

Jesús Rosales-Carreón and César García-Díaz (2015)

Exploring Transitions Towards Sustainable Construction: The Case of Near-Zero Energy Buildings in the Netherlands

Journal of Artificial Societies and Social Simulation 18 (1) 10<<http://jasss.soc.surrey.ac.uk/18/1/10.html>>

Received: 30-Oct-2013 Accepted: 22-Jul-2014 Published: 31-Jan-2015



Abstract

This paper examines the use of qualitative information in the construction of an agent-based model in order to study the growth of near-Zero Energy Buildings (*nZEBs*) in the Netherlands through the innovation systems perspective. Drawing on desktop research and semi-structured interviews, this paper offers two major findings. First, we observed that the difficulties to the development of *nZEBs* have been shaped by interaction and institutional barriers: the inner complexity of the building sector has decisively impacted on the growth of *nZEBs*. Second, exploring interviewees' understanding of the system via an agent-based model has brought fresh insights about the problem. Overall, this is a call for an interdisciplinary approach to understand the changes required for *nZEBs* in their path for a successful adoption. Agent-based computational modelling, complemented with knowledge that was elicited from several stakeholders within the building sector, has helped to inspect the implication of common beliefs in the course of shaping possible futures toward a transition to *nZEBs*.

Keywords:

Agent-Based Model, Near-Zero Energy Buildings, Innovation Systems, Knowledge Elicitation, Systemigrams



Introduction

- 1.1 The EU (European Union) has developed the "Europe 2020" growth strategy, in which "climate change and energy sustainability" plays a crucial role as one of the five main targets (European Commission 2013). The EU has stated in "Europe 2020" the following ambitious goals: i) GHG (Greenhouse gas) emissions 20% lower in 2020 than in 1990; ii) 20% of energy from renewable resources; and iii) 20% increase in energy efficiency. From these objectives, both the first and the second ones have become a policy measure in the Netherlands (Verhagen 2012). The building sector accounts for 20% of the total energy consumption in the Netherlands (Menkveld & Beurskens 2009). Considering near-Zero Energy Buildings (*nZEBs*) as those with extremely low energy needs that largely depend on renewable resources, Directive 2010/31/EU Article 9 requests "Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings" (European Parliament 2010). Although the importance of energy-neutral housing is recognized by the Dutch government, in practice the construction of *nZEBs* has not become a reality (Faber & Hope 2013).
- 1.2 The transition from building traditional housing towards building *nZEBs*, however, is a difficult and complex process that goes beyond technological challenges. Furthermore, little is known about how this issue can be approached. Therefore, the challenges of *nZEB* development are numerous, including understanding the interests of the several actors that are part of the system. Not all actors involved in this transition discern problems in the same way (Newell 1990; Jorna 2006; Rosales-Carreón 2012). Consequently, the perception of barriers that impede the transition towards more energy efficient buildings may differ significantly from one actor to another.
- 1.3 One of the challenges lies in understanding the knowledge that actors possess and share, which has important implications on either facilitating or hindering the transition towards the construction of *nZEBs*. This paper examines, first, the way different actors perceive barriers that hamper the transition towards construction of *nZEBs* in the Netherlands. Second, it provides insights on how this knowledge is disseminated within the system. Given the pluralistic nature of the problem, we have approached the study from an interdisciplinary perspective. Interdisciplinary research integrates perspectives from two or more bodies of specialised knowledge to solve problems whose solutions are beyond the scope of a single discipline (Schoot-Uiterkamp & Vlek 2007). Therefore, this paper aims at integrating several perspectives (knowledge management, systems innovation, energy efficiency, and agent-based modelling (*ABM*)). From information gathered from different actors in the construction sector, we built a simple computational model that served as a vehicle to explore different scenarios for *nZEB* diffusion. The next section explains the proposed approach, which ultimately aimed at formulating a model that represents how relevant actors involved in *nZEB* construction interact.



Approach

- 2.1 This paper considers a systematic way of incorporating knowledge from several actors into an agent-based (AB) model that helps to explore possible scenarios for the diffusion of *nZEBs* in the Netherlands. The purpose of the model is not to faithfully capture all aspects and details of the Dutch building system. Rather, the purpose of it is to enrich our understanding of the key knowledge-related processes that are present within the system. We propose to structure the development of an agent-based (AB) model around six steps. First, the system and its boundaries must be clearly defined. Second, knowledge regarding how different actors represent the building system has to be elicited. The third step consists in identifying the barriers that impede the progress towards the edification of *nZEBs*. Fourth, after discussing the qualitative findings among experts (e.g., researchers), the model is formulated. The model is then shared and discussed with some stakeholders. The fifth step consists in carrying out different simulations once the model has been (internally) validated. Finally, the results are discussed in order to disclose important implications for the deployment of the innovation system. Figure 1 depicts the steps needed to build an AB model based on elicited knowledge.

Figure 1. Building process coupling knowledge elicitation with an agent-based (AB) model

Case Study: Near-Zero Energy Buildings in the Netherlands

- 2.2 Relevant frameworks for system analysis can be found in the literature on innovation systems. The innovation systems perspective has gained prominence in policymaking since the 1990s as it provides a qualitative explanation for the sources of innovation and economic growth that covers the role of policies and other institutions (Romer 1993). Different innovation systems concepts have been scrutinized in the literature, including national systems of innovation (Freeman 1987; Lundvall 1992; Nelson 1993), regional innovation systems (Asheim & Coenen 2005; Cooke et al. 1997), sectoral systems of innovation and production (Malerba 2002) and technological systems (Hekkert et al. 2007). In this paper, we approach the subject through the innovation systems perspective in general, and through a sectoral innovation system viewpoint in particular, where the level of analysis is the Dutch building sector.
- 2.3 A sectoral innovation system (SIS) can be defined as "a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products." (Malerba 2002: 250). Klein Woolthuis et al. (2005) summarize failures or barriers—as we called them—into four basic categories: i) infrastructural (i.e. physical infrastructure), ii) institutional (i.e. norms), iii) interaction (i.e. relations in networks), and iv) capability (i.e. lack of non-physical resources). This classification allows identifying causes that hinder innovation. In our study, we first try to get insights into the main barriers that impede the construction of nZEBs. We present a model that depicts the interaction among relevant stakeholders.
- 2.4 As stated by Malerba (2002), the basic components of a sectoral innovation system are: 1) product, 2) actors, 3) information processes, and 4) interactions (including competition and complementarities among actors / technologies). Accordingly, a depiction of the main actors and interactions within the nZEB sector is shown in Table 1. There are four main phases in the project of developing new buildings. The planning phase starts when an initiative is normally taken by a property developer. A project management team is appointed to coordinate the project. Then, a drafting of the contract by both parties follows. Afterwards, during the design phase, specifications are developed. Finally, the design is communicated to the contractor(s). After the design phase, the actual construction of the building takes place. That is the realization phase. Once the building is constructed the project manager and the property developer inspect it. The last phase is the delivery phase, where the building is sold (or rented). House owners provide feedback on the delivered property by means of energy consumption and—sometimes—by demanding buildings with a specific energy performance.

Table 1. Actors involved in the different phases of near-zero energy buildings construction

	PLANNING		DESIGN		REALIZATION		nZEB
	Initiative	Pre-Design	Architectural Design	Execution Design	Manufacture	Assembly	Advertis
Property Developer (Public body: Housing Corporations, Private)							
Project Management							
Building Company							
Contractors							
User (Home Owner/Tenant)							
Knowledge Institutions							
National Government							
Financial Institutions							

- 2.5 Institutions also affect the system. The national government dictates laws and provides guidance on the planning process, construction standards, financial schemas (i.e. subsidies, mortgages) and procurement aspects. Government influences knowledge institutions through grant programs and development policies. Government also provides information to potential homeowners. Knowledge institutions develop and disseminate technology and knowledge of sustainability. Last, financial institutions provide loans to property developers and to potential home owners.

Knowledge Elicitation

- 2.6 As mentioned above, interviews were conducted to explore the possible barriers that hinder the building of energy-neutral houses. The selected interviewees were:
- *Project Managers*: Six project managers were interviewed. They have an overall insight on the sector. They play a primary role in construction projects since their viewpoints affect the characteristics of the buildings to be constructed.
 - *Housing corporations*: Three representatives of housing corporations were interviewed. These organisations are non-profit associations. They ensure an adequate supply of affordable, good-quality homes for those with middle and lower incomes.
 - *Municipality*: Five civil servants from different municipalities were interviewed. The municipality plays the role to carry out policies, regulations and subsidies in the region. It assumes the responsibility of a regional development authority. These regulations might be compromised between high levels of energy performance and cost considerations.
 - *Building companies*: Three representatives from different building companies were interviewed. Building companies have experience and knowledge in technical aspects of construction. However, their influence on key decisions may be limited, especially if they work in isolation.
 - *Contractors*: Three contractors were interviewed. These actors contract with other organizations for the construction of buildings. They possess—literally—hands-on experience in the sector.
 - *Knowledge institutions*: Two scholars in the field of energy resources and the building environment were interviewed. Not only do they develop knowledge in technical aspects of construction, but also in the social impact that this sector has.
 - *Financial institutions*: One representative from a financial institution was interviewed. These actors are mainly concerned with the risk and return of the investment.
 - *Users*: Three users were interviewed. Users benefit from energy efficient construction / retrofitting, although they may not be able to invest in energy efficient measures.
- 2.7 These actors' profiles were chosen for their essential role in the building system, as depicted in Table 1. The participants were randomly selected while looking for recent building projects in the province of Utrecht, the Netherlands. The participants have been involved in both successful and unsuccessful projects. Interviewees' participation was totally voluntary and no incentives were offered to encourage them to participate.
- 2.8 The interviews were conducted face-to-face with an approximate duration of one hour. Semi-structured interviews were used to allow actors to make an elaborated explanation of their opinions. The interview consisted of two parts. In the first part, demographic data was gathered. In the second part, the interviewees were asked several questions regarding the process of building houses with energy consumption nearly equal to zero, namely nZEBs. However, the interviewees were not asked directly for the systemic barriers. Questions aimed at providing indications of the four basic barriers a system can have (see previous section). For the sake of understanding perceptions related to infrastructural barriers, the interviewees were invited to elaborate their thoughts on inputs and technologies needed to build an nZEB. In order to get information about institutional barriers, we enquired about viewpoints related to legislation. Asking interviewees about desired changes in the building environment allowed inspection of their insights about interaction barriers. Finally, capability barriers were identified by enquiring about the sources of information used by the interviewee and his/her particular knowledge with regard to nZEBs. The interview guide that was followed can be found in Appendix A.
- 2.9 Miles and Huberman (1994) argue that the richness of the information derived from the interviews has the strength to reveal critical interactions of complex social phenomena. However, they also acknowledge the fact that qualitative case studies may suffer from limitations. In order to guarantee the validity of the answers we obtained, we followed the directives proposed by Wolcott (1990) during the knowledge elicitation process: i) elaborate an interview guide, ii) pre-test the interview guide, iii) avoid the modification of the interview guide structure during the interviews, iv) refrain from talking but rather listen carefully, v) produce annotations that are as precise as possible, vi) write in an early way, vii) employ a unique format to transcript the interview, and viii) corroborate the information with the interviewee.

Data Analysis

- 2.10 Once the interviews are finished, copied, and authorized by the interviewees, the data derived from the interviews is analyzed. For that, we used qualitative content analysis, which is one of the procedures for analyzing textual material (Bauer & Gaskell 2000). According to Flick (2006), qualitative analysis looks for understanding of new situations and supports the discovery of new information. Qualitative methods are appropriate in contexts where it is necessary to first identify the variables that might later be tested quantitatively. In each response key ideas were identified. These ideas were merged into core themes. Below, we present some results categorized according to i) the different phases of nZEBs construction and ii) the barriers that may hinder the innovation adoption.

Planning Phase

- 2.11 Interviewees often mentioned the limited resources that municipalities have in order to keep up with their initial ambitions of building energy-neutral homes. Hoppe and Faber (2011) have also identified this situation. They suggest that this is a major cause of the gap between ambition and realisation of energy-neutral projects. In our study, several interviews showed that municipalities do not lay enough emphasis on the requirements of energy performance stated in the European energy policy.

"Such an agreement [...] on building energy-neutral homes by 2020]...these are mainly policy targets, but they are not really maintained. If you do not follow them it does not mean that you cannot construct. It does not mean that you will get a fine either or that you will get into trouble whatsoever." — *Housing Corporation*

- 2.12 It appears that municipalities cannot make their voices heard. Part of their income relies on land prices. Developers have a negative connotation with regard to "energy-neutral building costs". Additionally, they prefer to keep a construction routine that is well known to them. Furthermore, housing associations lose part of their income through the "landlord tax". Also, there are concepts that are not well understood—or explained—by the different actors within the building sector. For example, two related notions are "energy-neutral house" and "energy performance certificate" (EPC).

"There is a poor communication related to these issues. For example, I do not know if neutral energy also means an EPC of zero." — *Project Manager*

Interaction Barriers

- 2.13 The economic crisis that began in 2008 hit the housing market hard. House prices have fallen sharply. In addition, Dutch energy regulations became stricter, thereby construction costs rose.

"Today's consumers simply cannot buy a house. Not to mention an energy-neutral house, this costs additional 20,000 euros." — *Project Manager*

Institutional Barriers

- 2.14 A number of other important emerging barriers include issues with laws and regulations. Several respondents used the rental sector as an example of restrictive regulations. For example, sometimes the rental limit price for social housing is designated as a limit for energy-neutral homes. The rental limit prescribes a maximum price so that social housing remains affordable for low-income consumers. However, in this situation, the extra costs for building an energy-neutral house are not taken into account.
- 2.15 Also, regulatory inconsistency is a source of confusion. Once, a municipality stopped the building of a biomass plant because of a change in regulations. This caused irritation among actors:
- "Then I think: Yes, Rich, make sure you take your responsibility, and take it fast otherwise there is the possibility of a sudden change." — *Municipality*
- 2.16 Faber and Hoppe (2013) also refer to the problem of regulatory inconsistency. They argue that social support for energy efficient measures has decrease due to abrupt policy revisions. Both the rental limit and the aesthetics committee fail to take into account advantages of energy-neutral housing. In addition, inconsistent policy increases uncertainty and narrow down initiatives in energy-neutral building.
- 2.17 The complete analysis was summarized into a matrix. Table 2 exemplifies a glimpse of it.

Table 2: Determination of barriers for the construction of *nZEBs*.

	KEY IDEAS	BARRIER	PHASE
INTERVIEWEE			
"The municipality establishes private agreements. No building permit can be refused if you do not build according to the (...) agreed measures, but when in disagreement to the legal requirements."	Municipalities do not put enough emphasis on the requirements for energy performance included in the energy performance certificate (EPC).	Interaction	Planning and Design
"Builders and contractors have been long accustomed to squeeze subcontractors. They [builders and contractors] always go for the lowest price. A kind of fighting culture prevails in the construction sector."	The choice of a particular contractor is mainly based on price. This forces contractors to focus on cost reduction. This situation prevents the use of more energy efficient systems.	Interaction	Design and Realization
"Today's consumers simply cannot buy a house. Not to mention an energy-neutral house, which costs additional 20,000 euro."	It is complicated to invest in energy-neutral housing projects in the current housing market.	Institutional	Delivery
"The regulations make it difficult for us to build energy-neutral homes (...). We wanted to install solar panels on a meadow. We wanted to generate and deliver energy to our tenants. Well, this is not possible according to the government."	Restrictive regulations exist for the installation of certain materials used to build energy-neutral homes.	Institutional	Design and Realization

- 2.18 The matrix relates opinions from the different interviewees (first column) with key ideas behind those thoughts (second column). It appears that the infrastructure and the capability needed to implement *nZEBs* are already there. It also appears that the main barriers result in institutional impediments and interaction complexity.

Agent-Based Modelling for Near-Zero Energy Buildings

- 2.19 The core concern is how to foster the construction of *nZEBs* that enable energy consumption reductions, amidst a landscape of a decentralized set of purposeful interacting actors. The intricacy of the dynamics and interaction of heterogeneous participants in the adoption of better practices has called for a computational approach to study such problems (Squazzoni 2008). Computational approaches have been used to understand different implications of adoption scenarios (e.g. Schilperoord et al. 2008).
- 2.20 The growth of ABM coincides with how the views and thinking about urban systems has changed (e.g. Crooks 2012). Rather than adopting a reductionist view of systems, whereby the modeller assumes that cities operate from the top-down and results are filtered into the individual components of the system (see Torrens 2001), researchers are now adopting viewpoints that emphasise relationships among entities (O'Sullivan 2004). This change follows the realisation that planning and public policy do not always work in a top-down manner, and that aggregate conditions develop from the bottom-up (i.e., emerging from the interaction of a large number of elements at a local scale).
- 2.21 Our objective is to explore scenarios than might assure the construction and sale of *nZEBs*, which consequently will lead to an eventual energy consumption reduction. The situation depicted here might be considered as a diffusion problem. Yet, our approach differs from other diffusion-related works in at least two aspects: (i) diffusion models emphasise the positive externality effect of adoption, which is commonly represented by a probability function that depends on the current number of adopters (cf. Delre et al. 2007); (ii) other works (e.g. Schwarz & Ernst 2009) use well-known psychological frameworks to inspect susceptibility to innovation adoption. In contrast, our work deals with agents that possess different perceptions regarding barriers that impede the construction of *nZEBs*. These agents define certain qualitative courses of action that are contingent upon several factors (Bharwani 2004), such as prices, comfort levels, variable-specific sensitivities, and sales expectations. Additionally, our work aims at a systems design approach, and not merely at studying the determinants of specific consumption patterns (cf. Azar & Menassa 2012).
- 2.22 Therefore, the use of an AB model is expected to bring forth courses of action that help *nZEB* construction practices to be adopted. The next sections offer details on how the elicited knowledge is integrated into a conceptual map, and how this map serves as an input for building a framework for agent specification. It is noteworthy to say that our modelling approach mainly considers the interaction elements (Table 2) and not the institutional elements. This might be a first stage of a longer research process, since modelling interaction-, information- and economic-related elements ("organizational physics") is much easier than including institutional or cultural components ("organizational chemistry" and "organizational biology"). See Levitt (2012) for a discussion on this.



Mapping Qualitative Data into Conceptual Maps

Development of a Systemic Diagram

- 3.1 Results from collected qualitative data were confronted with the elaboration of a systemic diagram, similar to what is known as a "systemigram" in systems engineering (Boardman & Sauser 2008). Systemigrams were originally conceived to convey both structured prose and graphical representations, which result in a map of entities and their interactions that reflect strategic plans (Blair et al. 2007). Systemigrams, inspired by "soft systems methodologies" (e.g. Checkland 1999), aim at visually representing strategic courses of action in enterprise architectural design. Systemigrams may involve multiple viewpoints from team members, and allow representing different flow alternatives, from which "money flow" is usually a very insightful one (cf. Boardman & Sauser 2008).
- 3.2 As Boardman and Sauser (2008) point out, there are many other types of conceptual maps. However, they argue that the advantage of systemigrams is their emphasis on holistic thinking and strategic purpose, rather than linear thinking and procedural plans. For that, these diagrams deploy a network-based representation where nodes correspond to entities like actors and factors of interaction, while links represent actions that relate such nodes. Nodes are labelled with nouns, while links are labelled with verbs. Some additional rules that Boardman and Sauser (2008) mention as requirements to build good systemigrams include: (i) diagrams (congruent with the mainstay) should read from top left to bottom right, (ii) ideally, the ratio of nodes to links should be approximately 1.5, (iii) crossover of links should be avoided.
- 3.3 Importantly, we have used Boardman and Sauser (2008)'s systemic diagrams with a clear different purpose than the one these diagrams are usually used for in systems engineering. It is noteworthy to mention that, although systemigrams have the main objective to unveil counterintuitive dynamics in the search of strategic alternatives for enterprise architecture, here the idea is to reveal all the simultaneous forces and interdependencies among actors and factors so that it is made explicit the implications and limitations of government actions in fostering sustainable construction. A first difference is that actors in the system under study have different, and conflicting, strategic goals, and operate in a rather decentralized fashion. They do not belong to a team with a unified strategic purpose and cannot be boxed into a participatory scheme in order to come up with a manifesto of sustainable construction. However, building a systemic diagram allows representing the multiple interests of actors in a conceptual model that is able to reflect the process dynamics in a visual way. A second difference is that we chose to categorize the two major flow dynamics in the same diagram (knowledge and money), according to our interpretation of the text of the interviews.
- 3.4 After reviewing and synthesizing the text of the interviews, we came up with a graphical networked representation of the system that was shared with both actors of the system and researchers with expertise on the sustainable construction sector. The conceptual map has been refined according to their inputs and suggestions.
- 3.5 The interviews revealed a focus on mainly two types of flows: knowledge and money flow. There are knowledge asymmetries among the different actors in the system. Moreover, money flow is an important driver of behaviour because ours is an economic-driven system where some of the main behavioural triggers are related to construction costs, house prices, energy consumption savings and financial standing. In other words, while knowledge flow partially considers construction-related practices, money flow represents a powerful way to materialise economic incentives and explore the economic viability of the overall system. An additional feature we incorporated into the diagram was a classification of links as to their predominant nature (i.e. considering whether the link largely represents an interaction through knowledge- or money-related transfers). Hence, the diagram simultaneously displays both "money flow" and "knowledge flow" for the sake of having a unique representational visual.
- 3.6 The proposed systemic diagram can be observed in Figure 2. Our systemic diagram illustrates two types of nodes: actors themselves (e.g. government, municipality, contractors, etc.) and factors of interaction

among actors (e.g. prices, *nZEB* designs, loans, etc.). The state of such factors can be modified according to the actions (connecting links) of actors and/or other factors.

Identification of Main Money Flow and Knowledge Flow Asymmetries

- 3.7 The nature of the intricate interdependence among actors is clearly depicted in the systemic diagram (Figure 2). Many issues that hinder the diffusion of sustainable practices were already mentioned by the interviewees. For instance, while the property developer initiates and delivers the final energy-neutral homes, he or she has little monitoring power on subsequent cost transfers to clients. Also, energy reduction capabilities are not fully internalized in the money flow dynamics towards consumers' willingness to buy a near-zero energy (*nZE*) home, and therefore *nZE* home advantages lack of enough appeal to them. On top of that, there is a lack of enforcement from governmental authorities toward municipalities, which face a dilemma between fostering construction of *nZEBs* and their own financial viability through land sales.

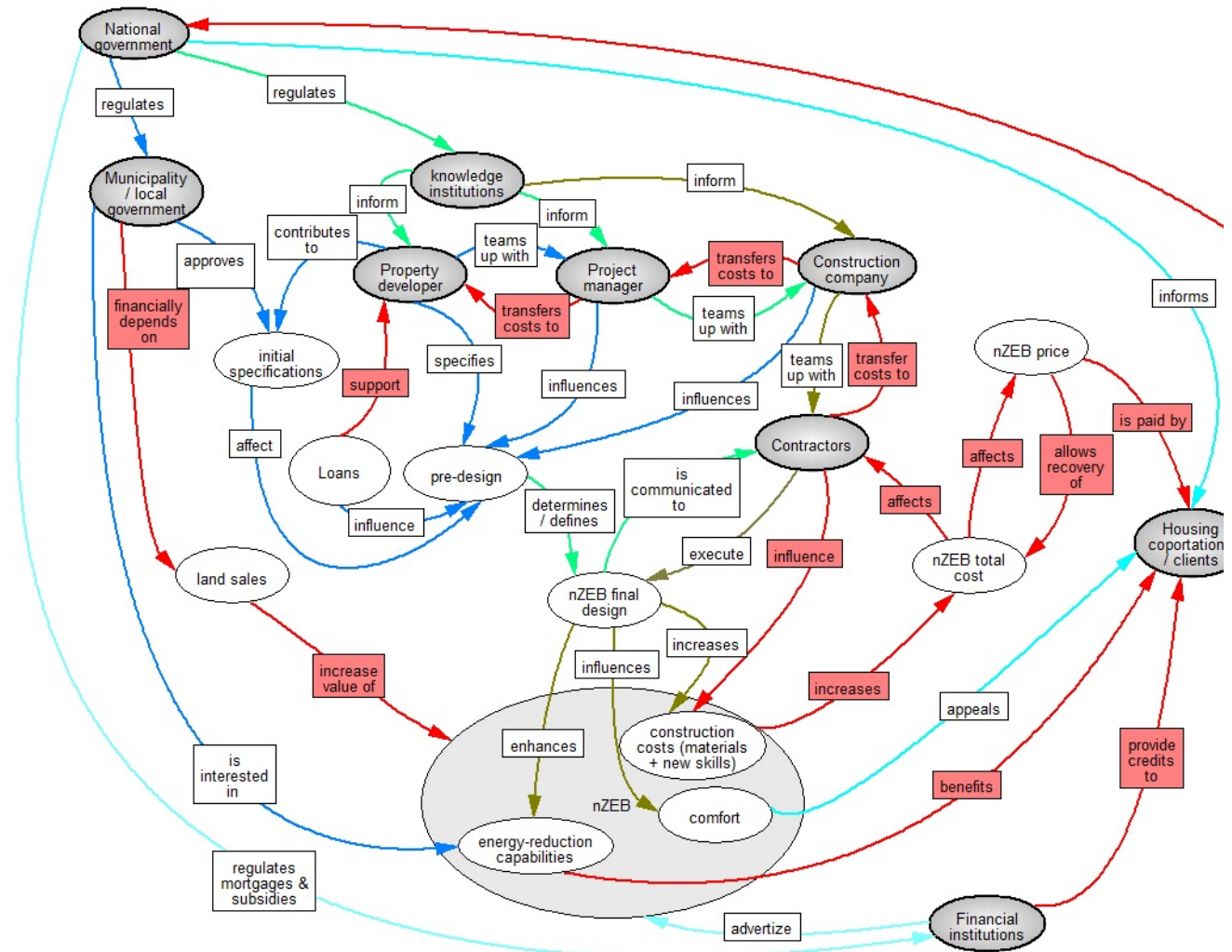


Figure 2. A systemic diagram depicting actors (dark gray ellipses) and relevant factors of interaction (white ellipses). Red colour represents "money flow", while the remaining colours represent "knowledge flow" according to planning, green = design, khaki = realization, and cyan = delivery.

- 3.8 The systemic diagram reveals other conflictive issues not explicitly addressed through interviews: (i) interviewees call for an internalization of energy reduction capabilities on *nZE* home rental prices for home owners (in case that owner rents the property to someone else); however, it can be observed that such internalisation might only work if it is embedded at multiple stages of the *nZEB* production chain, since otherwise it would imply home renters ending up transferring the energy saving benefits to house owners, which might deter potential home renters from considering *nZE* homes. Also, (ii) knowledge flow and money flow appear to follow different dynamics. From the diagram, it is possible to envisage that an intensive knowledge flow dynamics is presented at the upper part of the construction chain, while the money flow

dynamics is more salient in the lower part. This implies that some actors that are, in principle, interested in *nZEB* homes appear to have no clear economic-driven incentives to impulse construction of *nZEBs* (e.g. construction companies), although they possess a good degree of knowledge (e.g., they are involved in construction designs, are informed by knowledge institutions, and possess a good insight about construction costs).

Building an Incidence Matrix

- 3.9 We used the systemigram to build an incidence matrix: a matrix that relates actors and factors (placed in both row and columns) and their action-related link. The matrix allows clearly identifying the number of actions a single actor performs or receives, which denotes her or his scope of influence. Discernment of knowledge and money flows permits identifying specific action triggers: diffusion of desirable practices depend on how relevant actors consider knowledge at their disposal to set future courses of action, within the frame of money incentives.
- 3.10 Although the rich picture provided by the systemic diagram shows detailed intricacies of the system, the matrix provides a criterion to choose which actors and interactions will be part of an AB model in a clearer way. For instance, the national government has three regulatory actions on other three actors, has one more of information provider, and receives feedback regarding energy consumption savings. From these, the one related to energy savings is the only action categorised as part of the money flow. All of this implies that government has a monitoring role that can be parameterised (with no assignment done to a specific agent called "government") and fed back according to energy savings. Likewise, it is possible to see that the municipality has three actions: approving permits for initial home specifications, considering energy consumption reduction an important variable, but financially depending on land sales. In other words, approving specifications and attending land sale requests are actions in conflict, but they are both forces of municipality's behaviour.
- 3.11 Knowledge institutions have an information dissemination role (three actions), and thus we considered it convenient not to include them as an agent in the model (in any case, such an information can be parameterized, since it does not take any effect on knowledge institutions' behaviour). A snapshot of the incidence matrix is presented in Table 3.

Table 3. A sample snapshot of the 22 × 22 incidence matrix (9 actors plus 12 factors of interaction). Actor are specified in black, factors of interaction in blue, knowledge flow actions in black, and money flow actions in red.

	National Government	Municipality	Knowledge institutions	Property developer	Financial institutions	Project manager	Construction company	Contractors	Clients	Initial specifications	Pre-design
National Government		regulates	regulates		regulates mortgages & subsidies				informs		
Municipality										approves	
Knowledge institutions				inform		inform	inform				
Property developer						teams up with				contributes to	specifies
Financial institutions									provide credits to		
Project manager				transfer costs to			teams up with				influences
Construction company						transfer costs to		teams up with			influences
Contractors							transfer costs to				
Clients											
Initial specifications											affect
Pre-design											

- 3.12 After analyzing the incidence matrix, we came up with a set of actor groupings and a categorisation of their representative actions. The following table (Table4) summarises activities categorised as part of either the knowledge or the money flow dynamics that were used as input for the AB model.

Table 4: Knowledge and money flow components by actor type

Actor / set of actors	Knowledge flow component	Money flow component
Municipality / government	Energy consumption data	Land sales
Property developer / project manager	<i>nZEB</i> construction technologies from knowledge institutions	Construction costs
Construction company / contractors	Additional worker training in <i>nZEBs</i> construction	Construction costs

A First Framework for a Qualitative Simulation

- 4.1 Using Table 4 as a basis, we proceeded to specify a framework for ABM. The succinct summary presented in Table 4 was used to select main actors / drivers of the construction process dynamics that the computational model should include. Importantly, the model was also built to reflect the implications of the conceptual map (the systemigram). Additionally, it was aimed to serve as a tool in the shaping of viable courses of action that might enlighten potential strategies for the diffusion of sustainable construction. Next, we present such a framework and explain the main components of the simulation model.
- 4.2 There two important elements of scope in the following modelling framework:
- i. (i) As mentioned earlier, we constrained the framework to the "organizational physics" side of the problem (Levitt 2012). That is, we focused on the interaction and informational elements of the sustainable construction dynamics, not on the institutional elements.
 - ii. (ii) The qualitative data serves as input to build a qualitative simulation (Valente 2005). The simulation is intended to serve as a tool for inspecting the implications of what interviewees perceive. In no way we are attempting to confront model's results against past data, since this model aims to support the design of future strategies for the construction sector (which need to be complemented with other qualitative tools). Our work does not look for explanation. Instead, it attempts to provide a set of plausible scenarios for further intervention.

Environment

- 4.3 We assume a grid-like city endowed with $n \times n$ cells, each of which can sustain either an *nZE* or a normal home. We have set $n = 25$. Each cell can have one of six potential states: (i) unused land, (ii) spotted / occupied land by a project developer, (iii) land under sale permission request, (iv) land under a construction permission request, (v) land hosting a built *nZE* home (either sold or on sale), or (vi) land hosting a normal home (sold or on sale).

Modelling municipality's attention

- 4.4 As said, from the incidence matrix it is possible to see that there are three actions that dominate municipality's attention: (i) the money-flow related dependence of land sales ("Municipality – depends on – Land sales"), (ii) the knowledge-flow related actions of approving *nZEB* specifications ("Municipality – approves – Initial specifications"), and (iii) becoming interested in energy-reduction capabilities ("Municipality – is interested in – Energy saving capabilities"). To represent the conflict between the dependency on land sales and the interest in energy use reduction, we model the municipality as an agent whose incentives are embodied in a utility function represented by $U_{m,t}$. It is composed of two pieces, one related to land sales and another one related to energy consumption reduction. Formally speaking, we conceive a single agent call "municipality" (i.e., there is only one municipality per simulation run). Generally speaking, the municipality's utility function may be defined according to the following equation:

$$U_{m,t}(L, N_t) = \omega L_t + \alpha(E_{normal} - E_{nZEB})N_t, \quad (1)$$

where ω corresponds to a fraction of income due to sale of land (L) occurred at time t (if any); coefficient α is a scale factor that corresponds to the energy saving fraction (per *nZEB* home) that (positively) affects the municipality's utility function; coefficients E_{normal} and E_{nZEB} are the average energy consumption and the near-zero energy building consumption per time step, per construction, respectively; N_t is the cumulative number of sold *nZEB*'s at time t .

- 4.5 We assume that $E_{normal} = E_{nZEB}$, and that the benefit from a land sale is much larger than the maximum gain from an *nZEB* energy consumption reduction. That is, $\alpha E_{normal} = \gamma L$. This statement comes from assuming that, although at the national level government is interested in reducing country-level energy expenditures, local government sees only a marginal benefit from it and strongly depends on land sales. For our model, we have set $\gamma = 0.3$, $\alpha = 0.1$, $E_{normal} = 10$, $E_{nZEB} = 5$, and $L = 50$.
- 4.6 At every time step t , the municipality has to allocate time between attending an *approval for land sale*, and studying a *construction permit request* (which might lead to the construction of an *nZEB*). This is done by assigning a service probability according to some tracking scores (these scores work in a similar fashion to a Q -learning algorithm). At every time step t , the municipality keeps track on two scores, Q_i^t for each option i (house, land) and updates them according to the observed revenue at time $t-1$. For instance, the land-related indicator shows:

$$Q_{land}^t = \begin{cases} (1 - \delta)Q_{land}^{t-1} + \delta\omega L, & \text{if land is sold at time } t \\ Q_{land}^{t-1}, & \text{otherwise} \end{cases} \quad (2)$$

Coefficient δ represents an *adoption rate* (δ is set to 0.75 in the baseline model) that quantifies how valuable is the most recent information regarding the cumulative one. Then, the probability of giving priority to a *land sale request* is represented by:

$$P(land)_t = \frac{Q_{land}^t}{\sum_i Q_i^t} \quad (3)$$

- 4.7 Likewise, attention over house construction requests is controlled with an indicator that increases according to the number of constructions that become *nZEB*'s and are eventually sold to clients. This score is computed as follows:

$$Q_{nZEB}^t = \begin{cases} (1 - \delta)Q_{nZEB}^{t-1} + \delta\alpha(E_{normal} - E_{nZEB})N_t, & \text{if } N_t > 0 \\ Q_{nZEB}^{t-1}, & \text{if } N_t = 0 \end{cases} \quad (4)$$

$P(nZEB)_t$ is computed as $1 - P(land)_t$. Just like land sale requests, the maximum number of total home construction requests is $n \times n$, the size of the lattice. The initial value of both Q -related scores is 1 at time $t = 0$.

Behaviour of Property Developers, Project Managers and Contractors

- 4.8 From the systemic diagram, we observed that property developers, project managers and construction companies jointly decide on *nZEB* pre-designs, which ultimately influence the final *nZEB* design. In addition, construction companies and contractors transfer their operational costs to project managers and ultimately to developers. Although design decisions are predominantly informational (according to both the systemic diagram and the incidence matrix), the money flow dynamics reflects a cost transfer chain from contractors up to project developers. Therefore, for practical purposes, we make the simplifying assumption of merging these three actors in the same agent, which we label with the generic term of "developer". Upon approval for construction granted by the municipality agent, the developer has to decide whether to build an *nZEB* or a normal home. The decision on building an *nZEB* is linked to different cost options. Therefore, we assume two different cost variables, C_{nZEB} and C_{normal} , to represent cost figures of *nZEB* and normal homes, respectively. Also, we assume that $C_{nZEB} = C_{normal}$. The utility function of this agent is defined as $U_{developer} = P_{house} - transCost - L$, where $P_{house} = \{P_{nZEB}, P_{normal}\}$ is defined as the home price paid by a client ($P_{nZEB} = P_{normal}$), and $transCost$ is the cost incurred in home manufacturing (C_{nZEB}, C_{normal}). We set $C_{normal} = 50$ and $C_{nZEB} = 100$. Decisions on building either type are linked to demand expectations (that is, after checking consumer's propensity to buy at time t . See next section). We define $P_{normal} = (C_{normal} + L) * (1 + markup)$, where $markup$ is a coefficient ranging from 0 to 1 (we assume $markup = 1$), and the

starting value of P_{nZEB} as a multiple of P_{normal} (several values are also explored. See next section).

- 4.9 In addition, and according to the interviews, *nZEB* construction companies *take more construction time* due to the additional training workers need to get in order to build *nZEBs* ($t_{nZEB} = t_{normal}$). We initially set such construction times as $t_{nZEB} = 10$ time steps and $t_{normal} = 5$ time steps. This is consistent with the previous assumption of having construction costs higher for *nZEBs* than for normal constructions. Construction times are initially expected to have an impact on municipality's assessment of requests, since Q scores for the municipality are partially updated according to the total number of sold *nZEBs*. That is, construction lags are expected to generate delays in *nZEB* sales (however, we will see further below this is not true). Also, in our examples next, we assume the existence of 10 developer agents.

Clients

- 4.10 A client (or a group of them) might be of three types: house corporations, developers and private ones. Our modelling approach here markedly considers private clients. Clients are not explicitly modelled as agents. Instead, we indirectly use a proclivity indicator to buy a house, which allows developers to assess expected and realized profits (so that they can decide which house type to build). Clients evaluate buying a home partly according to *Comfort*, and not to energy savings—according to the interviews—, through their utility function $U_{client,t}$. Also, we assume that clients' preferences (i.e., comfort) are uncorrelated with construction types. That is, for a specific client, a normal house might be more (or less) appealing than an *nZE* home, as to idiosyncratic reasons. Also, a buying decision is restricted to budgetary constraints. Such budgetary constraints are not explicitly represented in client's equations, but we rather assume that a price increase lowers the chances of acquiring an *nZE* home (recall that $P_{nZEB} = P_{normal}$). There might be many ways to represent client's behaviour, but a very general, standard form is a Cobb-Douglas representation (Adner & Levinthal 2001), where the client confronts both comfort and price in order to make a decision. Additionally, sensitivities to price and comfort can be easily included. Therefore, we consider price-related and comfort-related elasticities (γ and $1-\gamma$, respectively; $0 < \gamma < 1$). We then assume that the proclivity a consumer has for buying a house, H , depends on its price (*Price*) and its perceived quality (or *Comfort*). Then we define:

$$H = \psi \left(\frac{1}{Price} \right)^\gamma Comfort^{1-\gamma}, \quad (5)$$

where γ ($\gamma > 0$) corresponds to a scale factor. Comfort levels are integer numbers on a scale from 1 to 10. ("1" indicates zero comfort, while "10" stands for maximum comfort). Coefficient γ is calibrated to obtain $0 = H = 1$, so that H is, in fact, a probability:

$$\psi = \frac{1}{\left(\frac{1}{P_{normal}} \right)^\gamma 10^{1-\gamma}}. \quad (6)$$

Thus, Equation 5 illustrates that, for a given value of γ , the proclivity to sell (or buy) a home decreases with increases in prices, and goes up with increases in comfort levels. While we assume that normal houses have a stable (i.e. constant) price, we also assume that a higher number of available *nZEBs* for sale, N_t , corresponds to a decreased price value:

$$P_{nZEB,t} = \theta_1 (N_t' + 1)^{\theta_2}. \quad (7)$$

Coefficients θ_1 and θ_2 are the price scale factor and the (approximate) inverse of the price elasticity of demand, respectively ($\theta_1 > 0$, $\theta_2 < 0$). The value of θ_1 is set taking into account that $P_{nZEB} = P_{normal}$ even when $N_t = 0$ (we use $\theta_1 = 2P_{normal}$ as a baseline value, but change it to explore alternative scenarios). Coefficient θ_2 allows several values but we set it to -0.1 in order to keep $P_{nZEB} = P_{normal}$ across different simulations.

- 4.11 To avoid asymptotic decrements in probabilities when the price dramatically increases, we assume that the probability to buy a home, H , only makes sense when a consumer's participation constraint, U_o is fulfilled (Adner & Levinthal 2001). U_o indicates the minimum accepted utility to consider buying a house. Below such minimum utility value, the probability to buy (or sell) a home is zero. Such minimum utility value is set assuming that the least interesting case for a consumer would be a house with joint maximum tolerable price and minimum possible comfort. Being congruent with the previous definition of $\theta_1 = 2P_{normal}$, such value is:

$$U_o = \psi \left(\frac{1}{2P_{normal}} \right)^\gamma (1)^{1-\gamma} = \psi \left(\frac{1}{2P_{normal}} \right)^\gamma. \quad (8)$$

For each house construction possibility (i.e., each "patch" in the grid-like city) there is a potential consumer. Therefore, for each patch, two comfort levels are generated from a uniform distribution, one related to a normal home, the other one related to an *nZE* home. With such values, developers assess profits expectations and, according to which one is higher, decide to build either a normal or an *nZE* home.

Consideration of Other Actors

- 4.12 Of course, any modelling decision has to trade off richness of representation against parsimoniousity. Examination of the systemic diagram and the incidence matrix allowed us to come to some choices regarding model boundaries. For instance, given the fact that financial institutions' decisions can take effect through influence on minimum participation constraints, and that knowledge institutions' actions can indirectly be represented through changes in construction times and construction costs of *nZEBs*, we decided to leave out explicit representations of them in the present model. Likewise, national government, which may affect municipality's attention toward land sales, is indirectly represented through the Q -related scores that define the municipality's course of action. Yet, with these modelling simplifications, an interesting process dynamics is captured. Obviously, all the above-mentioned actors and more elaborated decisions-making processes can be incorporated in later exercises, but at this stage we opt for the Occam's razor principle.



Model dynamics and main results

- 5.1 Taking into account the definitions of Q_{land} , Q_{nZEB} , N , N' , P_{normal} and P_{nZEB} , the model dynamics is better described through the pseudocode in Appendix B. As mentioned above, Q -related scores (which determine municipality's attention probabilities) are initialized to one, so the first probability calculations on municipality's attention probabilities are set to 0.5. The model shows the interplay among land sales, construction permit requests, house construction and sales to clients, and reveals how the space is populated with the two house types. We let the model run for 5000 time steps in all scenarios and inspect diffusion numbers, which are the proportions of sold normal homes and *nZEBs* with respect to total construction capacity. We also inspected *nZEB* price behaviour and municipality's attention probabilities.
- 5.2 At $t = 0$, we assumed all space corresponds to unused land. Noteworthy to say is that a different starting configuration could be thought of. A starting partial occupation of space implies that the number of starting unused cells is lower (with respect to the case where all space is set as unused land). That could be the case when, at $t = 0$, there is a starting non-zero number of built (normal) homes. Such a modified starting setting would affect the total capacity for house construction, but would not impact the dynamics of Q -related scores. Moreover, that situation would just reveal lower *nZE* home diffusion numbers in the long run (consistent with having less construction capacity) without affecting the overall qualitative behaviour of the model. Therefore, we kept our assumption of a full unused space at $t = 0$. A diagram illustrating the conceptual model and the snapshots of the model's interface are shown in Figure 3 and Figure 4, respectively.

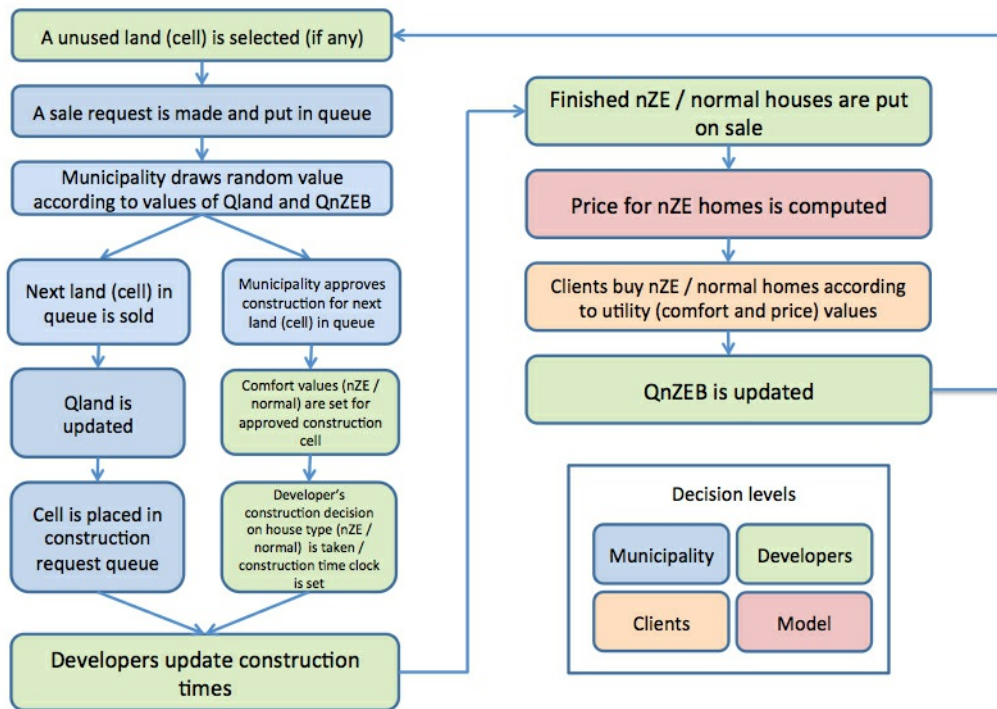


Figure 3. Conceptual model flow

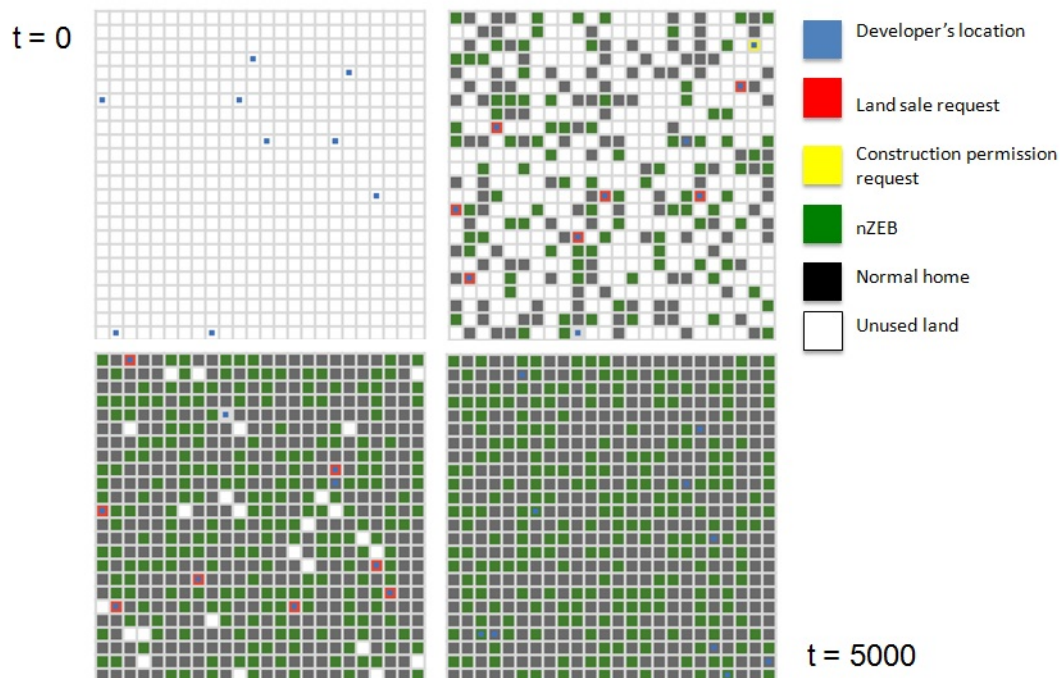


Figure 4. Snapshots of model's behaviour over time

5.3 We built nine different scenarios (100 runs each) using different values for γ , whose increase makes larger the initial difference between P_{nZEB} and P_{normal} (those values are $1.2P_{normal}$, $2P_{normal}$ and $5P_{normal}$). Jointly, we also varied the strength of price sensitivity with respect to comfort sensitivity (i.e., γ took values of 0.1, 0.5, and 0.9). A first case we analyzed was the effect of the relative difference between price and comfort sensitivities (that is, variations of γ for an initial P_{nZEB} slightly higher than P_{normal} (i.e., $\gamma_1 = 1.2P_{normal}$). Results reveal that, for the case where price sensitivity is lower than comfort sensitivity ($\gamma = 0.1$), low diffusion numbers (less than 20% of total construction capacity for each house type) are observed (Figure 5). Also, municipality's attention switched from land sales to construction requests over time (Figure 6). A main explanation for the latter result is the depletion of land, which forces the municipality to switch its attention towards (*nZEB*) home construction requests. However, this behaviour is not enough to boost the relatively low *nZEB* construction figures over the simulation horizon (Figure 5).

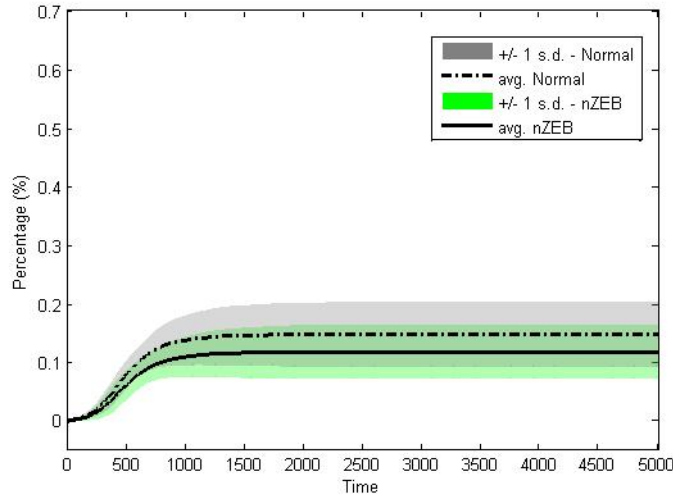


Figure 5. Average diffusion (number of sold homes over total construction space) when price sensitivity is lower than comfort sensitivity ($\gamma_1 = 1.2P_{normal}$, $\gamma = 0.1$). Shadowed regions indicate a one standard deviation variation over all runs.

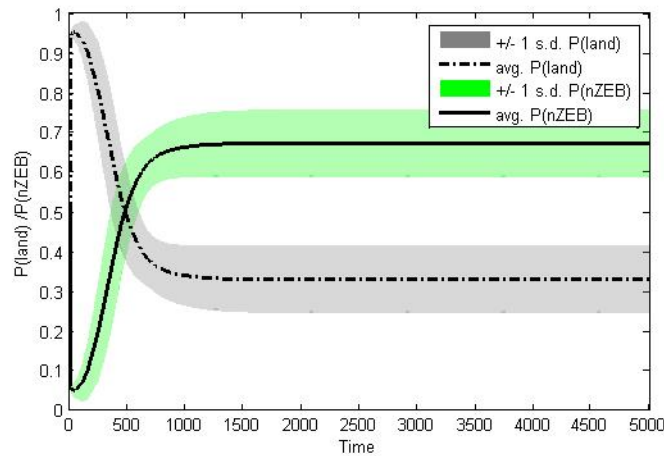


Figure 6. Average municipality's probabilities of attention when price sensitivity is lower than comfort sensitivity ($\gamma_1 = 1.2P_{normal}$, $\gamma = 0.1$). Shadowed regions indicate a one standard deviation variation over all runs.

5.4 An increase in price sensitivity (from $\gamma = 0.1$ to $\gamma = 0.5$) while maintaining $\gamma_1 = 1.2P_{normal}$ makes clear a dominant diffusion in favour of normal houses (Figure 7). Municipality's attention switch of focus from land sales to construction permission requests is even sharper with $\gamma = 0.5$, favouring *nZEB* construction (Figure 8). This eventually leads to a higher diffusion of *nZEB*'s with respect to the case of $\gamma = 0.1$, but a much lower figure than the number of normal homes (compare Figure 7 with Figure 5). Likewise, we inspected cases (not reported here) where consumers are much more sensitive to price than to comfort variations ($\gamma = 0.9$), which resulted in a full diffusion of normal homes with no incentives for *nZEB* construction from developers.

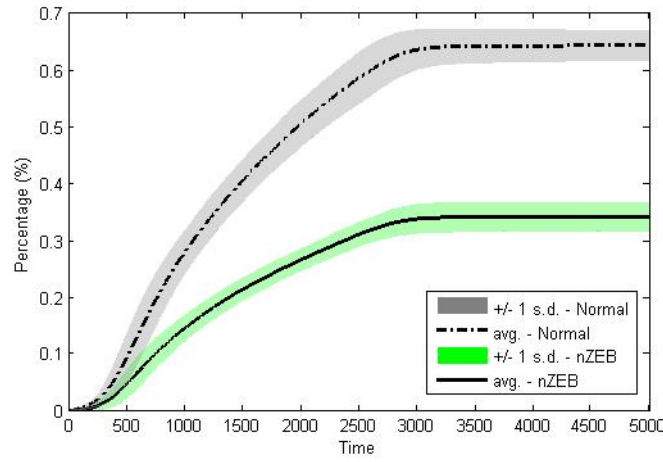


Figure 7. Average diffusion (number of sold homes over total construction space) when price sensitivity and comfort sensitivity have equal strength ($\gamma_1 = 1.2P_{normal}$, $\gamma = 0.5$). Shaded regions indicate a one standard deviation variation over all runs.

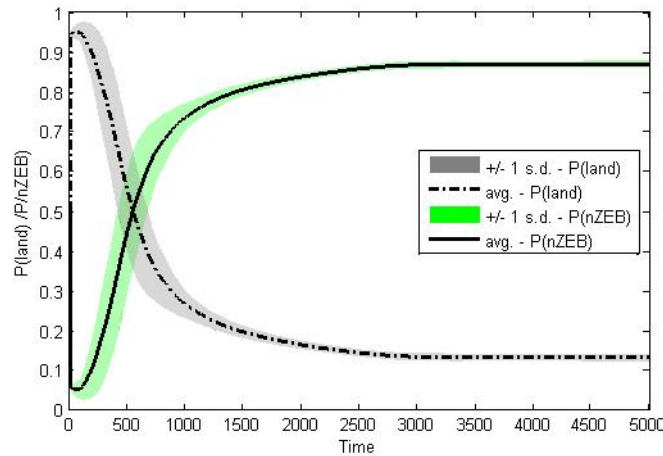


Figure 8. Average municipality's probabilities of attention when price sensitivity and comfort sensitivity have equal strength ($\gamma_1 = 1.2P_{normal}$, $\gamma = 0.5$). Shaded regions indicate a one standard deviation variation over all runs.

- 5.5 Similar inspections were carried out in a second set of scenarios, where we assumed a larger initial difference between *nZEB* and normal home prices (i.e., $\gamma_1 = 2P_{normal}$). The evolution of both *nZEB* price and the probabilities of attending requests, $P(land)$ and $P(nZEB)$, remain almost invariant with respect to the first set of cases presented (cases where $\gamma_1 = 1.2P_{normal}$). However, the number of sold *nZEB* constructions dramatically increases in comparison with that first set of cases. This would imply that (i) a client's weaker focus on price, (ii) a marked attention on comfort, and (iii) higher incentives for developers to build *nZEBs*, as a result of larger price differences between *nZEB* and normal homes, might help boosting up the number of *nZEB* constructions (see Figure 9). Nonetheless, this positive effect on *nZEB* diffusion tends to get undermined as clients become more sensitive to prices (i.e., when the value of γ increases).
- 5.6 An extreme price difference between *nZEBs* and normal houses occurs when $\gamma_1 = 5P_{normal}$. Developers are stimulated to build *nZEBs* due to the larger price difference between *nZEBs* and normal homes (Figure 10). However, success on sales depend on fulfilment of utility participation constrains, which depend on the relative sensitivity between comfort and price. A very high *nZEB* diffusion occurs when clients are more comfort- than price-conscious (see P_{nZEB} behaviour over time in Figure 11). Nonetheless, an extremely price sensitive client (i.e., $\gamma = 0.9$) will never buy an *nZEB* home, and *nZEB* diffusion might never occur (see Figure 12).

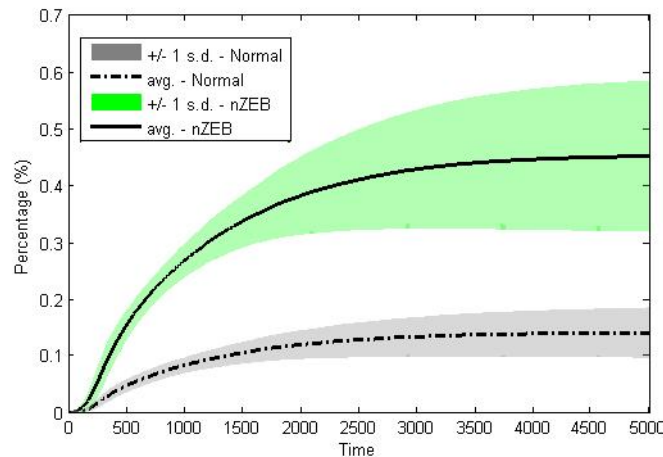


Figure 9. Average diffusion (number of sold homes over total construction space) when price sensitivity is lower than comfort sensitivity ($\gamma_1 = 2P_{normal}$, $\gamma = 0.1$). Shaded regions indicate a one standard deviation variation over all runs.

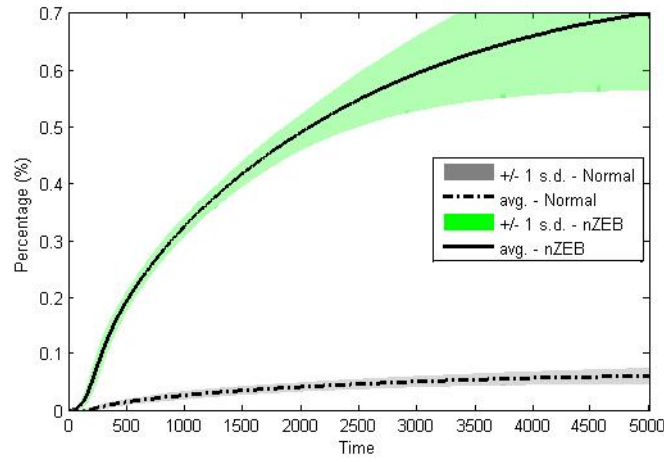


Figure 10. Average diffusion (number of sold homes over total construction space) when price sensitivity is lower than comfort sensitivity ($\tau_1 = 5P_{normal}$, $\tau = 0.1$). Shaded regions indicate a one standard deviation variation over all runs.

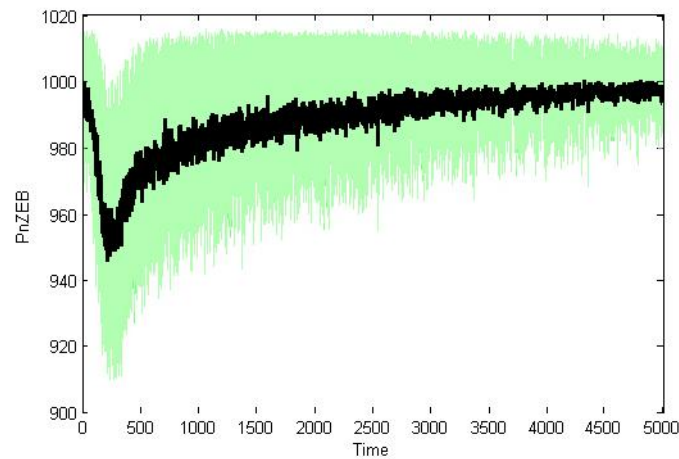


Figure 11. Average price behaviour when price sensitivity is lower than comfort sensitivity ($\tau_1 = 5P_{normal}$, $\tau = 0.1$). Shaded region indicates a one standard deviation variation over all runs.

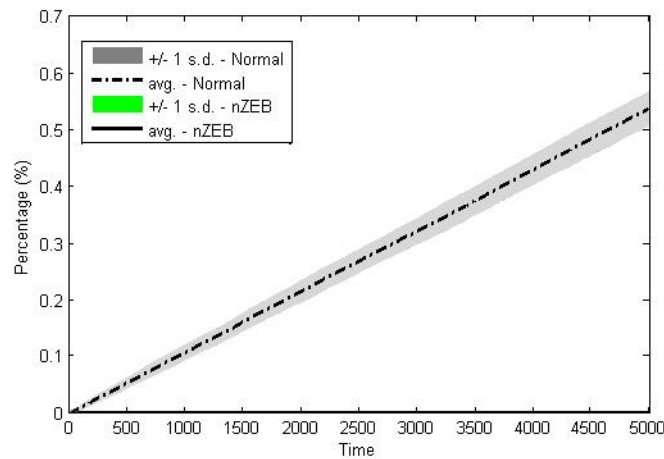


Figure 12. Average diffusion (number of sold homes over total construction space) when price sensitivity is higher than comfort sensitivity ($\tau_1 = 5P_{normal}$, $\tau = 0.9$). Shaded regions indicate a one standard deviation variation over all runs.

5.7 Knowledge assimilation of new construction techniques can be an important factor in system's evolution. That is, improving construction times might have a positive impact on increasing the diffusion of nZEB homes. We built an additional analysis scenario by varying construction times and exploring outcomes of the model. Interestingly, changes in nZEB construction times, which were regarded as a key factor in the nZEB house market by interviewees, did not reveal any significant impact on diffusion behaviour. Figure 13 illustrates the model dynamics when $t_{nZEB} = 10 * t_{normal}$ (a much larger time difference than what Figure 6 revealed). It can be observed that differences in construction times do not alter significantly diffusion numbers. In other words, the price/comfort relative sensitivity appear to have a much stronger impact than construction time improvements.

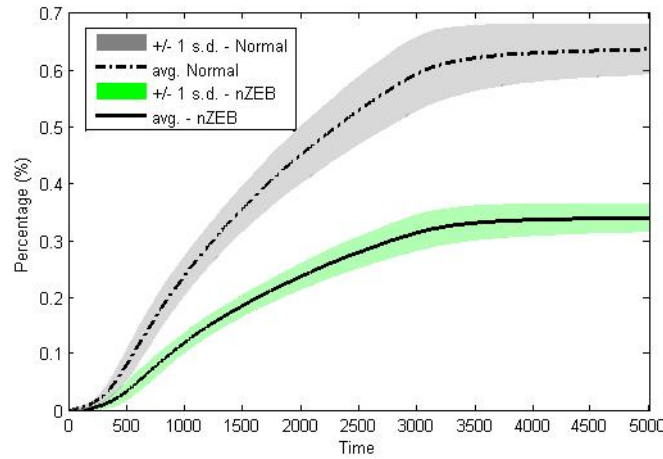


Figure 13. Average diffusion (number of sold homes over total construction space) when price sensitivity and comfort sensitivity have equal strength ($\gamma_f = 1.2P_{normal}$, $\gamma = 0.5$) and $t_{nZEB} = 10 * t_{normal}$. Shadowed regions indicate a one standard deviation variation over all runs. Compare with Figure 7.

- 5.8 All the previously presented results bring up some additional important points: First, economic-driven incentives are important for developers to generate interest in building *nZEB* homes. In our model, such incentives are purely driven by price differentials (although they might also relate to cost reductions in real life). However, the success of increased offer of houses has to go hand in hand with an increased focus on intervening clients' sensitiveness to factors other than prices. Higher incentives for construction (even if they imply significant cost reductions), coupled with extremely price sensitive clients will not produce the desired effect. Such price sensitiveness might lose dominance if, for instance, comfort perception is forced to correlate with potential energy savings (through, say, emphasising the importance of factors like environmental friendliness in the mind of consumers). In such a case, important diffusion figures could be reached. Additionally, a focus on optimizing building processes in terms of construction times has shown to have a very marginal impact.

Conclusions

- 6.1 The European Union has put special emphasis on the diffusion of *nZEBs*. By 2020, all new buildings will have to demonstrate very high energy performance. European countries are seeking to restructure their building environment and stimulate energy efficiency investments. Policy measures have been also introduced in order to achieve this goal. Building energy codes are probably the most frequently used instrument designed to increase the energy efficiency of buildings (El-Shagi et al. 2014; Jacobsen & Kotchen 2013). Other authors like Sesana and Salvalai (2013) argue that efforts should be also directed towards Life Cycle Methodologies (LCEA, LCA, LCC and LC-ZEB) in order to improve the design of *nZEBs*. Fragments of the literature on *nZEBs* have also focused on identifying their social acceptance (cf. Brown & Vergragt 2008; Heiskanen et al. 2013). Heiskanen et al. (2013) mostly speak of acceptance barriers in nine countries (Austria, Bulgaria, Czech Republic, Finland, France, Germany, Italy, Romania and Spain). They argue previous analyses have illustrated that "differences in barriers and drivers are in many cases greater among building owner groups than among countries" (Heiskanen et al. 2013: 3). Context specific factors of *nZEB* adoption include geography, infrastructure, history and culture, policy, markets and companies, experts and professional communities, citizens and social movements, and media ((Heiskanen et al. 2013: 5). For a very detailed analysis, we remit the reader to their comparative study.
- 6.2 Other few studies (not necessarily related to EU countries) have aimed at tackling the problem from a modelling perspective. For instance, (Fonseca i Casas et al. 2014) modelled the energy performance at specific levels of an *nZEB*. They calculated the energy demand of a building through its life cycle using a simulation based on the Specification and Description Language (SDL). An ABM approach is also carried out by Azar and Menassa (2012) to study energy consumption in commercial buildings.
- 6.3 Nevertheless, to the best of our knowledge, attempting to understand the construction sector combining innovation theory, qualitative approaches and agent-based modelling offers an unexplored avenue for research. We used an interdisciplinary approach to understand some implications of the perspectives held by different actors regarding the transition toward *nZEBs*, which have become the basis for description and formulation of a computational model. The systematic qualitative inquiry on involved actors was found to be an effective tool to improve formal modelling, since it provided a much better understanding of the knowledge and money flows within the system under study. This exercise also indicates that, given the nature of the problem under study, multiple perspectives (where ABM might be one of them) are needed to tackle this problem.
- 6.4 Simulation modelling offers a relevant, yet partial view, to building possible future states of the system. However, the fundamental motivation for modelling arises from a lack of full access to data related to the diffusion of *nZEBs*. One very important limitation is that we have focused on modelling the informational and money related dynamics of the problem ("organizational physics"), which is much easier than attempting to model institutional and evolutionary features of it ("organizational chemistry" and "organizational biology") (cf. Levitt 2012). Even in the explicit, yet complex, informational view of the problem, results that challenge actors' viewpoints are interesting because they force such actors to develop new paradigms to intervene the system. The AB model reveals some interesting drivers of building construction dynamics; yet, institutional barriers still need to be included / complemented with other qualitative points of view in future research.
- 6.5 Regarding our modelling approach, it is important to recall that we have disaggregated entities only to the point where having informational/money flows distinctions is important to drive the behaviour of the model. For instance, agents like developers, constructors and project managers are involved in mutual cost transfers, whose disaggregation do not offer additional insight from such an organizational physics perspective. Nevertheless, inclusion of institutional / interaction barriers would lead the model to a whole different perspective ("organizational chemistry"). Such an inclusion might also generate an increased level of complexity and (possibly) need a new set of interviews. Important factors to consider beyond the "organizational physics" lenses are (i) the degree of power (im)balance among actors (which could lead to effectively consider developers, constructors and project managers separately) (cf. Sibertin-Blanc et al. 2013; Abdollahian et al. 2013), and (ii) alternative diffusion processes, like those related to cultural transitions of social practices on the demand side (cf. Holtz 2014).
- 6.6 As any exercise that attempts intervention, not explanation and generalization, our approach is country—and sector—specific. In addition, it was not our intention to provide a richly detailed computational model able to capture all the micro details revealed in the interviews, but rather to use a complementary set of qualitative tools (conceptual maps and incidence matrices) that helped to decide on the most representative elements that might drive systems' behaviour. Our aim was also to illustrate that (i) qualitative information is relevant even in systems where a money (i.e., quantitative) flow is explicit, and that (ii) even parsimonious modelling representations might challenge beliefs that are commonly held among actors in the system.
- 6.7 We hope this kind of exercises prove to be fruitful for stakeholders. Our experience with this work is that even communicating the conceptual systemigram to stakeholders is a challenge. However, we also think that building models for design purposes can bring on new perspectives that could lead to change mental paradigms and to the consideration of policies never thought before.

Acknowledgements

We are grateful to our interviewees in the Netherlands for their time and contribution. We also thank the different colleagues who have provided valuable comments to our work, and the participants at the 9th Conference of the European Association for social Simulation (ESSA) in Warsaw (September 16-20, 2013). We remain solely responsible for any errors and omissions in the findings and interpretations expressed in this paper.

Appendix A. Interview guide

General Data

- 2 Name:
- 3 Contact Information: (e-mail, telephone, address)
- 4 Age:
- 5 Background (profession):
- 6 Organization:
- 7 Position (and years in this position):

Introduction

Dear Sir / Madame, We would like to understand the factors involved around the diffusion of near-Zero Energy Buildings. We know that you are an active professional within the Dutch building sector. Therefore, we would like to learn from you so others can benefit from your knowledge and your experience. This interview is confidential and your name will only be known by the researchers to assure the validity of the study. The interview consists of 15 questions and it will take 1 hour approximately. Please, feel free to express any thought you may have. Before starting the interview, may I ask your permission to record the

conversation? Furthermore, is there anything else you would like to know before starting the interview? Otherwise, we will proceed to begin..

Questions

1. What are your main professional activities?
2. What is your knowledge regarding energy efficient households?
3. How do you get the information regarding houses with an EPC=0?
4. What do you think about the technologies / products for building a house with an EPC=0?
5. How implementable are these technologies/products?
6. How is the concept of EPC=0 promoted within the building system?
7. How do the new EPC 0 techniques match within the current legislation?
8. What changes in the system would benefit you in order to (design/build/develop new legislation for/buy) houses with an EPC=0?
9. What factors do you take into account when you (design/build/develop legislation for/buy) a new house
10. What are the main reasons to decide (or not) to (design/build/develop legislation for/buy) an energy-neutral home?
11. Please, think about the projects you have been involved in the last year, what considerations have you made when (designing/building/developing legislation for/buying) your home?
12. What changes would benefit the (design/building/developing legislation for/buying) houses with and EPC=0?

Closing

This was the last question. We appreciate your participation. Is it possible to contact you in case we need some clarification while transcribing the interview? Also, if you are interested, we can provide you with feedback regarding this research. Thank you for your collaboration!



Appendix B. Model dynamics pseudocode

```
for time = 0 to number_of_time_steps
    Developers randomly place a land-sale-request out of unused cells
    Municipality puts land-sale-request in land sale request queue
    Municipality draws a random_value
    if random_value < Qland / (Qland + QnZEB)
        Municipality attends next cell in land sale request queue
        selected land-sale-request is sold
        Municipality updates Qland
        put sold land in construction-license-request queue
    else
        Municipality selects next cell in construction license request queue
        Developer in charge sets new construction project on selected cell
        Selected cell randomly sets comfort values for both nZE and normal houses
        Developers compute expected profits of building either nZE or normal house
        Developers decide to build either nZE or normal house
        Developers set construction time clock
    end
    Developers with houses under construction update their construction times
    if developers have completed construction times
        houses are declared finished and put on sale
        set Normal_houses = the number of finished normal houses
        set N' = the number of finished nZE houses
        move developer to a new location among unused cells
    end
    pnZE is updated according to N'
    for each Normal_houses
        compute utility_from_buying_normal house
        draw random_value
        if random_value < utility_from_buying_normal
            update number_of_sold_normal houses
            update profits for developer
        end
    end
    for each N'
        compute utility_from_buying_nZE house
        draw random_value
        if random_value < utility_from_buying_nZE
            update N
            update profits for developer
        end
    end
    Municipality updates QnZEB
end
```




References

- ABDOLLAHIAN, M., Yang, Z., & Nelson, H. (2013). Techno-social energy infrastructure siting: sustainable energy modelling programming (SEMPPro). *Journal of Artificial Societies and Social Simulation*, 17(1) 1: <http://jasss.soc.surrey.ac.uk/16/3/6.html>.
- ADNER, R., & Levinthal, D. (2001). Demand heterogeneity and technology evolution: Implications for product and process Innovation, *Management Science*, 47(5), 611–628. [doi:10.1287/mnsc.47.5.611.10482]
- ASHEIM, B.T., & Coenen, L. (2005). Knowledge bases and regional innovation systems: Comparing Nordic clusters, *Research Policy*, 34(8), 1173–1190. [doi:10.1016/j.respol.2005.03.013]
- AZAR, E., & Menassa, C. (2012). Agent-based modeling of occupants' impact on energy use in commercial buildings, *Journal of Computing in Civil Engineering*, 26(4), 506–518. [doi:10.1061/(ASCE)CP.1943-5487.0000158]
- BHARWANI, S. (2004). *Adaptive Knowledge Dynamics and Emergent Artificial Societies: Ethnographically Based Multi Agent Simulations of Behavioural Adaptation in Agro-climatic Systems*, Ph.D. thesis, University of Kent, 369 pp.
- BAUER M. & Gaskell, G. (2000). *Qualitative Research with Text, Image and Sound*. London, UK, SAGE Publications.
- BLAIR, C. D., Boardman J. T., & Sauser, B. J. (2007). Communicating intent with systemigrams: Application to the network-enabled change. *Systems Engineering* 10(4): 309–322. [doi:10.1002/sys.20079]
- BOARDMAN, J. & Sauser, B. J. (2008). *Systems Thinking: Coping with 21st Century Problems*, Boca Raton, FL, CRC Press. [doi:10.1201/9781420054927]
- BROWN, H.S. & Vergragt, P. J. (2008). Bounded socio-technical experiments as agents of systemic change: The case of a zero-energy residential building, *Technological Forecasting and Social Change*, 75(1), 107–130. [doi:10.1016/j.techfore.2006.05.014]
- BRYMAN, A. (2008). *Social Research Methods* (3rd ed.), Oxford, Oxford University Press.
- CHECKLAND, P. (1999). *Systems Thinking, Systems Practice*, Hoboken, NJ, Wiley.
- COOKE, P., Uranga, M. G., & Etzebarria, G. (1997). Regional innovation systems: Institutional and organisational dimensions, *Research Policy*, 26(4–5), 475–491. [doi:10.1016/S0048-7333(97)00025-5]
- CROOKS, A. T. (2012). The use of agent-based modeling for studying the social and physical environment of cities. In: *Complexity and Planning: Systems, Assemblages and Simulations*, (De Roo, G., Hiller, J., & Van Wezemael, J., eds.). Burlington, Ashgate Pub. Co., pp. 385–408.
- DELRE, S. A., Jager, W., & Janssen, M. (2007). Diffusion dynamics in small-world networks with heterogeneous consumers, *Computational and Mathematical Organization Theory*, 13(2), 185–202. [doi:10.1007/s10588-006-9007-2]
- EL-SHAGI, M., Michelsen, C., & Rosenschon, S. (2014). Regulation, Innovation and Technology Diffusion. Evidence from building energy efficiency standards in Germany. *Discussion Papers 13, DIW Berlin*. Berlin.
- EUROPEAN COMMISSION. (2013). *Europe 2020* Retrieved February 13, 2013, from European Commission: http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm
- EUROPEAN PARLIAMENT (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of building. *Official Journal of the European Union*. L 153/13–L 153/35.
- FABER, A., & Hoppe, T. (2013). Co-constructing a sustainable built environment in the Netherlands—Dynamics and opportunities in an environmental sectoral innovation system, *Energy Policy*, 52, 628–638. [doi:10.1016/j.enpol.2012.10.022]
- FLICK, U. (2006). *An Introduction to Qualitative Research*. London, UK, SAGE Publications.
- FONSECA I CASAS, P., Fonseca i Casas, A., Garrido-Soriano, N., & Casanovas, J. (2014). Formal simulation model to optimize building sustainability, *Advances in Engineering Software*, 69, 62–74. [doi:10.1016/j.advengsoft.2013.12.009]
- FREEMAN, C. (1987). *Technology Policy and Economic Performance: Lessons from Japan*, London, UK, Pinter.
- HEISKANEN, E., Matschoss, K., & Kuusi, H. (2013). Report on specific features of public and social acceptance and perception of nearly zero-energy buildings and renewable heating and cooling in Europe with a specific focus on the target countries D2.6. of WP2 of the Entranze Project.
- HEKKERT, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007). Functions of innovation systems: an approach for analyzing technological change, *Technological Forecasting and Social Change*, 74(4), 413–432. [doi:10.1016/j.techfore.2006.03.002]
- HOLTZ, G. (2014). Generating social practices. *Journal of Artificial Societies and Social Simulation*, 17(1) 1: <http://jasss.soc.surrey.ac.uk/17/1/17.html>. [doi:10.18564/jasss.2333]
- HOPPE, T. & Faber A. (2011). Waarom de energietransitie van de woningsector niet opschiet. *Milieudossier*, (4), 21–25.
- JACOBSEN, G. D. & Kotchen, M. J. (2013). Are building codes effective at saving energy? Evidence from residential billing data in Florida, *Review of Economics and Statistics* 95(1), 34–49. [doi:10.1162/REST_a_00243]
- JORNA, R. J. (2007). Knowledge dynamics: a framework to handle changes in type of knowledge. In: *Advances in Knowledge Management Vol. 3., 15 Years of Knowledge Management* (Schreinemakers, J. F., & Van Engers, T. M., eds.), Würzburg, Ergon Verlag, pp. 25–46.
- KLEIN-WOOLTHUIS, R., Lankhuizen, M., & Gilsing, V. (2005). A system failure framework for innovation policy design, *Technovation*, 25(6), 609–619. [doi:10.1016/j.technovation.2003.11.002]
- LEVITT, R. E. (2012). The virtual design team: designing project organizations as engineers design bridges, *Journal of Organization Design* 1(2), 14–41. [doi:10.7146/jod.6345]
- LUNDVALL, B.-Å. (1992). *National Systems of Innovation. Towards a theory of Innovation and Interactive Learning*, London, UK, Pinter Publishers.
- MALERBA, F. (2002). Sectoral systems of innovation and production, *Research policy*, 31(2), 247–264. [doi:10.1016/S0048-7333(01)00139-1]
- MENKVELD, M. & Beurskens, L. (2009). *Duurzame Warmte en Koude in Nederland*. Petten, ECN.
- MILES, M., & Huberman, A. (1994). *Qualitative Data Analysis: An Expanded Source-book* Thousand Oaks, CA, SAGE publications.
- NELSON, R. (1993). *National Innovation Systems. A Comparative Analysis*. Oxford, UK, Oxford University Press.
- NEWELL, A. (1990). *Unified Theories of Cognition*, Cambridge, MA, Harvard University Press.
- O'SULLIVAN, D. (2004). Complexity science and human geography, *Transactions of the Institute of British Geographers*, 29(3), 282–295. [doi:10.1111/j.0020-2754.2004.00321.x]
- ROMER, P. (1993). Idea gaps and object gaps in economic development, *Journal of Monetary Economics*, 32(3), 543–573. [doi:10.1016/0304-3932(93)90029-F]
- ROSALES-CARREÓN, J. (2012). *Mind and Soil. Knowledge Aspects of Sustainable Agriculture*, PhD dissertation, University of Groningen, 221 pp.
- SCHILPEROORD, M., Rotmans, J., & Bergman, N. (2008). Modeling societal transitions with agent transformation, *Computational and Mathematical Organization Theory*, 14(4), 283–301. [doi:10.1007/s10588-008-9036-0]
- SCHOOT-UITERKAMP, A. J. M., & Vlek, C. (2007). Practice and outcomes of multidisciplinary research for environmental sustainability, *Journal of Social Issues*, 63(1), 175–198. [doi:10.1111/j.1540-4560.2007.00502.x]
- SCHWARZ, N., & Ernst, A. (2009). Agent-based modelling of the diffusion of environmental innovations: An empirical approach, *Technological Forecasting and Social Change*, 76(4), 497–511. [doi:10.1016/j.techfore.2008.03.024]
- SESANA, M. M., & Salvalai, G. (2013). Overview on life cycle methodologies and economic feasibility for nZEBs. *Building and Environment*, 67, 211–216. [doi:10.1016/j.buildenv.2013.05.022]
- SIBERTIN-BLANC, C., Roggero, P., Adreit, F., Baldet, B., Chapron, P., El-Gemayel, J., Mailliard, M., & Sandri, S. (2013). SocLab: a framework for the modelling, simulation and analysis of power in social organizations. *Journal of Artificial Societies and Social Simulation*, 16(4) 8: <http://jasss.soc.surrey.ac.uk/16/4/8.html>.
- SQUAZZONI, F. (2008). A (computational) social science perspective on societal transitions, *Computational and Mathematical Organization Theory*, 14(4), 266–282. [doi:10.1007/s10588-008-9038-y]

TORRENS, P. M. (2001). Can geocomputation save urban simulation? Throw some agents into the mixture, simmer, and wait, *Centre for Advanced Spatial Analysis (University College London) Working Paper*, 32, London.

VALENTE M (2005). Qualitative simulation modeling. Working paper, Università dell'Aquila.

VERHAGEN, M. (2012). *Nationaal Hervormingsprogramma 2012*, 's-Gravenhage: Ministerie van Economische Zaken, Landbouw en Innovatie.

WOLCOTT, H. F. (1990). *Writing Up Qualitative Research*, London, UK, SAGE publications.