Agent-Based Modelling of Collective Decision-Making in Energy-Efficient Retrofitting
A Case Study on Owner-Occupied Apartment Buildings

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English summary

This thesis examines the collective decision-making process in Dutch homeowners' associations (VvEs) regarding energy-efficient renovations (EER), a crucial issue given that about a fifth of Dutch homes are governed by VvEs requiring supermajority votes for retrofits, and many such groups struggle to reach agreement due to divergent member circumstances and strict rules. The research asks how socio-demographic, financial, regulatory, social, and building-specific factors influence a VvE's ability to agree on EER adoption, and how agent-based modelling (ABM) can help identify strategies to overcome deadlocks. Three sub-questions focus on (1) the barriers and motivations perceived by VvE members and experts, (2) the impact of each category of factors on the decision process and outcome, and (3) potential policies or strategies to break impasses and accelerate collective retrofit decisions.

Literature on collective retrofitting decisions highlights several key obstacles. Financially, VvEs with mixed-income membership often face opposition from those unable to afford the costs, even when subsidies or loans are available. Strict decision rules, such as a two-thirds or three-fourths vote requirement and attendance quorums, mean a small number of dissenters or apathetic members can halt progress. Social and organisational challenges further complicate matters: VvE boards often lack experience with the complex retrofit process, and internal conflicts or perceived inequities, e.g. when only certain residents benefit significantly from an improvement, can erode trust within the community. Prior studies have catalogued these barriers and explored household retrofit adoption in general, but few have modelled the internal collective decision dynamics of VvEs. Thus, a gap remains for an approach that simulates how individual attitudes, social influences, and formal voting rules interact in this context.

Methodologically, the study combines empirical case analysis with simulation. Two Dutch VvEs deliberating sustainability upgrades were examined to collect detailed data: household demographics, financial and energy profiles, social networks, and attitudes toward retrofitting were gathered through surveys, while interviews with residents and experts provided qualitative insights on barriers, motivations and regular decision-making processes. These inputs informed the design of an ABM representing a VvE's decision-making process. The model treats each household as an agent with distinct characteristics and retrofit preferences, regarding cost, comfort, and environmental benefit. Agents interact by sharing opinions and influencing each other, reflecting social dynamics within the association. The VvE's institutional rules, the attendance quorum and voting threshold, are explicitly represented, requiring sufficient consensus among agents for the retrofit to be approved. The ABM was calibrated with data from the case studies so that the base configuration outcomes match the actual decision-making process of the studied VvEs.

Running the ABM with case-study data showed that the model could reproduce the actual decision outcomes of those VvEs, confirming its validity. Analysis of different factors' effects revealed that financial capacity, such as the VvE's budget and members' willingness to pay, was crucial but not solely decisive: even well-funded associations could stall if other conditions were unfavourable. Institutional factors like voting requirements also influenced results: lowering the required majority tended to increase the likelihood of agreement, although this

effect varies over different model runs. Social factors show mixed patterns. Since social influence can either raise or lower an agent's opinion, depending on the opinion of those influencing the agent, factors influencing these social influence mechanisms show differing results. The building's context, through factors such as current energy performance and the expected gains of the renovation, likewise swayed opinions, where a retrofit promising substantial energy savings, for instance, generated stronger enthusiasm. Changes to gas-related variables, when compared to similar changes to electricity-related variables, generated large and at times counterintuitive effects due to the high cost and CO_2 production of gas.

To explore ways of overcoming deadlocks, the validated model was used to test various policy scenarios. Simulations showed that financial incentives, like higher subsidies or lower loan interest percentages, accelerated collective decisions most by lowering the barriers for hesitant or cash-constrained members. Loosening institutional requirements, by removing the attendance quorum and reducing the voting quorum, either showed a slight boost or an unexpected reduction in the implementation rate, likely due to the stochastic variation in the model. Incentives focusing on increasing information or awareness showed mixed results since the current information gain system reduces uncertainty for all agents, including those with negative opinions regarding the retrofit, which limits the ability of the ABM to realistically model targeted information campaigns promoting the benefits of the retrofit.

Overall, this research shows that the success of collective decision-making in VvEs depends on the interaction between financial feasibility, regulatory constraints, social influence processes, and the technical characteristics of the building, where some are more influential than others. While policies focusing on financial support and eased voting rules enhance decision success, interviews with experts highlight the importance of professional facilitation in the collective decision-making process. Experienced VvE managers can mediate discussions, translate technical and financial aspects, and maintain trust throughout the process. Although many VvEs in the Netherlands already employ these managers, experts note that their level of expertise, proactiveness and willingness to support sustainable retrofitting often remains limited, making them insufficiently equipped to effectively guide VvEs through the EER process. Theoretically, this study contributes by linking individual behavioural strategies and opinion dynamics under real-world VvE governance structures, offering an empirically grounded tool for understanding complex group behaviour. Societally, it provides guidance for policymakers and VvE boards: combine financial relief and regulatory reform with professional and social support to accelerate collective sustainability decisions in the built environment. An improved ABM, combined with a dashboard interface that visualises the effects of policy interventions for specific or representative VvEs, could offer valuable support in participatory sessions with stakeholders such as VvE boards or municipalities.

Dutch summary

Deze scriptie onderzoekt het collectieve besluitvormingsproces binnen Nederlandse Verenigingen van Eigenaren (VvE's) rondom energiezuinige renovaties (EER). Dit is een relevant vraagstuk, omdat ongeveer een vijfde van de Nederlandse woningen onder een VvE valt en dergelijke renovaties vaak een gekwalificeerde meerderheid vereisen. Veel VvE's worstelen met besluitvorming doordat leden uiteenlopende belangen hebben en de regels strikt zijn. Het onderzoek richt zich op hoe sociaal-demografische, financiële, institutionele, sociale en gebouwgebonden factoren de kans beïnvloeden dat een VvE instemt met een EER, en hoe Agent-Based Modelling (ABM) kan helpen om besluitvormingsdeadlocks te doorbreken. De drie deelvragen richten zich op (1) de door leden en experts ervaren barrières en motivaties, (2) de invloed van verschillende soorten factoren op het proces en de uitkomst, en (3) mogelijke beleidsopties of strategieën om de besluitvorming te versnellen.

De literatuur over gezamenlijke renovatiebesluiten laat zien dat er meerdere structurele belemmeringen bestaan. Financieel ontstaat vaak weerstand bij huishoudens die de kosten niet kunnen dragen, zelfs wanneer subsidies of leningen beschikbaar zijn. Daarnaast zorgen strenge besluitvormingsregels—zoals een twee-derde- of driekwartmeerderheid en hoge opkomstvereisten—ervoor dat een klein aantal tegenstemmers of afwezigen de besluitvorming kan blokkeren. Ook sociale en organisatorische factoren spelen een rol: veel VvE-besturen hebben beperkte ervaring met complexe renovatieprojecten, en spanningen kunnen ontstaan wanneer sommige bewoners meer profiteren dan anderen. Hoewel eerdere studies deze problemen beschrijven, ontbreekt het aan onderzoek dat de interne groepsdynamiek van VvE's daadwerkelijk modelleert. Daarom is behoefte aan een aanpak die laat zien hoe individuele voorkeuren, onderlinge beïnvloeding en formele regels gezamenlijk het collectieve besluit bepalen.

Het onderzoek combineert casestudies met simulatie. Twee Nederlandse VvE's die een verduurzaming overwogen zijn onderzocht. Via enquêtes is informatie verzameld over demografie, financiële positie, energieverbruik, sociale interacties en attitudes tegenover de renovatie. Interviews met bewoners en experts boden aanvullende inzichten. Deze gegevens vormden de basis voor het ABM, waarin elk huishouden wordt weergegeven als een agent met eigen kenmerken en voorkeuren. Agents beïnvloeden elkaar via gesprekken, en institutionele regels zoals het aanwezigheidsquorum en de stemdrempel bepalen of een renovatie kan worden goedgekeurd. Het model is gekalibreerd met casusdata zodat de basisuitkomsten overeenkomen met het daadwerkelijk besluitvormingsproces van de onderzochte VvE's.

De simulaties laten zien dat het model de echte uitkomsten van beide casussen goed kan benaderen. De analyses tonen dat de financiële positie van een VvE en haar leden belangrijk is, maar niet allesbepalend: ook financieel sterke VvE's kunnen vastlopen wanneer andere condities ongunstig zijn. Institutionele factoren, zoals de stemdrempel, hebben eveneens invloed: het verlagen van de vereiste meerderheid verhoogt in veel modelruns de kans op instemming, hoewel een onverwachte afname in één analyse-run laat zien dat dit effect afhankelijk is van de stochastische variatie in het model. Sociale factoren laten gemengde effecten zien: onderlinge beïnvloeding kan zowel positieve als negatieve standpunten versterken. Gebouwkenmerken spelen ook een grote rol: VvE's met hoge potentiële

energiebesparing tonen gemiddeld meer steun voor renovatie. Variabelen die betrekking hebben op gasverbruik en gasbesparing genereren opvallend grote en soms tegenintuïtieve effecten, vanwege de hoge kosten en CO_2-impact van aardgas.

Om te onderzoeken hoe besluitvorming kan worden verbeterd, zijn verschillende beleidsopties getest. De simulaties laten zien dat financiële maatregelen, zoals hogere subsidies of lagere rentetarieven, de besluitvorming het meest versnellen doordat zij de drempel verlagen voor huishoudens die twijfelen of financieel beperkt zijn. Aanpassingen in de regels, zoals het schrappen van het aanwezigheidsquorum of het verlagen van de stemdrempel, lieten eveneens verbeteringen zien, hoewel dit effect afhankelijk bleek van de stochastiek in het model. Maatregelen gericht op extra informatie of bewustwording leverden gemengde resultaten op, omdat het huidige model elke vorm van kenniswinst op dezelfde manier verwerkt—ook wanneer een huishouden negatief staat tegenover de renovatie. Daardoor kan het model gerichte informatiecampagnes die specifiek de voordelen van de renovatie benadrukken nog niet realistisch nabootsen.

Samenvattend laat het onderzoek zien dat succesvolle besluitvorming in VvE's voortkomt uit de wisselwerking tussen financiële haalbaarheid, institutionele regels, sociale invloed en de technische kenmerken van het gebouw. Hoewel financiële ondersteuning en versoepelde besluitvormingsregels de kans op succes vergroten, benadrukken experts dat professionele begeleiding eveneens cruciaal is. Ervaren VvE-beheerders kunnen discussies structureren, technische en financiële informatie vertalen en vertrouwen behouden tijdens het proces. Echter, volgens experts is de kennis en betrokkenheid van veel beheerders rond duurzame renovaties momenteel beperkt.

Theoretisch draagt deze studie bij door individuele gedragsprocessen en groepsdynamiek te koppelen aan de feitelijke besluitvormingsstructuren binnen VvE's. Maatschappelijk biedt het onderzoek concrete handvatten voor beleidsmakers en VvE-besturen: combineer financiële ondersteuning en aangepaste stemregels met professionele en sociale begeleiding om collectieve verduurzamingsbesluiten te versnellen. Een verbeterde versie van het ABM, gecombineerd met een dashboard dat de effecten van beleidsmaatregelen op specifieke of representatieve VvE's visualiseert, kan daarbij een waardevol hulpmiddel vormen in participatiesessies met bijvoorbeeld VvE-besturen of gemeenten.

Abstract

This thesis examines collective decision-making in Dutch homeowners' associations (VvEs) concerning energy-efficient renovations (EER), a process often hindered by diverse member interests, financial barriers, and strict voting rules. As around one-fifth of Dutch homes fall under VvEs that require supermajority approval for shared investments, their decision-making capacity is crucial for meeting national climate goals. The study explores how demographic, financial, regulatory, social, and building-specific factors affect these decisions, and how Agent-Based Modelling (ABM) can identify strategies to overcome decision deadlocks.

Empirical data were collected from two Dutch VvEs, each with around 30 members, through surveys and expert interviews, providing insights into household finances, social interactions, and attitudes toward retrofitting. These data informed an ABM simulating the decision-making processes of the two cases, representing each household as an agent with individual preferences regarding cost, comfort, and environmental benefit. Agents interact through opinion exchange under institutional rules requiring attendance and voting quorums. The model was validated by comparing key behavioural patterns such as attendance and voting rates from the simulated base configuration with those observed in the two case studies.

Simulation results show that financial capacity strongly affects decision success: VvEs with greater savings or higher investment willingness reach agreement more easily. Relaxing voting thresholds generally improves outcomes, although some scenario runs showed an unexpected decrease, likely due to stochastic variations in the model. The effects of social dynamics are more complex: high trust and constructive communication can foster consensus, but when discussions amplify doubts or negative perceptions, they can entrench opposition and delay progress. Building characteristics and expected energy gains further shape support, while uncertainty about costs and benefits remains a key barrier. Policy experiments indicate that financial incentives are most effective in breaking stalemates, while informational campaigns yield mixed results because the model reduces uncertainty for all agents, including those opposed to renovation.

The study concludes that successful collective retrofitting decisions depend on balancing financial feasibility, institutional flexibility, and social cohesion. ABM proves valuable not only for analysing these interdependencies, but also as a sandbox for exploring "what-if" policy and governance interventions before they are implemented in practice. The findings suggest that financial support and adjusted voting rules should be combined with professional facilitation: experienced VvE managers can mediate discussions, translate technical details, and maintain trust throughout the process. The research contributes theoretically by linking behavioural and institutional mechanisms within collective decisions, and societally by providing policymakers and VvE boards evidence-based guidance to accelerate energy-efficient renovations through both structural and social support measures.

Keywords

VvE governance, Collective decision-making, Energy-efficient renovation, Behavioural heterogeneity, Agent-Based Modelling

List of abbreviations

ABM	=	Agent-Based Model
AHP	=	Analytic Hierarchy Process
CO_2	=	Carbon Dioxide
DES	=	Discrete-Event Simulation
EER	=	Energy-Efficient Renovation
EGT	=	Evolutionary Game Theory
HOA	=	Homeowners' Association
LNS	=	Level of Need Satisfaction
ODD (+D)	=	Overview, Design concepts, Details (and Decision)
OFAT	=	One Factor At a Time (sensitivity analysis)
UNC	=	Uncertainty
VvE	=	Vereniging van Eigenaren (Dutch for Homeowners' Association)

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1. Introduction

1.1. Problem definition

In 2022, the Dutch Ministry of the Interior and Kingdom Relations published a document stating the goals for creating a more sustainable Dutch built environment by 2030, along with the policy points that will be implemented to reach these goals (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). These goals are set based on the European climate law, set by the European Union, which states that EU countries should reduce their net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (The European Parliament and the council of the European Union, 2021). Furthermore, this law also states that by 2050, these countries should have no net emissions of greenhouse gases. In the document by the Dutch Ministry of the Interior, a clear plan is given to reduce the greenhouse gas emissions produced in the built environment by at least 55% by 2030, compared to 1990 levels, and even aiming for a 60% reduction by 2030. This interim reduction enhances the feasibility of achieving net-zero emissions by 2050.

To make these emission reduction goals more tangible, some concrete subgoals are set for 2030 by the Ministry of the Interior. These goals include insulating 1.5 million owner-occupied homes and 1 million rental properties, having 1 million hybrid heat pumps installed in existing buildings, and realising 500.000 new connections to the district heating network (warmtenet) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). A large number of policies are also introduced that will help in reaching these subgoals by 2030, ranging from increased subsidies and incentives to new norms and standards in the built environment.

Implementing these Energy-Efficiency improving renovations (EER) is perceived as a large commitment with a lot of challenges by most. Firstly, one has to know how the large range of possible EER options would impact their home and its energy efficiency. Then, a choice has to be made between these options that best fit the house and its inhabitants. This option preferably lowers their energy consumption and increases their thermal comfort while keeping their investment costs as low as possible. Since most of these options require a significant investment, some form of external financing is often used to help in paying for the renovation. Several subsidies (Rijksdienst voor Ondernemend Nederland, 2025a, 2025b) and loans (Nationaal Warmtefonds, 2025b) are created specifically for these energy efficiency renovations, each with its own target group, requirements, downsides, benefits, and application process. This intricate process partly explains why, in a study by Conradie & Vegt (2024) between 30% and 57% of respondents indicated they certainly would not plan any EER in the coming three years.

The challenges associated with implementing an EER are especially experienced by residents of apartment buildings with owner-occupied units. The homeowners' association of these buildings, Vereniging van Eigenaren (VvE) in Dutch, must decide collectively on any improvements to the shared spaces and elements of the building. For each of the 135.000 VvEs in the Netherlands, any that is willing to implement an EER has to get between ⅔ and ¾ of the members to agree on the renovation plans of the building before the renovation can commence. Because of the large difference in financial situations and personal motivations

among the members of a VvE, it can be very difficult to reach a consensus. Meanwhile, governmental aid for EERs seems to focus more on dwellings that are not part of an apartment building. For example, families with a low income can apply for a loan with 0% interest at the Warmtefonds as long as they are not part of a VvE (Steenkamp, 2023). Given that approximately 20% of the housing stock in the Netherlands includes a VvE (Centraal Bureau voor de Statistiek, 2023a), it is essential to improve the decision-making process for EER in VvEs so that a 60% reduction of greenhouse gas emissions by 2030 can be reached.

In this research, the collective decision-making process of VvEs will be studied, modelled and evaluated. By performing an in-depth case study of 2 apartment buildings with VvEs, one in the Groningen region and one in the Eindhoven region, the influencing factors of the inhabitants, buildings and the VvE's voting regulations regarding the collective decision-making process will be studied. Furthermore, interviews will be held with experts in the field of sustainable renovation of VvEs to map the workings of the decision-making process of VvEs. Using this information, an Agent-Based Model (ABM) will be created and validated, which can simulate the collective decision-making process within a VvE based on a set of input parameters gathered from the studied VvEs. This model can give valuable insights into what is required to speed up this process among VvEs in the Netherlands. It can also be used to simulate the process of specific VvEs and create valuable insights into the factors influencing the speed and success rate of its decision-making process.

1.2. Research questions

Many VvEs are stuck in collective decision-making deadlocks, repeatedly failing to reach the required voting quorum over successive meetings and often experiencing increasing polarisation among members regarding the proposed EER. After several years without tangible progress, these VvEs tend to abandon their renovation plans altogether. Since 20% of the Dutch housing stock consists of apartment buildings with a VvE, this greatly hinders the completion of the goals set by the Dutch government that will lead to a sustainable Dutch built environment. This research will address this issue by investigating the collective decision-making process of VvEs and analysing them using an ABM. For this, the following research question will be answered.

How do socio-demographic, financial, regulatory, social and building-specific factors influence collective decision-making on energy-efficiency improving renovations in Dutch homeowners' associations (VvEs), and how can Agent-Based Modelling help identify effective strategies to overcome collective decision-making deadlocks?

This research question considers five types of factors: socio-demographic, financial, regulatory, social, and building-specific, to provide a comprehensive overview of influences on these decision-making processes. The influence of basic socio-demographic information of the households in the VvE, such as household size, age and education level, on the decision made will be studied. With financial factors, factors like the income level of VvE members and the savings in the VvE account will be considered. Regulatory factors will look at the VvE's specific regulations influencing the voting process, namely the voting quorum and the attendance

quorum. Social factors look at the trust and conflicts within the VvE and the influence of members on the decisions made by others. Finally, building-specific factors will include factors like the construction year and energy label of the building.

Since this is quite a broad research question, three sub-questions are created, based on which the research will be structured.

Which barriers and motivations do members of VvEs and experts in the field perceive related to collective decision-making processes regarding energy-efficiency improving renovations?

To what extent do socio-demographic, financial, regulatory, social and building-specific factors affect the process and outcome of decision-making processes in VvEs?

Which policies or strategies could contribute to overcoming collective decision-making deadlocks and accelerating energy-efficient retrofitting agreements within VvEs?

1.3. Research design

This thesis is structured in a clear empirical-modelling sequence. First, a targeted literature review on Dutch VvEs and ABMs regarding household EER adoption identifies the main barriers hindering collective renovation decisions, outlines the institutional settings of VvEs, describes the decision rules typically used in practice, and summarises the modelling choices available for individual, social, and collective behaviour. Next, semi-structured conversations with VvE experts such as consultants, board members and municipal support staff are used to ground the review in current practice, to clarify procedural details such as attendance and quorum rules, to obtain contact leads for possible participating VvEs in this case study, and to ask their opinion on the main barriers VvEs face in this decision-making process. Based on these interviews and the literature review, the first sub-question can be answered. In addition to VvEs contacted through these experts, individual VvEs are approached directly to ensure the VvEs studied differ in location, size, EER status and other characteristics.

While these VvEs and experts are contacted, the ABM is created in Python based on the gathered insights. The barriers identified in literature and interviews are translated into corresponding model variables and behavioural mechanisms, refined through an iterative process and expert feedback to ensure the simulation reflects how VvE decision-making processes unfold in practice. The model is first tested using data simulated through AI to spot and tackle any inconsistencies.

Based on the data requirements of the model, a survey is designed and distributed to 2 of the previously contacted VvEs to elicit the variables required by the model, covering household characteristics, attitudes toward energy measures, perceived norms within the building, uncertainty and perceived behavioural control, and VvE-specific procedures relevant for collective decisions. These VvEs are selected based on their number of members, ranging between 20 and 50 members. This size range is chosen since in smaller sized VvEs, one member can have a disproportionately large impact on the model outcome. Larger VvEs often experience overly complex voting processes, where regularly a large part of the building is owned by an external company.

The collected data is then cleaned, and missing data is generated, replacing the missing information of households, through the analysis of gathered data and regional averages. The two VvEs are then tested separately with the model, after which a sensitivity analysis shows the impact of the model parameters on the outcome, highlighting the reliability of these parameters and their impact on the model outcome. Parameters with an unexpectedly high influence are altered where possible, reducing their impact on the outcome and ensuring they are configured in such a way that the model outcomes reflect the outcomes of the case studied VvEs. With the input parameters correctly configured, a similar analysis to the sensitivity analysis is performed over nearly all the variables of the model. Through this analysis, the impact of different types of variables on the outcome of a decision-making process of VvEs is studied, thus answering the second sub-question of this study. Similarly, different scenarios are tested, exploring the impact of different policies on the models' outcome, thus answering the final sub-question.

1.4. The importance of the thesis

The primary goal of this research is to understand the cause of deadlocks in the collective decision-making process of VvEs with planned energy efficiency retrofitting projects. While previous studies have explored the barriers and deadlocks hindering this sustainable renovation, this thesis goes a step further by modelling the internal dynamics of the decision-making structure. It will focus on how individual preferences, financial constraints, social influence, and building characteristics influence the voting outcome of a VvE structure and how policies and strategies can be designed to accelerate the decision-making process.

A secondary goal of this research is to effectively model the decision-making process of a VvE with an ABM. While previous studies have identified barriers and behavioural patterns, they often remain descriptive without looking at the internal dynamics of the decision-making process of VvEs. Since VvEs are complex systems, made up of a group of vastly different households whose decisions are interdependent, traditional analysis methods are not suited to study them at the level of detail required for this study. Traditional survey or econometric approaches can identify correlations between household characteristics and renovation outcomes, but overlook the interactions and social influence of agents that shape collective decisions. ABM addresses this limitation by modelling each household as an individual agent with its own characteristics and decisions to be made. This approach enables the study of the interaction of agents and the influence of certain characteristics on the decision outcome. This modelling method also allows the testing of different policy scenarios to study the possible outcome of these policies. By doing so, the model helps identify which factors and interventions are most effective in overcoming decision-making deadlocks within VvEs.

1.5. Reading guide

In the following chapter, the literature review will be conducted. This review will discuss both the current state of ABM in the context of EER and collective decision-making processes, as well as the structure and functioning of VvEs in the Netherlands. It identifies the research gap

and provides a theoretical foundation for the model. The Methodology chapter then explains the ABM used for this research in detail, following the ODD+D protocol. This chapter outlines the model's structure, assumptions and implementation, providing a complete overview of how the model is designed and how VvE's collective decisions are modelled. After this, the data collection chapter elaborates on the surveys and interviews that were conducted, how the VvEs and experts in the field were contacted and how the data was prepared for usage in the model. In the 5th chapter of this thesis, the results of the survey and the model simulation results are presented. It analyses how the different factors influence the decision-making process and evaluates the impact of various policy scenarios. In the 6th chapter, limitations of the model are discussed and recommendations for future research are discussed. The final chapter draws conclusions based on the model's findings and reflects on the relevance of the research. Some acknowledgements, the references and the appendices follow this chapter.

2. Literature review

In this literature review, both the current institutional structures of VvEs are discussed, as well as the current state of the art of ABMs modelling EER adoption and collective decision-making processes. This ensures the following parts of the thesis are based on theories and knowledge grounded in literature. In the first part of this literature review, the decision-making structure and financial structure of VvEs are explored. This is done by elaborating on the structure of VvEs and how the decision-making process regarding EER adoption in the building is handled. The barriers experienced by VvEs deciding on EER adoption are also highlighted. In the section following this chapter, different modelling methods are compared, which could model the collective decision-making processes of VvEs, from which ABM is chosen as the most promising option. The study of EER adoption using ABMs is then studied by comparing the current literature available in this field of research. This section is followed by a study of the possibilities of ABMs to study collective decision-making processes, by focusing on the theories for social network formation and opinion dynamics. The final section highlights the research gap this thesis will try to fill and synthesises the chapter, highlighting the choices which will be made based on the literature review.

2.1. VvEs and collective decision-making

Institutional and financial structures of VvEs

In the Netherlands, each apartment building containing owner-occupied apartments has a VvE. This VvE is an association of all homeowners of the building, which ensures all decisions regarding the building's shared spaces and elements are made collectively. Each VvE has a board, made up of homeowners of the building or external parties, who represent the VvE and ensure all agreements are upheld. This board is appointed by the homeowners of the building. This board also leads the meetings of the VvE, where troubles are shared and solved, the condition and maintenance of the building are discussed, and new investments in the building are voted on. In most cases, the majority of votes decides what is being done. However, for some larger investments concerning the shared spaces or elements of the VvE, like most EER investments, ⅔ or ¾ of the votes have to be in favour of the investment for it to be executed, as determined by the national government (Ministerie van Volkshuisvesting en Ruimtelijke Ordening, 2023b). These voting sessions also have a minimum attendance requirement for it to be accepted, where ½ of the possible votes should be represented at the meeting. If this requirement is not met, the meeting is cancelled, and within 2 to 6 weeks, a new meeting should be held to hold a new voting session. At this second meeting, no attendance quorum is required; thus, the voting can take place regardless of the number of votes represented (stichting !WOON, n.d.). An exception to this rule is voting on alterations of the 'splitsingsakte'. This document states, among others, which parts of the building are owned by the VvE and which share each owner has in the building (VvEBelang, n.d.-a). This share, often based on the apartment's size, determines how much their vote weighs during voting sessions and how large their monthly contribution is. Since the 'splitsingsakte' is the fundamental document of each VvE, voting sessions regarding major changes to this document require all owners to be present at the meeting and agree on the change. When a voter cannot be present at a meeting,

they can send a representative to the meeting to vote in their place (VvEBelang, n.d.-b). This representative can be another member of the VvE, a third party or, unless specifically specified in the VvE's documents, one of the board members of the VvE. The representative can either get a full proxy from the owner, giving this person the authority to speak and vote on their behalf, but on their own initiative. Furthermore, the representative can also get a target proxy, for which the representative has to vote as specified by the owner.

Each homeowner in the apartment building is obliged to send a monthly contribution to the VvE's savings account, which is used to cover all expenses to clean, maintain and renovate the shared spaces and elements of the building. The amount in this savings account is, however, often not enough to cover the cost of an EER, since these investments often require significant changes to the building. On average, the cost per apartment is between €15.000 and €20.000 (VvE.nl, 2025). Due to the relatively recently announced plans of the government to create a more sustainable housing stock (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022), most VvEs have not yet had the time to save a sufficient amount to cover an EER. In case the savings account does not cover the cost, the missing amount can be paid by taking on a loan as the VvE from the Warmtefonds. The Warmtefonds was set up by the National government in 2013 to aid homeowners in the financing of EER. For most renovations, the VvE can apply for a loan with a maximum of €35.000 per apartment and an interest rate between 3.29% and 3.69%. These loans have to be repaid in 10, 15 or 20 years (Nationaal Warmtefonds, 2025c). If the VvE opts for a full building renovation under the *Zeer Energiezuinig Pakket* (ZEP, or Very Energy-Efficient Package), which combines multiple energy-efficiency measures, the maximum loan amount can increase to €91,000 per apartment. These loans for a ZEP renovation can also be repaid in 30 years, under a 3.71% interest rate.

The loaned funds are deposited into a construction escrow account, which the VvE can access by submitting a reimbursement form. To pay off the loan and the added interest, the monthly contribution of the members will often increase greatly. For example, members of a VvE in Amsterdam went from a monthly contribution of €150 to €360 in 1 year due to the planned EER, where 5 years prior, this contribution had only been €80 (Steenkamp, 2024). Important to mention here is that the loan is linked to the apartments of the VvE, not the members. Thus, if an owner decides to move out of the building, the repayment of the loan will no longer be the responsibility of that owner.

Barriers to sustainable renovation of VvEs

The problems experienced during the collective decision-making process of a VvE concerning EERs can be broadly categorised in three parts: Financial problems, regulatory problems and other, often social, problems (Elgendy, Mlecnik, Visscher, & Qian, 2024). Nearly all VvEs planning an EER experience some sort of financial problem. This often occurs when the VvE has a mixed structure with both high and low-income households. These low-income households may already struggle to pay for their monthly expense, especially with the rapidly increasing cost of energy over the last years. For these people, the extra monthly cost of a large investment or the high upfront cost will be the most significant, and it might make them

unable to keep living in the building. Unless aided, this group will most likely not agree on the planned investment, and others in the building might vote against the investment to prevent their neighbour from ending up on the street.

The national government has some subsidies available to aid VvEs in this process. Subsidies are available to finance process guidance advisors, research required to prepare for EER and some energy-efficiency improving measures themselves can also be financed partially (Rijksdienst voor Ondernemend Nederland, 2025c, 2025b). This last one is, however, only available for certain insulation measures, including several insulation options, double or triple-glazed glass, a heat pump or a connection to the district heating network. Furthermore, the subsidy can be applied for a maximum of 15% of the cost of the sustainability improvement if one improvement is done, and 30% if the renovation includes two different improvements (Rijksdienst voor Ondernemend Nederland, 2025c; Vereniging eigen huis, n.d.). However, VvEs experience that this claimed coverage of 30% of the cost in reality only accounts for about 10% of the cost (Steenkamp, 2024). The average cost of the renovations with which the subsidy is calculated by the government, is often drastically lower than the real cost of the renovation.

Some municipalities also offer extra aid to lower these financial barriers. Several municipalities offer a discount on the interest rate for loans taken from the Nationaal Warmtefonds. However, this currently seems to only be the case for the municipalities of Den Haag and Leidschendam-Voorburg, both offering a decrease of up to 0.5% from the interest rate (Nationaal Warmtefonds, 2025a). Furthermore, some municipalities and other parties also offer their own subsidies for certain energy-saving measures, which can be stacked on top of the subsidies issued by the national government. It can, however, be difficult for homeowners to be aware of all the possible channels where they might find subsidies suitable for their situation. For this, Milieu Centraal (n.d.) has created an online tool which can be used to identify all the possible subsidies that can be applied in a region.

A second type of obstacle often experienced during the collective decision-making process of a VvE relates to the regulations imposed on the VvE by the government. Since ⅔ or ¾ of the VvE has to vote positive for a measure to be adopted, and at least half of the votes should be represented at a voting session, a small number of uninterested members or members who are against the proposed EER can prolong the decision-making process of a VvE by years, if the VvE even manages to finally get enough voting rounds with a positive consensus. Having the majority of votes does not matter as long as a couple of inhabitants keep voting against the measure. However, the government plans to change the regulations in 2026, lowering the voting quorum to 51% of the represented votes when deciding on EER measures in VvEs, while simultaneously lifting the attendance requirement (Ministerie van Volkshuisvesting en Ruimtelijke Ordening, 2023a). However, from the interviews performed with experts in the field of VvEs and EER adoption, scepticism regarding the effective introduction of these new regulations in 2026 was heard. Doubts were shared regarding the actual introduction of these regulation changes in the coming year, expecting a delay in the implementation of these proposed changes. Another doubt concerned the speed of implementation of the new quorum levels by VvEs, since a change of quorum levels of a VvE requires the adaptation of the VvE's 'splitsingsakte'. As indicated before, major changes to this document require a

positive vote of all members of the VvE, which can prove to be a difficult and time-consuming process for many VvEs.

Furthermore, the intricate process of executing an EER and applying for a loan and subsidies for the renovation is also often experienced as a large obstacle to overcome. VvEs with an inexperienced board regularly have troubles related to the EER process and the regulations that go with it. These VvEs often have difficulties with discovering which energy saving measures are available, which are best suited to their building, how to apply for the right subsidies, how to apply for the loan of the Warmtefonds and how to guide the voting process if not all members agree on the investment. It can be a very intricate process, requiring a lot of time from the board members of the VvE. For example, the Warmtefonds requires that a VvE requesting a loan for an EER send them 25 different documents throughout the entire process. Steenkamp (2024) indicates that this loan application process can easily require 200 hours of a board member's time from start to finish.

To reduce the difficulty of this process, several platforms have been set up by the government and some municipalities to aid VvEs in finding all the information they require, asking their questions to professionals and sharing their own experiences (Ministerie van Volkshuisvesting en Ruimtelijke Ordening, 2023b). A VvE can also choose to use the aid of an experienced VvE manager or an energy coach who can help guide this process. These experts can take over a part of the process, using their expertise and network to ensure the process goes smoothly. However, for this, the members have to be convinced of an extra cost during the EER process.

Finally, some VvEs experience specific and often personal problems during this process. Perceived inequalities regarding the benefits of the retrofitting are often the cause of these internal problems. Take roof insulation as an example, the benefits of which are only experienced by those living on the top floor of the building. In such a case, the entire VvE has to pay for an improvement only experienced by a small number of the residents of the building. In cases like these, those who will benefit less from the retrofitting will be more likely to vote against the proposed measure, especially if they have a bad history with those who benefit more from the retrofitting. These problems can split the VvE in two, creating a hostile environment and further slowing down current and future decision-making processes. In 2024, 21% more conflicts within VvEs were reported compared to 2023, which is most likely due to the increased pressure on VvEs to apply for sustainability measures. (NederlandVvE, 2025).

2.2. Modelling approaches for EER adoption within VvEs

As can be concluded from the previous paragraph, VvEs are intricate social networks. They consist of a large number of different actors, each with their own agenda. Furthermore, the voting process of VvEs can differ quite a bit among different VvEs, although this difference is kept at a minimum through regulations issued by the national government.

In current literature, there is a clear lack of studies attempting to model a VvE or a Homeowners' Association (HOA), especially combined with the adoption of an EER. Some studies have created a model to study the formation process of a homeowners' association

(Cheung & Meltzer, 2014; Wojciechowski, n.d.), using a survival analysis model and a community action model, respectively. Others have studied whether the presence of HOAs impacts other factors, like Meltzer & Cheung (2014) did for the property value using a hedonic model. One study was found which specifically studies the group decision-making process of VvEs (Nava-Guerrero, Hansen, Korevaar, & Lukszo, 2021). This last study uses an ABM to study the group decisions made in VvEs regarding the heat transition. However, this study fails to include any social interaction factors in the model, which is an important part of the collective decision-making process of VvEs. Due to the low amount of prior models used in literature studying VvEs adopting an EER, several models which can simulate social networks are compared to see which modelling technique best fits the simulation of VvEs adopting an EER.

An often-used model type concerned with simulating complex social interaction mechanisms is ABM, which is a computer simulation with which interactions between agents and their environments can be studied. An ABM is created by assigning attributes to individual agents. Based on these assigned attributes, the agents interact in a certain way with other agents and the environment in the simulation (Columbia Mailman School of Public Health, n.d.). An ABM runs in cycles, where each cycle represents a certain time interval. Each cycle, every agent determines which decision they make based on their current situation and the current state of their environment. Agents can also look at other agents and the decisions they have made, and change their behaviour accordingly. In the field of the built environment, ABM is especially popular since it allows the implementation of different policy scenarios. The effect of these different scenarios on the individual agents, the entire agent population and the environment can be studied in great detail, allowing policy makers to study a policy's effect before implementing it in reality. ABM also have some downsides. To model the decisions made by the agents, a high level of understanding of the decision-making process of the studied subjects has to be gained. This often results in extensive studies before the creation of the model. And since ABMs often attempt to model the decision-making process as realistically as possible, the underlying code of these models often quickly becomes highly complex. Furthermore, the large number of parameters used often results in problems during the acquisition of data. Some data may be hard to convert to a numerical value, while for other data, it is hard to find an exact and validated number. Validation of the model is also hard because of the model's complexity, and since models often contain unobserved reactions (Columbia Mailman School of Public Health, n.d.).

A second model type, which is occasionally used to study social networks and EER adoption, is the concept of Evolutionary Game Theory (EGT) (Fan & Li, 2025; Yao & Shao, 2022; Zheng et al., 2025). EGT is an adaptation of game theory, which studies the decisions made by a set of agents where the decision of one agent can influence the outcome for another agent. A well-known example of game theory is the prisoners' dilemma, where two criminals are asked to confess to their crime. If both agents remain silent, they have to serve one year in prison; if both confess, they serve two years in prison. If one confesses and one remains silent, the confessing agent goes free, while the one who stays silent serves 3 years. EGT is adapted from game theory to take into account how the decision-making strategy of the agents changes over time. Where game theory studies a single decision made by several agents, EGT looks at several decisions over time and changes the decision-making strategy of individual agents after

each decision that is made. This thus leads to the spreading of successful strategies, while the strategies with less favourable results fade out (Stanford Encyclopedia of Philosophy, 2021). The individual decision-making process of agents is, however, limited in its complexity. Agents simply follow a predetermined strategy and do not look at the parameters of their current situation or make a decision based on those, as is done in ABM. These strategies can be modelled to represent realistic decision-making strategies; however, the adaptive decision-making of agents remains limited. Individual decision-making based on policy changes is also not something EGT excels at. While policies can be implemented in an EGT model, the effects of these policies on individual decision-making are hard to model. These policies mostly directly change the payoff of a certain strategy; however, modelling the underlying changes of certain policies on the decision-making process of agents is not possible. Due to the limited modelling of individual decision-making processes, the complexity of implementing an EGT is relatively low.

Another frequently used model to model social networks and decision-making processes is the discrete-event simulation (DES). DES simulates a complex physical system by looking at this system as a set of chronological events. These events alter the state of the system and the agents in it and can lead to future events (Ndih & Cherkaoui, 2015). The agents in these systems make individual decisions based on these events and their outcomes. These decision-making processes are, however, lacking in complexity. Often, the decision made by an agent is predetermined based on the state of the system and the events that have happened. Thus, the agents don't interact with other agents to alter their decisions. DES does allow the testing of many different scenarios, thus being a popular method to test new policies with (Allen et al., 2015). Just as with EGT, since DES is limited in studying individual decision-making processes, the complexity of most Discrete-event models is low. However, simulating more complex systems can increase this complexity.

Other types of models are frequently used to model complex decision-making processes. However, these do not apply to the case of this thesis. Some, like system dynamics, don't look at individual agents but at the system as a whole. Others, like the Markov decision process, are not able to create heterogeneity among the actors or lack social interaction between the actors.

In Table 1, a comparative overview is created of the three modelling approaches discussed earlier. The table indicates whether each model type supports specific characteristics that are essential for the modelling approach required in this thesis. These characteristics are chosen based on the characteristics of the decision-making process of VvEs. Important in these processes are the heterogeneity and individuality of agents, where each household makes its own decision based on its own situation and opinion. Furthermore, social interactions between the agents are an important requirement for the model used. Interactions and discussions between members of VvEs often occur during the decision-making process to convince each other of their opinion. This is an important part of the process, influencing the final vote of the members. One of the few models found studying VvEs and their decision-making processes (Nava-Guerrero et al., 2021) did not include these interactions, and the authors indicated that this is an important part which should be included in future models.

The temporal dynamics are chosen as another characteristic in the table below since these EER decision-making processes can spread out over multiple years and multiple voting rounds. During this time, factors of both the households and the VvE may change. Furthermore, the total time elapsed before the EER is accepted is an important factor to compare the model's outcome with the real outcomes of VvEs. Since this thesis aims to test policies which positively influence the decision-making process of VvEs, the possibility of simulating different policies in the model is essential. Finally, the complexity of the modelling technique is added, which might help in deciding between two modelling techniques which score equally on the other indicators.

Based on the information given in Table 1, the ABM is the logical model type to use for this thesis. An ABM allows the modelling of the individual as well as collective decision-making processes in great detail, thus being a logical choice for this thesis. ABM often require a large amount of different data types. This will thus have to be taken into account when preparing the model. The fact that the only other papers in this field of research also use an ABM (Derkenbaeva, Hofstede, van Leeuwen, & Halleck Vega, 2023; Nava-Guerrero et al., 2021) also confirms this as a logical option.

Table 1: Comparison of modelling approaches

	Heterogenous agents	*Individual decision-making*	*Social interaction*	*Temporal dynamics*	*Policy simulation*	*Complexity*
ABM	Yes	Yes	Yes	Yes	Yes	High
EGT	Yes	Limited	Yes	Yes	Limited	Medium
DES	Yes	Limited	No	Yes	Yes	Medium

2.3. Agent-Based Modelling of decision-making processes regarding EER

As concluded in the previous part of this thesis, ABM will be the model type used to answer the questions set for this research. As can be seen in Table 1, an ABM is a suitable tool to study the complex social network system of VvEs, characterised by agents with different motives and attitudes, a mix of individual and collective decision-making and strong social interactions. ABM's ability to test the impact of different policies and scenarios will also be of great value to this research.

In the studied ABM literature, a distinction can be made between models of individual adoption and models of collective governance. The first category focuses on how individual households decide to adopt energy-efficient technologies based on their personal characteristics. These models simulate diffusion processes where households independently make decisions influenced by factors such as their personal preference or their economic situations. The second category introduces group decision-making mechanisms, in which interdependent households are bound by shared rules and procedures. Here, decision outcomes depend not only on individual attitudes but also on collective dynamics and social influence.

The thesis will build on both categories: it draws from the behavioural and policy insights of individual adoption ABMs while using these in a collective decision-making context. Section 2.3. reviews the literature on individual EER adoption models, while 2.4. elaborates on ABMs that simulate collective decision-making processes and the social interaction mechanisms underlying them.

2.3.1. Previous studies

The concept of modelling complex systems has existed since the early 19th century, with mathematical models used to study physical, biological, and social phenomena. In the 20th century, computational pioneers such as Enrico Fermi and John von Neumann laid the groundwork for simulating complex systems, particularly through stochastic modelling and cellular automata. One influential example is Conway's Game of Life from 1970, a cellular automaton that demonstrated how simple local rules can lead to emergent global behaviour. Although not a true ABM, it inspired further developments in the field. The segregation model developed by Thomas Schelling in 1971 is widely regarded as the first agent-based model in which autonomous agents interact within a spatial environment. With the growing computational power of the 1990s, ABM matured into a widely used method for studying complex systems in fields such as sociology, ecology, and economics.

At the end of the 20th century, the first ABMs in the field of the built environment were developed. Since then, the number of studies including ABMs in the field of the built environment has been growing, with around 60 studies per year published regarding ABM in this field of research in 2020 (Stieler et al., 2022). However, studies using ABM to simulate EER adoption of households have only become an emerging trend over the last 15 years. With the emerging interest in the reduction of greenhouse gas emissions through the improvement of the energy efficiency of buildings, the interest in models simulating the adoption of EER among households has grown. Through these models, policymakers can study which policies would work best in stimulating households to adopt an EER, and researchers can study emerging trends and behaviour of households. In 2010, a study by Faber, Valente, & Janssen (2010) first used ABM to simulate the adoption of a new energy-efficient technology. Since this initial study, ABM has been used more and more to study the EER adoption of households.

To gain a comprehensive insight into the current body of literature in this research field, a search for studies researching EER adoption through an ABM was conducted. Through the use of the keywords ("agent-based" OR "agent based" OR "agent-based model" OR "ABM") AND ("energy efficiency retrofit" OR "energy-efficient renovation" OR "EER") AND (adopt* OR diffus* OR uptake), a large number of studies were found. Through manual selection, the studies using ABM to study EER adoption of households were selected. 2 studies reviewing the current literature in this field of research were also found, which were scanned for further relevant studies. 14 of these studies were selected and read, all using ABM to simulate EER adoption.

A large range of different energy-efficient technologies has been implemented in these ABM studies. Some studies focus on the adoption of a single technology, like Faber et al. (2010) for

micro-CHP, Snape, Boait, & Rylatt (2015) for the heat pump or Friege (2016) for insulation. However, later studies often examine multiple energy-efficient technologies. This creates a more realistic simulation, since a household not only decides whether they will invest in an energy-efficient technology, but will also decide on which technology this will be. Some of these studies investigate a range of different technologies with the same function. For example, the research by Pavlović, Ivezić, & Živković (2022) and Sopha, Klöckner, & Hertwich (2013) both study the adoption of different heating systems, or Cao, Choi, & Zhao (2017) examine the adoption of different high-efficiency lighting technologies in the residential sector. However, most studies consider a broad set of different energy-efficient technologies. For example, Derkenbaeva et al. (2023) analyse the adoption of double glazing, insulation, heat pumps and solar panels in Amsterdam or Nava Guerrero, Korevaar, Hansen, & Lukszo (2019) who include different heating systems and insulation levels. The inclusion of these different types of technologies closely simulates the real decisions households face these days, where an increasing demand for energy-efficient homes has led to a surge of innovation and a steady increase in options to choose from.

2.3.2. Synthetic population design

Within the studied literature, a large difference in the population generation method used and the studied area is detected. Several studies focus on implementing a realistic decision-making theory for the agents, but put little effort into creating a realistic world and agents to make these decisions. Often, the data used is based on the demographics of an area. The studied area is split up into several areas with somewhat homogeneous demographics. These household demographics are then based on the area they are located in. This method, though it does not create a fully realistic model of the individual households, can help in understanding the effects of certain policies on different areas and is especially useful when a large study area is chosen, such as the Amsterdam region for Derkenbaeva et al. (2023). Other studies, like those from Cao et al. (2017) and Pavlović et al. (2022), try to create a more realistic representation of the studied area by conducting a survey among residents of the study area and creating households based on the answers from this survey. While this population generation method does create the most realistic representation of the real world, collecting data from each household in the studied area can be an incredibly time-consuming task. Other studies are less concerned with using empirical data and generate households semi-randomly, such as in Nava Guerrero et al. (2019). These studies have a less predictive nature and focus more on exploring theoretical scenarios or identifying general trends rather than creating insights that can be used for a specific area. Du, Han, & de Vries (2022) identified that a large number of studies regarding ABM for EER adoption lack the use of empirical data, stating that there is a clear need for the development and calibration of ABM based on substantial real-world data.

The type of agent used in ABM studies concerning EER rarely changes; most studies using only one and the same agent type, namely households. These households make decisions based on their own situation and the situation of households around them. In some studies, additional agents are added to the households to further influence the decision-making

process of the households, such as the research from Moglia, Podkalicka, & McGregor (2018), where sales agents and information agents are added, who respectively further push the sale of a certain technology to households or provide additional information regarding certain technologies to the households. Dello Russo, Hoffenson, Lytle, & Wu (2022) use an additional agent in the form of power plant companies that can opt to construct new power plants of a certain type to provide an energy supply according to demand. Most other studies, however, choose to represent outside influence implicitly, through different policies or a variable influencing the decision-making process of households. Nevertheless, both Dello Russo et al. (2022) and Moglia et al. (2018) indicate that the addition of different agent types in their model added value to the research.

2.3.3. Individual decision-making theories

Several methods are used to model the individual decision-making process, a popular theory being the Theory of Planned Behaviour (TPB) by Ajzen (1991). Several of the studied models have chosen to use TPB to model the decisions made by households, such as Sopha et al. (2013). Hesselink & Chappin (2019) also indicate this as a popular theory in ABM studying EER adoption. This theory models how individuals make decisions based on three key factors: their attitudes toward the behaviour, often parametrised as the expected comfort change or cost, the subjective norm, indicating the social pressure the agent experiences from other agents, and perceived behavioural control, which determines how easily the agent thinks executing a certain option would be. Combining these factors for a household partially shapes the behavioural intention of this household, which decides whether a certain behaviour is carried out. Policies or further information can be added to the model to further shape and influence this behavioural intention. TPB is a popular decision-making theory due to its structural clarity, which makes it relatively easy to implement into an ABM. Furthermore, the required variables can be gathered from households with relative ease through a survey.

Another commonly used theory is the Consumat theory by Jager (2000). This theory models decision-making by categorising individual behaviour into four strategies: Repetition, Deliberation, Imitation and Social comparison. The decision-making strategy a household chooses is based on its level of need satisfaction, quantifying how satisfied the agent is with the current or future situation, and the household's uncertainty regarding the decision that has to be made. A predetermined uncertainty threshold and a level of need satisfaction threshold determine in which quadrant the agent falls, where each quadrant represents one of the four strategies. Households in the repetition category will repeat previous behaviour. Those in the deliberation group will update their mental map by calculating the expected consequences of each opportunity. Those in the imitation category will look at the surrounding agents or those in their social network and choose the most popular decision from that network. Finally, an agent in the social comparison category will combine the strategies of the imitation and repetition categories, where the agent chooses the optimal option from previous experience and experience from its network. Some studies have altered the categories of individuals' behaviour, but a similar structure exists among studies using the Consumat theory. Several of the studies researched used the Consumat theory to shape the decisions made by

the households (Derkenbaeva et al., 2023; Maya Sopha, Klöckner, & Hertwich, 2011; Moglia et al., 2018).

A third decision-making theory, scarcely used as the sole determinant of a household's decision, is a discrete choice model. With this theory, each household determines the utility of the different decisions that can be made. The utility of each choice is quantified using a set of different variables, after which the agent's choice between the options is often probabilistic, where options with a higher utility have a higher chance of being selected (Du, Han, Sun, & de Vries, 2024). In other cases, such as with Meles & Ryan (2022), the agent chooses whether or not to choose an option based on an utility threshold. While this decision-making theory is relatively easy to implement in an ABM, its modelling possibilities are limited. When opting to include non-observable variables in the model, such as social interactions, using only a discrete choice model often does not suffice. In this case, combining another decision-making theory with the discrete choice model is a frequently used solution.

2.3.4. Policy simulation in ABMs

Among the studied models, different policies are used, testing their influence on the decisions made by the population. These policies are implemented in the models by changing a certain variable or set of variables used in the decision-making process. Most studies incorporate some form of financial policy in their model, differing between subsidies and other financial incentives, reduced energy prices or the availability of loans. These policies lower the financial threshold of households, thus enabling more households to adopt the EER. In the policy document from the Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2022), in which the planned changes to the Dutch building sector are proposed, which will ensure the 60% greenhouse gas reductions in 2030 are met, most policies are also in this category. Increased subsidies, 0% interest loans and tax changes are some of the policies aiming to reduce the financial burden of EERs for households. Other policies in the studied literature try to raise the household's knowledge or reduce its uncertainty through information campaigns, audits or coaching sessions. The increased awareness or reduced uncertainty of these policies helps households decide, as promoted in the information spreading policy. These policies are also often seen in the proposed policies from the Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2022), which proposes a national information platform where homeowners can find all the required information in one place, as well as other policies aiming to increase awareness and knowledge regarding EER for households. A third policy category, which is seen in both the studied literature and the document of the Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2022), concerns existing regulations. Several of these policies try to increase a household's willingness to renovate by reducing the hassle they have to go through when opting for an EER. Some policies alter the norms and standards, thus making it easier or cheaper to implement an EER; others look at ways to reduce the work and time needed to adopt an EER by lowering the time needed to apply for an EER. Alongside these 'pull' instruments, several 'push' instruments are also deployed through these policies. Both in the models and in the Ministry's documentation, new norms or standards making certain measures obligatory or banning other, non-sustainable, measures are proposed or used. Other

policies in the literature or the document from the Ministry aim to increase access to certain sustainable measures, increase the quantity of or innovation in companies installing or selling EERs or increase the subjective norm of EER.

2.4. Agent-Based Modelling of Collective Decision-Making Processes

The field of research for this thesis, ABMs modelling the collective decision-making of EER-related decisions, is scarcely studied. Few models are found that attempt to model these decisions (Derkenbaeva et al., 2023; Nava-Guerrero et al., 2021). From these, the study of Nava-Guerrero et al. (2021) includes collective decision-making as an integral part of the model. In this study, the group decision-making process of VvEs regarding the heat transition through an ABM is modelled. In this model, individual households located in a neighbourhood with several VvEs first calculate the lifetime costs of different combinations of energy-efficiency improving measures, preferring the combination with the lowest lifetime cost. Options requiring approval of the VvE, such as a heat pump, or requiring approval of the neighbourhood, such as a district heating network, first require that a sufficient number of agents in the VvE or the neighbourhood also prefer this option. A VvE quorum and a neighbourhood quorum determine the threshold these voting sessions have to pass for the measure to be adopted. If the quorums are passed, at the next time step, the households in the area adopt the measure. One time step in the model by Nava-Guerrero et al. (2021) equals one year. If the quorum is not passed, however, the households only adopt their preferred EER, which does not need to pass a group decision. Though this model has several similarities with the ABM proposed for this thesis, it also has several shortcomings, as also indicated by the authors. Being the first ABM attempting to model group decisions regarding EER, the authors aimed at creating an explorative model, paving the way for future quantitative models. The data used is not empirical, and the individual decision-making process of agents is simplified, lacking factors such as the decreased efficiency of heating systems or relevant transaction costs. Furthermore, the group decision-making process is very simplified, lacking any form of external or social influence on the group decision-making process. Agents neither deliberate with one another nor consider others' decisions. Furthermore, the heterogeneity of the quorums used among the different VvEs is also a simplification of reality.

The study by Derkenbaeva et al. (2023) includes group decision-making similarly into their model, where it is an option which can be enabled or disabled. This option allows households in apartment buildings to choose the option of installing PV panels, which is only executed if the number of households in the building individually deciding on this option exceeds the quorum set in the model. Thus, while both studies attempt to include these group decisions in their model, both include them in a simplified manner, which does not reflect how these decisions are made in the real world.

While ABMs concerning group decision-making of EER adoption are scarce, the mechanisms behind these group decision-making processes have been studied in great detail. By elaborating on these theories in the following paragraphs, the implementation of a realistic group decision-making process in an ABM can be achieved. First, the theories behind social

network structures will be studied, after which the theories behind social influence dynamics will be elaborated.

2.4.1. Social network structures

Social networks are an essential component of many ABMs. Often, a social network structure is included in the model to broaden the information availability of an agent. Based on this information, an agent may choose or reject a certain option based on the experience of other agents in its social network with that option. In ABMs that use the Consumat theory as the basis of their individual decision-making process, a social network is essential. To enable an agent to choose the imitation or social comparison option proposed in the Consumat theory, the agent should be part of a social network. Some models, like the one from Du et al. (2024), use the social network structure more extensively to determine the agent's decision-making process. Here, agents also interact within their social network to convince each other of their economic attitudes, which in turn will help in determining which decision they will make. In this model, the size of an agent's network determines how likely that agent is to convince another agent of their beliefs.

To realistically model a social network in an ABM, a social network theory should be followed. A large range of social network theories exists, each trying to determine what shapes a social network in its own way. Below, some of the regularly used theories in ABM are briefly elaborated. For this, the overview of social network theories given by Gamper (2022) is used.

A first and often used social network theory centres around the concept of homophily. This concept states that individuals with similar traits will form social networks together. These traits can be socio-demographic traits such as age, income, occupation or education, but other characteristics, such as beliefs or attitudes, may also group certain individuals. Gamper (2022) states that homophily can influence social network creation in two ways: Individuals simply select other individuals who are similar to them, or individuals influence others in their social group with different traits and make them more similar to them. One may, for example, over time convince others in their social group of their beliefs or make them adapt certain behaviour.

Another concept related to social network theory is the concept of preferential attachment. Preferential attachment relates to the idea that those who already have a large number of social connections find it easier to gain new connections compared to those with a low number of social connections. Individuals seeking new social connections will be more likely to make this connection with someone who seems popular, and those who already have a large social network will be more likely to find new connections through this network than those with a small social network. Gamper (2022) further indicates that certain traits of individuals will make them more popular and thus increase their social network size. Intelligent, rich and extroverted individuals may, for example, find it easier to create new connections compared to individuals without these traits.

A third concept in the field of social network theories is the concept of small-world networks (Watts & Strogatz, 1998). This type of network has groups with a high rate of connections

between a small number of individuals. However, some individuals in these groups have connections to members of another social group which otherwise is not directly connected to the group. With these so-called long-range connections, the number of steps needed to connect any individual to any other individual is drastically reduced. Figure 1 contrasts a regular network, a random network and a small-world network. In the regular network model, each node is only connected to the closest nodes, while in the random model, nodes are connected at random to other nodes. The small-world network model falls in between these two models, where most nodes are connected to their neighbouring nodes, with some random long-range connections between the nodes.

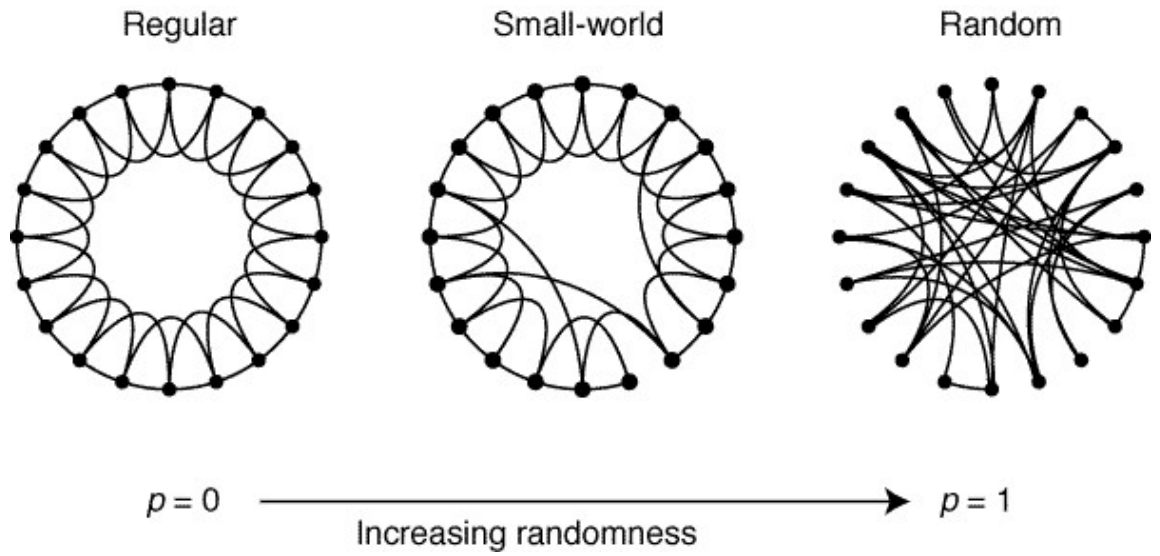

Figure 1: Different types of networks (Watts & Strogatz, 1998)

Gamper (2022) describes a theory closely related to the small-world networks, namely the theory of structural holes. Structural holes are missing links that would connect two social groups. Individuals who fill these holes by creating this connection will thus connect these social groups, and with it, they will be the gateway of information and resource transfer between these two groups. With this, they have a strong position, enabling them to decide which information and resources are passed on to the other group and how this is transferred. By filling these structural holes, the individual creates long-range connections typical of Small-world networks.

A final theory that will be highlighted here is the clique theory. Gamper (2022) describes a clique as "an aggregation of actors in a large network." Cliques are highly connected social groups, where individuals are directly connected to each other. They often are characterised by a high level of activity and solidarity. This high level of activity will ensure that individuals in these cliques share information and resources among each other before it is shared with members of the larger social group they are part of. This will thus result in an uneven distribution of information and resources among the members of the social group.

2.4.2. Social influence dynamics

Through social networks, agents can exercise influence over other agents in their network. This can be done directly by discussing with these agents or indirectly through social proof and normative pressure. A large number of different opinion dynamics theories exist, differing in use case, observed behaviour and possible opinion states. In this section, several theories are outlined that could apply to the use case of this thesis. However, first, the possible observed behaviour types and opinion states are explained.

According to Flache et al. (2017), three types of behaviour are observed in social influence theories: Consensus formation, where the opinion of all agents grows towards an in-between consensual opinion, Clustering, where groups of agents cluster around differing opinions, and Bi-polarisation, where agents grow towards either of two opposing opinions. A depiction of these types of opinion dynamics can be seen in Figure 2. Some opinion dynamics will always show one of these behaviour modes, while others can show differing behaviours based on the input parameters. In their study, Kleerekoper, Coates, & Han (2018) differentiate between the 2 types of opinion states used in the different opinion dynamics theories. They distinguish between discrete models, which enable agents to hold one of a finite set of opinions, and continuous models, which allow agents to hold any value along a continuum. In this section, a selection of the available social influence dynamics theories is made, differing in their observed behaviour and possible states.

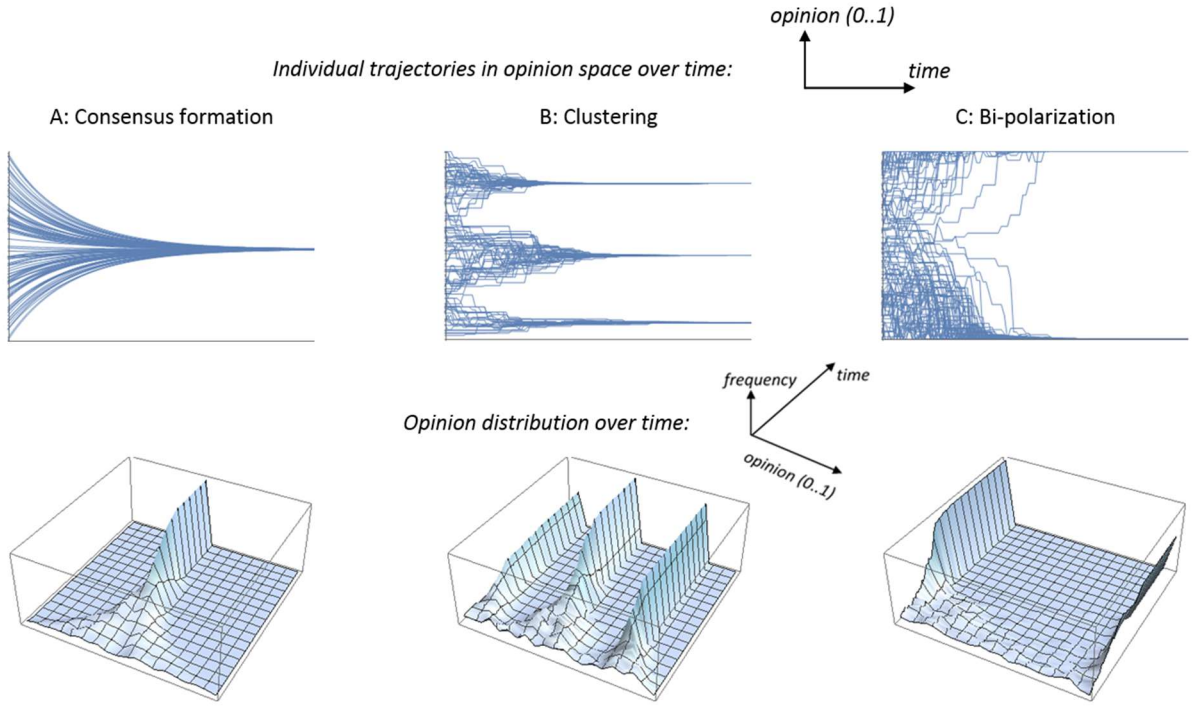

Figure 2: Types of opinion dynamics generated by Agent-Based Models (Flache et al., 2017)

The theory of Bounded Confidence (Weisbuch, Deffuant, Amblard, & Nadal, 2003) is a continuous model with which clustering and consensus formation are observed. Agents pair up in couples and discuss their opinions with each other. The difference between the opinions of the agents determines if they keep their opinion as it is, or change their opinion towards the opinion of the other agent. A threshold is set, and when the difference between the opinions of the agents is lower than this threshold, their opinions move towards each other.

The value of this threshold determines whether the model will show the formation of clustering or a consensus opinion.

A model similar to the Bounded Confidence model is the Relative Agreement model (Deffuant, Amblard, Weisbuch, & Faure, 2002). This is also a continuous model, showing clustering, consensus and bipolarization behaviour. Similar to the Bounded Confidence theory, agents pair up to discuss their opinions with each other. Here, however, each agent also has an uncertainty regarding their opinion, indicating how uncertain they are of their opinion. The agent with the highest uncertainty will be persuaded by the opinion of the other agent. The more uncertain agent's opinion is moved towards the opinion of the more confident agent based on the opinion overlap of the two agents. Thus, if their opinions are quite similar, the opinion will change less than if their opinions differ greatly.

The Voter model (Clifford & Sudbury, 1973; Holley & Liggett, 1975) is a relatively basic discrete choice model which can show consensus and clustering behaviour. At each time step, an agent randomly selects a neighbouring agent and copies the opinion of that neighbour. After several time steps, patches appear of like-minded agents, which often grow out to a population of like-minded agents over time. This theory captures low-effort social imitation, where agents align with whoever they last interacted with, with no further argumentation occurring between the agents.

Another discrete choice model is the Sznajd model by Sznajd-Weron & Sznajd (2001), which models fast local consensus formation within populations. In this model, 2 neighbours are selected and their opinions are compared. If they share the same opinion, all other neighbouring agents change their opinion to this opinion. If their opinions differ, nothing else happens. The basis of this theory is the persuasive power of groups, where individuals will change their opinion if a large group has a differing opinion.

A final social influence dynamics theory discussed here is the Social Impact Theory (Nowak, Szamrej, & Latané, 1990), which is a continuous model showing consensus and clustering formation. In this theory, an influenced agent is impacted by the sum of the social impacts of their neighbours. For each neighbour, their impact is calculated based on their level of persuasiveness, based on factors such as status or credibility, their immediacy, which represents the closeness of the relationship between the agents, and the opinion of the influencing agent. The influenced agent's opinion is then changed based on the resulting positive and negative social impact of the surrounding agents. Through the persuasiveness level, the leading role of certain board members or experts in the field can be modelled, who often grow a local and growing area of consensus around them.

2.5. Research gaps and modelling choices

Concluding this literature review, the gaps observed in the studied literature are summarised, highlighting the different directions this thesis could take by tackling one or multiple of these gaps. Furthermore, modelling choices made for this thesis's model are explained based on the literature studied.

Research gaps

Based on the reviewed literature, a clear gap exists in the modelling of VvE decision-making processes. Such models are scarce, while those that do try to simulate this process use simplified, homogeneous regulatory mechanisms. Furthermore, the lack of empirical data usage for the 2 studies found modelling VvE decision-making processes (Derkenbaeva et al., 2023; Nava-Guerrero et al., 2021) means both studies are only suited for explorative research.

The model of this thesis will attempt to address this gap by creating an empirically based ABM simulating collective decision-making processes of VvEs adopting EER. In the literature review, several barriers were found to be faced by VvEs in this decision-making process. Many barriers experienced by VvEs are related to the cost of the EER. High implementation costs of the EER, large income differences between households of the building, high interest rates on loans and a small portion of the renovation being subsidised are discussed as potential dealbreakers for VvEs willing to adopt an EER. Other experienced issues are related to the regulations, both of the voting process of VvEs, as well as during the preparation and implementation of the EER. The high minimum attendance and voting quorum set by the government lead to prolonged voting processes, and when the VvE has agreed, applying for a loan from the Warmtefonds becomes an intricate and time-intensive task. Further barriers often occur through the social interactions between agents, where inequality of the perceived benefits can lead to conflicts within the VvE, further slowing down the process. The model of this research will include several of these barriers when simulating the decision-making process of VvEs. A central part of the model will focus on the financial situation of individual households, including a possibility for loan and subsidy application by the VvE. The application process of the loan and subsidy is, however, not included in any way in this model to reduce the model's complexity. The attendance and voting quorum of a VvE is included and can differ among the VvEs based on the levels gathered during the case study. Another central part of the model will be the social influence of agents on each other, both passive and active. However, conflicts between members of the VvE will not be included implicitly in the model. This model tries to include the basics of social influence dynamics in VvEs, reducing the overall complexity of the model.

Beyond these main gaps, current ABMs on EER adoption among individual households also highlighted some gaps which could be further addressed. Where most studies only use the household as an agent, the scarce studies including other agents in their model perceived this as adding value to the model and its capabilities. In the context of a VvE, a logical added agent would be a board member or a VvE manager. Through the social influence of these agents, the role of leading agents during the collective decision-making process could be studied. However, in this model, no further agents than the household are added. Even though this would have likely proved valuable to study the decision-making process of VvEs, the scope of the model had to be limited due to the time constraint of this research. The identified research gap and whether they are addressed in this thesis can be seen in Table 2.

Table 2: Research gaps found in the literature review

Gap identified	*Addressed in thesis*
Lack of ABMs simulating collective VvE decision-making	Yes
Absence of empirically grounded models capturing VvE decision-making	Yes
Limited incorporation of social influence mechanisms among VvE members in decision processes	Yes
Neglect of conflict dynamics and unequal benefit perceptions within VvEs	No
Missing representation of board members or managers as distinct agent types influencing VvE decision-making	No

Modelling choices

The literature studied in this literature review suggests that ABM is the most suitable approach to study collective EER decision-making in VvEs. It handles heterogeneous households, explicit interactions, and temporal dynamics and allows for the testing of policy scenarios. Alternative approaches, such as EGT and DES, can capture parts of the decision-making process, but are unable to model all that is required of the model. This aligns with the existing models studying collective decision-making regarding EER adoption, both of which choose the use of an ABM.

For individual decision-making, the Consumat framework is chosen for two reasons. First, it explicitly links uncertainty and need satisfaction between deliberation, imitation, repetition and social comparison. These different opinion-forming strategies match the variability of the members in a VvE, where some members only listen to their own opinion and situation, while others tend to look more outward to also include the opinions and situation of their neighbours in their decision. The second reason, which simultaneously also partially explains the choice of the Relative Agreement theory as the social influence dynamics theory used in the model, is the central usage of the uncertainty variable in the theory. Members of VvEs are regularly unsure whether the proposed EER will benefit them or not, in some cases opting to leave the choice to the other members of the VvE. In conversations with VvEs and experts in the field, which will be discussed in more detail in chapter 4, this low interest in the proposed EER and the low attendance rate at voting sessions are seen by many as the main issue slowing down the decision-making process. Therefore, the central use of uncertainty in both the individual decision-making mechanism as well as the social influence dynamics ensures that the importance of the uncertainty is reflected in the model. Furthermore, the number of parameters and complexity of the model are reduced by reusing certain parameters for different parts of the model.

A second reason to choose the Relative Agreement theory to map the social influence dynamics in the model is the fact that this theory, as well as some of the others discussed, allows the mapping of a continuous opinion of the agents. In VvEs deciding on EER adoption, often several of the members are seen as extremists, being either fully supportive of the proposal or fully against it. However, most of the members will fall somewhere in between. Thus, mapping a continuous opinion of these agents will best reflect the real situation.

The social network structure of the model will most likely closely represent a small-world network, where neighbours tend to converse most with each other simply through the high frequency of encounters they will have when living next to each other. Some agents will have connections with non-neighbouring members, for example, caused by a shared interest or hobby. Furthermore, the board members of the VvE will likely also experience strong connections with each other, and other members might also have a connection with these board members. This thesis will perform a case study of 2 VvEs and conduct a survey with the households of these VvEs, the collected data of which will help in further defining the social network structure of these VvEs.

Despite growing ABM literature on household EER adoption, collective decision-making within VvEs adopting EER remains largely unexplored. The few ABMs that include this group decision-making process do so in a highly simplified manner, using homogeneous quorums and omitting any external or social influences on the collective decision made. The overarching gap is the absence of a theory-grounded, empirically informed ABM treating collective decision-making in VvEs as a process in which, among others, social influence shapes household opinions which are aggregated under realistic VvE rules. This thesis will fill this gap by including the modelling choices as explained previously in an ABM, and testing this model on gathered data from several case-studied VvEs.

3. Methodology

In this chapter, the Agent-Based Model is documented using the ODD+D protocol (Müller et al., 2013), an extension on the ODD protocol (Grimm et al., 2006, 2010) by explicitly treating human decision-making in the model. The ODD protocol is a framework designed to standardise the documentation of ABMs. Next to the focus on human decision-making, the ODD+D protocol (Müller et al., 2013) adds subsections and guiding questions to the ODD protocol. The structure of the ODD+D protocol is followed, starting with an overview of the model by explaining the model's purpose, entities and process schedule, after which different design concepts of the model, such as the mechanisms driving the model and the theoretical assumptions, are discussed. In the final section, the details of the model, the initialisation details and input data are stated.

3.1. Overview

3.1.1. Purpose

The purpose of this model is to answer the 2nd and 3rd sub-questions of this thesis:

To what extent do socio-demographic, financial, regulatory, social and building-specific factors affect the process and outcome of decision-making processes in VvEs?

Which policies or strategies could contribute to overcoming collective decision-making deadlocks and accelerating energy-efficient retrofitting agreements within VvEs?

The model thus has two objectives. Firstly, the model quantifies how different household characteristics, social dynamics and institutional rules shape the likelihood of EER adoption of the VvE. By including these different factors when simulating realistic voting rounds, passive and active social influence and individual decision formation, the model can discover the impact of these factors. These insights can help VvEs to anticipate critical barriers and perform a more effective decision-making process.

Secondly, the model tests the effectiveness of different policy interventions and governance strategies. By simulating financial, informational and regulatory interventions, the model provides a controlled environment which can be used to test and compare the impacts of these interventions. This can support VvE boards and policymakers by identifying strategies which are most likely to accelerate EER adoption among VvEs.

3.1.2. Entities, state variables and scales

This model includes three core entities: household agents, a VvE entity and the environment. These components jointly represent the individual decision-makers, the institutional constraints which they have to follow and the physical context of the building and the policies applied to the region it is located in. These different entity types and the main variables falling under these entities are shown in Table 3. This information is discussed in more detail below the table.

Table 3: Model entities and main variables

Entity	*Variables*
Household	Finances willing to invest - Initial opinion - Knowledge level - Preference weights - Close connections trust levels - Sensitivity to choice of others
VvE	Attendance quorum - Voting quorum - VvE members - EER cost - EER energy savings - EER comfort improvement - Month and Voting round counter
Environment	Loan interest rate - Loan share - Loan duration - Subsidy amount - Energy price and CO_2 production per kWh – Maximum model duration -Phase duration

Household agents represent individual VvE members deciding to oppose or support the adoption of an EER by the VvE. They are heterogeneous and characterised by their available finances, their comfort level, their level of CO_2 production and how important they perceive these three factors. With these factors, the current Level of Need Satisfaction of each household can be calculated. Furthermore, a knowledge level together with the household's sensitivity to the choices of other agents determines their Uncertainty. Together, the Level of Need Satisfaction and the Uncertainty determine which decision-making strategy the household uses, in turn determining how their opinion is determined. The social network of the household partially determines which households the household discusses with, through which the agents adapt their opinions based on each other.

The VvE entity then determines which regulations are followed during the voting process of the VvE. This includes the attendance quorum and the voting quorum. Furthermore, the VvE entity contributes to the available finances of the households through the VvE savings account. The VvE entity also stores how many and which households belong to the VvE. Finally, the VvE entity also contains information regarding the proposed EER, such as the expected energy savings and cost of this EER. Through this, the households can determine their future Level of Need Satisfaction, adding or subtracting these values from their initial values.

Finally, the environment entity stores information used equally by all VvEs in the model. These are factors like the available national subsidies, the loan duration and the interest rate of said loan. Other parameters of this entity, referred to as model parameters later in this chapter, include, among others, the gas and electricity prices and CO_2 production ratios and the factors determining the number of voting and discussion rounds, and the duration of these rounds in months. Furthermore, another factor determines the maximum number of months the model runs before it is stopped.

3.1.3. Process overview and scheduling

One time-step in the model represents one complete decision round: an individual decision-making phase, followed by a discussion phase, and then a collective decision-making phase. In the first phase, each household simultaneously determines its initial opinion. This is done by looking at their comfort level, available finances and CO_2 emissions from their energy usage, which together determine the Level of Need Satisfaction. On the other hand, the household's

Uncertainty is calculated by looking at their knowledge level and how much their opinion differs from the opinions of others. Through the values of these two variables, each household chooses a decision-making strategy, which in turn determines how its initial opinion is calculated. With this opinion and the uncertainty, each household goes into the discussion phase, forming pairs with other agents and adapting the opinion based on the opinions and

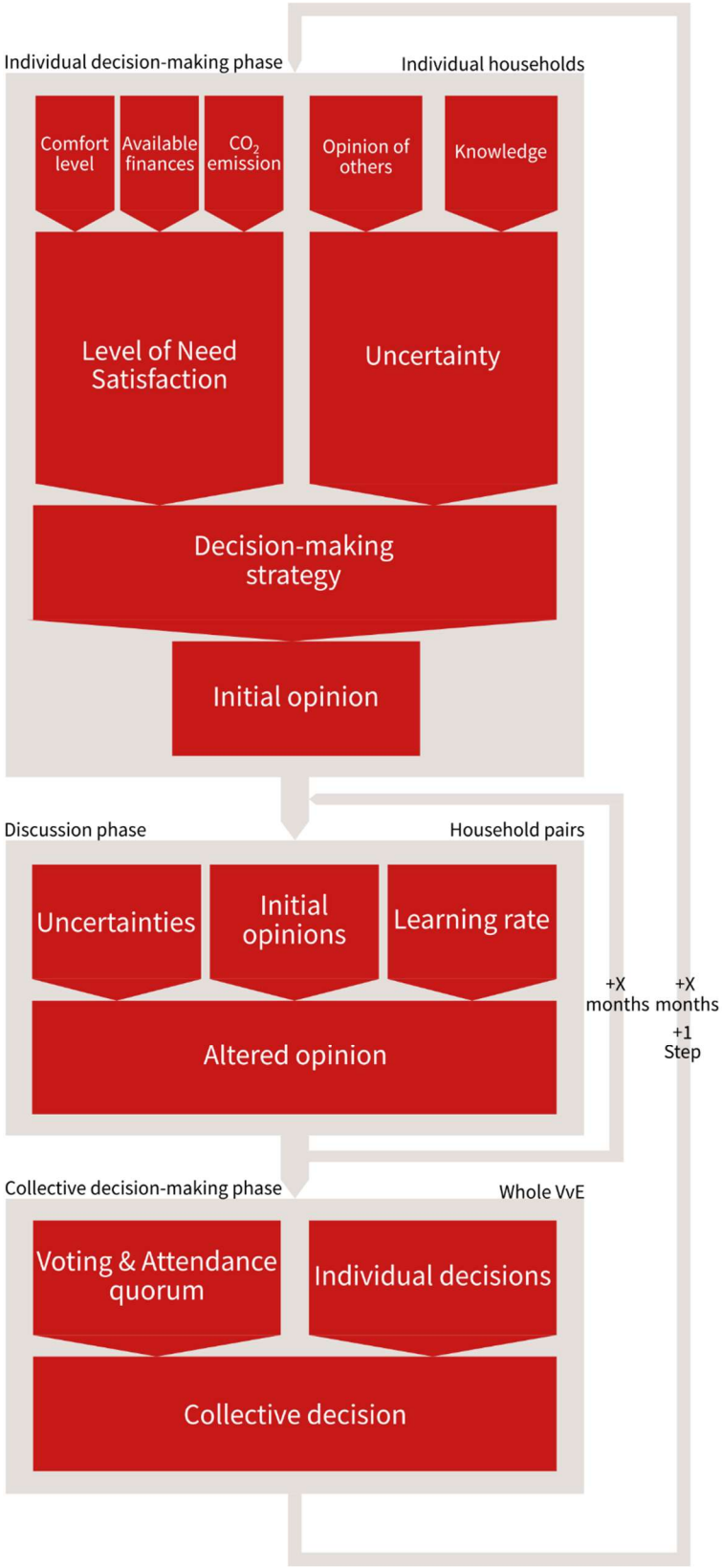

Figure 3: Process overview of the ABM

uncertainties of the paired agents. Several discussion rounds are held with all the agents still willing to discuss, each round increasing the number of months elapsed. After the agents have stopped discussing, their altered opinion determines their individual decision in the collective phase, in which, based on the voting and attendance quorum of the VvE, the VvE's decision and the number of months it took to reach this decision are calculated.

The model process repeats itself after the collective decision phase if two conditions are met: the month counter of the model is below the maximum number of months set in the model parameters, and the number of voting rounds with a positive outcome is below the number of positive voting rounds determined in the model parameters. If the maximum number of months has been reached and the required number of positive voting rounds is not obtained, the VvE's final decision will be to not implement the EER, while if the number of positive voting rounds required is reached, the VvE's final decision will be to implement the EER.

3.2. Design concepts

3.2.1. Behavioural foundations

The main theory underlying the model is the Consumat theory by Jager, Janssen, & Vlek (1999). The individual decision-making phase of households is based on this theory, allowing agents to choose between different decision-making strategies and determining their opinion based on the chosen strategy. Following the implementation of this theory in the first model phase, several discussion rounds following the relative agreement model (Deffuant et al., 2002) transform the initial opinion of a household into a final opinion. Nearly all the values for variables used when implementing these theories in this model differ between the households, thus creating highly heterogeneous agents. This data is determined through data collection procedures of case-studied VvEs, where nearly all variables used are defined for each individual household based on a list of questions. This is discussed in more detail in the Data Collection chapter. Through this heterogeneity, each household's behaviour can differ from the behaviour of other households based on their specific input variables, thus allowing the study of different combinations of variable values and how these impact the agent's behaviour. This heterogeneity ensures a realistic decision-making process, but also increases the level of detail required during the collection of the data. In this paragraph, the implementation of the Consumat theory and the Relative agreement model in this ABM are discussed, and the variables creating these heterogeneous agents are discussed. In Appendix 1, the system architecture of the different parts of the ABM is shown, providing a clear and detailed overview of the model's workings.

Drivers and barriers of households

To form an initial opinion regarding the EER, each agent categorises the advantages and drawbacks of the proposed EER in three elements: the comfort of the EER, the financial aspects of the EER and the environmental impact of the EER. Two of these three categories, finances and environmental awareness, are often used as the main driving categories for sustainable

renovation (Kamari, Corrao, & Kirkegaard, 2017; Nava Guerrero, Korevaar, Hansen, & Lukszo, 2019). The third category in this model, comfort, is used as the third state variable here, since this is for many one of the main reasons to go for an EER. Each agent might perceive the importance of the economic, environmental and comfort aspects of the EER differently. Therefore, each agent (i) has a preference value for comfort level (P_i^c), financial safety (P_i^f) and environmental concern (P_i^e), indicating their respective importances. These factors, just as nearly all factors in this model, can have any value between 0 and 1, where 0 indicates that this category is perceived as very unimportant by this household, and 1 indicates large importance for this household. The sum of these three values will always add up to a total of 1, ensuring that each household has the same total importance multiplier.

Next to a preference for these three categories, each agent also has a current state of these three categories. This is the state of that household before the implementation of the EER. The current state of the comfort level (C_i^c) indicates how comfortable the house of that household is during the year, averaging the comfort level of the summer and winter months. Here, a 0 indicates a highly uncomfortable home, while a 1 is a very comfortable home.

The current available finances (C_i^f) of each household is calculated using several different variables, both agent variables as well as variables from the VvE. Firstly, the money a household is willing to invest in this EER is combined with the part of the VvE's savings account that the VvE is willing to invest in the EER. This second variable is first divided by the total members of the VvE to create a household-specific number. Even though both these variables are predetermined, they will change over time as the model progresses. In the model, the time progression is stored in the number of months that have elapsed. For each elapsed month, the VvE savings are increased by the monthly VvE contribution of all members, and each household's amount they are willing to invest is increased by a portion of their monthly income they are willing to set aside for EER investments. Furthermore, the model includes settings to enable the use of a loan or a grant per household. The grant is simply added to the household's available finances. The loan increases the available finances by converting the total loan into a partial upfront payment, where a percentage of the EER cost can be financed externally. The remaining percentage, not covered by the loan, is paid by a down payment covered by the available finances. The repayment obligation is reflected through a loan penalty, which slightly reduces the household's effective post-EER finances. This captures the trade-off between immediate affordability and long-term financial burden when financing energy-efficiency renovations through loans.

The factor determining the current state of the CO_2 production (C_i^e) of a household is based on the yearly electricity and gas usage of a household and a multiplication factor which converts this to kilograms of CO_2 per year. This multiplication factor will be standardised over all households among all VvEs, equalling the average Dutch conversion factor from electricity and gas to CO_2.

By adding or subtracting the change the implementation of an EER will bring to the comfort, finances and CO_2 production of a household from their respective current state values, the final state of each household can be calculated. These change values are VvE entity parameters

that are established beforehand per VvE.. The comfort change (E_i^c) is the increased comfort experienced in homes after implementation of the EER. The cost (E_i^f) is the result of the installation cost per household minus the yearly savings on energy costs resulting from the implementation of this EER, and potentially an extra penalty caused by the loan repayment. For this, a time horizon is used, indicating over how many years these savings and repayments are calculated. Finally, the CO_2 change (E_i^e) is calculated by multiplying the gas and electricity savings this EER will, on average, bring for a household by the multiplication factor discussed above. These new numbers represent the post-EER situation of a household regarding their comfort level, finances and CO_2 production. The financial and CO_2 situations are both still in real numbers, in € or in kg CO_2, but both have to be recoded to a value between 0 and 1. They are divided by normalisation factors, which are set so that a household with a financial situation or CO_2 production equal to an average Dutch household will get a value of 0.5 for these values. This is discussed in more detail at the end of Chapter 4.

Level of Need Satisfaction and Uncertainty

With these factors calculated, the Level of Need Satisfaction (LNS) can be calculated for each household. For each household, the current Level of Need Satisfaction ($LNS_i^{current}$) and the post-EER Level of Need Satisfaction (LNS_i^{EER}) are calculated. Equations 1 and 2 show how these values are calculated by multiplying the preference values by the respective state variables, after which the 3 values are combined into one LNS value.

$$eq.1: LNS_i^{current} = P_i^c \times C_i^c + P_i^e \times (1 - C_i^e) + P_i^f \times C_i^f$$

$$eq.2: LNS_i^{EER} = P_i^c \times (C_i^c + E_i^c) + P_i^e \times (1 - (C_i^e - E_i^e)) + P_i^f \times (C_i^f - E_i^f)$$

Next to the LNS value, the Consumat theory also uses an Uncertainty value (UNC) to determine the decision-making strategy of a household. The Uncertainty of an agent is determined partly through their knowledge level (K_i), which is the average of occupational knowledge and previous EER experience of the household and the received and looked-up information regarding the planned EER. This knowledge variable is an essential part of many ABMs regarding EER (Derkenbaeva et al., 2023; Du et al., 2024; Stavrakas, Papadelis, & Flamos, 2019) and thus also included here as a central variable. In this model, a high knowledge level, being closer to 1, will result in a lower uncertainty of the agent. The second part of the household's Uncertainty is determined by the difference between their opinion (D_i^{prev}) and the average opinion of the VvE ($\overline{D_n^{prev}}$) The absolute difference between this average opinion and the agent's opinion of the previous round is multiplied by a sensitivity factor (S_i), indicating how sensitive the agent is to the choice of others, determined for each individual agent. A similar mechanism is used in many ABMs on EER, often called the neighbourhood effect (Derkenbaeva et al., 2023; Nava Guerrero et al., 2019; Pavlović et al., 2022). Through this effect, households whose opinion differs more from the general opinion in the VvE will become more uncertain regarding the truth of their beliefs. Equation 3 shows how the Uncertainty is calculated, which is loosely based on the model implementation by Van Oel, Mulatu, Odongo, Willy, & Van der Veen (2019).

$$eq.3: UNC_i = (1 - K_i) \times \left(\left|\overline{D_n^{prev}} - D_i^{prev}\right| \times S_i\right)$$

Consumat implementation

After the uncertainty and LNS values are calculated, the decision-making strategy of the agent can be determined. The range of possible UNC_i and $LNS_i^{current}$ values are split into 4 quadrants using the LNS^{min} and UNC^{max} values set as model parameters, with each quadrant representing a decision-making strategy. When an agent's UNC_i is below the UNC^{max} threshold, this agent will be relatively uncertain of their own knowledge regarding the EER. This agent will then choose a strategy which looks at the situation or opinion of other agents to fill their own knowledge gap and thus still make a somewhat informed decision. They will thus choose either the Inquiring or the Imitation strategy. On the other hand, if their uncertainty is above the threshold, they will be certain of their own knowledge and either choose the Optimisation or Repetition strategy, and thus only look at their own situation or opinion. A similar system is used for the LNS^{min} threshold. If the $LNS_i^{current}$ of the agent is below this threshold, their current Level of Need Satisfaction is relatively low. They will actively seek to improve their situation either by going for the Optimisation or Inquiring strategy. If their current Level of Need Satisfaction is already higher than the threshold, they are already content with their situation and will choose either the Repetition or Imitation strategy.

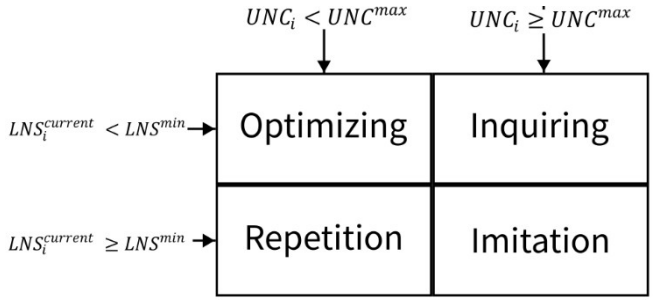

Figure 4: Strategy choice matrix

After this strategy has been chosen based on these values, the Opinion of the agent (O_i) can be formed. The formulas (Equation 4) for this are different for each strategy. An agent who is using the Optimising strategy will look only at their own current and possible future Level of Need satisfaction. The opinion of this agent is calculated by calculating the ratio between the agent's potential new and current Level of Need Satisfaction. This ratio is then put into the sigmoid function (Equation 5).

$$eq.4: O_i = \begin{cases} \sigma\left(\dfrac{LNS_i^{EER}}{LNS_i^{current}}\right), & if\ Optimising \\ O_i^{prev}, & if\ Repetition \\ (1 - S_i) \times LNS_i^{EER} + S_i \times \overline{LNS_n^{EER}}, & if\ Inquiring \\ \overline{O_n^{prev}}, & if\ Imitation \end{cases}$$

$$eq.5: \sigma = 1 - (1 + e^{(-3*(X-1.15))})$$

The resulting graph of the sigmoid function can be seen in Figure 5. If an agent will have a significant improvement in its situation, at least 1.15 times better than the old situation, the opinion will be 0.5 or higher, and a positive vote will be given. An agent which uses the Repetition strategy simply repeats the opinion it had at the previous voting session. If this is the first voting session, an initial opinion will be used, which is gathered for each agent in the questionnaire. If the agent uses the Inquiring strategy, this agent will look at the new Level of Need Satisfaction the EER will bring them, and ask around their close connections for their values. How much they look at the situation of their peers is based on how sensitive they are to the choices of others (S_i). Finally, an agent using the Imitation strategy will simply imitate the opinion of the other VvE members. For this, the opinion of the previous voting session is used, where, just as with the Repetition strategy, in the first round, the initial given opinion of these agents is used. Each of these formulas in Equation 4 calculates the opinion of the household, where a 0 indicates a fully negative opinion regarding the EER, and a 1 indicates a fully positive opinion regarding the EER.

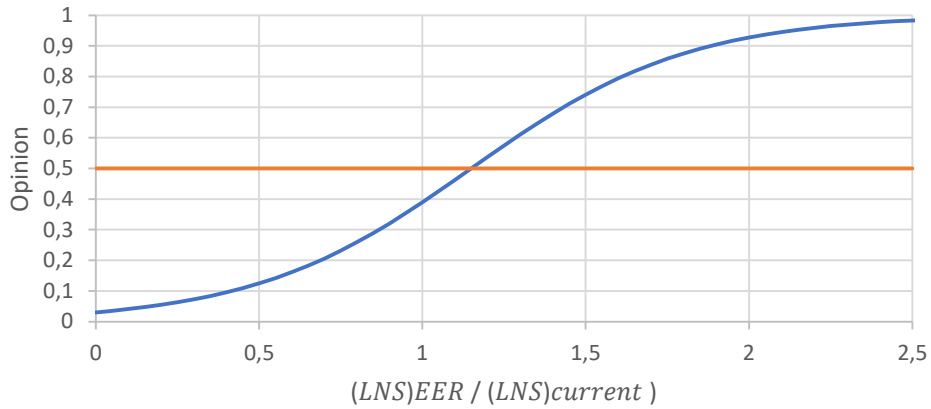

Figure 5: Results of Sigmoid function for Optimizing strategy

Relative Agreement implementation

Before the agents go into the second model phase, where they discuss with other agents, the interest of each agent is determined. Since the literature review showed that a low interest and attendance rate are barriers often experienced by VvEs, the interest and attendance are also included in this model. When the Uncertainty level of an agent is above a certain threshold level, the agent will become uninterested in the EER and will not be included in the other mechanisms of this step in the model.

All interested agents then go into the discussion phase, from which the individual behavioural mechanisms and formulas used are discussed here, while the social interaction mechanisms are elaborated in 3.2.2.

In the discussion phase, several discussion rounds are held where agents pair up with other agents to discuss the proposed EER. These agents discuss with each other based on the relative agreement model (Deffuant et al., 2002), where the opinion update formula stated in Equation 6 is used.

$$eq.6: O_i^{new} = O_i + \mu_{ij}\left(\frac{O_{ij}}{UNC_j} - 1\right) \times (O_j - O_i)$$

This equation used the Uncertainty (UNC) and opinions (O) of the two agents i and j to determine which direction the opinion of agent i changes to and by how much this opinion changes. Two other factors used in this formula are the Opinion overlap (O_{ij}) determined through the formula in Equation 7, and the learning rate μ_{ij} stated in Equation 8.

$$eq.7: O_{ij} = \min(O_i + UNC_i,\ O_j + UNC_j) - \max(O_i - UNC_i,\ O_j - UNC_j)$$

$$eq.8: \mu_{ij} = \mu_0 \times T_{ij} \times S_i \times \alpha_s$$

The opinion overlap indicates the overlap of the opinion and uncertainty of the two agents, determining how much these agents differ and thus how strong the opinion change will be. The learning rate of the agent is based on various types of variables: partly determined through a global model parameter, partly through the relationship between the two discussing agents, and partly through the input parameters of the agent itself. This range of variables ensures that the learning rate can take on a large variety of different values, differing greatly between agents within the same VvE or even for one agent over different steps of the model or different discussion rounds in the same discussion phase, determining, for a large part, how the opinion of an agent changes each discussion round. The first variable in Equation 8 is the base learning rate (μ_0), a model parameter which thus doesn't change over the course of a model run. Through this variable, the impact the discussions have on the agents in the model can be adjusted easily for all agents in the model. The second variable (T_{ij}) indicates the trust agents i has in agent j, determining how much agent i trusts the knowledge and opinion agent j has regarding the proposed EER. Since this trust value is a perception of one agent regarding another agent, this value can differ greatly based on the agent pair used. The third variable (S_i) has been used in previous parts of the model and is the Sensitivity to the choice of others. Agents who are more sensitive to the opinion of others will be easier to convince of the opinion of others and move more towards their opinion. Finally, the strategy multiplier (α_s) is based on the chosen decision-making strategy of agent i, where the strategy chosen by the agent in the previous model phase determines how much the agent's opinion changes during the discussion round. Equation 9 shows the different values for the different strategies, where the Imitation strategy gets the highest strategy multiplier, since here agents choose to purely look at the opinion of others, and inversely, the Repetition strategy gets the lowest multiplier since agents there only look at their own previous situation. These numbers are not based on any literature or research but were determined through logical reasoning and studying the impact of different values on the discussion round's results.

$$eq.9: \alpha_s = \begin{cases} 0.3, & if\ Optimizing \\ 0.15, & if\ Repetition \\ 0.6, & if\ Inquiring \\ 0.8, & if\ Imitation \end{cases}$$

3.2.2. Social interaction and collective processes

Since VvEs are constructs with a high level of social interaction between the members, social influence is an important element when trying to simulate the decision-making process of a VvE. This paragraph focuses on the different social interaction mechanisms present in this model, discussing how social networks are formed in the model, how agents are influenced by each other and how the collective decision of the VvE is formed.

Social networks

In the model, each agent can be part of two types of social networks. The first network, the VvE, includes each agent of the same VvE. This network simply stores which agents are in the VvE; however, no specific relations or interaction intensities between agents are modelled in this network. Agents use the information from this network to determine the general opinion of members of the VvE, which in reality would be known through previous voting sessions of the VvE.

The second social network in this model includes the close connections of individual agents, which are those households in the VvE where a specific household has the most positive interactions with. These close connections are gathered for each household through the data collection procedure, where households are asked to list several households they would indicate are their closest connections. During the data collection, these close connections are indicated as 'People you regularly have meaningful conversations with. Not just saying 'hi' in passing, but interactions lasting several minutes.' These close connections were planned to be used at several stages of the model, to model how agents discuss more frequently with agents they are close with, and how they may adjust their opinion more easily based on the opinion of their close connections. Initially, these close connections were used by agents using the Imitation and Inquiring strategy when forming their initial opinion. However, as will be discussed in more detail in the Data Collection chapter, most of the households in the studied VvEs indicated they have no connections in the VvE at this level of closeness. This low level of close connections meant that throughout the model, where necessary, the impact through the close connections network of an agent was changed to an impact by all agents in the VvE. This does create some unrealistic situations, where, for example, an agent using the Inquiring strategy is now expected to know the Level of Need Satisfaction of all agents in the VvE. Where previously, an agent could inquire with the handful of close connections they have regarding their Level of Need Satisfaction, they are now modelled to do this for all members of the VvE. However, if this change was not made, a large number of the agents would lack data when determining their opinion, thus creating errors in the model.

Where the first social network discussed above does not have any specific network structure, since no relations are present between the agents in this network, the second network does show a specific network structure. Through the data collected from the two case-studied VvEs, the households that indicated to have one or multiple close connections within the VvE showed that these connections were mainly with the neighbouring households in the VvE. Furthermore, a small number of members also had connections with members on other floors

of the building. From the 3 network types defined by Watts & Strogatz (1998) as discussed in 2.4.1, these close connection networks within the studied VvEs thus most resemble a Small-world network structure.

Social interactions

Throughout the model, both passive and active social influences help in shaping the opinion of the agents. In the first phase of the model, the individual decision-making phase, agents look at other agents to determine their own Uncertainty and Initial opinion, thus allowing households to passively influence each other. Meanwhile, in the second phase of the model, the discussion phase, the agents exert social influence on other agents through discussions, thus actively influencing each other.

Three instances of passive social influence are included in the first phase of the model. Initially, when determining the Uncertainty of each household, which is in part determined through the average opinion of the other VvE members (Equation 3). If the agent's opinion at the end of the previous model step differed from the general opinion of all members of the VvE, the agent will doubt the certainty of the information forming the basis of their opinion. With a larger difference between the agent's opinion and the VvE's opinion, this doubt and thus the agent's Uncertainty will increase more. Since the opinion of the previous step is used here, each agent is assigned an initial opinion as an input variable, which is overwritten at the end of the first phase of the model when the agent determines its initial opinion. This assigned initial opinion is gathered through the data collection process, where each participant is asked their current opinion on the EER.

The second and third forms of passive social influence can occur when an agent forms their initial opinion. One of the reasons the Consumat theory was chosen as the central decision-making mechanism in this model is its inclusion of social influence during an individual's decision-making process, which is reflected in this part of this ABM. When an agent uses the Inquiring strategy, the opinion is formed partly based on the expected future Level of Need Satisfaction of all other agents in the VvE (Equation 4), while if the agent uses the Imitation strategy, the opinion is formed solely based on the opinion of all VvE agents in the previous model step. Either of these strategies is chosen when the agent's Uncertainty is above the UNC^{max} threshold, thus indicating that the agent feels too Uncertain about their knowledge and beliefs regarding the proposed EER to base their opinion only on their own information.

The discussion phase models the active influence agents exert on each other during discussions. While the basic workings of this phase have already been discussed in 3.2.1, this part focuses in more detail on the social influence aspects that are yet left undiscussed.

Through the social network of agents, agent pairs are formed at the start of each model step. In this, agents have a tendency to choose an agent in their close connections network to discuss with. This tendency, indicated as the Partner Chance model parameter, thus determines how likely it is that the agent will discuss the EER with someone they already regularly interact with. Agents who do not have any close connections will not be able to

choose from their close connections and will thus always be paired with anyone from the VvE. After the agent has determined which social network the discussion partner will be taken from, the agent randomly chooses any agent in that network, who then together form a discussion pair for this discussion round. After two agents are paired, their social roles are determined. The agent with the lowest Uncertainty value of the two will become the influencing agent, indicated as agent j in Equations 6,7 and 8, while the agent with the highest Uncertainty value becomes the influenced agent, agent i. The social influence here is one-sided; thus, the influencing agent exerts influence on the other agents, while no influence of any kind is exerted on the influencing agent. With these roles divided, the learning rate of agent i can be determined, where the S_i and α_s values of the agent can be determined, and the base learning rate (μ_0) is taken from the model parameters. The trust of agent i in agent j is stored as an input parameter of the agent if agent j is in its close connections list. When the close connections of the respondents were asked, their trust in those connections was also gathered. However, if agent j is not in the close connections network of agent i, the base trust factor from the model parameters will be used. This factor stores a global value indicating how agents will trust those in the VvE they do not regularly interact with.

After having changed the opinion of one of the agents through this discussion, the stopping condition for both agents is checked, deciding whether they will perform another discussion round. This condition is based on the number of discussion rounds in this discussion phase the agent has participated in where its opinion was left unchanged. If an agent experiences no change in opinion after several rounds of discussing, the agent will not see the added value of participating in more discussions and will stop participating in the discussions of this discussion phase. The No Change Stop model parameter determines after how many rounds without a change in opinion the agent stops discussing. In the following discussion round of the discussion phase, only agents who have not stopped discussing can be chosen by agents to pair up with, thus reducing the pool of possible discussion partners with each round. If at the start of a discussion round the number of agents still willing to discuss is below the Active Agents Threshold determined in the model parameters, the VvE will determine that too few people are still willing to discuss, and the discussion phase will be end and the next phase begins.

Collective decision-making

In the final phase of the model, the collective decision-making phase, the members of the VvE come together and vote to determine the VvE's decision for this model step. In reality, social influence would also play a large role in these voting rounds, where, in this gathering of agents with largely differing opinions, agents will discuss with each other and hear the opinions of others in the VvE. In the model, however, all these discussions are moved to the discussion phase, and in this final phase, agents will only cast their vote based on the outcome of the previous phase.

For each agent who participated in the discussions, the opinion at the end of the final discussion round they participated in is used to determine their decision (D_i). If the agent's opinion is higher than 0.5, they will vote for the implementation of the EER (1), while an opinion of 0.5 or lower means the agent will vote against the EER's implementation (0). This decision formation logic can also be seen in Equation 10.

$$eq.10: D_i = \begin{cases} 1, & if\ O_i > 0.5 \\ 0, & if\ O_i \leq 0.5 \end{cases}$$

Following these individual votes of all interested members of the VvE, the average of the decisions of al VvE members $(\overline{D_n})$ is compared to the voting quorum of the VvE (Q_V), as can be seen in Equation 11. From this, the outcome of this model step of the VvE is determined, which could either be Yes, indicating the VvE has voted to implement the EER during this voting round, or No, indicating the VvE is not planning EER implementation after this voting round.

$$eq.11: D = \begin{cases} Yes, & if\ \overline{D_n} \geq Q \\ No, & if\ \overline{D_n} < Q \end{cases}$$

Now the model will calculate the months elapsed during this model step by looking at the number of discussion rounds and the attendance rate at the voting round for each VvE. If the attendance rate, thus the percentage of interested agents in the VvE, is below the attendance quorum of the VvE, the first meeting is cancelled, and a second meeting is held in 1 month with all the interested agents. This second meeting will continue no matter the number of members present, in line with the regulations set by the national government as discussed earlier in the literature review. A meeting cancellation does, however, not create a different result, since the same agents as in the first meeting participate, and no further discussions will happen in between. Thus, the only influence this has is that it adds an extra month to the decision-making process of the VvE. By counting the number of discussion rounds and checking whether the first voting session was cancelled, the total number of months this model step took can be calculated using the model parameters Months per discussion round and Months per collective phase.

The total duration of the model, as well as the number of positive voting rounds achieved by the VvE until now, are then checked against the two model termination rules, deciding if another model step is performed. If the number of months elapsed equals or exceeds the Max months model parameter, the model is terminated. If at this termination the total number of voting rounds where the VvE decided to implement the EER is below the Required Yes rounds model parameter, the VvE will have failed at implementing the EER. However, if at this point or at an earlier stage in the model, the VvE reaches the required number of Yes rounds, the VvE model will be terminated, and the VvE will have succeeded in implementing the EER. For VvEs, several positive voting rounds are often needed before actual EER implementation can start. VvEs often organise one round to vote for the financing of a research into the possible EER options, one round to vote on which option to choose and one round to vote for the financing options of this EER.

If the model is not terminated, the entire process will start over again from the individual decision-making phase, where some financial variables are updated. Based on the monthly

VvE contribution made to the VvE, the VvE's savings account is updated to include all the contributions made since the start of the model, multiplying the contribution per member by the total members and the months elapsed. Similarly, each household's monthly savings that they are willing to invest in the EER, multiplied by the number of months elapsed, is added to the total amount the household is willing to invest. Thus, at the start of each model step, each household's available finances will have increased compared to the last round's situation, resulting in a changing Level of Need Satisfaction. Another variable that will change in the new model step is the initial opinion of each agent. These new opinions can change the Uncertainty of an agent through an altered difference between the household's opinion and the general opinion of the VvE. Through the changing of the Uncertainty and Level of Need Satisfaction, an agent might choose to use another decision-making strategy, thus calculating their opinion differently. However, if an agent chooses to use the same strategy, the opinion will still change since it is calculated based on different numbers through the changing of the opinion and the Level of Need Satisfaction of all agents.

3.2.3. Model assumptions and simplifications

As mentioned in several instances in the previous sections, several choices have been made during the creation of the ABM with the intention of reducing the complexity of the model. In this section, the simplifications and assumptions made are discussed, clarifying where limitations exist in the model's representation of reality and supporting a transparent interpretation of the simulation results.

Firstly, when selecting the households used in the model, only the apartments with owner-occupants are included in the model. The households in the rented-out apartments are not considered during the decision-making process. They will only be used when calculating the cost of the EER per apartment, thus splitting the total cost over all the apartments in the building. Including the occupants of these rented out apartments as agents does not reflect the reality, since these renters have no influence whatsoever in the decision-making process of the VvE. The external parties, owning these rented out apartments, could be included. However, these parties are often extremely hard to reach, and they would require different types of input data, since they do not inhabit the apartment.

Secondly, the agent's preference values for financial safety, comfort level and environmental impact are predetermined for each agent and fixed throughout the model runs. Similarly, knowledge levels, sensitivity to the choices of others and trust in other agents are also static values. Though these values are different for each household, they will not change over time in response to interactions or learning behaviour, which might be the case in reality.

Another assumption made is that agents perfectly perceive the opinions, uncertainties and Need Satisfaction levels of all other agents when required. No misinterpretation or level of uncertainty is included in this sensing process, thus allowing each agent to directly use the value of any other agent if required. Furthermore, agents are also not able to sense or predict the effects of the EER on their own. Based on interviews with board members of the case

studied VvEs, these expected or real costs, energy savings and comfort improvements are determined and used directly by all agents of the VvE.

The interest of an agent, determining whether they participate in the discussions and voting of that round, is determined through their Uncertainty factor. If the Uncertainty of an agent is above the Interest threshold, determined in the model parameters, the agent loses Interest in the EER. Above this threshold, the agent is too uncertain regarding its opinion, caused by a lack of knowledge gathered or through a greatly differing opinion compared to the average opinion of the VvE, and will not be tempted to partake in the discussions and voting for the EER. This is a simplified representation of the interest determination of an agent, where, in reality, the lack of interest of an agent can be caused by many different reasons. Some reasons mentioned during the talks with the VvEs and experts were language barriers, plans to move out soon, a lack of time to attend the meetings and study the provided information, or old age, where residents think they will not benefit long from the proposed EER. This study did not focus on finding the sources of low interest among VvE members, and thus, it was also not attempted here to include a realistic implementation of the interest determination.

The model includes a social network of close connections for each agent, selecting which agents this agent will be influenced by most often. However, due to the limited number of close connections indicated by the households in the case studied VvEs, the impact of these social networks had to be reduced. Therefore, at several instances, instead of only the household's close connections, all the members of the VvE were used to determine certain variables. While this is required to ensure the model works correctly, it creates an unrealistic assumption where agents are expected to know the exact value of certain variables for all agents. Furthermore, the resulting social networks are relatively small due to the limited social connections in the studied VvEs. Additionally, these social networks of close connections are static and predetermined. In reality, however, through discussions with other members in the VvE, possibly those sharing the beliefs of a household, households might add new close connections to their social network.

The financial calculations of the model also have some simplifications. The cost of the EER is calculated based on the implementation cost minus the energy savings in euros over a set number of years. However, maintenance and operational costs are not included in this part. Furthermore, when determining the monthly contributions of VvE members, each member will pay the same monthly contribution. These contributions will in reality often differ per apartment based on the area of the apartment. Similarly, during the voting process, some VvEs give differing voting weights to members with different apartment sizes. Since both case-studied VvEs had relatively similar-sized apartments, this was not included in the model.

Furthermore, when calculating the finances and CO_2 production of the gas and electricity of each household, the average Dutch ratios are used. In reality, different apartments can have different energy providers, thus having differing costs and CO_2 productions. The added complexity the inclusion of these different providers would add to the model and data collection procedure resulted in the simplification used here.

A final simplification discussed regards the usage of different voting rounds. As explained previously, VvEs often have different voting rounds discussing different parts of the implementation process, often one for the financing of the initial research into the possible options, one to choose the EER option and one to vote for the financing and possible loan the VvE has to take. Since these rounds all concern different topics, households may have changing opinions over these different topics, and the voting mechanisms and time spent on each round may also differ. However, modelling these different possible round types was too complex to include in this model, since no research was conducted on all the differing types of voting sessions VvE's might conduct.

In the model, a limited form of stochasticity is introduced to reflect the variability of social interactions. During the discussion phase, agents are randomly paired with a discussion partner. With a fixed probability, stored in the Partner chance model parameter, an agent is matched with one of its close connections; otherwise, a randomly selected VvE member is chosen. If an agent has multiple close connections, the discussion partner is randomly selected from this list. Agents without any close connections are always paired with a randomly chosen VvE member. This probabilistic pairing mechanism introduces variation in discussion outcomes, even when identical input data are used. Since no fixed random seed is implemented, each model run may produce different discussion pairings and collective outcomes. However, in the separate analysis script used for the sensitivity and scenario analyses, a fixed random seed is applied to ensure reproducible outcomes across Monte Carlo runs. This distinction allows the model to keep its realistic stochastic elements in the discussion phase, while reproducibility in the analysis phase is possible.

3.3. Details

3.3.1. Implementation details

The model is implemented using the Python programming language. To run, visualise and analyse the model successfully, four separate code files are needed. The first code calculates the preferences of each agent using a Analytic Hierarchy Process (AHP). This creates a new file in the input folder, storing these preference values. This file is required to run the second code file, which runs the ABM. This file requires 3 other files to be present in the input folder, one storing the agent data, one storing the VvE data and one storing the EER data. The third code file is run if the Streamlit webpage is required. This code uses the ABM code file to run the model in an online web environment, and creates graphs highlighting several changing aspects of the agents and VvE. Screenshots of this webpage are added in Appendix 4. This code is recommended to run when quick analysis of different model configurations is wanted.

For a more in-depth analysis, a fourth code is made. This code first runs a sensitivity analysis, altering a large range of variables, most by increasing and decreasing the value of these variables for all agents by 25%. This percentage was chosen to ensure that all new values stay within a realistic range. If a higher increase were used, more and more agents would have values outside of the permitted bounds of the value, which is often between 0 and 1. However, a lower percentage would reduce the observable effect of the changing variables. Through

these variable changes, different values are studied, reflecting the outcome of the model. These values are the implementation rate, indicating in how many of the runs the VvE implemented the EER, the average percentages of 'Yes' votes during the first and last voting rounds of all runs, and the average duration in months it took the VvEs in the different runs to complete the decision-making process. For each changed variable, the model is run 500 times per VvE, after which average results can be calculated per variable change. Through these averaged values, the impact of the change of one variable in a certain direction on the entire model can be studied. Studying these variable changes shows how some variables impact these model outcomes more significantly compared to other variables, and the correctness of the directional changes caused by these changing variables can be validated through logical thinking. Thus, through this method, the variables exerting an extremely high influence on the model, as well as the variables behaving unexpectedly, can be identified. Furthermore, this analysis can also be used to determine which variables in the model are important in determining a positive outcome in the decision-making process, answering the second sub-question of this research.

Next to the sensitivity analysis, the same code also runs a scenario analysis. 5 scenarios are created based on the barriers found and the policy study in the literature review, each scenario changing some of the model's input variables compared to the base configuration. For these scenarios, a similar method is used as in the sensitivity analysis, running 500 model runs per scenario and studying the average outcome variables. The scenarios used are explained in more detail in the following paragraph.

All code files, as well as the input data files used for this model, are accessible through the TU/e GitHub page.

3.3.2. Model setup and scenario design

To prepare the model for the analyses discussed later in this thesis, the setup of the model's base configuration is discussed here, together with the different scenarios used to study the several policy implementations. However, the first part of this section will focus on how the different types of parameters used in this model are determined, providing a transparent foundation for how the model is initialised.

Parameter foundations

The model uses a combination of empirical, calibrated and procedural parameters. Empirical parameters are derived directly from data, mostly collected through the two case-studied VvEs. This data includes, among others, each household's available finances, comfort level, annual gas and electricity usage and environmental impact, but also the expected benefits for each VvE when implementing a specific EER. Furthermore, some values, such as the average electricity cost and CO_2 production, are gathered from sources such as the CBS. Some values can be used directly in the model, while others first have to be calculated from the gathered data. For example, the preference values gathered from each household regarding financial

safety, the comfort level and environmental impact are first converted to a preference weight through an AHP calculation. The empirical parameters form the heterogeneity of the agents and the VvEs, ensuring that the base configuration reflects realistic decision-making processes, rather than synthetic assumptions.

Some of the other parameters used are calibrated parameters. These parameters can not be observed directly from the studied VvEs, but are calibrated through running the model with different parameter values and studying the outcome. This includes variables such as the threshold values for the Level of Need Satisfaction and Uncertainty or the base learning rate. Through several iterations, these variables were tuned so that the model outcome reflects the situations of the case studied VvEs. The model outcomes used here were the EER implementation rate, the percentage of positive votes during different voting rounds, and the duration of the model run in months. These could be compared to the voting percentages during the voting rounds of the studied VvEs, the number of months their decision-making process took and their final or expected outcome.

Finally, procedural parameters describe aspects of the VvE decision-making process that are used to determine how the agents and the VvE follow the decision-making process. Examples of these parameters are the required number of voting rounds, the duration of a collective decision-making phase or the chance for an agent to pair up with a close connection as a discussion partner. Some of these values could be determined through the interviews with experts and VvE members, such as the number of voting rounds or the average duration taken to plan and execute a voting session, while others, such as the chance to pair with a close connection, are difficult to determine and are thus filled in through intuition and logical reasoning.

Base model configuration

The base model configuration represents the most realistic depiction of the two studied VvEs, serving as the reference point for changes made in the analyses performed with the model. In this configuration, each agent is assigned the parameters gathered during the data collection phase. The initial values of the VvEs are also set at those values gathered from the VvE surveys and the interviews with the board members. Furthermore, the model parameters, storing values used by all agents of both VvEs in the model, are determined through publicly available data, calibration, interviews or logical reasoning, as explained in the previous section. An overview of all the model parameters used in this ABM can be seen in Appendix 2A. Each parameter is explained briefly here, and the values of these parameters in the base model configuration are given. In Appendix 2B, for some of these parameters, an explanation is given on how these values are determined.

The initial values of two parameters are discussed briefly here to avoid confusion, namely, the attendance and voting quorum. As can be seen in Appendix 2A, these values are set at 0%, which would indicate that the VvEs in the model don't have to pass any attendance or voting quorum during the voting rounds. These parameters are, however, included in such a way in the model that if they are set to 0, the quorum values used in reality by the case studied VvEs

are used, with each VvE using its own values. However, if in the model parameters these parameters are assigned a value other than 0, the model will use these new values as the quorum values for both VvEs.

Scenario configuration

In the literature review of this thesis, different types of barriers experienced by VvEs trying to adapt an EER were determined. Based on these barriers, different scenarios are designed which can be implemented in the model. These scenarios change a variable of the agent, VvE or model parameters, while keeping the rest of the parameters at an equal value as in the base model configuration. These scenarios reflect policies that could be implemented by the government to aid VvEs. By analysing how the results of the outcome of the decision-making process of the studied VvEs change, compared to the base configuration, the effect of these policies on VvEs can be determined.

A major barrier reported by VvEs concerns the financial feasibility of the EER. In the model, several parameters directly affect the financial situation of households or the cost of the proposed EER, in turn determining the formation of the initial opinion of households. Therefore, scenarios focusing on this barrier can be easily implemented into the model.

The two scenarios relating to the financial feasibility change the loan and subsidy granted to households, since these aspects could be best adjusted through governmental regulations. The first scenario, as can be seen in Table 4, increases the loan share parameter by 0.1 compared to the base configuration, allowing households to fund a larger part of the EER's cost through the loan, and lowers the interest rate by 1 percentage point. Lowering the loan interest rate of the Warmtefonds loan is already being done by some municipalities, allowing VvEs in that municipality to take on a loan at a lower interest rate. However, at the time of writing this thesis, only 2 municipalities allow a reduced interest rate for it's inhabitants: the municipality of Den Haag and the municipality of Leidschendam-Voorburg (Nationaal Warmtefonds, 2025a). The second scenario implemented applies the same parameter changes as the first scenario, while adding a subsidy of €2500 for each household.

Another barrier experienced by VvEs is the regulations set by the government, which all VvEs must follow. This focuses specifically on the minimum attendance and voting quorum values, which, for voting sessions regarding EER implementation, require 51% of the votes to be represented at the meeting, and at least 67% of the votes to be positive to pass the vote. In the VvE-Versnellingsagenda of the Ministerie van Volkshuisvesting en Ruimtelijke Ordening (2023a), lowered quorum levels are proposed, which will be implemented in 2026. These lowered quorum values, namely a 0% attendance quorum and a 51% voting quorum, are the changes implemented through the third scenario. The quorum values of both VvEs will be set to these numbers, allowing the study of what the effect would be on the two studied VvEs when this policy is implemented in the near future.

The third type of barrier determined through the literature review is related to social influences, slowing down the decision-making process through disagreements between

parties and conflicts. Through talks with experts regarding VvEs and EER adoption, the implementation of VvE managers in each VvE in the Netherlands was considered a viable solution. By installing a well-trained VvE manager in each VvE, the decision-making process of the VvE can be shortened, arguments can be solved before they lead to conflicts, and the VvE will have a source of information at each meeting whom they can trust. However, since no VvE manager has been implemented in the model as a separate agent, the effects of a manager on the decision-making process have to be modelled through changing the parameters that this manager would affect. The more structured collective decision-making process provided through a trained and experienced VvE manager is modelled by lowering the required number of voting rounds with a positive vote by 1, and decreasing the time needed to plan and execute a voting round by 1 month. Furthermore, the knowledge provided through the VvE manager is included by increasing each agent's received information parameter, being one of the 4 parameters determining the agent's knowledge level, with a factor of 1.4.

The final scenario models an information campaign provided by the government, which is a type of policy often used by the government. For example, through governmental aid, Milieucentraal (n.d.) has set up the information platform verbeterjehuis.nl, trying to gather all the information a household or VvE would need when planning a sustainable renovation. This information campaign policy is implemented in the model by increasing the received and looked-up information variables of all households by a factor of 1.25. This factor is lower than the factor used in the VvE manager policy, since here the agents still have to look up the information themselves, where a VvE manager would provide them the information, thus making it more likely that a household will receive the information. Furthermore, in the information campaign policy, the base trust level of all agents is increased by 0.1. Since all households in the VvE now have more knowledge concerning the EER implementation, during discussions, agents will trust the information spread by the other agent more.

Table 4: Tested scenarios

Scenario	*Variables and values*
Extra loan	Loan share: +0.1
	Loan interest: -1% point
Extra subsidy and loan	Grant per household: + €2500,-
	Loan share: +0.1
	Loan interest: -1% point
Lowered Quorums	Voting quorum: 51%
	Attendance quorum: 0%
VvE Manager	Months per collective phase: -1
	Required yes rounds: -1
	Received information: *1.4
Information campaigns	Received information: *1.25
	Looked up information: *1.25
	Base trust factor: +0.1

3.3.3. Input data

The largest part of the data used in this research consists of empirical data collected through surveys designed and conducted for this research. Two medium-sized VvEs were selected to enable a comparative analysis of collective decision-making processes while keeping data collection manageable within the time constraints of this research. Medium-sized VvEs, defined here as VvEs with between 10 and 50 members, were chosen because they offer a balance between complexity and representativeness. In smaller VvEs, individual households can disproportionately influence the outcome of the VvE's decision-making process, while VvEs with more than 50 dwellings require a time-intensive data collection process if door-to-door data collection is required. Moreover, large VvEs often include a high share of rented apartments owned by housing associations, further complicating collective decision-making.

Both VvEs have around 30 member households and are approximately 50 years old. The buildings share a similar residential typology, both being primarily occupied by owner-inhabitants, with 27% of the apartments being rented out in one VvE and 45% in the other. Despite these similarities, the two VvEs differ in several important aspects. Geographically, one is located in the south of the Netherlands, while the other is situated in the north, reducing potential location-specific biases. They are also at different stages of the decision-making process: one has already implemented its EER in 2024, whereas the other is still in the initial research phase. Furthermore, the cost and expected energy savings of the two VvEs EER differ substantially; for one VvE, the total cost is nearly 3 times higher, but its expected savings are also 3 times greater. These contrasts provide a useful basis for examining how contextual and financial conditions shape collective decision outcomes.

Missing data, from the studied VvEs, from missing respondents or respondents who stopped halfway through the survey, is generated through the gathered data, and, where necessary and possible, combined with publicly available local data to generate two VvEs with all their households represented in the data, each household representing a heterogeneous agent used in the model. Further details on the survey design, data collection and generation procedures are discussed in the following chapter.

4. Data collection

As indicated before, a large and important part of this research is the data collection part. As can be seen in the methodology section, the model requires a large amount of household-specific data for each agent, determining the current situation, social connections and attitudes of the heterogeneous agents, thus allowing each agent to base its opinion on their determining characteristics. Furthermore, VvE-specific data allows the modelling of differences between the case-studied VvEs, adding the differing financial situation of the VvE and the expected impacts of the proposed EER as factors influencing the agent's opinion. Since no data is available publicly in the required level of detail, this data will be collected as part of this study. First contact will be made with a large number of companies working with VvEs, as well as VvEs themselves. Through meetings with these parties, the model will be refined to further match the individual and collective decision-making process as experienced by them. Through these conversations, contact information of VvEs with experience in the EER process will be gathered, and these VvEs will be contacted and asked to participate in the research. For each of these VvEs, 2 surveys will be filled in. After these surveys are filled in by the board and members of the VvE, the data is checked for errors or inconsistencies and any missing data is generated, after which it can be implemented into the model.

4.1. Data sources

For this research, representatives of 23 different institutions that work with or are in contact with VvEs have been reached. Most of these respondents were contacted through a LinkedIn post. Furthermore, referrals of these initial respondents and some personal contacts resulted in the final number of contacts. 19 of these representatives have replied to this initial contact, and with 17 of them, an online meeting, call or in-person conversation was held. These 17 individuals represented a large range of different types of institutions that work with VvEs in greatly differing manners. The full list of these contacts can be seen in Appendix 3A. Several of these were companies that advise VvEs planning to conduct an EER, guiding them through the entire process from initial research to financing. Several VvE managers were also met with, who have a closer and frequent connection with VvEs. Furthermore, a meeting with a Belgian company that trains Belgian VvE managers shed some light on the situation outside of the Netherlands. A number of these 17 institutions were housing associations, which often own apartments in buildings with VvEs and have a high urgency due to governmental regulations to create a more sustainable housing stock by 2030. Some associations helping and guiding VvEs with EER, as well as representatives of Dutch municipalities and the Dutch Ministry of Housing and Spatial Planning, helped in sharing their experiences from a social and regulatory perspective. Finally, a lawyer specialised in condominium law shared her opinions and experiences from a judicial perspective.

All of the representatives of these companies in Appendix 3A were asked to share contact information of possible VvEs to include in the research. Most tried to help in some way, and several came up with some interesting VvEs in the end.

With most of these representatives, a short discussion was held regarding the topic of the sustainability improvement of VvEs. This was not the initial goal of these conversations, which was gathering VvE contact data, and for this reason, these discussions were not all held in a structured way. As a result, in several discussions, certain important questions or topics were left undiscussed, and other important points were not noted down. However, most of the model and important variables to include in it were discussed. Next to important variables to include in the model, some also shared their opinion on the situation of VvEs in the Netherlands and shared what they perceive to be the main barrier VvEs face when trying to undergo an energy efficiency improving renovation. Appendix 3A shows that these experts indicated the interest and attendance rate in VvEs, as well as the priorities and expertise of VvE managers, were the main perceived barriers which have to be tackled. Low attendance rates lead to the cancellation of voting sessions, further prolonging the decision-making process and increasing the effort the VvE board has to take to achieve a successful completion of this process. Furthermore, many indicated that the often low expertise of VvE managers regarding sustainable renovations, as well as their limited involvement in the decision-making process, is an area with a large potential for improvement. Multiple issues with VvE managers were mentioned through these interviews: the lack of knowledge, many being trained and qualified to handle just the regular maintenance jobs, the extra cost for a VvE wanting to involve their manager in the decision-making process, and a growing trend of VvE managers quitting their jobs quickly, contributing to a shortage of experienced managers. Finally, several of the experts mentioned that the responsibility lies with the government or municipality to reduce the difficulty of the EER adoption process for VvEs, either by changing regulations or by increasing funding or subsidisation to VvEs and other involved parties.

Either through these companies above, through personal contacts, through the initial LinkedIn post and some referrals from the supervisors of this graduation thesis, a set of 15 VvEs were contacted. In Appendix 3B, some information regarding these VvEs is noted. Not all VvEs responded, and for others, it was decided early on not to continue when the VvE did not match the research requirements. Therefore, some information in this table is not filled in since it was not collected. These VvEs came from a range of different regions in the Netherlands, situated mostly around Eindhoven or in the Randstad region. Most had between 40 and 60 apartments, some fully inhabited by the owners, others with up to 70% of the apartments rented out by external parties or private owners. Most were stalled in the EER adoption process, while 4 VvEs had successfully completed an EER, and 2 were still in the decision-making process. The number of VvE members, the specific EER process of the VvE and the willingness of the VvE to participate in the research resulted in a selection of 4 VvEs to continue with.

4.2. Data collection procedure

Each VvE included in this research was studied using 2 separate surveys. The first survey, which was filled in by one of the board members of the VvE, includes data on the VvE, the building and the EER that the VvE plans to execute or has executed. The second survey is filled in by the individual households in these VvEs. These surveys collect data regarding the household's

characteristics, opinion on the EER and social connections. These questionnaires can be seen in Tables 5 and 6.

Table 5: Data requirement list acquired once per VvE

Category	*Question*
Building information	What is the yearly electricity usage of the building?
	What is the yearly gas usage of the building?
	What is the energy label of the building?
	What is the heating system used in the building?
VvE information	How many members does the VvE count?
	Who are the board members of the VvE?
	How were these board members selected?
	What is the monthly contribution paid by members of the VvE?
	How many years does it typically take the VvE to decide on major investments that impact the entire building, such as installing solar panels, replacing window frames, or insulating cavity walls?
	How often does the VvE have a voting session on these major investments?
	What is the attendance and voting quorum to validate and pass a decision on these major investments?
EER information	What is/was the most recently proposed energy-efficiency improving renovation (EER) for which a voting session was/will be held?
	Are the renovation works for this EER already finished?
	How much money is in the savings account of the VvE (before any expenses were made for this EER)?
	How much of your VvE's savings account will go to this EER?
	What is the expected implementation cost of this EER?
	To what extent do you expect the EER to improve the thermal comfort in the building?
	How much will the EER save on gas usage for the building?
	How much will the EER save on electricity usage for the building?
	Were there any other energy-efficiency improving renovation projects undertaken by the VvE in the past 5 years, and if so, which?
Voting sessions	How many voting sessions have you undertaken until now/in total, for the EER from the previous questions?
	What were the vote outcomes and attendance levels during these voting sessions?

For all of the 4 VvEs included in the research, contact was made with the board member or VvE manager of the VvE. Through this contact, the surveys were shared with the board of the VvE and all households in the VvE. Due to time constraints, only the VvE in Groningen and one of the VvEs in Eindhoven were included in the following part of the research. One of the other VvEs failed to send out the survey to the households in time, and the other did not have the required information to fill in the survey for the board, as well as received nearly no response to the household survey. Since the other two VvEs were contacted in time, several responses could be gathered before the collection deadline. Through several reminders to the households to fill in the survey, as well as a door-to-door visit to all households in one of the

Table 6: Data requirement list acquired once per household

Category	*Question*
Socio-demographic information	What is your apartment number?
	Do you own or rent this apartment?
	What is your age?
	What is your gender?
	Do you live together with a partner in this apartment?
	Do you have a child/children living in this apartment?
	What is your household size?
	What is your household's monthly net income?
	What is your highest achieved education level?
Current situation	How comfortable do you currently find your home in terms of temperature?
	What is the current yearly electricity usage of your apartment?
	What is the current yearly gas usage of your apartment?
Social connections	With which other members of this VvE do you have strong positive connections?
	How often do you, on average, speak with these connections in a month?
	How much would you trust information regarding sustainable renovation coming from these connections?
EER situation	How necessary do you think the most recently proposed/implemented energy-efficiency improving renovation in your building is?
	How much of your household's savings are you currently willing to set aside for investing in an energy-efficiency improving renovation?
	How much of your household's monthly net income are you willing to set aside for investing in an energy-efficiency improving renovation each month?
	How important is thermal comfort to you, compared to financial safety, when deciding on an energy-efficiency improving renovation?
	How important is thermal comfort to you, compared to environmental concern, when deciding on an energy-efficiency improving renovation?
	How important is financial safety to you, compared to environmental concern, when deciding on an energy-efficiency improving renovation?
	To what extent would you let the opinion of people important to you influence your decision to adopt an energy-efficiency improving renovation?
Knowledge	How many energy-efficiency improving renovations have you previously undertaken in your own home(s)?
	To what extent do you think your occupation has helped you understand the benefits and challenges of installing energy-efficiency-improving renovations?
	To what extent have you received information about this energy-efficiency improving renovation and its financing possibilities from professionals or technical experts?
	To what extent have you actively looked into information regarding this energy-efficiency-improving renovation yourself?

VvEs with paper forms, several households in both VvEs filled in the household survey. Furthermore, both board surveys were filled in as thoroughly as possible.

As indicated above, some of the surveys were filled in on paper forms through a door-to-door collection procedure. However, most respondents filled in the survey, created in Limesurvey. All data was gathered and combined into an Excel file.

To ensure full anonymity of respondents, only the household's house number was requested in the survey. The address, building name or exact location was not stored, only the city in which the building is located. Each VvE received a separate survey with its building ID in the title, allowing responses to be correctly linked to the respective VvE without revealing identities. All data collection and storage procedures complied with the EU General Data Protection Regulation (GDPR). Participation was voluntary, and respondents could only proceed after agreeing to the informed consent statement at the start of the survey. All responses were stored and processed anonymously for research purposes only.

Lastly, it should be noted that the participating VvEs were all associations that had already discussed or proposed an EER. This focus was necessary to ensure that all respondents had the same EER in mind when filling in the survey; however, it also introduces a degree of selection bias. Other, less sustainability-oriented VvEs that had not yet considered potential renovations could not be included in the research; thus, only the VvEs already engaged with sustainability topics were included. Furthermore, several VvEs that were deadlocked in the decision-making process were contacted, but all of them were not included in the end due to the selection process. The board members of these VvEs either indicated that reaching all the members would be very difficult or impossible, due to poor relations within the association or a lack of digital communication channels, or that the VvE was deadlocked due to a specific issue not captured in the model. For example, in one case, the housing association owning a large part of the building halted the EER, thus stopping the EER decision-making process, while all VvE members were enthusiastic.

4.3. Data quality and response rate

Due to the relatively high level of detail required in the survey for the board members of the VvE, some difficulties were experienced by the board members in filling in the complete surveys. Data like the building's electricity usage or the expected electricity savings of the EER were especially hard to determine. However, through further conversations with the board members and through a report exploring the possible benefits and costs of several EERs executed at one of the VvEs, the missing data could be filled in and finetuned sufficiently. This will be further elaborated on in the following paragraph.

The quality of the responses gathered through the survey for each household of the VvE was quite low, as can be seen in Table 7. Firstly, the response rate was relatively low. In one of the VvEs, through multiple reminders from the board, 8 out of 35 VvE members completed the survey. Furthermore, 19 more respondents started the survey but did not finish it. Most stopped at the first page, either by not giving consent to use their data, which automatically closes the survey, or by manually exiting the survey. 4 respondents gave consent but exited

the survey later, most at the second page of the survey, and some halfway through the survey. Thus, while 27 out of the 35 VvE members opened the survey, less than 1/4th of this VvE's members completed the survey. Furthermore, from these 8 complete responses, several had filled in incorrect data. Either because of a misinterpretation of the question or because the respondent did not want to share this data. This will also be further discussed in the next paragraph.

For the other VvE, the data gathered through the household-specific survey were even lower. After 2 reminders, none of the 22 households in the VvE had filled in the survey, while 6 had opened the survey but stopped at the first page. Therefore, it was decided together with the board of the VvE that it would be best to personally go to all households in the building with printed out surveys with a request to fill them in on the spot. However , a large number of residents were not at home, only managing to speak to 8 residents, which resulted in 6 filled-in surveys. Since the VvE board did not know which apartments were occupied by the owners and which were rented out, these were also partially filled in by renters. In the end, 3 surveys were collected from VvE members of this VvE, thus collecting data of about 14% of the VvE's members. These 3 surveys were, however, filled in completely, with all the questions answered at the required level of detail. The short face-to-face introduction could have been the cause of this, giving respondents a higher level of trust in anonymous usage of the data and a feeling of sympathy for the interviewer. The 3 gathered surveys of the renters were filled in partially, since not all of the questions asked could be answered by these individuals.

Table 7: Descriptive statistics of the response rates

ID	*VvE members*	*Opened surveys*	*Completed surveys by VvE members*	*Response rate*
1	35	27	8	23%
2	22	14	3	14%

4.4. Data preparation

As a first part of this paragraph, the VvE and EER specific data will be discussed, and the alterations made to this data will be explained. A short introduction of the buildings will also be given; however, this will not go into too much detail to ensure the data of the respondents in these buildings stays anonymous. After this, the household-specific data is explained, and the data generation of the missing agents is elaborated.

In Table 8, some of the general data of the VvEs studied can be seen. The VvE in Groningen, built in 1980, has 48 apartments, 35 of which are owned by the residents. The other 13 apartments are owned by external parties and rented out. The external parties have the voting rights in the VvE; thus, they should be included as agents during the voting sessions. However, these externals are incredibly hard to reach, with most VvE boards not even knowing which apartments are rented out. Furthermore, not all information required for household agents, such as the comfort level, is known by these agents. It was therefore decided not to include these rented-out apartments and their inhabitants or owners in the simulation.

There are 3 different amounts of monthly contribution to the VvE paid by different members in the VvE. However, these differ by a couple of euros; thus, the middle amount, at €241, will be used for the model. The VvE has saved €220000 in their savings account, and the apartments have an energy label of D or E.

The second building, located in Eindhoven and built in 1972, has 40 apartments, 22 of which are inhabited by members of the VvE. This VvE, as is also shown in Table 9, has already finished the renovation in 2024. The monthly contribution, saved finances, and energy label were all filled in for the current situation of the VvE. Through talks with the board, the current values were compared and rewritten to the pre-EER values. The energy label is not corrected for the new situation, since this value will not be further used in the research.

Table 8: VvE data of studied VvEs

ID	*City*	*Apartments*	*VvE members*	*VvE contribution*	*Saved finances*	*Energy label*
1	Groningen	48	35	€241,34	€220000	D/E
2	Eindhoven	40	22	€129,67	€400000	B

The first VvE is still in the research phase of the EER. The voting quorum of the VvE was unknown, since the input in the survey was not in line with the minimum value by law. Therefore, it was set at the same quorum as the second building, namely 67%. The attendance quorum of this VvE is 51%. The VvE has just had a voting session after the initial research by an external company was finished, showing the different possible retrofitting scenarios and choosing between one. 80% of the VvE was present at the voting round, and 100% of the attendees voted for an EER. The VvE now looks into an option which improves façade insulation, adds HR++ glazing to all the windows, enhances the roof insulation, makes the façade airtight and adds CO_2-controlled ventilation. According to the report provided by the external company at the voting round, this option will cost approximately €8.786 per apartment, and it will save around 7% on electricity use per apartment. The board member of the VvE who filled in the survey furthermore expects a significant increase in comfort in the building, rating an 8 on a 0 to 10 scale where 0 means no improvement and 10 indicates a drastic improvement.

The second building has already finished the renovation in 2024. The VvE has a quorum of 67% on yes votes needed for a vote on matters like an EER, and 71% of the members need to be represented at these meetings. The renovation costed on average €21.750 per apartment, thus €870.000 for the whole building. €600.000 of this was loaned from the Warmtefonds, raising the monthly contribution of the members from approximately €129,67 to €199,67. Furthermore, about 60% of the VvE's savings account, around €240.000 in total, was used for the renovation. Furthermore, around €34.000 was paid by governmental subsidies. The average electricity and gas savings of the building are not known; however, based on the savings experienced by the board members, this was set at 0% and 22% respectively, showing that this EER only focused on reducing the gas usage of the building. The board also experiences a significant increase in comfort due to the temperature in their apartment, giving a grade of 8.

Table 9: EER data of studied VvEs

ID	*EER done*	*Voting quorum*	*Attendance quorum*	*EER cost*	*Electricity savings*	*Gas savings*	*Comfort change*
1	No	67%	51%	€8.786	7%	-	8
2	2024	67%	71%	€21.750	-	22%	8

As stated above, the two VvEs that were chosen to continue with in this research were filled in by a small part of the members of the VvE. Since the model looks at the entire VvE and how the individual members of this VvE interact and make their decisions, the missing data of the other occupants of the building was generated using the collected data, averages of the region and some randomisation. These methods were used to both generate agents replacing the households which did not fill in the survey and to fill in data fields which were not filled in by respondents. Furthermore, several incorrectly filled-in data fields were corrected. Below, the filling in and generating of data for the agents will be discussed for each variable.

To use as much of the collected data as possible, all respondents who gave consent to use their data were gathered into an Excel file. As explained before, a large number of respondents quit the survey after the first few questions; however, the data they filled in could still be used to ensure the final data used is as empirical as possible. For both buildings, the list of respondents was created and based on the house numbers of these agents, the missing agents were appended to the file to get a full list of all the house numbers in the building. In the VvE located in Groningen, which will from now on be referred to as building 1, 36 new households were created and 12 households were collected from the survey. 1 of these households did not fill in the house number, which was therefore assigned a random house number not inhabited by one of the other respondents. Furthermore, 2 households filled in the same house number; however, the other filled-in data was different between the 2 agents. Therefore, one of the households was changed to a different house number. The VvE in Eindhoven, from now on referred to as building 2, had 6 filled-in surveys. Thus, the other 34 households were created similarly to building 1. Each of the respondents correctly gave up their house number; thus, no alterations had to be made here.

Since for both VvEs it was uncertain which households were owner-inhabitants and which were renters, all the data fields of all households in the buildings were filled. At the start of the model, the renters will be discarded immediately. However, creating these agents will help during the agent generation process when comparing the building's average of certain variables with the zip code's average. For both VvEs, it was known exactly how many of the apartments were rented out; thus, in the dataset, an equal number of agents were randomly set as renters.

The next variable in the dataset is the age of the respondent. The age could be filled in in 6 age groups: <25 years, 25-35 years, 36-45 years, 46-55 years, 56-65 years, and >65 years. 2 respondents failed to fill in this variable; however, both did fill in the household size and income level. One of the households, a one-person household with a relatively low income, was set at >65 years. When studying the gathered data, other single retirees showed similar income levels. The other, 2-person household, matched the income level of young couples and

was thus set at an age of 25-35 years. The other household's age levels are filled in by matching the average age distribution of the generated data with the actual age distribution in the street. This data at this level of detail can be found online (Allecijfers.nl, 2024), based on data provided by CBS. The source cited above will not lead to the actual page of the streets studied in this research, since this will remove the anonymity of the data. In Table 10, the count and average of the age groups in the generated population and the streets in question can be compared. The age of all generated households in the population was assigned randomly, while matching the age distribution of the street. Since none of the respondents filled in the age of <25 years, and the data from Allecijfers.nl (2024) showed a low number of residents in both streets of this age group, none of the respondents were assigned this age. Some children might live in these apartments; however, since the survey was filled in by the heads of the households, these children would not have filled in the survey.

Table 10: Age distribution of studied VvEs

	Age	*Population count*	*Allecijfers count*	*Population distribution*	*Allecijfers distribution*
Building 1	*25-35 years*	9	12	19%	20%
	36-45 years	11	13	23%	22%
	46-55 years	9	12	19%	20%
	56-65 years	11	13	23%	22%
	65+ years	8	10	17%	17%
Building 2	*25-35 years*	13	15	33%	33%
	36-45 years	13	15	33%	33%
	46-55 years	2	2	5%	4%
	56-65 years	3	3	8%	7%
	65+ years	9	10	23%	22%

The gender of the respondent was filled in by all respondents. The gender of the generated agents was assigned randomly based on the data available at the street level from Allecijfers.nl (2024). In Table 11, the distribution of both buildings can be seen. Since in both the gathered data as well as the available data from Allecijfers.nl (2024), other genders were not given; no genders other than male or female were assigned.

Table 11: Gender distribution of studied VvEs

	Gender	*Population count*	*Allecijfers count*	*Population distribution*	*Allecijfers distribution*
B.1	*Male*	27	40	56%	57%
	Female	21	30	44%	43%
B.2	*Male*	20	30	50%	50%
	Female	20	30	50%	50%

In all the gathered data, the household size was filled in correctly by the respondents. The household size of the remaining population was generated using the street's average household population gathered from Allecijfers.nl (2024). The distribution of this can be seen in Table 12. As can be seen, both household sizes are relatively low compared to the average

household size of 2.1 in the Netherlands (Centraal Bureau voor de Statistiek, 2025b). The data gathered through the surveys reflects this statistic, with most occupants indicating they live alone, and just a small number of respondents indicating to live as a couple. None of the respondents indicates having children living in their household. For the generated population, therefore, most households are assigned as 1-person households, some are indicated as 2-person households, and only 2 households are assigned as 3-person households.

Table 12: Household size distribution of studied VvEs

	Population average	*Allecijfers average*
Building 1	1.33	1.3
Building 2	1.55	1.5

By analysing the data gathered for the other variables determining the agent's state, different methods to generate this variable's data for the missing agents are chosen. Many of the missing data of the respondents were generated using Excel's NORM.INV function. This function applies a normal distribution defined by the group mean and standard deviation, producing realistic variations in the variables across the population. Each variable generated in this method is first analysed based on the socio-demographic data of the respondents. Correlations between the socio-demographic data of the respondents and the value of the variable are determined. If any correlations exist, the validity of this correlation is checked through logical reasoning and, where possible, publicly available data. 2 of the socio-demographic variables are found to correlate with some of the other variables generated, the age of the respondent and the household size. Both socio-demographic variables are divided into two groups: the age in young- & middle-aged, representing respondents aged between 25 and 55 years, or elderly, aged 56 years or older, and the household size being either singles or couples. The households with children are also placed in this last group. By grouping the respondents based on these variables, where in Table 13 each group's count of the gathered data and total population can be seen, the mean and standard deviation for some variables can be determined for each demographic group. These values can then be used to generate the data of the missing agents, based on their demographic grouping, which is more statistically robust than when basing it on the mean and standard deviation of all the building's respondents.

If, through reasoning and analysis of the gathered data, no correlation can be found between the socio-demographic data of an agent and the value of a certain variable, the generated agents are assigned a value based on the mean and standard deviation of all the building's respondents.

Finally, some other variables are not generated through Excel's NORM.INV function. Most of these variables were determined to be random for the agents, like the 4 variables determining an agent's knowledge, which can not be based on the average data of other agents. For these variables, each agent was assigned a random value within the allowable range of values of that variable. Other variables were not possible to assign randomly but had to be assigned manually. An example of this are the preference values, which can not be assigned

independently since the total has to add up to 1. This manual assignment is done semi-randomly, where the observed trends in the buildings are kept in mind during the manual assignment of variables. In Table 14, for all the generated variables, the generation method is stated.

Table 13: Demographic group distribution of studied VvEs

			Real population			Full population		
	ID	Demographic group	Count B.1	Count B.2	Count total	Count B.1	Count B.2	Count total
Age + Size	1	Young- & middle-aged singles	3	2	5	19	12	31
	2	Young- & middle-aged couples	2	1	3	10	16	26
	3	Elderly singles	6	2	8	14	8	22
	4	Elderly couples	1	1	2	5	4	9
Age	1	Young- & middle-aged (25-55 years)	5	3	8	29	28	57
	2	Elderly (56+ years)	7	3	10	19	12	31
Size	1	Singles (1 person)	9	4	13	33	20	53
	2	Couples (2+ persons)	3	2	5	15	20	35

Table 14: Generation data per agent variable

Variable	Generation method	Data level based on	Demographic grouping
Net monthly income	Normal distribution	Combined buildings	Age + Size
Comfort level	Normal distribution	Per building	Age
Electricity usage	Normal distribution	Per building	Size
Gas usage	Normal distribution	Per building	Age + Size
Close connections	Semi-randomly	Per building	-
Connection trust	Randomly	-	-
Initial opinion	Set to 5	-	-
Money willing to invest	Normal distribution	Combined buildings	-
Monthly savings ratio	Normal distribution	Combined buildings	-
Preference values	Semi-randomly	Combined buildings	-
Sensitivity to choice of others	Randomly	-	-
Knowledge factors	Randomly	-	-

In Table 14, it is also stated whether the data for the missing agents is generated based on the data from the respondents of the same building only, or of the two buildings combined. Some variables, such as energy usage, are building-specific and thus have to be calculated separately. Other variables, such as the monthly income, were, however, found to be similar for the respondents of the two studied buildings. As can be seen in Table 13, the number of

respondents for some demographic groups, especially in the second building, is extremely low. By combining the data of the two buildings was possible, the data used to generate the missing agents becomes more statistically robust.

Below, for each of the variables in Table 14, the generation of the data is explained in more detail.

The variable household net monthly income was generated based on the combined age and household size demographic groups. For each group, the average and standard deviation of reported income were calculated and used to estimate missing values. Since the number of respondents was limited in some groups, the data from both buildings were combined, as no significant differences were found between them.

To validate the results, national averages from the Centraal Bureau voor de Statistiek (2025c) were used as a reference. Income levels by age group and household size were extracted to verify whether the sample data followed similar patterns (Table 15).

Table 15: Household net monthly income combined of both studied VvEs

	Gathered data		*Dutch data*
ID	*Average*	*St. deviation*	*Average*
1	€ 3250,-	€ 755,-	€ 3388,-
2	€ 3600,-	€ 566,-	€ 5275,-
3	€ 2160,-	€ 666,-	€ 3250,-
4	€ 4750,-	€ 2475,-	€ 4083,-

During the data preparation, several issues with the comfort level variable were discovered. Firstly, the method which was planned to be used to calculate the post-EER comfort level, old comfort level + expected comfort change, does not produce satisfactory results. With a high comfort change, as is the case for both VvEs, this number will reach the upper limit for most households. Therefore, the post EER formula has been changed to a weighted interpolation formula. This formula, as can be seen in Equation 12, calculates the new situation $E_i^{c,new}$ by looking at the gap between the current level and the upper bound. The new comfort level moves towards this upper bound based on a weight k. After a study of the behaviour of the formula with different weights, a weight of 0.5 was set for this formula. This weight ensures the increased comfort is not too harsh, and not too soft. In this formula, agents with a low initial comfort level will experience a larger increase in comfort than those with a larger initial comfort level. A similar behaviour can be expected in the real world, where those with low comfort due to their room's temperature can benefit more from an EER than those with already high comfort.

$$eq.12: E_i^{c,new} = C_i^c + ((1 - C_i^c) * (E_i^c * k))$$

A second issue encountered when preparing the comfort level is the fact that the occupants of the second building had already undergone the EER in question when the questionnaire was executed. Therefore, using the gathered data directly here would lead to incorrect results. Therefore, the inverse of Equation 12 is executed on the values before usage. When calculating

the new comfort level with the implemented EER, the resulting value will equal the initial gathered value. This inverse formula can be seen in Equation 13.

$$eq.13: C_i^c = \frac{E_i^{c,new} - (E_i^c * k)}{1 - (E_i^c * k)}$$

When calculating the data used for generating the missing comfort data, the size demographic group is not used, instead only looking at the age of the respondents to determine the demographic group and the data used to generate the data. The group with ID 1 thus here refers to young- & middle-aged respondents, between 25 and 55 years, while the group with ID 2 refers to elderly respondents, who are 56 years or older. Since the comfort level of the two buildings differs greatly, as the gathered data also shows, the average and standard deviation are calculated and used separately for the two buildings. In Table 16, the average and standard deviation of the age groups of these 2 buildings are shown. These values are used in the NORM.INV formula of Excel to generate the comfort level during the summer and winter months for the missing agents and the agents who did not fill in this variable. The numbers generated are minimised at 0 and maximised at 1. Here, a 0 means fully uncomfortable, and 1 means fully comfortable.

Table 16: Comfort level distribution of studied VvEs

		Comfort level Summer		*Comfort level Winter*	
	ID	*Average*	*St. deviation*	*Average*	*St. deviation*
B.1	1	0.55	0.25	0.73	0.15
	2	0.45	0.37	0.68	0.29
B.2	1	0.61	0.25	0.56	0.1
	2	0.56	0.25	0.5	0.1

The yearly electricity usage of the households, as well as the yearly gas usage of the households, are also generated using the averages and standard deviations of demographic groups. The data of the second building is, however, first recalculated to reflect the situation before the EER was executed. The gathered data, representing the situation after the EER, is divided by the electricity savings of the EER, as given in Table 9. When the model then calculates the new situation, this value will equal the value gathered from the respondents. Due to several respondents not filling in the questions regarding electricity and gas usage, the averages and standard deviations used are calculated using the gathered data and data from the Centraal Bureau voor de Statistiek (2023b). This dataset from the CBS only shows different electricity usages among different household sizes, but no significant changes for different age groups. A similar trend was seen in the gathered data. Therefore, households were grouped on size when calculating the electricity usage. As can be seen in Table 17, the gathered data of the 2 or more person households in the first building shows a different behaviour than would be expected or is seen in the Dutch averages. The usage is lower for 2 persons than for a 1-person household. Furthermore, the 2-person households in the second building have only one filled in response to the electricity usage. Therefore, since the data of the 1-person households for both buildings is in line with the street's average electricity usage, gathered from Allecijfers.nl (2024), these averages and standard deviations are used directly to generate

the other 1-person households. To calculate the 2-person households, the 1-person household average and standard deviation are multiplied by the difference between 1 and 2-person households as calculated from the CBS data, which is approximately 1.44 times the usage of a single-person household.

Table 17: Yearly electricity usage (kWh) distribution of studied VvEs

		Gathered data		ZIP data	NL data	Used data	
	ID	Average	St. deviation	Average	Average	Average	St. deviation
B.1	1	2695	304	2530	1703	2695	304
	2	1925	884	2530	2453	3882	438
B.2	1	1479	228	1550	1703	1479	228
	2	2151	-	1550	2453	2131	329

For the gas usage, a similar method was used. In the first building, no gas is used for central heating or cooking. Most respondents also gave a 0 here, with one exception of a respondent indicating to use 600 m^3 of gas. After checking this with the board of the VvE, it was decided to set the gas usage of all respondents in the building to 0. For the second building, first, the values are divided by the given gas savings to calculate the situation before the EER. For the gas usage, the CBS data, however, did show a large difference between the elderly and young- & middle-aged groups, as can be seen in Table 18. Therefore, this data was calculated and generated for the 4 demographic groups. Similarly to the electricity usage data, the gathered data of the first demographic group was used to calculate the other demographic group averages and standard deviations. The CBS data showed that from group 1 to group 2, a multiplication of 1.33 was calculated, from group 1 to group 3, this was calculated at 1.28, and from group 1 to group 4, this was calculated at 1.6 times the usage. These multiplication factors were used to calculate all the required averages and standard deviations to run the NORM.INV formula in Excel for the missing data and the newly generated agents.

Table 18: Yearly gas usage (m^3) distribution of building 2

	Gathered data		ZIP data	NL data	Used data	
ID	Average	St. deviation	Average	Average	Average	St. deviation
1	533	482	610	957	533	482
2	858	-	610	1273	709	641
3	1036	-	610	1226	683	618
4	-	-	610	1531	853	771

The next variables in the survey regard the close connections of the agents. Their closest connections within the building, the frequency of interaction with the connection and the trust in the information given by the connection are asked. Looking at the gathered data, most respondents indicate they have no close connections with other households in the building. Some indicate having a connection with their neighbours. Here, households 2 apartments away are also indicated as neighbours. Furthermore, one household indicates having close connections with households elsewhere in the building. The generated agents are manually assigned close connections based on the gathered data, ensuring a similar distribution of

relation types. Most households that assigned a close connection are assigned 1 or 2 other households as close connections. An individual household is assigned 3 households as a close connection. A similar distribution is used for the generated data, where most have 1 or 2 connections, some 3, and a single household has 4 connections. For these connections, each household is randomly assigned a trust value. The connection frequency is not filled in since this data is not used further in this research. The connection trust shows no correlation in the gathered data, since this is simply based on the relationship between the two households. Therefore, these values are randomly filled in, with a value between 0 and 10. Here, a 0 indicates no trust and a 10 full trust.

Table 19: Connection relation distribution of studied VvEs

		No connections	*Neighbours*	*Other inhabitants*	*Neighbour + Other*
Gathered data	*Building 1*	6	2	1	0
	Building 2	4	1	0	0
Population data	*Building 1*	31	11	4	2
	Building 2	28	10	1	1

The next variable, opinion about the EER, is difficult to generate for the agents. Since this opinion is generated in the model early on and the initial opinion is only used for agents who choose the repetition strategy, this opinion is set at 5 for all the generated agents. This represents a neutral opinion, which will then be overwritten for most agents at the start of the model run.

The money willing to invest and the savings ratio are both generated using the responses of all agents of the combined buildings. The money willing to invest represents the amount of money the household would be willing to invest at this moment in an EER, while the savings ratio is the monthly amount a household would be willing to set aside from their income to invest in the EER. The data showed no correlation between these variables and the monthly income or the demographic groups. Some low-income households are willing to spend several thousand euros on the renovation, whereas high-income households are willing to spend a lot less on the renovation. Even some households that think the renovation is very important, giving it a 10, are still not willing to spend any money on the renovation. No real difference can also be seen in the responses between the two buildings. Therefore, one average and standard deviation are calculated and used for all generated agents and missing agent information.

Table 20: Money willing to invest and savings ratio of both studied VvEs

	Gathered data	
	Average	*St. deviation*
Money willing to invest	€1280,-	€1905,-
Monthly savings ratio	€68,-	€68,-

The preference values are assigned to respondents based on their answer to three questions comparing their preference to comfort, financial safety and the environment. The respondents

could fill in a value between 1 and 7, where a 1 indicated a strong preference for the left value above the right value, a 4 indicated equal preference and a 7 indicated a strong preference for the right value over the left value. The real data was analysed to show the general distribution of the three factors. This showed that most respondents value financial safety as the most important value, and valued the other 2 values as approximately equally important. A similar distribution was created for the generated agents and the missing data of respondents. The 3 values were recalculated into a number between 0 and 1 using a separate Python code. This code uses AHP to calculate a number between 0 and 1, where 0 indicates a low preference for this value, and 1 indicates a high preference. The three preference values combined always add up to 1. In case the consistency ratio of the calculated numbers is too high, indicating that the filled-in responses do not create a consistent preference value, the code changes the answers of the respondent slightly. This is done multiple times per respondent, after which the option with the lowest consistency ratio is chosen while keeping the answers as close to the original answers. For the generated agents, several answer options with a low consistency ratio are created and distributed randomly among the agents. The averages of this distribution were kept in line with the averages of the real data, as can be seen in Table 21.

Table 21: Preference value distribution combined for both studied VvEs

	Gathered data Average	*Population data Average*
Comfort – Financial safety	3.5	3.7
Comfort – Environmental concern	3.9	4.0
Financial safety – Environmental concern	4.6	4.5

The final 5 variables, the sensitivity to the choice of others, the previous EERs, the occupational knowledge, the received information, and the looked-up information, are all generated entirely randomly since no correlation could be found between these values and the household's demographic values. A household's sensitivity to the choices made by others, as well as the household's knowledge, will be based on variables other than the household's age and size. The previous EER question was asked to the respondents in three parts: the number of small renovations, medium renovations and large renovations carried out previously by the household. Here, a small renovation lasts a maximum of 1 day, a medium renovation lasts up to 5 days, and a large renovation lasts more than 5 days. Each small renovation counts for 1 point, a medium for 2 points and a large renovation for 3 points. These answers of the respondents were first recalculated into a number between 0 and 10. Then, for the generated agents and the missing respondent information, this number, as well as the other 4 previously mentioned variables, were generated randomly. Each household thus gets a random number between 0 and 10.

With these final variables generated, all the households in both VvEs are generated with all the information required to run the model. Most of the generated data is already in the right format, where nearly all variables are required to have a value between 0 and 1. However, some require a final recalculation before they can be correctly implemented in the model. Several variables are collected as a percentage, such as the gas savings or the attendance

quorum, and are divided by 100 before being implemented in the model. Several other values, such as the 4 values determining the household's knowledge or the initial opinion of the households, are stored in a 0-10 range. This scale is chosen for most variables asked through the survey since it is easier to interpret than a 0-1 scale. These variables are first divided by 10 before they are used in the model. Furthermore, the variables storing financial information of households and the VvE are stored in euros. This unit is converted into a number between 0 and 1 through a ratio value, ensuring that households with an average financial situation of all studied households would get a 0.5. Similarly, variables related to emissions are stored in kilograms of CO_2 and recalculated to a 0-1 range through a ratio based on the average emissions of Dutch 2-person households inhabiting apartments. The values and calculation of these ratio variables are further explained in Appendix 2.

5. Results & Discussion

In this section, the results of the ABM will be discussed in two parts. Firstly, the results of the sensitivity analysis and scenario analysis are provided and explained. The sensitivity analysis performed is a One Factor At a Time (OFAT) analysis, changing the values of a large range of variables one at a time. This OFAT analysis is also used to discover which factors impose the largest influence on the outcome of the model, thus answering the second sub-question of this research. For the scenario analysis, 5 scenarios are tested and compared to the base model configuration. In the second part, a number of these results are discussed further, explaining the observed behaviour of a number of variables and scenarios.

5.1. Results

Sensitivity analysis

In Tables 22 and 23, the results of the OFAT analysis for buildings 1 and 2, respectively, can be seen. A selection of 21 variables of the model is chosen to include in this analysis. Exclusion of variables happened for several reasons; another variable showing the same behaviour was already included, as is the case for 3 of the 4 variables determining the agent's knowledge level, the variable has a fixed and predetermined value, such as the variables determining the gas and electricity cost and CO_2 production, or the variable can not be changed without having to change other variables, which is the case for the preference values which together always have to add up to the value 1. After this selection, 27 variables were excluded, and 21 variables were chosen to analyse separately, most by lowering the value by 25% and increasing it by 25%. By using the same percentual increases and decreases as much as possible, the resulting changes caused by these increases or decreases can be compared among the different variables. For some variables, such as the number of positive voting rounds required, a percentual increase was not logical, instead going for numerical change. The value of this variable in the base configuration is put in brackets behind the variable name, while in the value column, the new values of these variables are stated.

To test the influence on the speed and success of the collective decision-making process, the difference of the 4 resulting variables compared to their value in the base configuration is calculated. These 4 result variables are the percentage of runs with a successful implementation of the EER, the average percentage of yes votes during the first and during the last voting round and the average duration of the VvE's decision-making process in months, thus the value of the month counter after termination of the model through a successful or failed EER implementation, averaged over the model runs. These results are based on the outcome of 500 runs per variable change; thus, with most variables being changed twice, 20500 model runs are performed per VvE for the OFAT analysis. Luckily, one model run is performed quickly, so the OFAT analysis of the two VvEs takes approximately 10 minutes.

In the top row of Tables 22 and 23, the values of the building under the base configuration are given. The rows below show how these values change when changing the input variable of that row. In the tables, significant changes in the implementation rate are highlighted, marking highly sensitive variables. These will be discussed later in the thesis.

Table 22: OFAT analysis results Building 1

Variable (initial value)	Factor(*) / Value	% EER implemented		% Yes first round		% Yes last round		Duration (months)	
		Avg.	St.dev	Avg.	St.dev	Avg.	St.dev	Avg.	St.dev
Base config.	-	41.60	49.34	74.45	6.13	44.73	35.56	19.58	5.73
Use loan (Yes)	No	-5.00	-1.12	+0.38	-0.19	-1.80	-0.58	+2.05	-1.55
Loan share	*0,75	-1.80	-0.34	+0.37	-0.19	-0.33	+0.04	+1.52	-0.85
	*1,25	+9.80	+0.69	-1.55	+0.99	+4.93	+0.79	-1.42	+0.22
Loan interest	*0,75	-	-	-	-	+0.18	+0.06	-0.04	-0.01
	*1,25	+0.80	+0.13	+0.04	+0.05	+0.31	+0.18	-	-
Grant per HH (€0,-)	€1000,-	+1.80	+0.27	-0.16	+0.20	+0.94	+0.03	-0.29	+0.08
	€2500,-	+6.20	+0.66	-0.81	+0.55	+3.02	+0.15	-1.05	+0.19
Monthly savings	*0,75	-0.20	-0.03	-	-	+0.02	+0.02	-	-
	*1,25	+0.40	+0.07	-	-	+0.14	-0.04	-	-0.01
VvE savings	*0,75	-0.20	-0.03	+0.01	-	-0.14	+0.02	+0.02	-0.01
	*1,25	-	-	+0.01	-	-	-0.02	+0.01	-0.01
EER cost	*0,75	+4.80	+0.58	-0.67	+0.49	+2.25	+0.52	-0.86	+0.19
	*1,25	-1.20	-0.22	+0.33	-0.18	-0.31	+0.01	+0.91	-0.40
Gas usage	*0,75	-	-	-	-	-	-	-	-
	*1,25	-	-	-	-	-	-	-	-
Gas savings	*0,75	-	-	-	-	-	-	-	-
	*1,25	-	-	-	-	-	-	-	-
Electricity usage	*0,75	+1.60	+0.25	+0.26	-0.14	+1.02	+0.19	-0.10	+0.04
	*1,25	-1.20	-0.22	-0.50	+0.49	-0.62	-0.12	+0.17	-0.07
Electricity savings	*0,75	-1.40	-0.26	+0.17	+0.04	-0.50	-0.02	+0.43	-0.17
	*1,25	+1.20	+0.19	-0.23	+0.20	+1.09	+0.24	-0.25	+0.08
Comfort level winter	*0,75	-8.20	-2.13	-0.86	+1.01	-5.13	-2.36	+0.88	-0.30
	*1,25	+7.60	+0.70	+0.31	-0.16	+4.37	+0.81	-0.78	+0.10
Attendance quorum	*0,75	-	-	-	-	-	-	-	-
	*1,25	-	-	-	-	-	-	-	-
Voting quorum	*0,75	+1.80	+0.27	-0.16	+0.09	+0.03	-0.83	-0.26	+0.10
	*1,25	+0.40	+0.07	+0.39	-0.19	+13.45	+3.18	+2.91	-3.05
Required 'Yes' rounds (3)	2	+2.60	+0.37	-3.65	+1.90	-0.37	-2.07	-2.51	+2.20
	4	+9.00	+0.71	+0.39	-0.19	+7.53	+2.08	+1.72	-2.29
Occupational knowledge	*0,75	+10.40	+0.67	+10.87	+0.03	+7.68	+1.71	-1.74	+0.28
	*1,25	-	-	-0.33	+0.89	+1.64	-0.58	+0.18	-0.03
Initial opinion	*0,75	**-41.60**	-49.34	-74.45	-6.13	-44.73	-35.56	+4.42	-5.71
	*1,25	**+58.40**	-49.34	+17.60	-1.91	+54.96	-34.00	-7.02	-5.36
Base learning rate	*0,75	+0.60	+0.10	+4.64	-2.00	+0.53	+1.14	-0.44	+0.17
	*1,25	+2.80	+0.40	-5.83	+1.44	+1.98	-0.79	+0.54	-0.53
Trust factor	*0,75	+0.80	+0.13	+4.44	-1.83	+0.65	+1.61	-0.42	+0.16
	*1,25	+1.80	+0.27	-5.61	+1.20	+1.79	-1.17	+0.64	-0.54
UNC max	*0,75	+15.80	+0.16	+22.18	-1.39	+12.66	+13.93	-2.47	+0.21
	*1,25	-18.20	-6.96	-23.69	-0.96	+1.87	+3.27	+4.00	-4.28
LNS min	*0,75	**+35.60**	-7.34	+0.16	-0.20	+22.34	-5.56	-3.94	-0.73
	*1,25	**-40.60**	-39.38	-20.39	+3.16	-30.39	-23.03	+4.65	-4.92

Because the ABM has a stochastic mechanism in the discussion phase, the base configuration values for both VvEs show substantial variation across the model runs. This is reflected in the relatively high standard deviation values seen in both tables. Especially the implementation rate and the average model duration show a noticeable spread across different runs, where Building 1 generally displays a higher standard deviation than Building 2. This aligns with the difference in implementation rate between the two buildings: the voting outcomes in Building 1 fluctuate more strongly across voting sessions, resulting in greater variability in aggregated model outcomes.

The base configuration of the first building has an EER implementation percentage of approximately 41%, indicating 41% of the 500 runs resulted in the VvE voting for the implementation of the EER. Averaged over 500 runs, the percentage of yes votes during the first voting round was approximately 74%. In the last voting round, this average percentage was lowered to approximately 45%. Thus, in this building, agents started with a mostly positive opinion regarding the EER. However, over time, agents developed an increasingly negative opinion regarding the EER. On average, the duration of the decision-making process took 19.6 months for the first building in the base configuration. The second building had, on average, a much larger chance of implementing the EER. 85.6% of the 500 runs resulted in a positive outcome regarding EER adoption in this VvE. While the percentage of yes votes in the first VvE saw a decreasing trend over the course of a model run, the second building increased from an average of 65% in the first round to an average of 79% of positive votes in the last voting round.

In Figure 6, for both buildings, some regularly occurring voting percentage trends can be seen. As can be seen in the figure, different model runs with the same input configuration will produce differing results. This is caused by the discussion partner pairing system, which randomly chooses a discussion partner for all agents during each discussion round. The opinion and uncertainty of the agent's discussion partner determine whether the opinion of the agent will change in that discussion round, and in which direction, with which magnitude. Thus, based on which agent pairs are formed, during each discussion round, a different trend of opinion change might be observed.

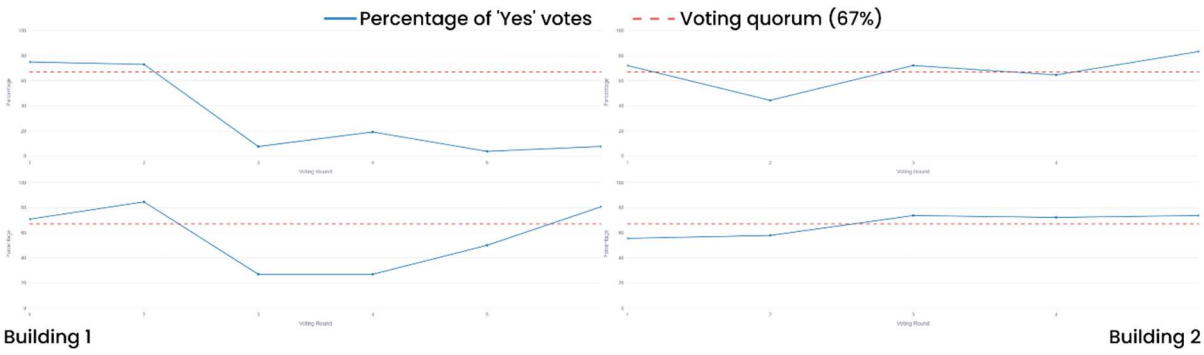

Figure 6: Observed Voting percentage trends of the two studied VvEs

Looking at the outcomes of the base configuration runs and the observed voting percentage trends of the two VvEs, clear differences emerge between the two buildings. These differences are partly reflected in the real behaviour of both VvEs, although the correspondence between model and reality is only partial. Compared to the second VvE, the model predicts that the first

VvE will have a less stable process with larger fluctuations and a greater likelihood of emerging disagreement. This aligns with the board member's expectations, who indicates how surprised she was when the during the first voting session, all members were enthusiastic about the proposed EER. She expects a large backlash from many members when the cost of the EER is presented during the next meeting. However, whether this anticipated backlash will occur is not yet known at the time of writing this thesis, and therefore, the model's prediction cannot be fully validated.

For the second VvE, both the real process and the model results indicate a smoother, more successful decision-making process. The board member of this VvE indicated that the EER adoption process progressed without opposition. She thinks that since the VvE had a sizeable financial reserve available, the VvE managed to pass the final decision in one year, through two voting sessions, both with an attendance rate of 84%, and unanimous support in both sessions. This successful decision-making process is reflected in the high implementation rate in the simulated base configuration. However, some differences remain: the voting percentages are slightly lower in the simulation, where a minority of members keep opposing implementation of the EER, and the simulated duration of the decision-making process is longer, over half a year longer than the real decision-making time. Reducing the number of positive voting sessions required in the model from 3 to 2, which is the number of sessions the VvE held before implementation, shortens this duration by 0.95 months to 18.1 months (Table 23), bringing it a bit closer to the real duration.

Thus, overall, the model seems to reflect the behaviour of the two different VvE's with relative accuracy compared to the real situation of these VvE's. A number of these results will be highlighted below. Unexpected trends and significant factors will be discussed in more detail in the discussion part of this chapter.

The exclusion of the usage of a loan reduces the implementation rate for both buildings, while having a significantly higher impact on the implementation rate for the second building compared to the first building. With a reduction of 21 percentage points, this variable is one of the variables influencing this building's implementation rate the most. Without the use of a loan, the average decision-making duration for both buildings increases by roughly 2 months. The grant allocation variable also increases the implementation rate and reduces the average duration in the first building, where a higher grant increases this effect. For the second building, however, the €1000 grant sees a slight reduction in implementation rate. This decrease of 2 percentage points will likely be caused by the near-saturation effect in this building, where most agents have already decided to implement the EER. This leaves little room for further improvement and makes small stochastic variations appear as minor decreases. A third influencing factor related to the financial situation of households is the implementation cost of the EER. In the first building, a reduced implementation cost increases the implementation rate and reduces the average duration, while an increased cost shows an opposite effect, though the effect seen on the implementation rate here is less significant. In the second building, less significant changes appear, likely due to the already high implementation rate.

Table 23: OFAT analysis results Building 2

Variable (initial value)	Factor(*) / Value	% EER implemented		% Yes first round		% Yes last round		Duration (months)	
		Avg.	St. dev	Avg.	St. dev	Avg.	St. dev	Avg.	St. dev
Base config.	-	85.60	35.14	65.01	12.90	79.07	15.51	19.07	4.27
Use loan (Yes)	No	**-20.80**	+12.66	+3.61	-1.25	-12.08	+4.97	+1.81	+1.28
Loan share	*0,75	-2.80	+2.63	+1.61	-0.04	-1.30	+1.89	+0.15	+0.24
	*1,25	+3.00	-3.33	+6.11	-2.78	+4.78	-5.45	+0.19	+0.23
Loan interest	*0,75	+1.60	-1.70	+0.96	-0.87	+0.90	-0.16	+0.10	+0.09
	*1,25	+1.00	-1.04	+0.40	-0.43	+1.72	-1.67	+0.06	-0.05
Grant per HH (€0,-)	€1000,-	-2.20	+2.10	+0.32	+0.30	-0.34	+0.73	+0.04	+0.22
	€2500,-	+0.80	-0.83	+0.63	-0.70	+1.50	-1.03	+0.10	+0.03
Monthly savings	*0,75	+1.00	-1.04	+0.31	-0.14	-1.22	+0.66	+0.09	-0.09
	*1,25	+1.40	-1.48	-0.27	-0.21	+2.38	-0.73	-0.01	-0.13
VvE savings	*0,75	-0.20	+0.20	-0.09	+0.01	-0.11	+0.17	+0.01	+0.01
	*1,25	-	-	+0.02	+0.04	+0.02	+0.03	+0.01	-
EER cost	*0,75	+0.40	-0.41	+2.61	-1.47	+3.22	-3.94	+0.02	+0.28
	*1,25	+0.80	-0.83	+1.14	+0.05	-0.27	-0.39	+0.14	+0.13
Gas usage	*0,75	-0.60	+0.60	+1.93	-1.16	+2.56	-5.74	+0.10	+0.79
	*1,25	-9.80	+7.73	+2.38	-1.79	+0.22	+0.31	+3.06	+0.27
Gas savings	*0,75	-1.60	+1.55	+1.71	+0.22	+0.29	+0.41	+0.25	+0.32
	*1,25	+1.80	-1.93	+3.79	-1.63	+3.85	-6.30	+0.74	+0.13
Electricity usage	*0,75	+8.60	-11.75	+2.09	-1.69	+4.79	-8.71	-0.52	-0.32
	*1,25	-18.00	+11.70	+0.62	-1.59	-3.13	-6.19	+3.73	+0.75
Electricity savings	*0,75	-	-	-	-	-	-	-	-
	*1,25	-	-	-	-	-	-	-	-
Comfort level winter	*0,75	**-40.00**	+14.71	-14.68	+0.86	-13.10	+8.83	+5.00	-0.03
	*1,25	+14.20	-30.67	+10.22	-5.69	+0.60	-10.32	-2.20	-1.07
Attendance quorum	*0,75	+0.40	-0.41	+0.01	-0.02	+0.31	-0.47	+0.01	-0.03
	*1,25	+9.20	-12.92	+5.64	-2.86	+5.39	-8.73	+2.06	-0.37
Voting quorum	*0,75	-11.40	+8.65	-4.91	+1.73	-9.30	+5.32	-0.66	+1.12
	*1,25	**-56.00**	+10.55	+10.29	-5.69	+8.27	-10.23	+6.72	-2.27
Required 'Yes' rounds (3)	2	**-23.60**	+13.44	-4.17	+2.23	-14.61	+8.03	-0.95	+3.10
	4	+11.40	-18.07	+9.29	-5.07	+6.67	-9.80	+2.40	-1.56
Occupational knowledge	*0,75	+8.00	-10.64	+5.73	-3.17	+4.89	-9.23	+2.18	+0.02
	*1,25	-9.00	+7.24	+1.23	+1.94	-1.81	-1.00	+0.14	+0.35
Initial opinion	*0,75	**-76.20**	-5.93	-33.21	-1.99	-12.56	+1.03	+6.73	-2.39
	*1,25	+9.60	-13.75	+8.82	-1.78	+8.57	-7.65	-2.04	-0.40
Base learning rate	*0,75	-1.60	+1.55	+1.00	-0.64	-0.45	+3.41	-0.34	+0.53
	*1,25	+1.80	-1.93	+1.71	-0.83	+2.68	-3.56	+0.45	-0.27
Trust factor	*0,75	+0.80	-0.83	-0.37	-0.67	+0.13	+1.70	-0.36	+0.12
	*1,25	+1.80	-1.93	+1.96	-0.34	+2.46	-3.28	+0.51	-0.26
UNC max	*0,75	-7.40	+6.19	+6.83	-4.09	+1.73	-4.25	+3.34	-0.16
	*1,25	+3.00	-3.33	-2.74	-2.36	+2.20	-6.22	+1.13	+0.15
LNS min	*0,75	+14.40	-35.14	+10.51	-5.86	+6.90	-10.65	-3.17	-1.75
	*1,25	**-84.00**	-22.58	-18.94	-1.22	-25.76	+5.89	+7.24	-2.39

When altering the gas usage in the second building, the implementation rate reduces for both an increase and a decrease in usage. Nearly all the result variables of the increased and decreased usage change in the same direction, while the changes for the increased usage are more significant in all cases. For the electricity usage, the two different directions of change do impact the result variable in different ways, as would be expected. Since the first building is not connected to the gas network anymore, no change is seen here for these variables; likewise, the change of the electricity savings of the second building has no impact since this EER only resulted in gas savings.

By lowering the comfort level of the agents, a lowered implementation rate and increased average decision-making duration are detected for both buildings. Increasing the comfort level creates an opposite effect on these resulting variables, with a similar significance for the first building and a smaller significance for the second building.

The 2 quorum values produce different results among the studied buildings when adjusted equally. Lowering the attendance quorum barely affects the outcome, while increasing this value sees some changes for the second building. Figure 7 shows the attendance rates and the standard, increased and decreased quorum levels for the two buildings. In the base model configuration, using the standard attendance quorum, the attendance rate of both VvEs is often well above the attendance quorum level. Thus, lowering this quorum level will, in most cases, not lead to more cancelled meetings, thus affecting the model outcome.

However, Figure 7 also shows that increasing this quorum level does cause meeting cancellations in the second building. The already high attendance quorum of 71%, compared to the 51% for the first building, increases to around 89% under the 1.25 multiplication factor, causing the simulated attendance to fall below this quorum level. This substantially increases the number of cancelled meetings, prolonging the decision-making process through the forced replanning of meetings. In contrast, the increased quorum of approximately 64% for the first building is still below the simulated attendance rate, thus not leading to any cancellations.

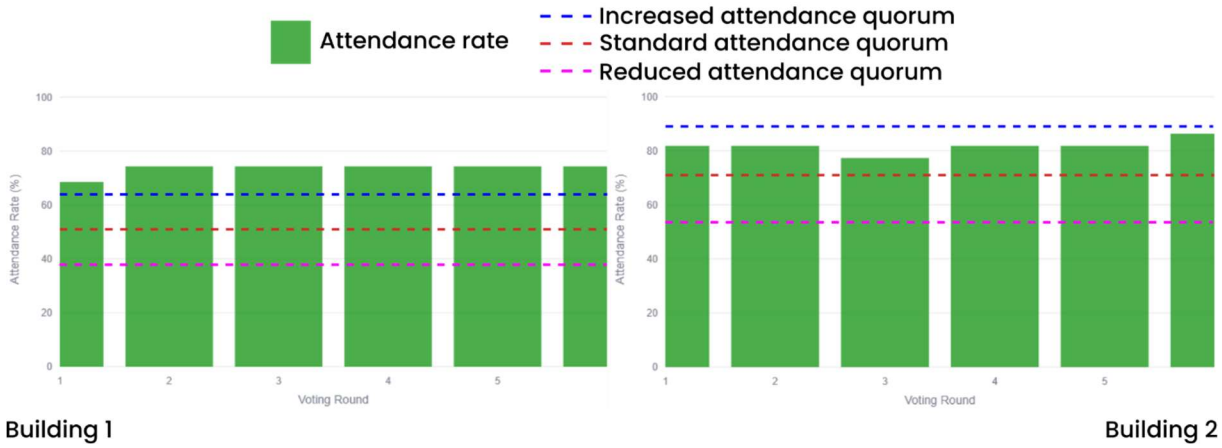

Figure 7: Attendance rates and changing attendance quorums of the two studied VvEs

Figure 7 also provides an insight into the simulated attendance rates themselves, allowing a comparison with the real attendance rates observed in the two studied VvEs. The first VvE had an attendance rate of 80% at its first and only meeting, while the second VvE's attendance rate

at both voting sessions was 84%. The simulated attendance rates of these two buildings, approximately 74% for the first building and 81% for the second, are relatively close to the real values. This suggests that using the Uncertainty value to determine the interest and attendance, where households with an Uncertainty of 0.75 or higher do not participate in the discussions and collective decision-making process, produces a reasonable approximation of the real-world attendance rates in these cases.

Increasing the voting quorum affects both buildings, but the magnitude of the effects differs strongly. For the first building, increasing the voting quorum barely influences the implementation rate, but it does extend the average decision-making duration by about three months. In the second building, the impact is much larger: increasing the voting quorum drops the implementation rate by 56 percentage points, and the average duration of the decision-making process increases by roughly seven months. From a modelling perspective, this result is expected. In the model, the voting quorum determines the proportion of agents that must vote in favour for a positive model step outcome. Increasing this proportion means that a larger share of the household opinions must align, making the voting outcome more sensitive to even a small number of opposing agents. This increases the likelihood of failed voting rounds, prolonging the overall process, and in more cases, preventing the VvE from reaching the required number of positive voting rounds before the two-year model limit is reached. Conversely, lowering the voting quorum reduces the alignment requirement between households and thus should increase the likelihood of a positive majority. This behaviour is spotted in the first building; however, the second building also sees a decrease in implementation rate with a decreased voting quorum. This behaviour is discussed further in the results discussion part.

While the increased voting quorum has a large impact on the implementation rate and decision-making duration in the simulation of the second building, the first building barely shows a change in implementation rate through this increased voting quorum level. This large difference in impact between the two buildings when increasing the voting quorum is explained by studying Figure 8 which shows observed voting percentage trends and different voting quorum levels. In the first building, increasing the voting quorum does, in most cases, not impact the implementation rate since the voting percentages of most voting sessions in this building are already well below the voting quorum. In the second building, this increase,

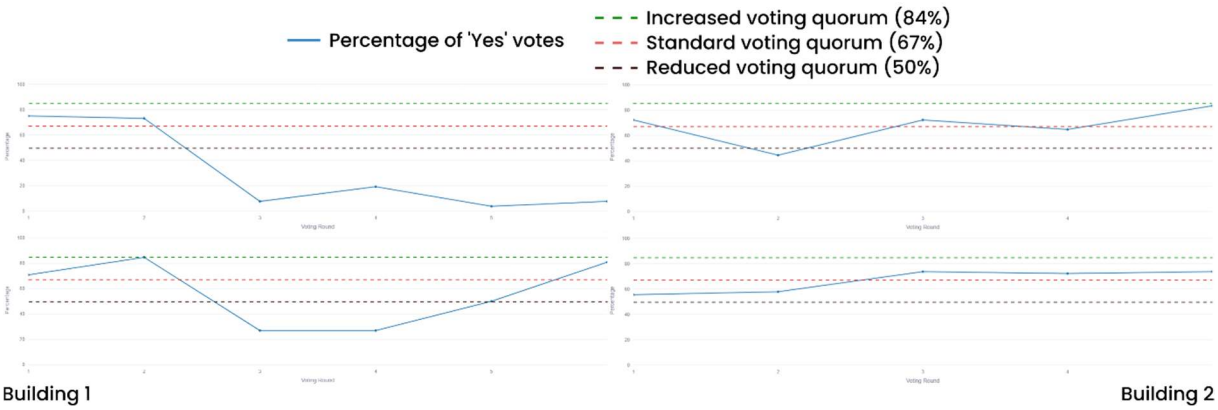

Figure 8: Observed Voting percentage trends and changing voting quorums of the two studied VvEs

however, causes many previously successful voting sessions to fall below the new threshold. Since in many voting sessions in the base configuration, the percentage of 'Yes' votes falls just above the voting quorum, this increased quorum ensures that this level of support is no longer sufficient to reach the required majority.

The initial opinion causes a large change to several of the result variables in both buildings. Lowering this factor by 25% for the first building lowers the implementation rate over the 500 runs to 0. While increasing it by the same percentage raises the implementation rate to 100%. The other result variables are also impacted significantly by these changes, with several of them also going to the minimum or maximum possible value. Similar results are shown for the second building. That this value is of such importance is not unexpected, being the basis on which decisions are made. However, the significance of this value and the impact this has on the model are surprising, especially since a new opinion is calculated for each agent in the beginning phase of the model, overwriting this variable. This factor's impact and possible alterations to reduce this are discussed later in this thesis.

The final 2 OFAT analysis results here concern the UNC_max and LNS_min thresholds. Changing these threshold values alters the distribution of decision-making strategies used by the agents. Only the LNS_min threshold is discussed here, since both thresholds influence the same underlying mechanism in a similar way, but changes in LNS_min have a stronger effect on the model outcome. Figure 9 shows the strategy chosen by each agent in the second building under the base LNS_min value and the two modified values. In these matrices, each dot represents an agent, based on its Uncertainty and current LNS value, with the four quadrants corresponding to the four Consumat strategies. The figure shows that the agents are positioned relatively close to each other, especially along the horizontal (LNS) axis. As a result, even a modest shift in the LNS_min threshold can move multiple agents to a different quadrant, changing the chosen strategies. For example, the number of agents selecting the Imitation strategy is 14 in the base configuration, 17 when the LNS_min is lowered, and 10 when this value is increased. This redistribution of strategies causes large changes to the implementation rate, decreasing by 84 percentage points in the second building through an increase in the LNS_min.

When multiple agents change their strategy, both their calculation method for determining their opinion and their strategy multiplier during the discussion phase change. For instance, an agent previously located in the Imitation quadrant, whose positive opinion is based on the generally positive opinions in the VvE, may shift into the Inquiring quadrant after increasing the LNS_min threshold. In that case, the agent will now base its opinion on the post-EER LNS values of itself and the other agents, instead of basing it on the opinion of others. If these LNS values are below 0.5, the agent's opinion may drop below the 0.5 threshold, turning a previously positive opinion into a negative opinion. A larger shift in the strategy distribution can thus create a larger group of agents opposing the EER, who in the discussion phase are less easily convinced of others' beliefs through their lowered strategy multiplier. Through the model's social influence mechanisms, these more negative opinions can then spread throughout the VvE, altering the collective opinion of the VvE, thus explaining the strong implementation rate reduction observed through a change in the LNS_min value.

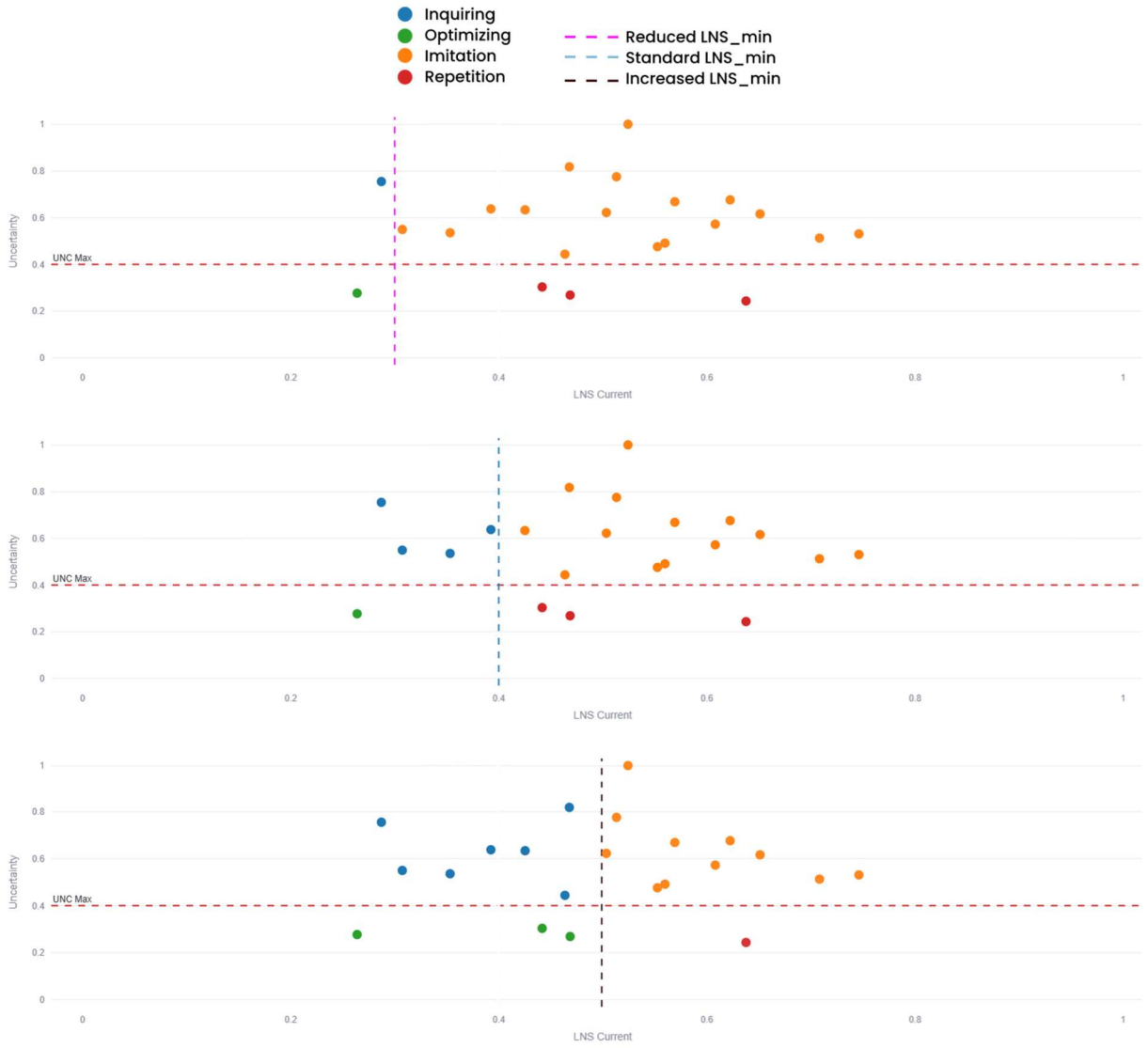

Figure 9: Matrices of strategy distribution under changing LNS_min values for Building 2

Scenario analysis

For the 5 tested scenarios, which are explained in further detail in 3.3.2, the implementation rate and average decision-making process duration under the different scenarios are compared with the base configuration of buildings. The variables covering the change in percentage of 'Yes' votes in the first and last voting rounds are not considered here, since it is more difficult to interpret how specific scenario changes would cause shifts in these voting percentages in real VvEs. In general, these values also fluctuate more strongly across model runs, making them less reliable indicators. For this reason, they were also discussed less extensively in the previous parts of this chapter. The results from these scenario analyses for both buildings can be seen in Table 24.

Table 24: Scenario analysis results

	Building 1				Building 2			
	% EER implemented		*Duration (months)*		*% EER implemented*		*Duration (months)*	
Scenario	*Avg.*	*St.dev*	*Avg.*	*St.dev*	*Avg.*	*St.dev*	*Avg.*	*St.dev*
Base config.	41.60	49.34	19.58	5.73	85.60	35.14	19.07	4.27
Extra loan	+6.20	+0.66	-1.03	+0.20	+0.80	-0.83	+0.02	+0.34
Extra subsidy and loan	+9.80	+0.69	-1.46	+0.22	+2.20	-2.38	+0.02	+0.23
Lowered quorums	+1.80	+0.27	-0.26	+0.10	-11.40	+8.65	-0.66	+1.13
VvE manager	+0.80	+0.13	+2.34	-2.19	-21.80	+12.96	-1.59	+3.59
Information campaigns	-18.60	-7.21	+4.23	-4.53	-3.40	+3.15	+1.00	+0.52

The first scenario, proposing higher loans at a lower interest rate, increases the implementation rate by 6 percentage points for the first building, while reducing the average duration by 1 month. For this scenario, the second building only experiences slight changes. The second scenario adds a grant of €2500 per household to the changes to the loan from the first scenario. Unsurprisingly, the results of the first building show similar results as in the first scenario, only with a slightly higher significance. The second building sees only a slight change to the implementation rate, which is also in line with the OFAT analysis of the grant variable for this building.

The third scenario lowers the attendance quorum to 0% and the voting quorum to 51%, according to the plans made by the Ministerie van Volkshuisvesting en Ruimtelijke Ordening (2023a) for 2026. While the first building is not influenced much by the changing quorum levels, the second building does see significant changes in an unexpected direction. This behaviour under decreasing quorum levels was also spotted in the previous analysis. In the discussion part, this unexpected behaviour is discussed more.

The fourth scenario, implementing a VvE manager in the VvE, reduces the months taken per collective phase as well as the required rounds of yes votes to 2, and multiplies the received information parameter of the agents by 1.4. With these changes, different effects on the outcome of the model emerge for the 2 buildings. The first building experiences a slight increase in the implementation rate, while the second building's implementation rate decreases by 22 percentage points. Furthermore, the first building has an increased average duration of 2.3 months, while the second building has a reduced average duration of 1.6 months.

The final scenario focuses on the implementation of information campaigns. These campaigns increase the received and looked-up information of the members, while also increasing the base trust factor, indicating agents perceive other agents as having a higher level of expertise, due to their increased information accumulation. This scenario only reduces the implementation rate and increases the average duration for both buildings.

5.2. Results discussion

The OFAT analysis results show a clear difference between the two studied buildings. While both share the same decision-making framework with the same model parameters, the differing variables of the households, VvE and the implemented EER ensure that the first building only implements the EER 41% of the time, while the second building nearly always votes for implementation with an 85% implementation rate. Looking at the difference in the characteristics of the two buildings, some clear distinctions are noticed. An important difference between these two buildings is the initial opinion of the respondents in the survey. Respondents could give their opinion regarding the proposed EER on a 0 to 10 scale, where 0 indicates the household is fully against the EER, and with a 10, the household fully supports its implementation. The respondents of the first building have an average initial opinion of 6.1, while those in the second building have an average opinion of 8.2. After filling in the opinion of the missing respondents with a medium-level opinion of 5, the difference between the average opinions of the two VvEs is lower, with the first VvE's opinion being 5.2 and the second VvE's opinion being 5.4. However, the high impact a change in this factor has on the implementation rate of the model, as shown in the previous section, does partly explain the large difference in implementation rate based on the small difference in initial opinion.

Furthermore, the financial reserves available by the second VvE are nearly twice as high as for the first VvE, while the number of VvE members in the second VvE is lower. Where, for the first VvE, approximately €3700 is available per household from the savings account to invest in the VvE, in the second VvE, each household has approximately €11000 available to spend on the EER from this savings account. This difference does, however, also only partly explain the high implementation rate, since the impact on the model outcome when changing this variable is limited.

A third, and likely most determinant factor resulting in the high implementation rate of building 2 is the high gas saving of 22% experienced after EER implementation. Though the impact of a 25% increase in Table 23 does not show a large impact on the implementation rate caused by this variable, an additional diagnostic check was performed here to better understand the role of these energy-saving differences between the two buildings. Unlike the 25% change in the OFAT analysis, this check multiplied and divided the electricity and gas savings ratios by 3, thus reducing the 22% gas savings of the second building to a number closer to the 7% electricity savings of the first building, and vice versa. By multiplying the gas savings of the second building by a factor of 0.33, making it roughly equal to the electricity savings of the first building, the implementation rate over 500 runs decreases from 85.6% in the base configuration to approximately 3%. When multiplying the 7% electricity savings of the first building by a factor of 3, the implementation rate increases by 16 percentage points to 57%. These results imply that gas-related savings have a much stronger leverage on the implementation rate than similar electricity savings. Thus, next to the high expected savings of the EER for the second building, the fact that this building reduces gas usage instead of electricity usage also helps in achieving a high implementation rate. This difference in impact is explained by the difference in the cost and CO_2 production of these two energy types, where natural gas is more expensive and produces more emissions than electricity, both important factors in the LNS calculation.

This high cost and CO_2 production of gas also likely causes the surprising emerging trends regarding gas usage and savings. When altering these variables, the implementation rate decreases and the average duration increases. These results are counterintuitive and likely caused by the complex dynamics of the gas usage and savings, influencing both the cost and CO_2. To further explain this behaviour, the effect of these variables under other multiplication factors was analysed and plotted in Figure 10.

The gas usage trend can be explained by the fact that, at lower usage levels, the financial gains from the EER decrease, thereby reducing the perceived benefits. Conversely, at higher usage levels, CO_2 production rises sharply, which lowers the overall LNS value. This indicates that the building's current gas usage is close to an optimal level for EER implementation.

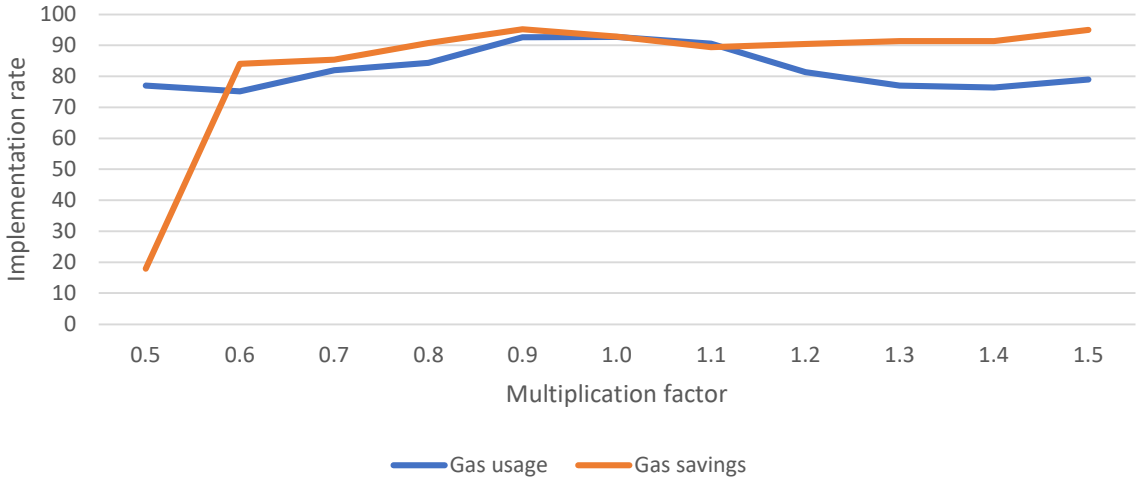

Figure 10: Gas usage and savings behaviour for Building 2

The gas savings variable shows a steep decline in implementation rate below a multiplication factor of 0.6. In this range, the reduction in energy consumption and CO_2 emissions of the EER no longer outweighs the high implementation cost of the EER. When gas savings increase beyond the level in the base configuration, the implementation rate remains relatively stable because the already high adoption level leaves little room for improvement. However, at a multiplication factor of 1.5, the implementation rate rises slightly above the baseline by 2.2 percentage points. Since most members are already convinced of the EER's benefits, only a substantially higher gas saving can persuade the remaining sceptical agents.

Two scenarios perform unexpectedly. Firstly, the VvE manager scenario reduces the implementation rate of the second VvE by 22 percentage points, while also reducing the average decision-making process duration by 1.6 months. The first building shows different results, with no significant change in the implementation rate and an increase of 2 months in the average duration. The information campaign scenario also shows surprising results, reducing the implementation rate and increasing the decision-making duration for both buildings. These counterintuitive outcomes arise from how knowledge is implemented in the model.

In the model, increased knowledge reduces the uncertainty of an agent, influencing their chosen decision-making strategy and strengthening their influence during the discussion rounds. However, this process applies equally to agents with positive and negative opinions, because the model does not distinguish between knowledge highlighting the benefits and the downsides of the proposed EER. As a result, the same modelled knowledge gain not only increases the confidence of agents supporting the EER but also strengthens the beliefs of those who oppose it. These better-informed agents can then convince more agents of their negative opinion during the discussion phase. In addition, lower uncertainty causes some agents to shift into different decision-making strategies, which changes both how their opinions are calculated and how strongly they are influenced in the discussion phase. Thus, increasing the knowledge level can greatly impact the collective decision-making process; however, because the model treats all knowledge as neutral rather than opinion-specific, the direction of this impact depends on the initial distribution of opinions and on the discussion pairs that are formed.

This mechanism explains why the two knowledge-based scenarios can produce negative effects in the model, even though these interventions would not be expected to reduce the support for an EER in reality. Information provided through a VvE manager or an information campaign would focus on the positive effects of the EER, and thus would unlikely reinforce the negative beliefs of agents. The two scenarios differ mainly in the strength of the knowledge increase, where the information campaign increases the overall knowledge level of households more than the VvE manager scenario. This will reduce the Uncertainty level of agents more, amplifying the negative opinions more, resulting in more failed voting sessions and a longer decision-making process. The reduced number of voting rounds and collective phase duration in the VvE manager scenario partly offset this effect in the second building, which sees a reduced decision-making duration.

While the analysis, due to the way the knowledge mechanism is modelled, does not show any promising results for the VvE manager scenario, talks with experts gave different insights. Through the insights of the expert interviews, this possible policy intervention will now be discussed more in-depth.

Through an interview with a VvE manager, it was mentioned that many other VvE managers lack the knowledge, intent or persistence to guide VvEs through the difficult process of EER adoption. A representative of the Municipality of Utrecht told a story of a VvE which, over the course of several years, had been advised by their manager to paint all their window frames annually, depleting their savings account and leaving almost no funds when the topic of sustainable renovation entered the agenda. Because VvEs tend to trust their manager's guidance, their competence and priorities can either delay or accelerate the EER process of VvEs.

A Belgian company training VvE managers helped in comparing the institutional differences of VvE managers in the Netherlands and Belgium. The requirements for becoming a VvE manager in the Netherlands are not strict, lacking any mandatory licenses, education or expertise by law. In Belgium, a VvE manager has to be registered and complete an internship before being allowed to start, raising the knowledge and credibility of the VvE manager.

Luckily, some VvE managers in the Netherlands are becoming increasingly proactive in supporting sustainable renovation. The second building studied in this thesis was helped by their VvE manager throughout the process, and indicated their involvement helped at several stages of this process. However, not all VvE managers are willing or able to assume this role, and those that do charge additional fees per meeting or raise the annual cost. Given that VvEs already face substantial EER costs, these extra management costs can easily become a barrier for the VvE's members. Governmental financing of VvE manager involvement could help in lowering this barrier. Combined with mandatory training programs for VvE managers, these managers could provide a much-needed boost to the EER transition of VvEs.

Another scenario tested in this research, the lowered voting and attendance quorum scenario, produced outcomes that diverged from the earlier expectations, expecting that it would positively influence the implementation rate and reduce the model duration. While the scenario in earlier runs performed during this research revealed small increases in the implementation rate for both buildings, as would be expected, a final analysis run suddenly showed an unexplainable reduction in the implementation rate under lowered quorum levels for the second building. This effect appears to arise from the stochastic mechanisms in the model, where different analysis runs with different discussion pairs create differing results under this scenario. However, due to the last-minute discovery of this result, the cause of this effect could not be studied further; thus, for now, no further explanation can be given for this behaviour.

The scenario tested whether removing the attendance quorum and lowering the voting quorum to 51% could substantially increase the likelihood of a successful EER implementation. These lowered threshold levels reflect one of the major new regulatory reforms the Dutch government plans to introduce in 2026. In the ABM, these thresholds are implemented in a simplified way. The attendance quorum determines whether the attendance rate of the first meeting is sufficient to hold a voting session; otherwise, the meeting is postponed by one month and repeated with the same members and the same opinions as in the first meeting. The voting quorum determines how the individual decisions of the households are translated into a collective decision, where the percentage of positive opinions must be equal to or higher than the voting quorum for the round to count as a positive outcome. If this is the case, this voting round's collective decision is to implement the EER; if the quorum is not met, the collective decision is to not implement the EER.

The implementation of the quorum rules reflects their formal function but does not influence any behavioural mechanisms in the model. In reality, with a high attendance quorum, such as 71% in the second VvE, board members will actively try to convince all VvE members to join the voting session. Lowering or removing this attendance quorum reduces this incentive, potentially lowering attendance and altering which opinions are represented during voting. Similarly, changing the voting quorum can also increase or reduce the active promotion of the benefits and downsides of the EER by both those promoting the implementation of the EER and those opposing it. In the model, however, quorum levels are purely procedural checks: they do not affect attendance behaviour or the formation of individual opinions. Lowering or increasing these thresholds, therefore, only changes whether a meeting is cancelled or

whether the round's outcome is classified as a positive or negative collective decision, but not how many positive or negative votes are cast.

Nevertheless, VvEs with a lower attendance rate than observed in the VvEs studied in this research would likely benefit from abolishing the attendance quorum, as this would prevent repeated meeting cancellations. The low attendance rates were also indicated by several of the interviewed experts as one of the main barriers for VvEs during the EER decision-making process. Furthermore, VvEs that are more evenly divided in their opinions than the two studied cases would be more strongly affected by lowering the voting quorum, as decisions could then pass with a smaller base of supportive members.

Finally, although this lowered voting quorum could help some VvEs to accelerate their decision-making, it also raises a concern about procedural fairness. By allowing that only 51% of the votes at a meeting session need to support the EER, situations can occur where 49% of the VvE's members would prefer not to implement the EER. While the negative opinion of these members is sometimes based on misinformation or a lack of knowledge, it is also often grounded in the household's financial inability to pay for the renovation. With the current higher voting quorum levels, situations already occur where households have to move out due to the increased cost of the EER implementation. By lowering this voting quorum, such situations may become more frequent, raising the question of whether accelerating the decision-making process through this measure constitutes a fair and justified regulation.

6. Model limitations and Recommendations

In this section, limitations of the current model are discussed, providing potential points of improvement for future studies in this field of research. Furthermore, recommendations are made for potential new mechanisms that could be added to similar ABMs to further enhance the realism of ABMs modelling the collective decision-making of VvEs regarding EER adoption.

6.1. Model limitations

After extensive model use and sensitivity analyses, flaws in several mechanisms driving the processes in the model were discovered. An important flaw is the large influence of the initial opinion of an agent on the outcome. Though this would not be a flaw if the initial opinion of all agents in the model were known, as is the case for the agents based on real data, filling in the initial opinion for the generated agents greatly influences their final opinion as well as the final opinion of other agents. Through two mechanisms in the model, an agent bases its state on the opinion of others. Both when determining their uncertainty, for which the difference between the agent's initial opinion and the general opinion in the VvE partly determines how uncertain they are, as well as when an agent chooses the decision-making strategy Imitation. Though these mechanisms are modelled based on theories and previous studies and behave as expected in most phases of the model, in the first voting round, the opinions used in the calculation are these filled-in opinions that are not based on empirical data. To reduce the impact of the variable, for each generated agent, the initial opinion was set at a neutral opinion level of 5. This ensured that the VvE did not have a strong negative or positive consensus before the model was even run, giving the agents the chance to decrease or increase their opinion from this neutral starting point. However, a more realistic alternative when working with generated agents would be to omit any initial opinion and let the agent determine this at the start of the model before it is used in any other mechanisms. An attempt was made to remove the impact of the initial opinion at a late stage in this research, when the significant impact of it was noted, by ensuring that in the first step, the uncertainty of an agent was only based on its knowledge, and certain decision-making strategies, namely Repetition and Imitation, could not be chosen. For the following steps, the original mechanisms were followed; since then, the agent had determined their new opinion themselves. This, however, did not make the results any more realistic, drastically changing the uncertainty and decision-making strategies of agents, and resulting in decisively lower implementation rates for both buildings.

The large impact that the decision-making strategy chosen by an agent has on their opinion is another limitation of the model. The UNC_max and LNS_min thresholds were both set at 0.4, since these values ensured the model mimics the VvE's real outcome the best. Whether the distribution of strategies resulting from these threshold values reflects reality is hard to confirm, since no data was gathered on households' preferred decision-making strategy. However, previous studies show that many VvE members have insufficient knowledge regarding the EER, therefore requiring key figures or a sustainability committee they can listen to (Hilhorst, Doms, Martens, & Bak, 2023). This type of socially guided behaviour corresponds with the Imitation strategy, which is also the most frequently used strategy by households in

both VvEs in the base configuration. Furthermore, Tiellemans, Kemperman, Maussen, & Arentze (2022) indicate that many VvE members are willing to make concessions to reach a collective decision. This behaviour aligns with the Inquiring strategy, which is the second-most used decision-making strategy by the simulated households.

While the threshold values in the base configuration thus ensure the VvE somewhat resembles real behaviour, the sensitivity analysis shows that a slight change in these threshold values will drastically change the outcome of the model. This sensitivity could be decreased by replacing these hard LNS and UNC boundaries with graded transitions. With this in place, an agent located around the UNC_max boundary between the Repetition and Imitation strategies in the LNS-UNC matrix would then base its opinion partly on its previous opinion and partly on the opinion of others in the building. If the agent is, however, placed further from this UNC_max boundary in the matrix, its opinion will be based more on either of the decision-making strategies. This could be extended even further by always basing each agent's opinion on the four decision-making strategies formulas, where the impact of each strategy on the agent's final decision is based on its position in the LNS-UNC matrix. In the updated version of the Consumat model by Jager & Janssen (2012), a similar mechanism is proposed, working with chances to create a continuum of decision-making strategies.

A third limitation of the model is the way the financial decision of agents is modelled. In the model, an agent determines their current available finances based on the VvE's savings account and a part of their own savings, both of which are updated through the monthly contribution of VvE members and an amount these members are willing to save monthly for the investment. Any potential loan or grant and the future energy savings are subtracted from the implementation cost of the EER, which is then compared to the available finances of a household. However, in reality, the financing structure of an EER within a VvE differs substantially from the modelled mechanism. The EER is paid solely by a portion of the funds in the VvE's savings account, while a loan from the Warmtefonds covers the missing funds. The amount and duration of this loan determine the interest rate and the size of the monthly repayments the VvE has to make to the Warmtefonds. The VvE members thus do not finance the EER personally from their own savings; instead, the monthly VvE contribution is increased so the monthly loan repayments can be paid by the VvE's savings account. In many cases, this increases the VvE contribution drastically, often doubling the contribution over the course of several years (Steenkamp, 2024). This system reduces the initial financial burden on VvE members compared to the modelled approach, spreading costs more evenly over time. When the impact of this difference on the financial situation of households was discovered, the surveys had already been sent out, and thus did not collect the data required to correctly model this alternate system.

Another limitation appears with the voting quorum level, as explained in the discussion of the scenario results. A decrease in implementation rate is measured for the second building under reduced quorum levels. However, the cause of this unexpected change was not determined due to the last-minute discovery of this behaviour. A contributing factor may be the strong stochasticity of the model, where repeated discussion pairings and social influence dynamics can amplify small variations across runs. In retrospect, the absence of a "no-interaction" model

makes it difficult to identify whether this deviation arises from the model's social influence mechanisms or from the implementation of the voting quorum mechanism itself. Creating such a model, where agents decide solely based on their own preferences and situation, could have clarified the cause of the observed behaviour of the voting quorum. Furthermore, such a "no-interaction" model could also have helped in better understanding the observed behaviour of other variables where significant changes or unexpected behaviour were observed.

6.2. Model recommendations

Some mechanisms were not included in this model, either to reduce its complexity or because the potential of these mechanisms was discovered in a late stage of this research. These recommendations for future ABM studies in this field of research are mentioned here. Furthermore, a recommendation is given for other studies trying to gather empirical data from VvEs.

As mentioned in the discussion of the scenario analysis, the knowledge factor is modelled in such a way that the impact of certain scenarios is not represented realistically in the model. Since a knowledge gain decreases the uncertainty of any agent, no matter their opinion, information campaigns focusing on the benefits of an EER also reduce the uncertainty of agents fully opposed to the EER. It would be better to model this uncertainty mechanism differently, allowing the differentiation between multiple types of knowledge gain and their impact on different agents.

Another interesting and beneficial addition for future ABMs in the field would be the inclusion of VvE managers in the model. This could either be done by adding these managers as a separate type of agent, impacting the mechanisms driving the decision-making process of households and the VvE as a whole, or by more implicitly including the impact a VvE manager has on the members throughout the model's framework.

A third potential extension concerns the inclusion of owners who do not inhabit their apartment. Many VvEs contain a substantial share of units rented out by external owners, such as housing associations or private investors. The renters of these units were not included in this model since they are not formal members of the VvE and do not participate in the decision-making process. This voting right is reserved for the external parties owning the rented-out apartments, whose decision-making logic fundamentally differs from that of owner-occupants. They do not experience the comfort improvements of the home, are not part of discussion networks within the building, and are typically motivated primarily by long-term financial returns.

Within the types of external parties, differences regarding their influence on the collective decision-making process are also observed. Owners with a small number of apartments owned in the buildings are less influential than housing associations, which can own the majority of apartments in the building. While some of the VvEs interviewed in this research indicated the housing association in their building simply agreed with the majority of votes in the VvE, others experienced active resistance from the housing association against the EER implementation,

thus making this external party their main barrier in the process. An interview with a housing association representative illustrated how these organisations apply portfolio-level prioritisations for EER implementation: buildings with poor energy labels, E, F or G, receive active support for renovation, D-label buildings are only considered if the VvE itself takes initiative, and higher-label buildings are often not considered. This shows that these parties can become important actors, based on the characteristics of the building and the VvE.

Including these external parties as a separate agent type would expand the representativeness of models for VvEs with mixed ownership structures. However, this requires a separate decision-making mechanism tailored to their financial and strategic considerations and a dedicated data collection method to gather the required empirical data. This last part can be challenging, where many VvEs indicate how difficult it is to reach these external parties, some not even aware of who these parties actually are.

A fourth potential inclusion to the model could be to make the Uncertainty mechanism more dynamic, further enhancing the social impact of agents on each other. In the Relative Agreement model, agents can also alter their uncertainty after a discussion with another agent (Deffuant, Amblard, & Weisbuch, 2004). This was not included in this model to slightly simplify the ABM and reduce the social impact experienced by agents through other households. However, by making the Uncertainty more dynamic, the discussion phase could further reflect the persuasiveness that highly certain agents have on those with a higher uncertainty.

A final part of this section focuses on the limitations experienced through the collection and usage of empirical data for this research. As could be read in the Data Collection chapter, low response rates were experienced for both studied VvEs, and other VvEs that were not included in this research only received responses from the board members of the VvE. This shows, as also experienced by many board members of these VvEs as well as experts in the field, that the interest of many VvE members regarding a possible EER is very low. Furthermore, the collection of several demographic characteristics of the household scared off a large part of the members who initially decided to start the survey, quitting after the first page of the survey. Though all data collected is anonymised, as is also clearly explained to the household through the board members and in the survey, many still were not willing to share their personal information required to run the model.

From the respondents who filled in the survey, a trend can be spotted where mainly the residents aged 65 years and older were willing to fill in the entire survey. This is likely due to the extra available time these retirees have, allowing them to invest more time into researching the benefits and downsides of the EER, raising their interest and awareness on the topic, thus increasing their willingness to share their opinion on the matter. During a workshop organised by VvE Belang, which was attended by the author, concerning effective communication within the VvE regarding the adoption of an EER, all other attendees were also elderly members of VvEs. Future research looking to reach high response rates through data collection among all members of a VvE would thus be advised to focus on VvE buildings with a high percentage of senior members, while also trying to reduce the quantity of personal data asked in the survey.

Through the gathered data of the VvE members who filled in the survey, the data of the missing VvE members was generated. This was done in Excel using normal distributions calculated based on the gathered data, often enriched through regional statistical numbers. Though this approach does create an agent base with similar opinions to other agents in the building, the low amount of gathered data, especially in the second building, lowers the realism of the generated agents. Furthermore, this method has limited capabilities in capturing correlations between different variables. A good alternative to this data generation method would be the use of AI data generation models. Such AI-based data generation methods could produce more realistic and internally consistent agent profiles by analysing and capturing the complex correlations between demographic, financial, and behavioural variables. This would improve both the representativeness and robustness of the model outcomes. However, due to limited time and a lack of knowledge on these models, for this research, manual data generation was conducted.

7. Conclusion

The study shows that the ABM developed in this thesis provides a clear explanation for why VvEs may experience the decision-making process for EER adoption differently. By capturing the main differences between the two case-studied VvEs, the model shows that the success of the collective decision-making process is determined through the interaction of social influence mechanisms, personal situations and preferences, the financial situation of the VvE and the potential benefits of the EER. By implementing different policy interventions, their potential in supporting faster and more reliable collective decision-making processes for VvEs in the Netherlands can be explored. The following sections elaborate on the scientific relevance of this thesis and the societal relevance for VvEs and policymakers.

7.1. Scientific relevance

This thesis contributes to the growing body of work studying EER adoption in households using ABM. It distinguishes itself by not only studying the decisions made by individual households, but also the collective decision made by VvEs on EER adoption. The scarcely available studies modelling collective decision-making of EER adoption failed to model the social dynamics in VvEs, simplified the procedural mechanisms of VvEs and did not use empirical data, a research gap this thesis tried to fill.

By combining the proven and tested Consumat framework and the Relative Agreement theory into one model, individual and collective decision-making processes, as well as social interaction procedures, are modelled into one ABM. The mechanisms of the model were based on experiences of professionals in the field of VvE and EER adoption, and the model was tested using empirical data gathered from two case-studied VvEs. This use of empirical data and interviews with experts proved highly helpful in understanding and modelling the intricate processes of VvE decision-making. This research method increased the credibility and interpretability of the simulated outcome, providing a replicable structure for future studies in the field.

When testing the model with the empirical data, the emerging outcomes align with the situation of the case-studied VvEs. However, a sensitivity analysis shows unexpected behaviour of several variables of the model, where a small change in these variables impacts the outcome of the model disproportionally. For this, improvements are proposed which could reduce these impacts, further increasing the credibility of the model. With these changes in mind, it can be concluded that the combination of decision-making and social interaction mechanisms in this ABM provides a strong basis for understanding how complex collective decisions emerge in VvEs.

7.2. Societal relevance

The goal of this research was to answer the following research question:

How do socio-demographic, financial, regulatory, social and building-specific factors influence collective decision-making on energy-efficiency improving renovations in Dutch homeowners' associations (VvEs), and how can Agent-Based Modelling help identify effective strategies to overcome collective decision-making deadlocks?

The research shows that financial capacity is an important factor, though not decisive, for determining the success rate of decision-making processes of EER adoption in VvEs. Regulatory conditions, such as the voting and attendance quorum, impact the studied VvEs slightly, where especially a lowered voting quorum shortened the average decision-making duration and increased the implementation rate in some cases. Factors shaping the frequency and impact of social interaction show mixed results, where an increase in the base trust level at times increased and other times decreased the implementation rate. This is caused by the fact that, in this model, as also is the case in the real world, discussions between agents can either improve or decrease the opinion of an agent regarding EER, based on the initial opinions of the agents. Finally, building-specific factors such as energy usage and the possible effects of the proposed EER had differing but often large impacts on the model outcome. Especially the gas usage and potential gas savings had large and at times contradicting impacts, caused by the large potential reduction of CO_2 production and energy cost of natural gas. Furthermore, due to the frequent and central usage of an agent's uncertainty regarding their opinion, measures reducing this uncertainty, such as increased knowledge, significantly impacted the decision-making process.

Several policies which are often used or proposed by Dutch policymakers regarding increased EER adoption of VvEs were implemented in the model and tested. This showed a large potential in policies focusing on reducing the financial burden of EER implementation, reducing average decision-making duration and increasing the implementation rate among VvEs. A policy focusing on reducing the attendance and voting quorum of VvEs showed mixed effects, at times contradicting the expected behaviour. The other tested policies, focusing on knowledge gain regarding the benefits of an EER, did not produce positive results, which is explained by the model's inability to distinguish between positive and negative information regarding an EER.

Beyond the analytical value provided, this ABM also carries potential practical relevance. The interactive dashboard developed for this thesis (Appendix 4) already demonstrates how stakeholders can immediately visualise the effects of different policy interventions on the decision-making outcomes of VvEs. The current dashboard can already easily be interpreted and used, without requiring any knowledge of coding or an ABM, allowing users to explore how changes in financial support measures, regulatory thresholds or social-interaction parameters influence the decision-making process. While the current version of the ABM still has some limitations, a further developed dashboard could become a valuable tool for municipalities and VvE boards when combined with future ABMs in this field. This tool could support participatory workshops, enabling stakeholders to experiment with alternative policy configurations and observe their effect on the VvEs' decision-making process.

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AI tools were used in a limited and supportive manner throughout this research. Most of the code used to create the Streamlit web application was created with the help of AI, specifically GitHub Copilot. Since the author had no experience with the coding of these web pages, and it will only be used to visualise the results, AI use was deemed appropriate for this specific use case. Furthermore, Copilot was used occasionally for the other codes to help in refining code components. In addition, ChatGPT was used to improve the academic writing style of this thesis.

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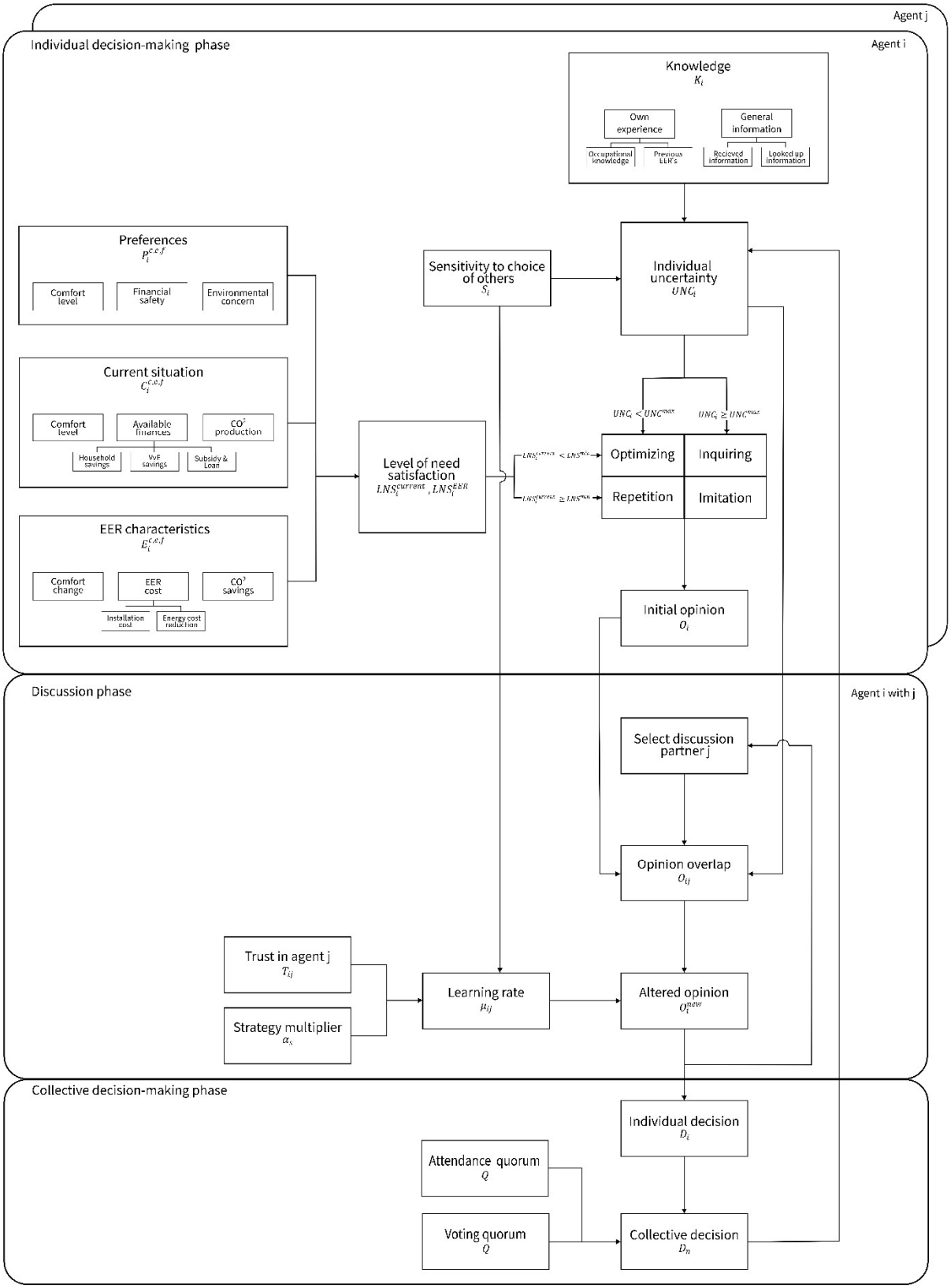
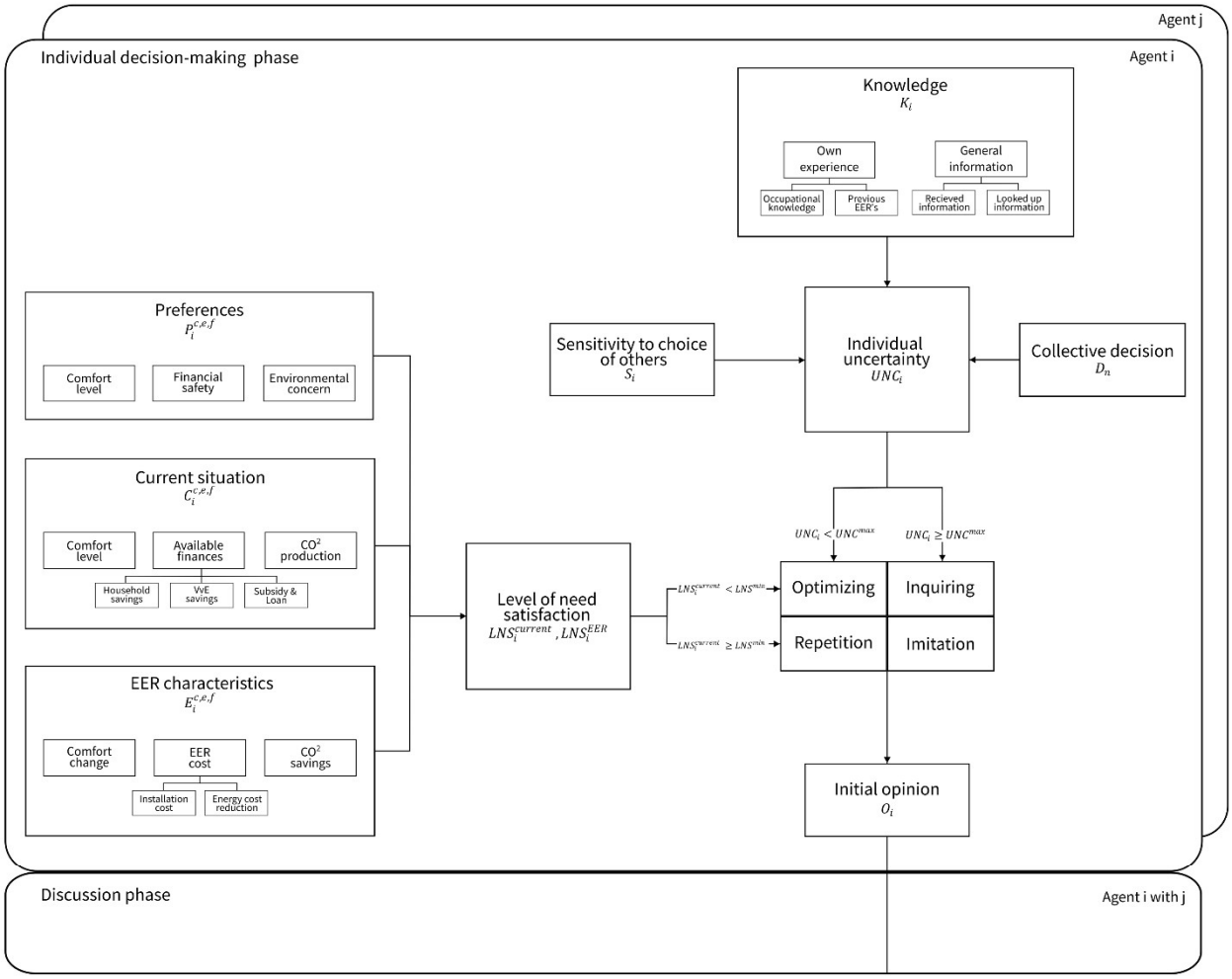
Appendices

Appendix 1: System architecture

1A: Total system architecture of the ABM



1B: Zoom in on the Individual phase of the System architecture of the ABM



Formulas

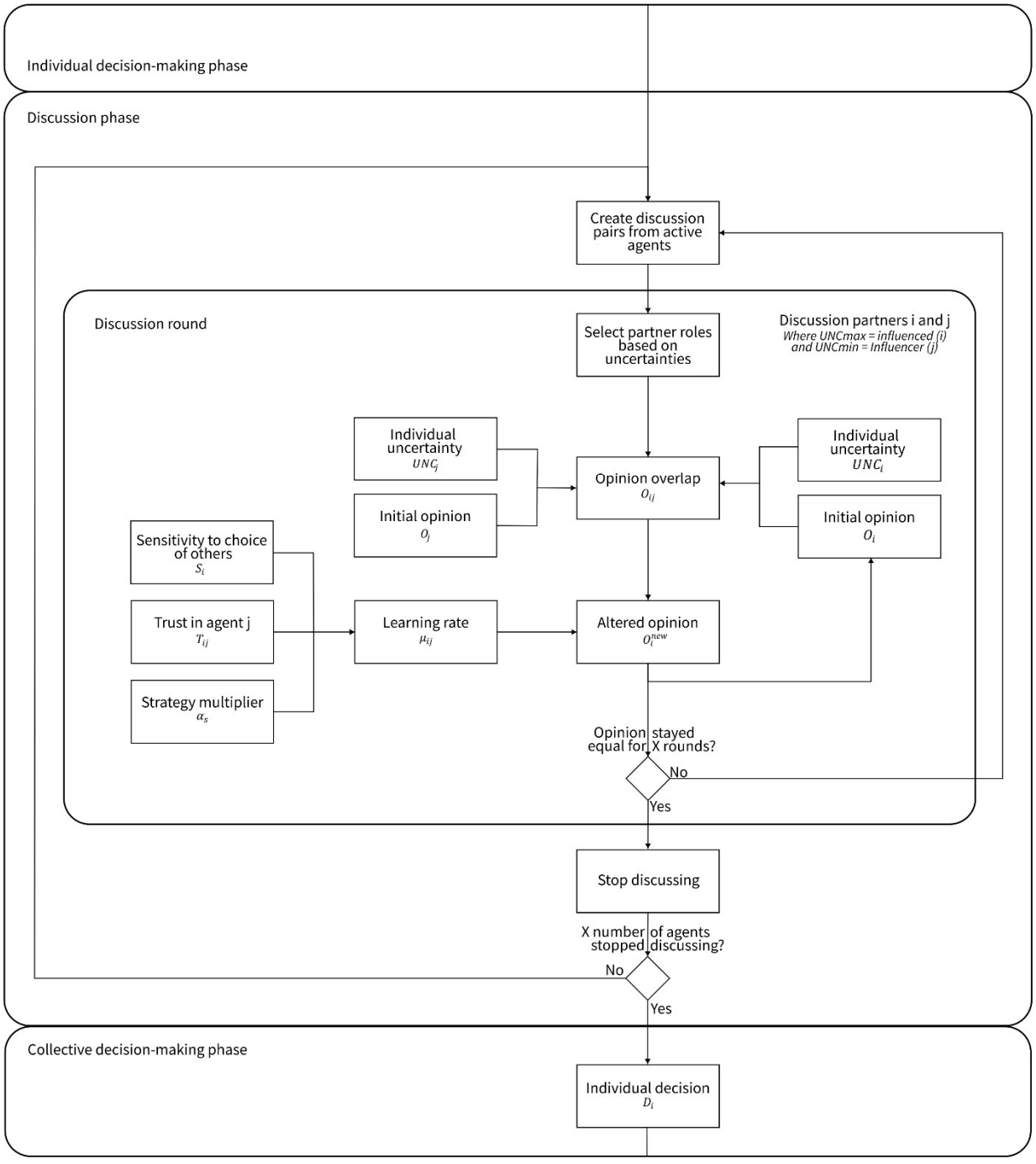
$$LNS_i^{current} = P_i^c \times C_i^c + P_i^e \times (1 - C_i^e) + P_i^f \times C_i^f$$

$$LNS_i^{EER} = P_i^c \times (C_i^c + E_i^c) + P_i^e \times (1 - (C_i^e - E_i^e)) + P_i^f \times (C_i^f - E_i^f)$$

$$UNC_i = (1 - K_i) \times (\left| \overline{D_n^{prev}} - D_i^{prev} \right| \times S_i)$$

$$O_i = \begin{cases} \sigma\left(\frac{LNS_i^{EER}}{LNS_i^{current}}\right), & if\ Optimizing \\ O_i^{prev}, & if\ Repetition \\ (1 - S_i) \times LNS_i^{EER} + S_i \times \overline{LNS_{n\ close}^{EER}}, & if\ Inquiring \\ \overline{O_{n\ close}^{prev}}, & if\ Imitation \end{cases}$$

1C: Zoom in on the Discussion phase of the System architecture of the ABM



Formulas

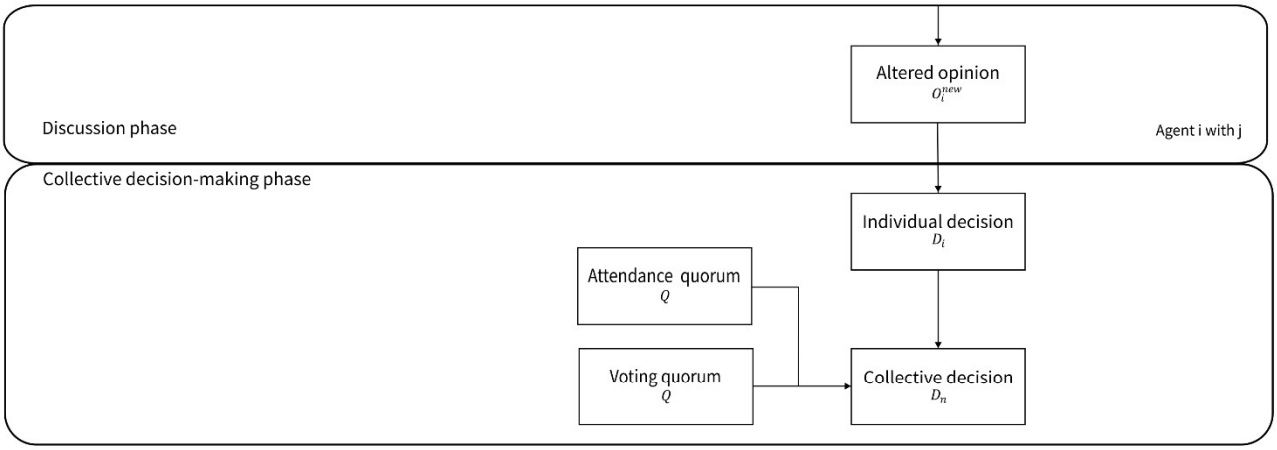
$$O_{ij} = \min\left(O_i + UNC_i, O_j + UNC_j\right) - \max(O_i - UNC_i, O_j - UNC_j)$$

$$O_i^{new} = O_i + \mu_{ij}\left(\frac{O_{ij}}{UNC_j} - 1\right) \times (O_j - O_i)$$

$$\mu_{ij} = \mu_0 \times T_{ij} \times S_i \times \alpha_s$$

$$\alpha_s = \begin{cases} 0.3, & if\ Optimizing \\ 0.15, & if\ Repetition \\ 0.6, & if\ Inquiring \\ 0.8, & if\ Imitation \end{cases}$$

1D: Zoom in on the Collective phase of the System architecture of the ABM



Formulas

$$D_i = \begin{cases} 1, & if\ O_i > 0.5 \\ 0, & if\ O_i \leq 0.5 \end{cases}$$

$$D_n = \begin{cases} Yes, & if\ \overline{D_n} \geq Q \\ No, & if\ \overline{D_n} < Q \end{cases}$$

Appendix 2: Model parameters

2A: Model parameter overview

Variable	*Description*	*Initial value base configuration*
Max months	Nr. of months before the model stops	24
Months per discussion round	Duration of a round where all agents choose and discuss with another agent	0.25
Months per Collective Phase	Months taken to plan and execute a voting session	3
Required Yes rounds	Nr. of positive voting rounds before the model stops	3
Attendance Quorum	Attendance quorum, overruling the VvE's quorum	0%
Voting Quorum	Voting quorum, overruling the VvE's quorum	0%
UNC_Max	Value used in determining the agent's strategy	0.4
LNS_Min	Value used in determining the agent's strategy	0.4
Interest threshold	Threshold Uncertainty value above which an agent is not interested	0.75
Base learning rate	Multiplication factor of an agent's learning rate	5
Base Trust factor	Agents' trust in agents not in close connections	0.4
Partner Chance	The chance that an agent chooses a close connection as a discussion partner	0.66
No Change stop	Nr. of discussion rounds with an unchanged opinion before an agent stops discussing	4
Active Agents Threshold	Threshold of active agents over total interested agents, below which the discussion phase ends	0.5
Time Horizon	Nr. of years from which the EER's energy savings are subtracted from the EER cost	20
Electricity-CO_2 ratio	Kg of CO_2 produced per kWh of electricity	0.33
Gas-CO_2 ratio	Kg of CO_2 produced per m^3 of gas	2.13
Electricity-Cost ratio	€ paid per kWh of electricity	0.27
Gas-Cost ratio	€ paid per m^3 of gas	1.33
CO_2 Ratio	Ratio by which the agent's real yearly CO_2 production is converted to a number between 0 and 1	4931
Finance Ratio	Ratio by which the agent's real available finances are converted to a number between 0 and 1	17500
Use loan	Whether a loan from the Warmtefonds is used to finance the EER	True
Loan share	Share of the implementation cost covered by the loan	0.7
Loan interest	Interest of the loan, based on interest rates from the Warmtefonds	0.0369
Loan term	Repayment duration of the loan in years	20
Grant per dwelling	€ received per household as a subsidy	0

2B: Sources and calculation explanations of model parameters

Electricity-CO_2 ratio: Based on CO_2-emissiefactoren.nl (2024b)

Gas-CO_2 ratio: Based on CO_2-emissiefactoren.nl (2024a)

Electricity-Cost ratio: Based on Centraal Bureau voor de Statistiek (2025a)

Gas-Cost ratio: Based on (Centraal Bureau voor de Statistiek, 2025a).

CO_2 ratio: Used to convert the energy usage of the agents from kWh to a number between 0 and 1. Chosen in such a way that an average Dutch household would get a value of 0.5. Based on data from Milieucentraal.nl (2023), an average Dutch apartment of 2 or more persons uses 840 m^3 of gas and 2050 kWh of electricity. Converted using the aforementioned ratios, an average household produces approximately 2465 kg of CO_2 from its gas and electricity usage. By multiplying this number by a factor of 2, this value is set at 4931. By dividing a household's CO_2 production by this number, a household producing this average amount of CO_2 would get a value of 0.5 for its CO_2 production.

Finance ratio: Used to convert the available finances of the agents from € to a number between 0 and 1. Chosen in such a way that an average Dutch household would get a value of 0.5. This number is based on the available savings of the household and the available money in the VvE's savings account. For this, the gathered data of the studied VvEs is analysed. In these buildings, the average available finances per household was €8750; multiplied by 2, this results in the Finance ratio of €17500.

Loan interest rate: Based on a standard loan at the Warmtefonds for a term of 20 years, at 3.69% (Nationaal Warmtefonds, 2025a).

Loan share: Based on the size of the loan taken by one of the studied VvEs.

Appendix 3: Interview and VvE contact lists

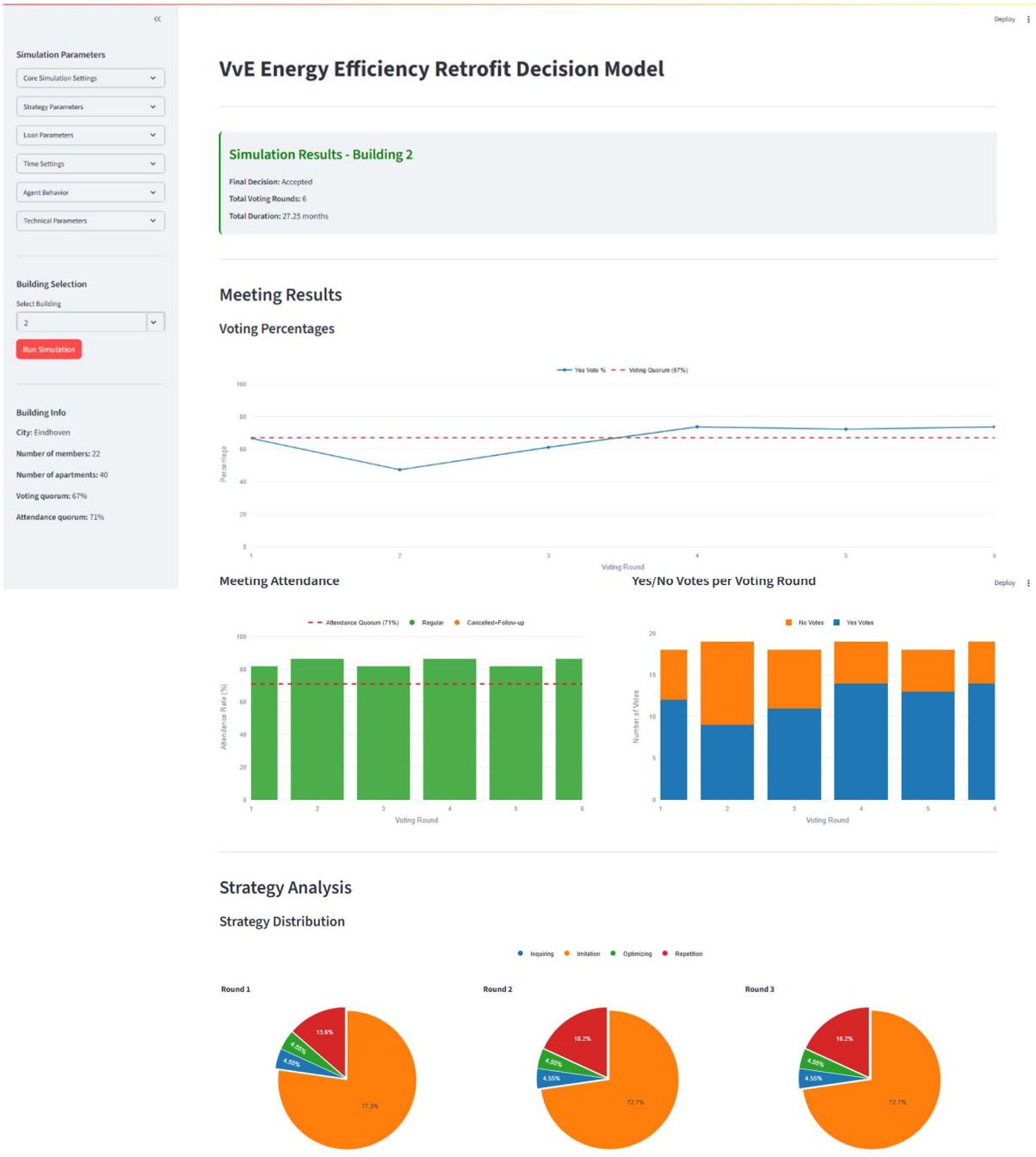
3A: Expert interview summary

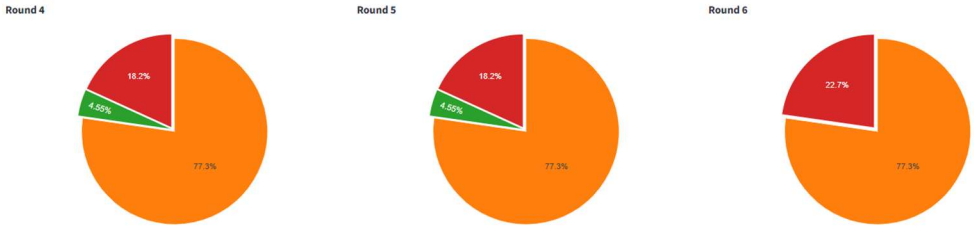
Type of Company	*Perceived main barrier to VvEs*	*VvEs sent*	*Channel*
EER advisor and process coordinator	Low perceived benefits for most resident types	-	Teams
VvE support organisation	-	-	Teams
VvE manager	Extra cost for VvE manager involvement	1	Teams
EER advisor and process coordinator	-	-	Teams
VvE manager trainer	VvE manager expertise	-	Teams
Academic engineering support group	-	2	Email
Sustainability advisor	-	2	Conversation
VvE manager	-	1	Teams
Project manager	Interest and attendance rates	-	Teams
Building contractor	-	-	LinkedIn
Project manager	-	-	LinkedIn
Construction management	-	-	Teams
Law firm	Interest and attendance rates / Intricate regulatory and legal processes	2	Teams
VvE support organisation	-	-	Email
Housing affordability foundation	-	-	Email
Sustainability consultancy	-	-	Conversation
Construction consultancy	-	-	Call
Regional government	-	-	Email
Energy-transition programme	-	-	Email
VvE support organisation	-	1	Conversation
National govermnent	-	-	Call
Regional government	VvE manager expertise and lack of interest / Low local subsidies	1	Teams
Housing association	-	-	Teams

3B: VvE contact summary

Region	*Apartments*	*EER status*	*Participates*	*Contact via*
Eindhoven	48	-	No	Graduation supervisor
Eindhoven	-	-	No	Graduation supervisor
Eindhoven	-	-	No	Graduation supervisor
Arnhem	128	Stalled	No	Bouwkundewinkel
Eindhoven	-	-	No	Bouwkundewinkel
Amsterdam	22	Stalled	No	LinkedIn post
Groningen	48	Starting	Yes	LinkedIn post
Amsterdam	-	Stalled	No	De Advocaten van Riet
-	80	Stalled	No	De Advocaten van Riet
Utrecht	-	Stalled	No	Milieucentraal
Eindhoven	40	Complete	Yes	VvEco
Eindhoven	59	Complete	Yes	VvE Platform040
Den Haag	43	Starting	No	Milieucentraal
Utrecht	42	Complete	No	Personal
Amsterdam	180	Complete	Yes	LinkedIn

Appendix 4: Streamlit web application screen capture

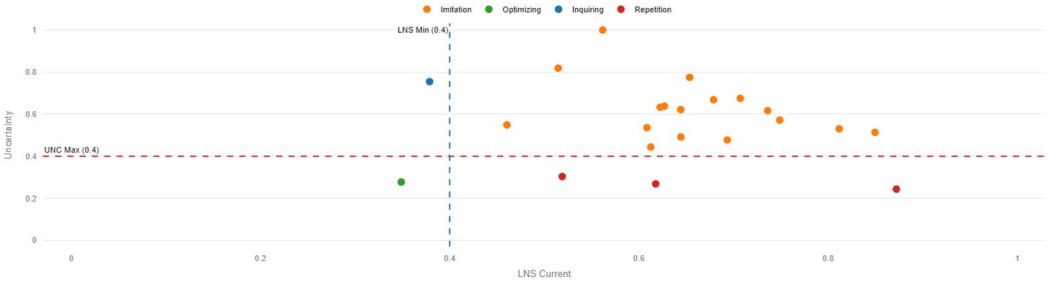




Level of Need Satisfaction and Uncertainty Quadrant Analysis

Select Voting Round

1



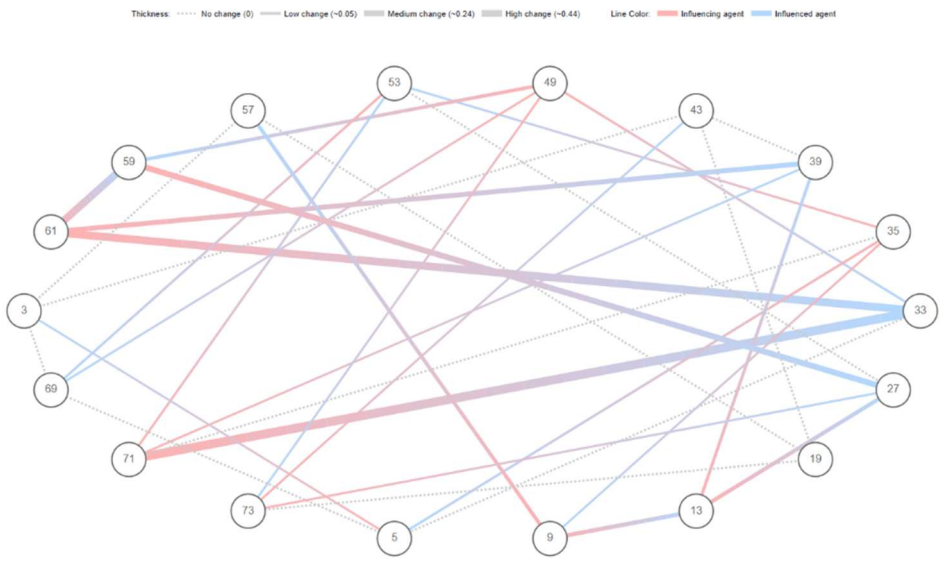
Discussion & Network Analysis

Deploy

Agent Discussion Network

Select Voting Round

1



Timeline

Deploy

Raw Data

Variable Evolution Over Time

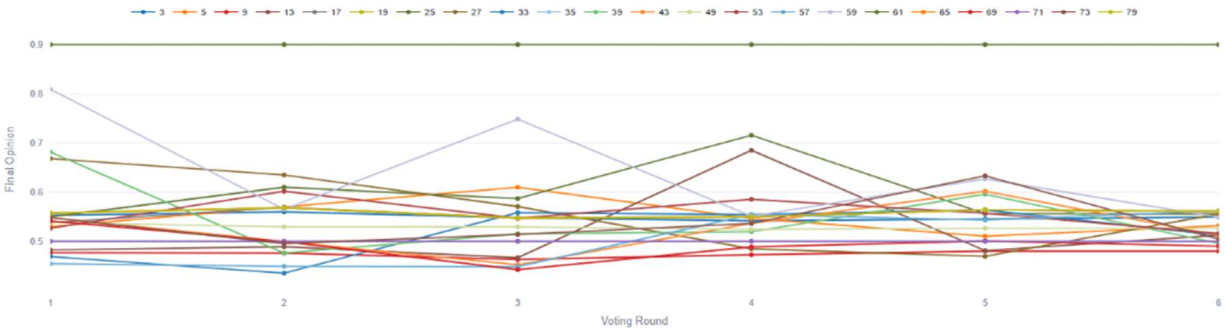
Select variable to display

Final Opinion

Select agents to display

All 40 agents selected

Show average line



Data Tables

Agent Data | Discussion Data | VvE Data

House number	Step	ID	Strategy	Uncertainty	LNS current	LNS EER	Comfort preference	Financial preference	Environmental preference	Comfort current	Post EER comfort	EER comfort	Financial current	Post EER financial	E
3	1	49	Imitation	0.53	0.812	0.745	0.2	0.2	0.6	0.689	0.789	0.8	0.623	0.189	
5	1	50	Imitation	0.491	0.644	0.62	0.637	0.258	0.105	0.664	0.772	0.8	0.623	0.24	
9	1	52	Optimizing	0.277	0.349	0.386	0.105	0.258	0.637	0.446	0.623	0.8	0.623	0.322	
13	1	54	Imitation	0.477	0.693	0.556	0.143	0.429	0.429	0.509	0.666	0.8	0.735	0.329	
17	1	56	Imitation	1	0.562	0.615	0.405	0.114	0.481	0.583	0.717	0.8	0.695	0.335	
19	1	57	Imitation	0.675	0.707	0.697	0.637	0.258	0.105	0.669	0.775	0.8	0.898	0.554	
25	1	60	Inquiring	0.755	0.379	0.388	0.072	0.279	0.649	0.564	0.704	0.8	0.627	0.311	
27	1	61	Imitation	0.669	0.679	0.607	0.333	0.333	0.333	0.619	0.741	0.8	0.736	0.347	
33	1	64	Imitation	0.638	0.627	0.389	0.143	0.714	0.143	0.594	0.724	0.8	0.645	0.272	
35	1	65	Repetition	0.269	0.618	0.508	0.455	0.455	0.091	0.423	0.608	0.8	0.765	0.337	