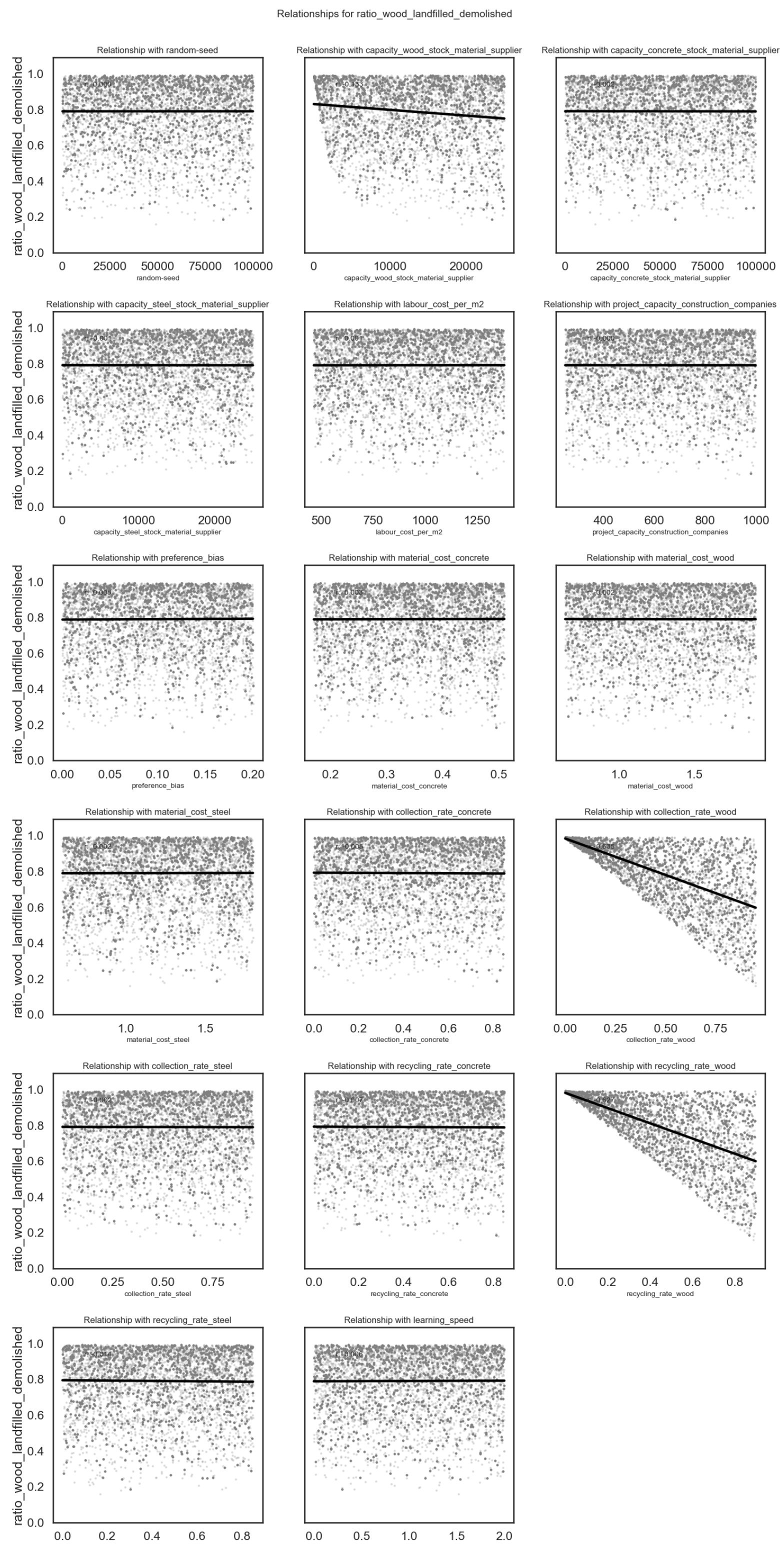

Figure 35: *Bivariate scatter plot for ratio_wood_landfilled_demolished_relationships.*

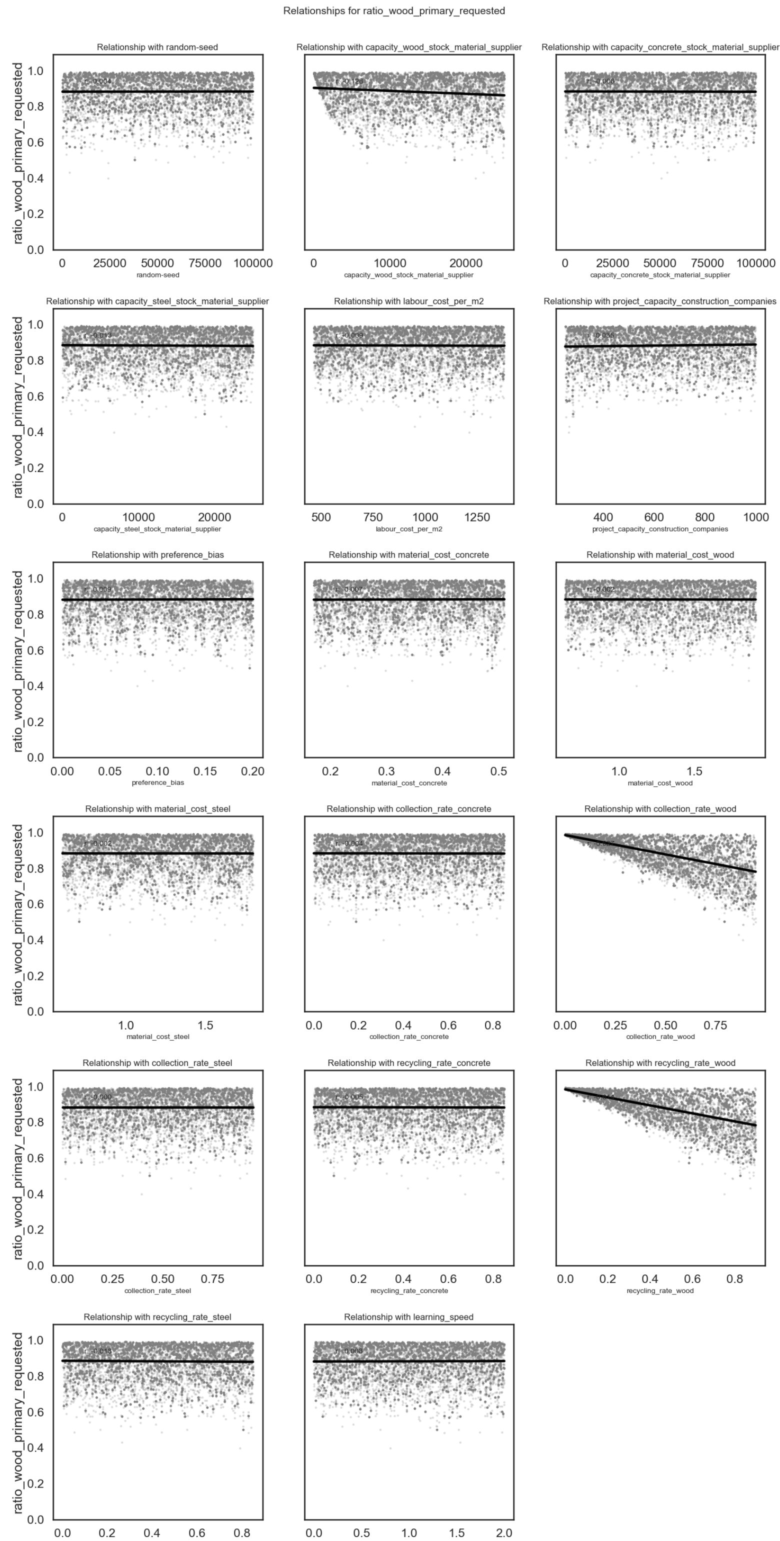

Figure 36: *Bivariate scatter plot for ratio_wood_primary_requested_relationships.*

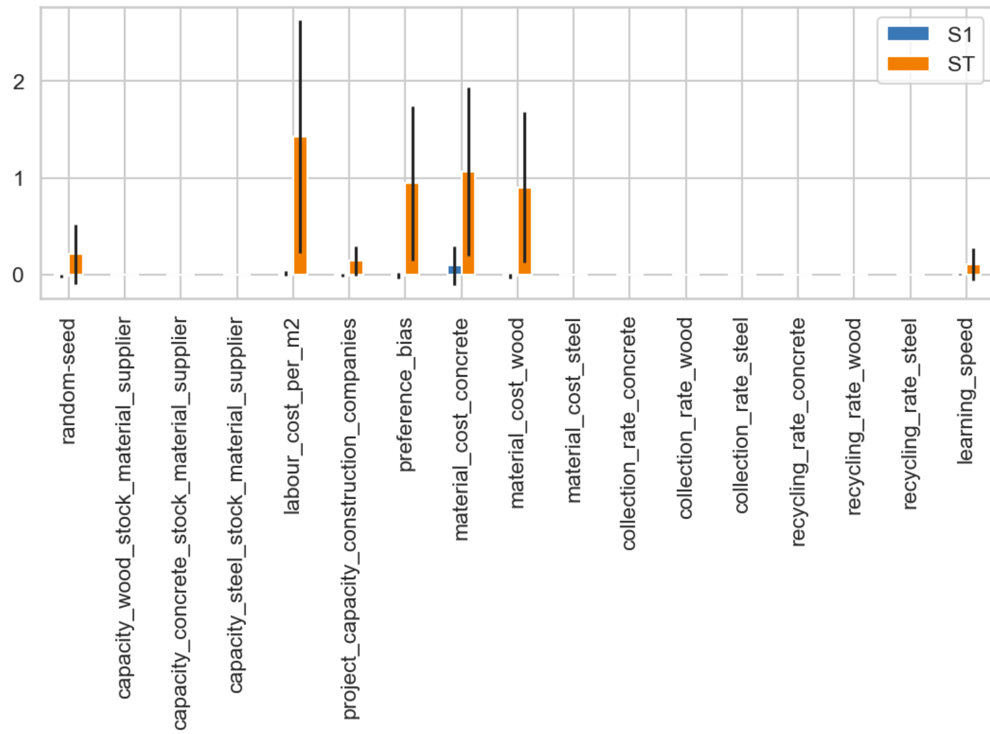

Figure 37: *Total and first-order indices for each input for wood_based_building_ratio*