Acceptability of hydrogen as a sustainable replacement of natural gas in households

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by

Vera de Jong

Student number: 4226089

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Graduation committees

Chairperson TPM	: Prof.dr.ir. I.R. van de Poel, Ethics/Philosophy of Technology
First Supervisor TPM	: Dr.ir. E.J.L. Chappin, Energy and Industry
Second Supervisor TPM	: Dr.ir. J.H. Kwakkel, Policy Analysis
Chairperson SEC	: Prof.dr. M. de Vries, Ethics/Philosophy of Technology
First Supervisor SEC	: Drs. C Wehrmann, Science Education and Communication
Second Supervisor SEC	: Dr.ir. S. M. Flipse, Science Education and Communication
Third Supervisor SEC	: Dr.ir. E.J.L. Chappin, Energy and Industry
External Supervisor	: Ir. T.E. de Wildt, Energy and Industry
External Supervisor	: Ir. Jaco Reijerkerk, TU Delft

Preface

This thesis is the written summary of an attempt to foster sustainability by improving the implementation of innovative energy technology. This thesis is a master thesis written for the Faculty of Technology Policy Analysis and Management and for the section Science Education and Communication of the Faculty of Applied Sciences.

This work describes an integrated perspective on the implementation of technology in society. We need to combine systematic and structured analyses with worldviews that are aware that the world is neither flat nor squared. Otherwise we will not come not very far with current environmental challenges. The master program of Complex System Engineering offers approaches to define and demarcate problems. Science Communication meanwhile gives the tools to make sharp corners a little rounder. Let's see how far we can get with this thesis!

Vera de Jong

October 2018, Delft

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I absolutely enjoyed doing my own research project and writing this thesis. Even though it was not always easy, I am happy that I had great freedom and responsibility. I also visited places, I would have never been if not for an interview or a meeting.

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Executive Summary

Hydrogen technology offers a promising opportunity to mitigate problems that arise due to the energy transition. It can enable storage and balancing for surplus in electricity production from intermittent resources as solar energy and wind power. Electrolysis converts green electricity into hydrogen. Hydrogen is suggested to be introduced into the current natural gas grid as sustainable replacement of natural gas in households. This allows for reduction of CO_2 emissions and heating buildings that are not easily insulated. The number of poorly insulated homes is difficult using electrical low temperature heat pumps.

Even though hydrogen offers many functional advantages, there are potential barriers that may restrain the introduction of hydrogen into the energy system. Often siting of large-scale renewable energy technologies such as wind turbines and solar panels, causes anxiety and societal opposition. The reason for opposition is often distrust in institutions and technology that fails to equally distribute costs and benefits amongst stakeholders, authorities and residents.

To prevent this for hydrogen infrastructure, this research studies how hydrogen technology can incorporate local values. This allows for adapting technology to local needs and involving households in decision making. Acceptable technology and a responsible process increase trust and acceptance when the infrastructure is actually adjusted. This research answers the question which technical design choices provide for an acceptable and responsible design of hydrogen distribution and domestic use to households in Stad aan ´t Haringvliet.

Stad aan ‘t Haringvliet is used as case to research how to identify values and capabilities that play a role when designing hydrogen infrastructure for a specific local context. A participatory modelling approach is developed and executed. The approach involves stakeholders and households in the process of developing an Agent-Based Model. The model simulates the acceptability of hydrogen technology for households and identifies issues to be addressed in the next project phases. The Capability Approach and Value-Sensitive Design form the conceptual basis of this research. The effects of technology on households is assessed in terms of valuable capabilities and individual well-being. Capabilities create well-being as they allow users to choose e.g. how to heat and what technology to buy.

The outcomes of this research are specific local requirements and general knowledge on how to develop acceptable technology. Hydrogen infrastructure is acceptable when it has only a small impact on households and offers comfort and security against the same costs as the current system. Higher costs are possibly acceptable when the new system reduces CO_2 emissions or offers higher comfort. However, technology alone is not able to incorporate the whole set of important values. Additional institutional measures as for example information, participation and support are required to gain long term acceptance.

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Abbreviations & Glossary

ABM	Agent-Based Model
CA	Capability Approach
CAS	Complex Adaptive System
Design	Composition of technical design choices for hydrogen in households
EMA	Exploratory Modelling and Analysis
Pilot	Hydrogen project in Stad aan ´t Haringvliet
PRIM	Patient Rule Induction Method
Scenario	Combination of different experimental settings that generate a possible future
VSD	Value-Sensitive Design

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1.Introduction

In the Netherlands the CO_2 emission must be reduced on short term, without increasing risks regarding security of supply and safety (Sociaal-Economische Raad, 2013). Alternatives to using fossil fuels as energy supply are gradually researched, developed and introduced. Alternatives include the production of electricity from renewable resources and electrification of the energy supply in the built environment and mobility. The current changes caused by transition of the energy system induce problems related to an unbalanced infrastructure due renewable resources and a lack of storage capacities due to electrification. Hydrogen is an alternative with great potential in resolving these and other challenges in the energy transition, in particular relating to reducing the use of natural gas and other fossil resources (van Wijk & Hellinga, 2018).

Hydrogen produced through electrolysis can balance the fluctuations caused by intermittent renewable resources. Surplus of electricity on windy and sunny days can be effectively used at a later moment when converted into hydrogen. Hydrogen can be stored in containers or underground facilities more easily than electricity. Shortages can be balanced by using stored hydrogen.

Also, hydrogen has the potential to replace the role of natural gas in households (Barbir, 2009). It can be used for heating and has some benefits compared to alternatives such as heat pumps and heat networks. Old and poorly insulated houses cannot be heated by low temperature heat produced by heat pumps and heat networks (van Wijk & Hellinga, 2018). The distribution of hydrogen through the existing gas network permits for reusing existing pipes and possibly also boilers. In some cases, only a small part of the installation has to be replaced (Leeds City Gate, 2016).

However, as with other renewable technologies, there is a chance that introducing hydrogen technology might encounter public resistance. Often new technologies are rejected for several reasons. Existing controversies of renewable energy technologies are one of the main reasons. These controversies are unequal distribution of costs and benefits of wind farms and the failure to compensate for disadvantages; conflict escalation between proponents and opponents of bio-fermenters due to unrealistic goals; bad communication and a lack of transparency during the siting process; distrust in authorities because of failed project management and non-participatory decision making (Moore & Hackett, 2016; Sovacool, 2014; van der Horst, 2007; Wolsink, 2000; Wüstenhagen, Wolsink, & Bürer, 2007). Attitude, social norms, perceived behavioural control and personal norm make actors to act in favour or against the development of new energy technologies (Huijts, Molin, & Steg, 2012). Research on perception of gene technology shows that trust in institutions or persons, influences perceived risks and benefits and therefore the acceptance of product (Siegrist, 2008). Users often distrust technology in terms of safety, or feel that their comfort decreases due to change (Siegrist, 2008). In fact, opposition and public resistance to wind turbines, carbon capture and storage and solar panels are important barriers for the Dutch energy transition (Devine-Wright, Batel, Aas, Sovacool, LaBelle, et al., 2017; Huijts et al., 2012; Wüstenhagen et al., 2007).

In large infrastructural projects related to the energy transition that appear to be controversial, measures are taken by project managers that aim to increase the acceptance and de-escalate possible conflicts. Stakeholders and affected residents are informed and involved during the process of siting and constructing the technology. Participative approaches for developing communication strategies and informing residents are supposed to mitigate for arising distrust and concern.

However, these approaches often fail to reduce conflict and slow down the construction of renewable energy technology because stakeholders feel manipulated or excluded (de Vries, 2016). Approaches to engage stakeholders towards the end of a project are not capable of creating acceptance on the long run and mainly aim to repair the damage that has already been caused. A problem is that common policies are not capable of seizing the situation before opinions have been formed. Stakeholders and the public haven often already chosen their positions within the debate. To effectively engage stakeholders activities must start earlier in the process (Reed, 2008).

"Very little has been done to educate people about the properties and safety of hydrogen, even though public acceptance, or lack thereof, will in the end make or break the hydrogen future" (Dunn, 2002). Because hydrogen has such high potential to play an important role in the energy transition (Barbir, 2009), it might be beneficial to gain more knowledge how the public opinion on hydrogen is shaped. Understanding effects of hydrogen technology on the public opinion better, may contribute to creating long-term acceptance of hydrogen and therefore foster the energy transition. Taking the perspective of acceptability possibly allows for approaching obstacles that may occur already in the design phase of technology. When technology does not exist yet, attitudes have not been formed and behaviour towards technology cannot be assessed yet. A useful approach for assessing possible effects may be considering individual capabilities of users for designing technology that incorporates values.

Participatory processes for increasing acceptability can generate better solutions in moral and functional terms (Devine-Wright, Batel, Aas, Sovacool, Labelle, et al., 2017; Prell et al., 2007; Reed, 2008). Thus, technological designs are not only 'good' in terms of efficiency, costs and environmental friendliness, but also good as considered by the users and stakeholders affected. This approach can increase adaptation and diffusion among target groups and the capacity of technology to meet local needs. Public trust in decisions and civil society increases through stakeholder participation, but only when transparent (Reed, 2008).

To further research the social and moral implications of hydrogen, with the purpose to create acceptance and to explore the effects of participatory processes, this research project considers the case of Stad aan ‘t Haringvliet where hydrogen is distributed into households. In this small town, hydrogen is to be used as a replacement of natural gas. It focusses on acceptability in terms of beforehand approvability for users and emending of values of households in technological design of hydrogen infrastructure. This research explores concrete values to be embedded in acceptable hydrogen infrastructure. Furthermore, non-technological aspects need to be explored as they might also affect adoption and acceptance (de Vries, 2016; Huijts et al., 2012).

1.1 Problem statement

The problem to be solved is a lack of knowledge of the moral and social impact of hydrogen infrastructure and a lack of understanding how to effectively create long-term acceptance.

The design of the system determines implications and benefits. However, the potential design choices have neither all been identified nor fully been worked out yet. Instead of mitigating negative effects, designs should inherently be morally acceptable. The aim is to foster successful implementation and gaining experience with hydrogen technology.

1.2 Research objective

The goal of this research is identifying mechanisms affecting acceptability of hydrogen in households that are relevant for making ‘good’ technical designs.

Identifying mechanisms affecting acceptability makes it possible to come to technical design choices in which the values and needs of households are considered. These designs anticipate to potential concerns. A challenge is to find a way to assess acceptability before defining and executing the project. An additional aspect of this research is exploring how to involve stakeholders during the process of defining and assessing acceptability. An exploration of the different factors enabling or disabling households to participate in the pilot in Stad aan ‘t Haringvliet and mechanisms that influence these enabling factors need to be better understood. This enables project leaders to anticipate to local needs and make better choices.

The project proposal in Stad aan ‘t Haringvliet intends to supply a district of the village with hydrogen. Choices on how to supplement natural gas still have to be made. The municipality, technical experts and local stakeholders such as the village council are recently researching the possibilities to feed hydrogen into the natural gas grid to replace natural gas by hydrogen gas. This means that in the future, the households of Stad are supposed to consume hydrogen as energy source instead of natural gas. The current natural gas grid is supposed to be reused to distribute hydrogen gas. Households can use adjusted boilers and eventually gas stoves for heating water and cooking.

It remains unclear what the potential moral and social implications of hydrogen in households are. Some experience has been gained in Leeds, UK (Leeds City Gate, 2016) and on Ameland (van Wijk, 2017). The village has carefully been chosen as location for the pilot. The effort of the municipality is to stimulate bottom-up change, where stakeholders themselves organise the transition to a hydrogen-based system. There is a close-knit community, and the village council, which represents residents, is eager to advance in removing natural gas from the local energy system.

The objective of the project has been determined, but the details remain unclear. A range of technical alternatives is discussed. The consequences for the acceptability and, ultimately, the acceptance of the new system remain unclear. To be able to create long-term acceptance, acceptable choices must be made at the very beginning of the project. This research aims to come to acceptable choices by applying the Capability Approach in combination with an Agent-Based Model and engaging stakeholders through interviews and a workshop. Chapter 2 presents the methods and argues their appropriateness to reach the objective.

1.3 Research questions

Which technical design choices provide for an acceptable and responsible design of hydrogen distribution and domestic use to households in Stad aan ´t Haringvliet?

The research question indicates that the research is geographically limited to Stad aan ‘t Haringvliet. It does not consider challenges related to the production of hydrogen. It solely focusses on the impact of distributing hydrogen and energy consumption. The research focusses on the acceptability of households. A lack of acceptance arises due to insufficiently including users and residents (Wüstenhagen et al., 2007)

The answer to this question is a number of technical design choices and additional measures to improve the performance of these choices. Answering the main research question reinforces the practical insights for the decision-making process in Stad aan ‘t Haringvliet but also leads to general considerations concerning the acceptability of hydrogen. The sub-questions provide a step-by-step approach for answering the main research question. This approach asks for applying different methods that depend on each other. The sub-questions are:

1. **Which aspects related to the acceptability of replacing natural gas by hydrogen in households can be used for the conceptualisation of the problem?**

2. **Which capabilities cause acceptability for households when assessing potential technical designs of hydrogen infrastructure for Stad aan ‘t Haringvliet?**

3. **What affects the acceptability of hydrogen distribution and domestic use for households?**

4. **What are the effects of different designs on capabilities of households given uncertain valuation of capabilities?**

5. **How to improve the acceptability of designs together with households in the realisation of hydrogen distribution and domestic use in Stad aan ´t Haringvliet?**

1.4 Outline

The next chapter outlines and argues which methods are needed to answer the main research question by separately researching the subquestions. The third chapter presents an elaboration of a novel conceptual frame which forms the fundament of this research. The forth chapter explores values by reviewing relevant literature and analysing the results of semi-structured interviews. The fifth chapter gives insights into how to conceptualise, formalize and specify an Agent-Based Model. Chapter six describes and argues the verification and validation steps executed. In chapter seven experiments are performed that identify key parameters for increasing acceptability. Chapter eight explains the results of an engagement workshop that deals with the issues identified by experimentation. The main research question is answered in the last chapter. The last chapter also presents some recommendations and reflects on this work.

2 Methodology

This research aims to develop and apply a frame that allows for developing acceptable designs of hydrogen technology. This work combines and integrates perspectives related to:

- Value Sensitive and Complex System Design;
- Responsible Research and Innovation;
- The Capability Approach(CA); and
- Agent-Based Modelling.

These concepts form the basis of a participatory modelling approach (Figure 1: Research Design). The research design presented indicates the topics and questions, the methods to find answers and the outputs of the different research steps. Additionally it indicates how the different steps are related and what outputs become input for following steps.

The research is limited to the acceptability of hydrogen for households. Based on literature it is assumed that problems with acceptance arise due to insufficiently including users and residents (Wüstenhagen et al., 2007). While stakeholders have the power to influence the project, households do not have a formal tool to get a say. This is where a lack of acceptance and opposition might arise.

2.1 Value Sensitivity

The Value-Sensitive Design approach (VSD) is an important starting point for developing morally acceptable technology. Literature about VSD claims that technology is not value neutral. VSD describes the transition from stakeholder values to design requirements. Research on VSD of energy technology indicates what values might be relevant for designing a hydrogen system for Stad aan 't Haringvliet (Albrechtslund, 2007; Borning & Muller, 2012; Ilse Oosterlaken, 2014).

2.1.1 Responsibility

The VSD is a positivist approach that theoretically leads to more acceptable designs. To tackle not only the theoretical challenge of creating an acceptable design but also generating practical value the responsibility of the process is considered. A practice orientated research approach to address this challenge is Responsible Research and Innovation (RRI).

"Responsible Research and Innovation is a transparent, interactive process by which societal actors and innovators become mutually responsive to each other (…)"

(vom Schomberg, 2011)

This research aims to develop and apply a frame that allows for coming to acceptable choices in a responsible way. RRI is considered a boundary condition for coming to a design choice. The interactive process mentioned by Vom Schomberg in this research is a participatory modelling process.

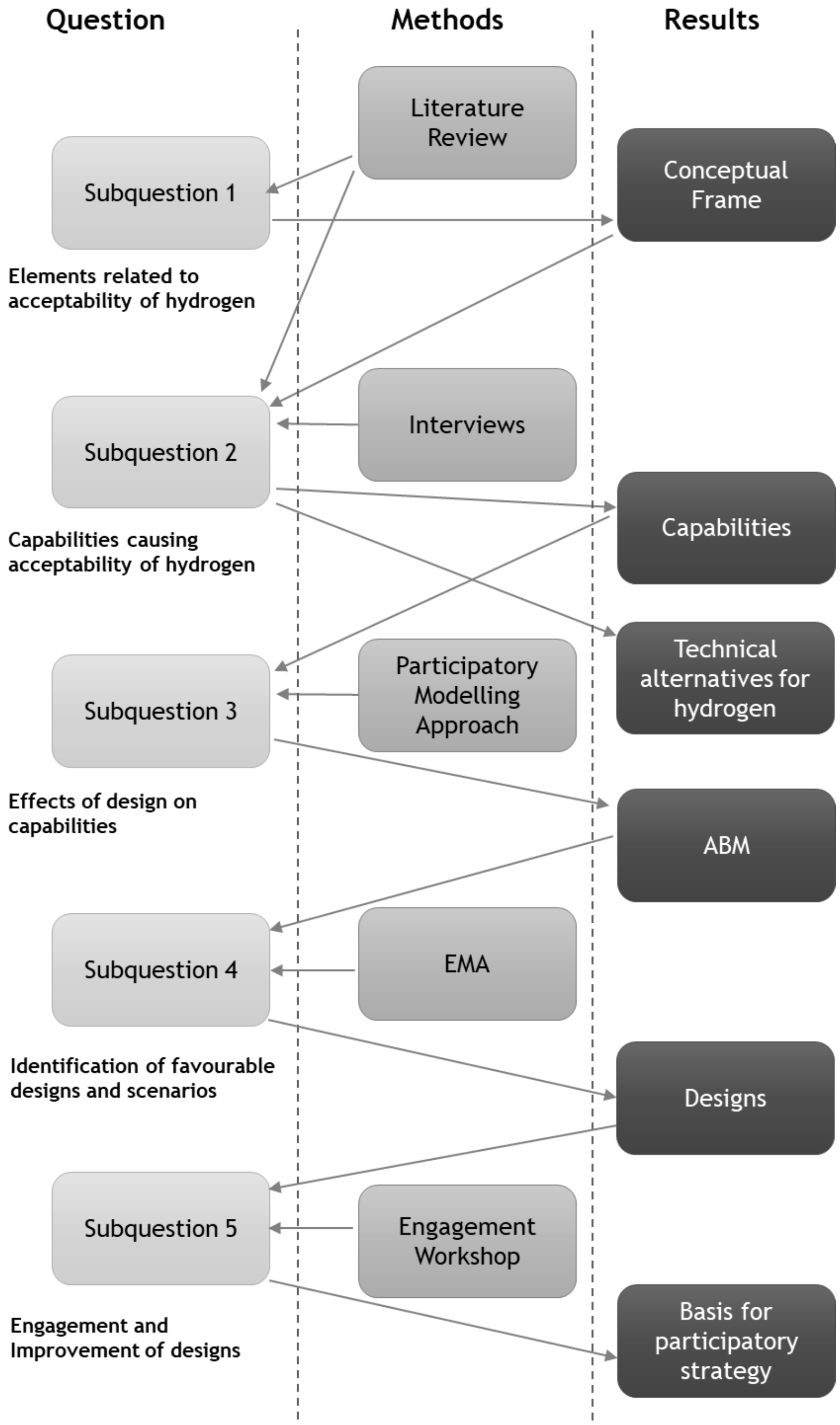


FIGURE 1: RESEARCH DESIGN

2.1.2 Incommensurability

An important topic addressed in literature on values and technology are value conflicts or moral dilemmas. A way to explain this problem is the concept of value incommensurability (Van den Hoven, Lokhorst, & Van de Poel, 2012). It considers that values are hardly comparable thus designs are hardly comparable in terms of moral acceptability. This problem needs to be addressed when designing and comparing the effects of designs.

2.1.3 Literature Review

To come to a conceptual frame a literature study is executed. Literature on Value-Sensitive Design (VSD), ethics in technology and on Responsible Research and Innovation (RRI) are the starting point. The search is specified by looking for relating literature on complex systems, energy transition and energy system change using a snowballing approach, thus searching for literature based on the reference list of a paper of interest. The starting points are (Correljé, Cuppen, Dignum, Pesch, & Taebi, 2015; Künneke, Mehos, Hillerbrand, & Hemmes, 2015; Ligtvoet, van de Kaa, et al., 2015). The benefit is that snowballing structures the research. It makes it easy to quickly find relevant literature and it can be assumed that reliable sources also refer to other reliable resources. A possible disadvantage is that important literature is not found.

Especially the paper of Künneke, Mehos, Hillerbrand, & Hemmes (2015) is an important starting point for looking for literature with values relevant for the capability approach. This paper describes the link between acceptability, values and the CA. To identify literature on values, scientific articles and books which specifically deal with human values related to infrastructure, complex systems and design are guiding. A list of keywords can be found in the Appendix A. To judge the quality of research the age (not older than 10 years) of the publication and the institute is considered.

Different interpretations of the most important writers of the CA are compared. The new conceptual frame is developed inspired by the elements identified in the CA, Value-Sensitive Design and Agent-Based Modelling. Recent papers in scientific journals on value assessment and embedding values in technological design are taken into considerations. The CA has been chosen as basic concept of this research. It has been proven useful when assessing ethics in technology (Hillerbrand & Peterson, 2014). Another choice could have been applying value hierarchies. They have been applied in correspondence with value sensitive design. However for this approach Correljé, Cuppen, Dignum, Pesch, & Taebi (2015) have already started to explore ways to come to responsible innovation through the CA. The benefits of developing a new framework is that it fits very well with the research goal. A shortcoming is that it has not been tested yet.

The search engines that are used to find additional literature are Scopus, Science Direct, and the homepage of the TU Delft Library. To gather data about the capability, approach the most important and recent writers have been identified. These are: Sen and Nussbaum who are the founders, Robeyns who writes comprehensive discussions and Ilse Oosterlaken who writes about the relevance of the Capability Approach for the assessment of technology.

2.1.4 CA

To be able to assess acceptability the approach chosen needs to fulfil some requirements. At first an approach is needed that considers moral acceptability in terms of beforehand approvability of a technology. Most approaches assess acceptance at a moment where attitudes and positions towards a technology are already formed. In this case an approach is needed that is able to deal with the assessment of technology that does not exist yet. This asks for a normative approach that is able to assess the future. The approach must also allow incorporating individual values in order to be moral and leave it to individuals to decide. Another boundary is that participation as for "a philosophy that emphasises empowerment, equity, trust and learning" (Reed, 2008). The approach therefore must consider individual factors that ensure that participants have the technical acceptability to engage effectively with the decision.

Frameworks described in current literature that are used to research the acceptance of technology are the Capability Approach (Kuklys, 2005; Künneke et al., 2015), Theory of Planned Behaviour (Ajzen, 1991; Wang, Fan, Zhao, Yang, & Fu, 2016) or the Frame of Social Acceptance (Devine-Wright, Batel, Aas, Sovacool, LaBelle, et al., 2017; Wüstenhagen et al., 2007).

The Theory of Planned behaviour focusses on behaviour based on attitudes towards a certain technology. Given the situation of hydrogen in households the approach is hard to apply as no attitudes have been formed yet. Households do not know much about hydrogen. This research does not aim to measure behaviour caused by technology but the moral implications for individuals.

The framework of social acceptance takes different aspects of acceptance into account. Among these aspects is the community acceptance which comes close to assessing individual experience of the system. The frame addresses the NIMBY (not in my backyard) problem and tackles political and process aspects of acceptance. However, it does not offer an approach how to incorporate values in planning of technology and siting. It is rather suited to develop mediation of conflicts that have already arisen (Wüstenhagen et al., 2007).

"Social acceptance refers to the fact that a new technology is accepted by a community and moral acceptability refers to the reflection on a new technology that takes into account the moral issues that emerge from its introduction."

(Künneke et al., 2015)

The Capability Approach is able to take individual factors into account that ensure that stakeholders are capable to participate. The approach allows for selecting a set of values to be incorporated as Sen leaves it to the researchers to fill in which capabilities are relevant. The

Capability Approach leads to operationalisation of values and considering individual differences between households. This makes it possible to come from individual moral acceptable to social community acceptability. Literature on the CA claims that “The Capability Approach is one of the most influential theories in contemporary debates on poverty, inequality and human development and (…) its structure fits well with the current discussion over sustainability and future energy scenarios.”

Other concepts could have been chosen to form the basis of this research. However, given the problem statement and state-of-the-art literature it seems a promising approach to combine CA with a participatory ABM approach. In the discussion the choice for the CA as basis for the conceptual frame is critically reviewed and assessed.

2.2 Participatory Modelling and Simulation

One important claim that can be found in literature about acceptance and participatory process is that participation should start as early as possible. Participatory processes often do not reach the estimated goals because they fail to engage stakeholders in the very beginning.

“When implementing a participatory process, stakeholder participation should be considered right from the outset, from concept development and planning, through implementation, to monitoring and evaluation of outcomes.” (Reed, 2008)

The practice has shown that involving stakeholders from the very beginning is not very effective as projects are often still abstract. Stakeholders struggle discussing plans that are not very concrete and lack information. Participatory modelling offers a process to deal with the abstractness of a project in a beginning phase.

Dealing with human being and human behaviour means dealing with a complex adaptive system (CAS). Humans are heterogeneous, depend on each other and respond to each other. Therefore, they show complex behaviour that is hard to explain and even harder to predict. Modelling and simulation are suitable to tackle the complexity. There are different ways to simulate human behaviour. System dynamics (SD), Discrete Event Simulations and Agent-Based Modelling (ABM) have different strength when it comes to simulating complex adaptive systems.

Modelling allows for drawing conclusions about a future system that has a high amount of complexity and therefore uncertainty. Experimentation makes it possible to explore different options without influencing the system. Another benefit is that it is relatively cheap to develop a simulation model.

2.2.1 Interviews

Empirical data is needed due to a lack of literature on the situation in Stad. Semi-Structured interviews are explorative but structured. Specific values related to infrastructure and domestic energy systems are gathered. Local characteristics are explored. The protocol can be found in Appendix B.

Eight interviews are conducted with two policy makers, two technical experts and four local stakeholders as a housing corporation and someone that installs heating system in households. This allows for sketching context, understanding technical solutions and gaining insights into local characteristics of households. The identity of interviewees must not be traceable. The interviews are mostly held in person at the office of the stakeholders. Two were held on the phone for practical reasons. The interviews took between half an hour and one and a half hours. The interviews were recorded by using a mobile phone and transcribed into word files. The benefit of semi-structured interviews is that they offer space to explore unknowns. The main limitation is that these interviews are difficult to compare. Interpretation of results becomes difficult. A limitation is that the interviewee is influenced by the interviewer. The way in which questions are formulated affect the answer.

TABLE 1: OVERVIEW OF INTERVIEWEES

Interviewee/ Event	Role	Relevance
Technical Expert 1	Expert asset management and responsible for exploring technical and financial alternatives for Stad aan 't Haringvliet amongst other projects	This expert has knowledge about investments and technical choices (within the legal space)
Policy Maker 1	Interviewee is working at Rijkswaterstaat and expert for the transition to sustainable hydrogen mobility	On overview is gained of general developments, the sense of urgency, legal barriers and available funding.
Policy Maker 2	Interviewee is responsible for the energy transition in Zuid-Holland and in several sustainable and innovative projects in the area	This expert is familiar with national and local policies and long-term planning of reducing CO2 in the province
Technical expert 2	Expert on gas quality and consumption who explores technical feasibility and	Information of availability of end user equipment is gained.

	economical attractiveness of reusing the grid, is involved in end user equipment	
Local Party 1	Director of a local organisation and expert for projects and technology	Knows effects of changes on users and the needs of users.
Local Party 2	Involved in sustainability and innovation on the island and amongst others facilitating the project in Stad	Is familiar with the residents of Goeree Overflakkee. Knows the state of the art of the project and the future steps planned
Local Party 3	Director of a local organisation who lives on the island	Involved in organising the pilot and realising hydrogen in Stad
Local Party 4	Owner of an installation company who lives and works on the island	Aware of needs of end users, what systems are trusted, and which are feared
Meeting with residents/ information evening March	Meeting with several parties as broad audience of local residents, entrepreneurs, interest groups, the municipality, the net operator, the corporations and an advisory party	First interaction with the residents of Stad. Possibility to examine the tone and reaction of residents without influencing.
Progress meeting May	Meeting with a group of representatives and same parties as during the meeting in March	Possible comparison to early meeting. Not all residents participated but a group of representatives that give insights into the sentiment of the households in Stad.

The interviews are analysed by transcribing and coding in ATLAS.ti. The goal of the codes is to explore in a consistent way technical alternatives and effects on households. When coding the whole transcript has been read first. After that, codes are assigned. After having assigned codes to serval interviews the coding is checked again to make sure no mistakes or biases occur. It is an *thematic coding approach* as the framework initially comes from literature but is also formed by the data itself (Urquhart, 2012). During coding, the code tree is reviewed, codes are merged or split and structuring by groups is iterated. This cause a consistent and concise analysis approach. The resulting approach can be found in Appendix C.

Coding makes it possible to maps the relevance of values of households in relation to the project in Stad. The codes allow for conceptualisation and operationalisation of the elements of the conceptual frame. Accordingly, the coding sustains choices for output parameters of the ABM. Benefits of listed coding is that it makes a structured content analysis possible and unstructured content manageable and meaningful (Bryman, 2015). A list of codes was developed beforehand. During coding this list was adjusted and specified. Limitations are problems with inter- and intra-code reliability (Bryman, 2015). Codes should be consistent between codes and over time. Furthermore, bias is an important issue. While qualitative analysis helps to explore, unconscious decisions could play a role. Opinions might be formed already. The codes might be interpreted in a way that supports this opinion. This can harm the identification of relevant new information.

The outcome of the interviews are technical design choices that need to be made. Based on the interview the conceptual frame can be filled with content. Conclusions can be drawn about mechanisms that play a role for the acceptability of technology. They lead to the conceptualisation and implementation of the Agent-Based Model. The process of data analysis, choices, conceptualisation and implementation is highly iterative. Modelling and qualitative data analysis, even though reported in two different chapters, have been executed in parallel.

The individual distribution of the identified values in not empirically researched by a survey for two reasons. The first reason is that doing a survey with several participants in a small and close community significantly increases the awareness for the subject and therefore influences the system. It is often hard to approach a sample that really represents the population as people more engaged and sensing more urgency for a topic are often more willing to participate than people that are sceptical or not involved.

2.2.2 ABM

Applying the frame of CAS to the technological transition in Stad ‘t Haringvliet determines the choice for a certain modelling approach. Different modelling approaches can tackle the problem however, ABM is chosen as it offers the most suitable and comfortable way for simulating human interactions. To tackle the problem in Stad aan ‘t Haringvliet three important elements of the system are tackled.

“ (1) diversity and individuality of components, (2) localized interactions among those components, and (3) an autonomous process that uses the outcomes of those interactions to select a subset of those components for replication or enhancement”

(Levin, 2002)

Households are diverse and have different properties (conversion factors) and values. Specific households communicate and react to each other following certain rules. Households change due to the information received from others. A modelling approach is needed that is able to simulate heterogeneity and interaction.

System Dynamics (SD) has its strength in reproducing and forecasting trends. It analyses complexity arising from a system´s structure and causality (Videira, Antunes, Santos, & Gamito, 2003). Disruptive events or time delays are easily simulated by using look-up functions (Borshchev & Filippov, 2004). However, the global development of the system is leading. The agents of the system do not have a central role. Individual differences are far more difficult to simulate in ABM. Discrete event simulation is capable of grasping probabilities and measuring flows and lead times. Bottlenecks can be identified by following entities (Borshchev & Filippov, 2004). However, it is hard to simulate interactions between entities during the process.

ABM considers the system and its dynamics bottom-up. Complex global behaviour emerges from individual behavioural rules. The way households interact shapes the acceptability of a system. ABM allows for easily integrating individuality of agents. ABM is capable to simulate the social interactions and exchange of information among households that lead to a certain public opinion about technology. Finally, ABM allows for tracing acceptability throughout time which makes it possible to come to long term insights.

The modelling approach described by Nikolic & Kasmire (2013) is applied as it offers a detailed and stepwise way to conceptualise, formalise, specify and implement an ABM (Table 2). This approach provides a structured way to formalise a model. The benefit of using this approach that it has specifically been developed to be applied far Agent-Based Models of socio-technical systems. The shortcomings of the approach are that it is very time consuming and that it is easy to lose track of the practical use of the model. The problem formalisation provides for a clear research question and a purpose of the model. The problem formalisation is the core of the further process and defines what problem is addressed by the model. The system identification is an enumeration of the system elements. The border of the system is determined by the problem formalisation. The system identification is an important step as it determines the complexity of the resulting model. The system identification must strictly follow the problem formalisation and model purpose.

The concept formalisation covers the dynamics that are part of the system. It is similar to the system identification step. As few as possible should be included and as much as needed. Schemes, formulas and graphs are good ways to keep track on this research step. The model formalisation is the translation of a system into something that can actually implemented in software. The purpose is very functional but must be executed carefully as flaws might occur. The real world is often difficult to translate into code. An iterative approach and the model verification help to check whether simplifications are correct.

Table 2: Modelling Approach described by Nikolic & Kasmire (2013)

Step	Description	Methods
Problem Formalisation	Identification of the problem, the problem owners and other actors involved	Qualitative analysis of the interviews
System Identification	Identification of internal structures, states, relationships, behaviours and interactions	System Diagram based on the interviews
Concept Formalisation	Making the schematic model understandable computer language and developing a software data structure	Values of parameters, identification of relations and the environment.
Model Formalisation	Narrative	List of actions in bullet points
Software Implementation	Implementation in programming environment	Programming in NetLogo
Model Verification	Evaluation whether the concept has correctly been implemented in programming	Single agent testing and behaviour tracing
Experimentation	Design of experiments that leads to the required insights to give an answer to the question	Formulation of hypothesis, simulating scenarios, Latin Hypercube Sampling, determining run tomes and repetitions
Data Analysis	Consists of four steps which are data exploration, pattern visualisation, interpretation and integration	Exploratory Modelling in Python
Validation	Answer to the question whether the model is able to answer the question formulated	Replication, structured qualitative data analysis of interviews
Model Use	Exploring practical aspects of using the model	Presentation and Engagement

2.2.3 Validation & Verification

Because human interactions and rules of adapting behaviour are so hard to operationalise, the model must be very carefully evaluated. Verification and validation are difficult. There is a lack of data to compare to model results to.

A structured way to go through verification and validation are described by Augusiak, Van den Brink, & Grimm (2014). The steps and approaches presented in Table 3 described in the paper offer a detailed and complete way to testify that the model is correct. The steps described provide for conclusions even with a lack of real-world evidence. The steps are more into depth than the steps suggested by Nikolic & Kasmire (2013). They mainly focus on the model output and the software implemenation. The method suggestde by Augusak et al. (2014) additionally considers basic assumptions of the model. The modelling process and the model outputs are evaluated.

TABLE 3: VALIDATION STEPS ADAPTED FROM (AUGUSIAK ET AL., 2014)

Step	Definition	Tool
Data evaluation	Assessment of the quality of data	List of model input and sources
Conceptual model evaluation	Assessment of the simplifying assumptions	Consult comparable models, use of uncertainties were no clear concept can be formulated, scenario workshop
Implementation verification	Testing for programming	Following single agents
Model output verification	Assessment of whether model output matches real-world observations	Tracing behaviour and global patterns
Model analysis	Assessment whether the model is sensitive to changes in parameters	Exploration of overall performance of the model doing a sensitivity analysis using EMA
Model output corroboration	Comparison of model predictions with new, independent data and patterns	Scenario Workshop

Doing the data evaluation, the quality of data used to parameterise the model is evaluated. A structured way to evaluate value is assessing a list of parameters and eliminate questionable data from unreliable resources. The conceptual model evaluation checks whether the conceptual model solves the problem. This step is difficult to execute. The conceptual model is hardly comparable to the real world. A way to deal with this challenge is looking at other models. Comparable concepts that have been proven useful are used as reference. Another way is comparing the conceptual model to the conceptual frame. The Implementation verification assesses whether the formulated concept has correctly been translated in to a computer model. In the case of ABM, it is useful to trace agent behaviour and follow individual agents to check whether there are any bugs or inexplicable behaviour. The model output verification is a step to testify the correspondence of the model and the real world. The outcomes of the model are compared to the reality. This is done by comparing findings from the interviews to the output of the model in terms of agent behaviour. The model analysis is an assessment of the ability of the model to solve the problem formulated. The sensitivity to changes in parameters is explored. This leads to implication for the interpretation of further research steps. The step of the model output corroboration steps is covered by bringing the model into practice. A scenario workshop based on the model results is used to show external validity of the model.

2.2.4 EMA & Experimentation

The case of Stad aan ' Haringvliet holds deep uncertainty due to its complexity but also due to a lack of data about specific mechanisms. Amongst households and stakeholders there is no agreement about what most important topics to discuss are. Information about the probability of social interactions and their results are unknown. Finally, it is undefined what exactly are desirable outcomes when it comes to acceptability of hydrogen (Kwakkel, Auping, & Pruyt, 2013).

This asks for a profound exploration and analysis of the ABM representing the households. Simple simulation in the ABM software NetLogo and a conventional sensitivity analysis are not capable of grasping the uncertainties caused by human interactions and values. The exploratory modelling and analysis approach (EMA) uses "computational experiments to assist in reason about systems where there is significant uncertainty" (Bankes, 1993). EMA is able to "capture the full breadth of uncertainty about the future in a small set of scenarios" (Kwakkel et al., 2013).

The goal of applying EMA is identifying outcomes of interest that are caused by a certain combination of uncertainties. This is called scenario discovery and a specific application , thus part of EMA (Kwakkel et al., 2013). It allows for identifying vulnerabilities. For producing regions of interest, the Patient Rule Induction Method (PRIM) is applied. This tool is part of the EMA workbench (Kwakkel, 2017) and allows for identifying subspaces in the data where output variables are significantly different from the their average with regard to the whole data set. 'Boxes' of the data input space are identified that lead to desirable outcomes (Kwakkel et al., 2013). This provides for a very structured, profound and reliable analysis compared to alternatives. The criteria to choose the right box are density and coverage. Density indicates the fraction of interesting cases (with the assigned high outcomes) inside the selected box. Coverage gives the fraction of cases that are not within the box. The higher both values, the better the outcomes.

In the case of Stad aan ‘t Haringvliet is the goal of experimentation and analysis with the EMA workbench creating input for the scenario workshop rather than optimisation. The analysis should indicate which choices on combination with certain circumstances possibly increase acceptability of hydrogen.

2.2.5 Engagement Workshop

The last research step is an engaging activity where stakeholders are asked to provide input. Literature on scenario workshops is consulted to develop a session where answers can be found about how to engage households and what topics to discuss with households in future project steps(Mulder, Petrik, Parandian, & Gröndahl, 2012; Nielsen & Hansen, 1997; Oreszczyn & Carr, 2008) . A scenario workshop is a method to explore possible futures together with a selected set of stakeholders or experts. As the term “scenario workshop” in this thesis might cause confusion because it is a term used for the EMA approach, the workshop is called *engagement workshop*.

The workshops follows three phases: criticism of the scenarios, visions and action plans (Nielsen & Hansen, 1997). Workshops comparing different solutions for a problem have been proven a useful tool to be a link between research and practice. The workshop generates data for the model corroboration, identifies short-comings of technical designs and provides measures to address these shortcomings. The results are recorded by camera, by audio recording and by taking notes based on some predefined questions and issues.

As the workshop is organised in the summer period the number of participants is limited. As the goals is especially related to households, it is crucial that residents of Stad aan ´t Haringvliet participate. During the workshop three representatives of the residents, two advisors of entrepreneurs, one member of the municipality involved in the project and two representatives of the wind corporation who during the last month became project leader and problem owner are participating.

The group of participants (Figure 2) chosen (eight people) is capable of giving insights into the perception of residents and assessing the scenario´s. The group is suitable to evaluate the acceptability of the scenarios and improve the scenarios as they are familiar with the situation in Stad aan ´t Haringvliet, the technical properties, opportunities and drawbacks and the values and interests of residents.

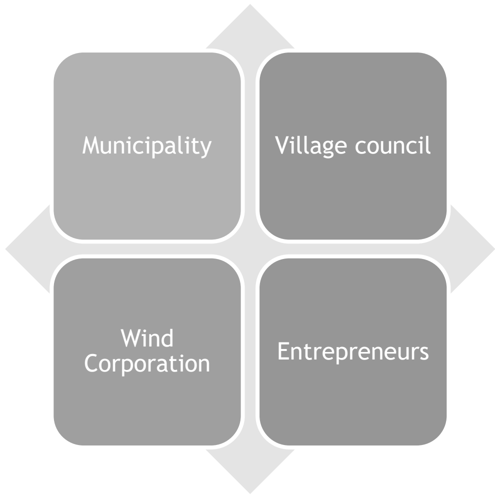


FIGURE 2: PARTICIPANTS

The session consists of 4 rounds (Figure 3). The first round is a short questionnaire were assumptions of the model are evaluated. The second round introduces the scenarios that have been developed based on the ABM. Participants get the chance to write down their first impressions and judge whether the scenario is acceptable according to the definition of acceptability used in this research. The third step is a brainstorm session where the most acceptable scenario is explored, and improvements are suggested. The last round is an evaluation of the work shop to finally answer the sub question asked and assess whether inclusion has been successful.

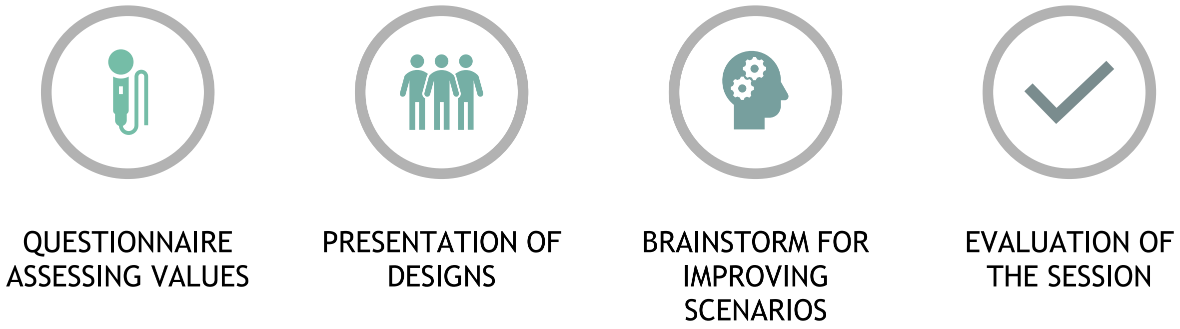


FIGURE 3: STRUCTURE OF THE WORKSHOP

The questionnaire evaluates the model assumption and assesses the importance of values. The designs are combinations of technical choices that are gained from the experimentation with the ABM. The brainstorm assesses the effect of designs. The description of the designs can be found in Appendix P. It consists of two elements: a problem identification and improving or supporting the scenarios. Finally, the use of the workshop is evaluated by a questionnaire. The forms can be found in Appendix O.

3 Conceptual Framework

To answer the first sub-question 'Which aspects related to the acceptability of replacing natural gas by hydrogen in households can be used for the conceptualisation of the problem?', this chapter describes a literature study. Based on this study a conceptual frame is formulated that integrates value sensitivity, capabilities and the complex system approach. This chapter consists of;

- A description and critical review of the capability approach;
- A novel conceptual frame; and
- Conclusions for the case and the next research steps.

3.1 The Capability Approach

This section compares different angles of the Capability Approach described in literature to come to definitions. These definitions are not necessarily exactly what can be found in literature but present the decisions made in this research. The definitions are interpretations that are useful when using the Capability Approach(CA) for assessing energy technology. These interpretations are needed to answer the sub-question and develop a conceptual frame. This section:

- Introduces the aim of the capability approach;
- Defines human well-being;
- Defines other core concepts described in literature on the CA: capabilities, functioning & conversion factor; and
- Defines acceptability of technology.

In general terms the CA discusses justice, equality, well-being and development based on evaluating human capabilities and freedom of choice (Appendix A). The founders of the CA are Amartya Sen and Martha Nussbaum. This study mainly follows the definitions given by Sen and summarized by Robeyns (2016) because Sen gives broadly applicable concepts that can be adapted to concrete situations. Using these definitions allows for identifying a specific set of capabilities for the case of Stad aan 't Haringvliet. Nussbaum defines a list of prescribed "central human capabilities" which measures well-being in general terms (Appendix A). This list is to general to come zo conclusions that help the stakeholders with developing a system design for hydrogen infrastructure together with households.

3.1.2 Well-Being

Well-being asses the ability of individuals to realise activities considered valuable. In this research the term "human well-being" is used to determine in whether a technology is morally acceptable or not. Human well-being is therefore defined as a set of "effective opportunities to undertake the actions and activities that [humans] want to engage in, and be whom they want to be" (Robeyns, 2003 p.3). People can either choose for comfort (e.g. driving a comfortable car) or consciously not choose comfort (e.g. taking the bike instead of the care, even though it rains) depending on what they one considers valuable. An important assumption is that the more freedom of choice a technology offers, the more acceptable it is, because it causes less restrictive long term effects (Künneke et al., 2015). Well-being can be interpreted as the personal satisfaction of an individual caused by technology.

Well-being is used to assess the moral acceptability of technology. Well-being described a mental state and indicates satisfaction of individuals by assessing their ability to do what they consider valuable.

3.2.2 Capabilities

Two concepts described in literature on the CA are used to evaluate human well-being: Functionings and capabilities. A capability is the ability to achieve well-being by choosing to undertake or not undertake certain actions related to technology such as saving energy, cooking, heating or being informed about technology. A list of values allows for relevant identifying capabilities relevant for the assessment of well-being related to hydrogen technology.

The distinction between functionings and capabilities is between the realised and the effectively possible, between achievements and freedoms to choose from different opportunities. A capability can be seen as ability to choose from a set of functionings because according to Robeyns (2016) "Capabilities are a person's real freedoms or opportunities to achieve functionings"

The set of opportunities to realize functionings, being and doings, determines a person's capabilities (Robeyns, 2003). Beings are states such as being scared, being informed and educated or feeling heard. Doings are activities that a person can undertake as cooking, heating or travelling. Whether a functioning is valuable depends on the context. The functioning itself thus is morally neutral. The Sen and Nussbaum claim that functionings (being and doing or utility and resources) should be less important than capabilities (freedom and options to do or be something). Essentially, it is stated that the value of an artefact depends on the capabilities of a person and the possibility to develop those, not on the artefact itself (Illse Oosterlaken & van den Hoven, 2012).

A capability is seen as the ability to choose from a set of activities or (mental) states. This freedom of choice causes or increases well-being. A capability does not indicate which choice an individual actually makes.

Each individual needs to assess his or her own well-being. There are potentially limiting or enabling factors that need to be checked. While a mobile phone is very useful for people that live in areas where signal is easily received, people, that live in mountains where there is no signal, experience less benefits even when they own exactly the same technology. The individual abilities and resources are called *conversion factors*.

Conversion factors are individual properties and resources that enable or disable capabilities.

The Capability Approach distinguishes between personal, environmental and social conversion factors. Personal characteristics are for example physical condition (e.g. health), skills and intelligence. Social characteristics are determined by public policies, social norms, practices, roles hierarchies and relations. Examples of environmental characteristics are infrastructure, institutions, public goods and climate. To achieve a certain functioning, resources such as money, knowledge and space are needed (Robeyns, 2003).

3.2.3 Acceptability

Acceptability is in this research considered in terms of individual well-being and freedom of choice. Acceptability increases when technology increases opportunities and freedom. Technology is less acceptable when it has restricting long term effects (Künneke et al., 2015). The objective of the conceptual frame is providing an approach for measuring the changes of well-being due to technological changes. Applying a specific list of capabilities that are related to hydrogen consumption in households allows for identifying specific bottlenecks and benefits of technological design choices.

Acceptability is in this research considered in terms of individual well-being caused by technology. Technology is acceptable when it increases the number of choices to realise things that an individual finds important or valuable.

3.3 Discussion of the Conceptual Frame

The conceptual frame presents a theoretical approach to assess acceptability based on the definitions retrieved from the literature on the CA, literature on values embedded in energy technology and change and the complex system approach described in the methodology section and appended by Ligtvoet, van de Kaa, et al. (2015). The framework aims to embed values in the design process.

This section presents:

- A new conceptual frame; and
- A guide for using the frame.

The frame forms the basis for section values and capabilities. Figure **4** shows the conceptual frame. It explicates how values, capabilities and acceptability may be related and determines relation between the elements that is considered thorough the following research steps. This new approach is needed because it allows for identifying a list of relevant values and related capabilities influencing acceptability. The frame links acceptability to the elements of complex systems which allows for the identification of the elements of an Agent-Based Model and model conceptualisation. Dynamic components are added to a static representation of capabilities. This allows for not only assessing one moment in time but exploring changes over time due to changing conditions.

The blue ovals in Figure **4** show the elements of the CA. The yellow ovals represent the concepts of literature on Value Sensitive Design. The transparent ovals are important elements of the complex system design approach. It is assumed that resources are unequally distributed amongst the same group of stakeholders and that they change over time. The arrows the influence of capabilities on acceptability. Depending on the situation it needs to be determined how many capabilities lead to acceptability. Values on the one hand are shaped by individual properties, but also indicate what capabilities must be considered when assessing for example hydrogen technology. The dotted line shows the scope of the system. It indicates that functionings, thus choices and achieving states, are not considered by the frame. Not all properties can and should be simulated. The Capability Approach highlights heterogeneity in conversion factors, but not in values. This is indicated by the dotted line crossing this oval. The Capability Approach distinguishes between personal, environmental and social conversion factors. Personal characteristics are for example physical condition (as health), skills and intelligence. Social characteristics are determined by public policies, social norms, practices, roles hierarchies and relations. Examples of environmental characteristics are infrastructure, institutions, public goods and climate. To achieve a certain functioning resources as money, knowledge and space are needed (Robeyns, 2003). The Capability Approach also describes the concept of adaptive preferences. This is a property of actors which makes their worldview adapt to their context and resources available (Oosterlaken, 2015).

The arrows indicate the direction of the relation between the concepts. The relation is described next to the arrows. Thus, when the number of capabilities increases, well-being increases. An increase of well-being makes a design choice more acceptable than a design choice that decreases well-being and restricts capabilities. Valuable individual capabilities may increase or decrease due to technology.

The dotted lines that crosses some concepts indicates that not all human values, individual differences or interactions need to be considered to come to insights about the acceptability of design choices.

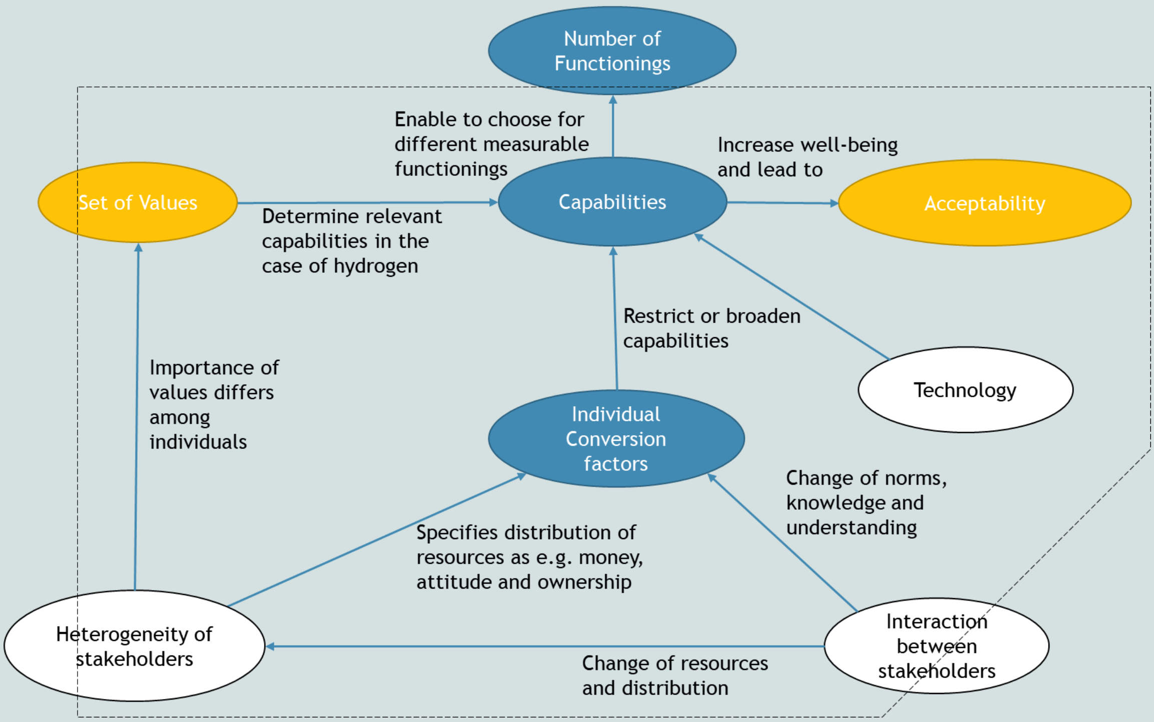


FIGURE 4: CONCEPTUAL FRAME TO ASSESS THE EFFECT OF TECHNOLOGICAL CHANGE

The set of values is determined by the set of stakeholders that is chosen to be considered. When identifying a global set of values, it is considered that different stakeholders value different things. Given a global set of values relevant capabilities can be determined. These allow for choosing functionings.

Specific individual functionings are out of scope of the conceptual frame because they indicate the choices that are actually made. Individual differences between stakeholders change due to interactions. Interactions do not only change the distribution of resources but also the environment by changing for example social norms.

Individual conversion factors are factors that determine whether individuals are capable of choosing. Individual resources and the effects of other stakeholders on the system form conversion factors that differ per household.

3.4 Conclusion

Which aspects related to the acceptability of replacing natural gas by hydrogen in households can be used for the conceptualisation of the problem?

To answer the question it is cleared what is meant by 'acceptability' and how acceptability is established. To elaborate on the aspects of acceptability and their relations, a new conceptual frame needs to be developed. Developing the frame allows for:

- Scoping acceptability of technology for households; and
- Getting better grip on the complexity of the project in Stad aan 't Haringvliet.

This chapter elaborates on literature and comes to choices of how to define and use certain terms in this research. The CA is developed to assess well-being in general terms. In this research the CA is applied to increase the acceptability of energy technology. The terms capabilities, well-being, freedom and acceptability are strongly related. Capabilities describe in this research a number of ways to come to a certain result. Taking CO_2 reduction as an example for a capability, having the capability means being able to determine whether and in which way CO_2 is reduced. Well-being then is a result of capabilities as for example being able to choose whether and how to reduce CO_2. It is a state that can be increased or decreased. Assessing well-being makes the effects of technologies on individual humans comparable but is not actually tangible but conceptual. It is a step towards making the effect of technology somehow scalable considering individual differences.

A benefit is that there is no bias caused by letting a researcher make assumptions about individual preferences, but by considering the number of choices effectively available given individual abilities and resources. Which capabilities lead to an increase of well-being when changing energy system depends on values individuals have with regard to energy system change. To narrow down the complexity and scope of the research somehow, not all potential capabilities are considered for measuring well-being, but capabilities related to energy system change. Getting to know more about levels of well-being and changes in well-being allows for making assumptions about acceptability of technology. The current technology can be taken as reference point because it has been proven acceptable for a majority of households.

The conceptual frame combines the elements of the CA with a complex system perspective. The elements of the conceptual frame are values, capabilities, acceptability, conversion factors, heterogeneity and interactions. This allows for assessing well-being and making assumptions about acceptability even under changing circumstances and for longer time periods. The conceptual frame allows for structuring problems that when developing technical solutions values of households can be embedded in the design of a novel system. A drawback of the frame is that it has not been tested yet. Studying the situation of Stad aan 't Haringvliet not only shows how to support and advise the local parties but also indicates how to embed values into designs.

4 Selection of Values and Capabilities

This chapter identifies values, capabilities and technical design choices that are relevant for realising acceptable hydrogen infrastructure in Stad aan 't Haringvliet. The chapter gives answer to the sub-question 'Which capabilities cause acceptability for households when assessing potential technical designs for Stad aan 't Haringvliet?'. To identify relevant capabilities, values that need to be embedded in technology are identified.

This chapter describes the selection process of values and capabilities. To identify which capabilities are relevant when assessing the acceptability of hydrogen infrastructure in Stad aan´t Haringvliet the steps take are:

- A review of literature on values for assessing technical designs and
- Results from eight interviews identifying technical options and their effects

4.1 Values in literature

This section elaborates the necessity of considering values when applying the CA for assessing the effects of hydrogen infrastructure. The CA does not indicate precisely which capabilities are to be considered. Additional literature on design is consulted to assure that relevant criteria are found for the assessment. Furthermore, it is argued why certain literature is considered to identify values and how to select the values that are further analyse in the next research step. This section includes:

- Defining the term 'values';
- Identifying relevant literature; and
- Identifying sets of values.

Literature about social impacts of energy systems and transition processes identifies several values (Demski, Butler, Parkhill, Spence, & Pidgeon, 2015; Künneke et al., 2015; Ligtvoet, van de Kaa, et al., 2015). This literature is reviewed as Künneke et al. (2015) make a first effort to make a link between values and capabilities, Demski et al. (2015) describe a broader context but explicitly consider the effect of energy system change and Ligtvoet, van de Kaa, et al. (2015) add the design and complex system elements. All papers are published in peer reviewed papers, present a number of relevant references and are referred to by other scientists.

4.1.1 Definition of value

A value is "an enduring belief that a specific mode of conduct or end-state of existence is personally or socially preferable to an opposite or converse mode of conduct or end-state of existence" (Rokeach, 1973 p. 5). Values influence human behaviour as they determine preferences and what is considered acceptable. Values are rigid and tend to change little over time. “Technological designs embody values”. Technology might strengthen or violate values held by stakeholders (Flipse & Puylaert, 2018 p.2). Smith & High (2017) state that “energy and energy infrastructure take on different values in different locations”. It can be concluded that values are dependent on the context and actor specific.

A value is “an enduring belief that a specific mode of conduct or end-state of existence is personally or socially preferable to an opposite or converse mode of conduct or end-state of existence” (Rokeach, 1973 p.5)

4.1.2 Künneke: Values & the capability approach

Künneke et al. (2015) describe values embedded in offshore wind energy systems (Table 4). They suggest addressing ethical issues taking values into account. Furthermore, they use the Capability Approach as value framework to develop a new framework for a normative evaluation of offshore energy systems. Although, their focus on offshore energy systems, some of the conclusions drawn on the relevance of certain values (e.g. security of supply or sustainability) are also applicable for a hydrogen-based energy system.

TABLE 4: VALUES EMBEDDED IN OFFSHORE WIND ENERGY SYSTEMS (KÜNNEKE ET AL., 2015)

Values embedded in offshore wind energy systems
security of supply
sustainability and environmental protection
(near) reversibility of physical assets
distributional justice
procedural justice
appropriate property and ownership configurations
privacy
safety

4.1.3 Demski: Public values for energy system change

Demski et al., (2015) have conducted research on public values related to energy system change from a holistic point of view. The effects of change on acceptability are evaluated, as well as public values and attitudes for the energy system as a whole. This makes it possible to draw conclusions without understanding all the complexities. The values that are identified conducting mixed-methods are summarized in Table 5. While the Capability Approach mainly focusses on a state of a human being at one moment in time, the values gathered by Demski et al., (2015) also consider the way of changing and not only the result.

Table 5: Public Values for energy system change (Demski et al., 2015)

Public values for energy system change	
avoiding waste	social justice
efficiency	fairness (honesty, transparency),
capturing opportunities	autonomy and freedom
environmental protection	choice and control
nature and naturalness	long term trajectories
availability and affordability	interconnected
reliability	improvement and quality
safety	

4.1.4 Ligtvoet: Values from Value-Sensitive Design literature

Expressing values is difficult and therefore it is hard to include moral values within designs of complex energy systems. Developing a Value-Sensitive Design means not only taking functional requirements into account but also addressing individual and social values (Ligtvoet et al., 2015).

Ligtvoet, Van De Kaa, et al., (2015) give a list of values that are related to complex technology and mentioned in literature on Value-Sensitive Design (Table 6). This list is more specific than the general list given by Nussbaum and individual values form a basis to identify capabilities created or restricted when introducing hydrogen to Stad aan 't Haringvliet.

Three system elements are highlighted that are applicable to the planned hydrogen system. The system is systemic as it consists of a number of components and subsystems. These subsystems are for example conversion installations, pipes and end user equipment. Multiple interactions take place as households have to make choices whether to support or reject the proposed change based on information and arguments and the system is indecomposable. Acceptability cannot be assessed without assessing effects of technology or social interactions. These system elements are included when devolving a conceptual frame.

Table 6: Set of values relevant when designing complex technologies

Functional Values	Social Values	Individual Values
accountability	cooperation	autonomy
correctness	courtesy	calmness
efficiency	democracy	economic development
environmental sustainability	freedom from bias	informed consent
legitimacy	identity	ownership
reliability	participation	universal usability
safety	privacy	welfare

tractability	trust	

4.1.5 Implications for the interviews

The functional values, social values and individual values described by Ligtvoet, van de Kaa, et al. (2015) form the basis for further exploration of capabilities and acceptability of technology. The list described by Künneke et al., 2015 cannot easily be operationalised to capabilities of individual users. While Demski et al., 2015 mainly addresses what Ligtvoet et al., 2015 would identify as functional or social values, Ligtvoet et al., 2015 add the dimension of individual values. Comparing public values for energy system change described by Demski et al. (2015) to the values of designing complex technologies (Ligtvoet, van de Kaa, et al., 2015) shows that there are many similarities. The abundant list of values given by Ligtvoet, van de Kaa, et al. (2015) is chosen as it covers the most important values identified in additional literature and specifies individual values.

This set of values identified by Ligtvoet, van de Kaa, et al. (2015) needs to be further specified because the values described are very abstract and global. Most values may be interpreted in different many ways. Some values on the list are very specifically related to ICT problems as e.g. privacy, tractability or identity. Those values are probably less important than safety, sustainability or autonomy. A selections of relevant values has to be made based on insights from local stakeholders and experts.

4.2 Specification of local factors

The interviews provide for two purposes regarding the data generated. The main objective of doing and analysing interviews is twofold. The first objective is identifying capabilities. The second purpose is understanding effects of possible technical choices on users and the identified capabilities. Capabilities depend on values but also on conversion factors. Thus, an overview is given of values related to relevant capabilities that haven been identified during the interviews. Conversion factors and resources are specified that necessary to have a certain capability (realise the functioning) are given. Valuable capabilities are identified by determining:

- Local values with regard to energy system change;
- Relevant conversion factors that determine capabilities; and
- The effects of technical alternatives.

To mitigate for the problem that the semi-structured interviews are difficult to compare, the interviewees are divided into three groups when coding and analysing the coding approach. The three perspectives play different roles for coming to conclusions about alternatives, capabilities and local values. Local stakeholders give precise information about local values and habits and what should be considered when assessing well-being. Policy makers illustrate a broader context with possible barriers or drivers. Policy makers additionally give insights into comparable projects and the effects of the choices made. Technical experts give an overview of the choices possible. Furthermore, they are especially concerned with costs. In the Appendix C a list with the final codes and the code groups can be found. The differentiation and substantiation with quotes of these perspectives can be found in Appendix D. The quotes are translated as the interviews were held in Dutch.

4.2.1 Values

The values and definitions provided by (Ligtvoet, van de Kaa, et al., 2015) are presented to the interviewees. The interviewees are asked to explain whether these values potentially play a role when changing the energy system and to what components of the system thy may be linked. The answers lead to a list of values. How conclusions are draw and based on which information from the interviews can be found in Appendix D. The values identified during the interviews are

- Affordability;
- Public Support;
- Participation;
- Comfort and welfare;
- Autonomy and choice;
- Fairness;
- Sustainability and
- Safety and security of supply

Substantiation based on quotes from interviews

Affordability plays an important role for comparing alternatives as heat pumps and heat networks, also timing plays a role for investments. According to technical experts, it depends on the timing because *"Short-term changes have a lot of impact, changes that can be announced in the long term have less [financial] impact. It can be done without nuisance."*

Technical experts furthermore claim that there must be some kind of consensus within the community that the solution proposed is a good solution. In some way the public opinion should be considered in the model. As there is *"no innovation without acceptance"*. Especially given the specific characteristics of the community of Stad aan 't Haringvliet choices should not be made without the participation of households.

"I think it is very important for residents to be involved. I also think it is good that the residents get their own group of representatives."

According to policy makers comfort must be considered as important condition for acceptability because

“nothing should change in use and comfort compared to the current system”.

Autonomy is mainly determined by financial resources of the residents. Fairness or equality seems not to be an issue yet. Sustainability in most cases seems not to weigh out costs.

“There will be a few who will do it for the environment.”

There is not much known about the safety and security of supply, but it is stated that poorer performance then the recent system is not acceptable. Therefore, this value can be excluded as the recent system is accepted. The information about and perception of safety play a role rather than safety itself.

“The system simply has to work always.”

4.2.2 Conversion Factors

To be able to develop technology that incorporates the values identified. The codes applied for the analysis of the interviews explore differences between households and characteristics that create differences when it comes to realising capabilities.

Properties of households that seem to play a role according to the information gathered by the interviews are affection with sustainability, the tightness of the community, caution when changes herald, financial independence, need for adjustment of homes and the perception of hydrogen. Based on this insights a list of overarching conversion factors relevant for modelling the system is determined. The factors are:

- Attitude;
- Information;
- Money;
- Housing Situation; and
- Insulation.

Substantiation based on quotes from interviews

According to local parties the number of people willing to actively participate and taking a proactive role in thinking about alternatives is unknown. However, there is a village council and small group representing residents that is actively participating in thinking about the future of the project.

“It is a bit inherent to island residents to be careful.”

The information given to households it essential for being able to realise capabilities. The proactiveness of residents differs, but it is unclear in what way. Technical experts claim that there is a lack of information and understanding of technical alternatives and the individual effects amongst residents and households. *"I have no idea what the perception of hydrogen is. Frankly, I think that the average resident in the Netherlands does not really know much about hydrogen."*

There are differences in the capabilities of residents to pay for renovation and new equipment. Local parties assume that the available income of households determines the acceptability of the project as it determines the capability to participate.

"We assume that a part of the population could do it [renovation] but we have a large part of the population living in the older homes that simply do not have the money to adjust housing."

The housing situation is determinative for the capabilities as tenants have less freedom of choice. Local parties think that a tenant cannot refuse if it is decided that we are going to supply hydrogen. The insulation of high numbers of houses is poor because in Stad aan 't Haringvliet there is "*relatively old property.*"

4.2.3 Alternatives and their effects

There are several alternatives when it comes to introducing hydrogen in the residential area of Stad aan ´t Haringvliet. However, from the interviews some seemed more likely, more discussed or practical feasible than others. This section highlights the according to the interviewees most important broadly defined technical alternatives. The most important ones are:

- All-electric;
- Pure hydrogen;
- Mix;
- Green Hydrogen;
- Heat Network; and
- Cooking.

The others are outside the scope to keep the results manageable. The codes identify where renovations and investments are needed.

Substantiation based on quotes from interviews

All-electric is mentioned by different parties as likely alterative for gas. However, it is also stated that this is not an option for all households as the house has to be sufficiently insulated.

"Heat-pumps heat with low temperature. Then it is important to insulate the house. These are quite high costs."

There does not exist equipment yet that is suitable for mixes and pure hydrogen at the same time. Therefore some interviewees, especially technical experts, have a preference for directly distributing pure hydrogen instead of gradually mixing

"From the end user equipment point of view it is easiest to make one choice. The device is suitable for one or the other."

The goal is to locally produce green hydrogen from surpluses produced by renewable energy technologies e.g. wind turbines. However, *"Green hydrogen is generally more expensive than grey hydrogen"* according to policy makers.

From the interviews with local parties it seemed that there are few opportunities to retrieve heat. There is more interest in gaining experience in bringing hydrogen into individual households.

"There are no industries that produce heat, so surface water would be the only alternative for a heat grid."

Local parties indicate that it might be more desirable to just heat with hydrogen. Fear seems to play a role here. On the other hand, not being able to cook in gas is also identified as a barrier for change.

4.2.4 Base Case

Based on the appreciation given by the different stakeholders a choice has been made on which design of hydrogen infrastructure is used as base case. Simply doing nothing is not an option as basis for comparison. The energy system will change. On what term should turn out when analysing the data generated. The base case is a solution where all-electric is available as alternative to hydrogen, where there is pure and green hydrogen that can only be used for heating but not for cooking as many local parties indicate that there might be safety issues.

4.2.5 Capabilities

Based on the values, conversion factor and alternatives identified a set of capabilities can be operationalised. These capabilities are:

- Choice for alternative ways of heating;
- Choice for quality and price of replacing equipment;
- Possibility of insulation;
- CO2 reduction; and
- Choose daily patterns with regard to cooking and heating

Even though safety is an important value according to stakeholders, no capability has been formulated that refers to safety. This is due to the fact that the system has to be as safe as the current system. Safety is considered a boundary condition of the technical design.

Affordability also is mentioned to be important for households. Affordability is incorporated in autonomy (or freedom of choice) due to the availability of resources. Thus the value of a design is not compared in terms of costs but in terms of providing autonomy.

Substantiation based on quotes from interviews

Choice depends on affordability thus, "*on the costs that have to be made.*" A local party states that it is not likely that *"one can use hydrogen in the long term and the other does not. Everyone has to do it to make it profitable"*.

When asking about safety a technical expert concludes that the safety of the system *"should not be worse than it is now, but it does not have to be better either"*.

Local parties claim that the new system needs to have added value when it comes to reliability, comfort of safety. It is assumed that these aspects are related to the experience of safety during cooking, sticking to daily patterns and availability of heat at any time of the day.

"It should have more value at least in one of those areas. Because why would you put money into something that is ultimately not better? That is my great fear because what we have now is reliable, safe and comfortable. I do not know yet what the added value is."

4.3 Conclusion

The concept of capabilities is quite abstract. Step-by-step narrowing down the concept leads to a number of concrete capabilities that are understandable for households and help to assess and compare technical designs by modelling and simulation but also in a participatory way.

Which capabilities cause acceptability for households when assessing potential technical designs of hydrogen infrastructure for Stad aan 't Haringvliet?

The capabilities that can be retrieved from values, conversion factors and effects of technical alternatives are:

- Choice for alternative ways of heating;
- Choice for quality and price of replacing equipment;
- Possibility of insulation;

- CO_2 reduction; and
- Choose daily patterns with regard to cooking and heating.

These capabilities form the basis of the assessment of a set of technical designs as they indicate the freedoms that households currently have. It is assumed that these freedoms and choices need to be sustained in future. If the freedom of choice does not change, the new technology is as acceptable as the current technology. The current technology can be used as benchmark as it has been accepted for serval years. However, some capabilities as for example reduction of CO_2, seem to become more important.

The capabilities determine the set of conversion factors. The conversion factors are the boundaries for having freedoms and choices. The conversion factors relevant for creating of hampering capabilities are attitude, money, information and the housing situation. Attitude and information indirectly determine whether households are aware of their freedom of choice. Money and being owner or tenant of a house are hard, functional criteria for having or not having choices.

The values that indicate which capabilities are important and must be considered are affordability, public support, process participation, comfort, autonomy, fairness, sustainability and safety and security. These values are identified by stakeholders and related to examples from the current system. It is a drawback that stakeholders find it difficult to think about a future system without having the functions of the current system in mind. However, the set of values is abstract enough to create space for out of the box policies and adjustments of the current design ideas.

The alternatives are all-electric, 100% hydrogen or mixing, green hydrogen or grey, and cooking on hydrogen or just heating. These alternatives represent some basic choices to be made by project leaders in collaboration with households and other local stakeholders. The alternatives described are no detailed designs but indicate directions and the most basic choices. The interviews show that the stakeholders struggle with making these choices. Because there is a lack of information how these choices affect the households. Some assumptions are by interviews that might be further explored.

The base case represents a design that is indicated by serval interviewees to be most likely. The base case considers 100% green hydrogen, offers the opportunity to choose for all electric but does not offer cooking in H_2. There are differences in optimism in views when it comes to developing acceptable hydrogen infrastructure. Especially the interviewees concerned with costs were more pessimistic about the possibility of increasing well-being than stakeholders involved in facilitating the process. The need for supporting and informing households was clearly addressed.

Heat networks are explicitly excluded in the next research step. It seemed that the prioritised option is hydrogen. Important parameters identified in the interviews are distribution of individual costs and investments for owners and tenants. No decisions have been made yet about the distribution of costs. Aside from technical solutions, knowledge about institutional, legal and process related changes have been shared. There are some options for funding, but there has not commitment been gained yet. The process of lobbying for institutional and legal change is still ongoing.

Safety is not addressed even though it is important. It is considered a boundary condition of all technical designs and therefore not explicitly addressed. Costs are not calculated but considered in the form of conversion factors and autonomy. So no conclusions can be drawn about public or private costs of individual households. However autonomy can be assessed due to affordability.

5 Agent-Based Model

This chapter provides the first part of the answer to the question: 'What effects the acceptability of hydrogen distribution and domestic use for households?'. This chapter describes the

- Problem formulation,
- Conceptualisation,
- Formalisation and
- Specification

of the modelling and simulation process.

First the problem is formulated by identifying the system and its elements. A problem statement and a modelling goal are defined. Secondly, the elements of the ABM are identified in the concept formalisation. The dynamics and behavioural rules of Stad are specified in the model specification. The implementation of the model is discussed and conclusions for the next steps are drawn.

5.1 Problem Formalisation

To assess what the effects of different designs on the acceptability for households are, a clear scope is chosen. This determines a system with inputs and outputs. The system is limited to the households of Stad aan ´t Haringvliet to be able to come to conclusions about the community acceptance. A system approach is chosen to identify and scope the effects of design choices. This approach deals with complexity caused by human heterogeneity, interaction and behavioural patterns.

5.1.1 System Formalisation

Acceptability is a complex phenomenon. It is hard to predict because it depends on many factors as individual properties of households, external factors of the environment. Prices, trends and internal uncertainties influence the system. In Stad aan 't Haringvliet, households are heterogenous with respect to:

- Types of houses;
- Spendable income; and
- Attitude.

The households interact by:

- Broadcasting and receiving information; and
- Spreading and adapting public acceptance.

The information available about the effects of hydrogen is spread amongst the community. It has been indicated by the local parties that opinions are shared. Thus, households mutually anticipate to each other.

Elements considered when modelling are:

- Different characteristics of households (called conversion factors in the CA);
- Changes of the environment (events and trends);
- Behaviour of households; and
- Adaptivity and interactions.

Adaptivity means anticipation of behaviour when changes occur. Complex behaviour in Stad means that it is hard to understand how the public opinion arises even when the knowledge and attitude of individuals is known. Residents influence each other. This leads to unexpected enthusiasm or scepticism.

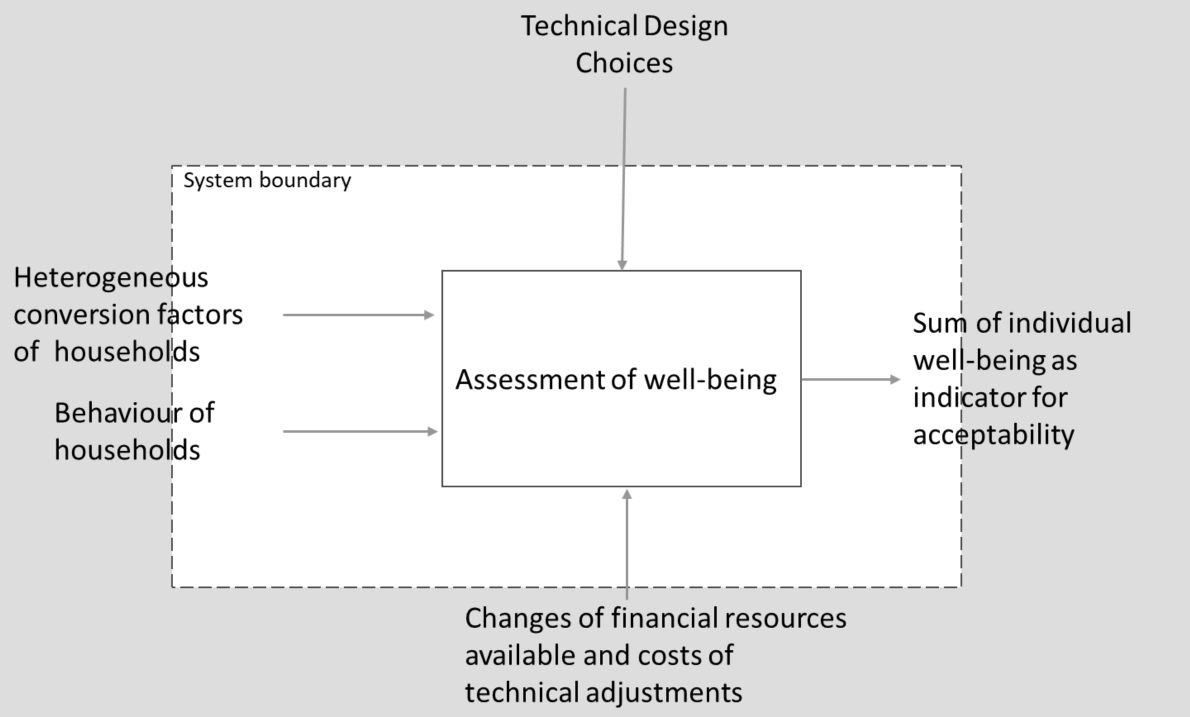


FIGURE 5: SYSTEM DIAGRAM

Figure 5 shows the system of Stad aan ‘t Haringvliet. The input from the left side is related to the households. The input from the bottom represents the technical choices. The input from above are the external factors as income and the need for insulation to switch to all-electric. Within the system individual households assess their well-being by asking whether they have the capabilities they want to have given their individual properties, the technical alternative and the external factor. The out is the conclusion whether the technology is acceptable.

5.1.2 Goal Formalisation

To successfully realise the pilot the project leaders of the pilot need an effective and affordable approach to make Stad aan ´t Haringvliet gas free. As there are many uncertainties about relations and behaviour of residents and other future trends of external factors assumptions are needed. However, these assumptions cannot be tested in the real world which makes simulation for exploration interesting.

The problem is that the effect of hydrogen technology on the capabilities of households and resulting acceptability is unknown.

To be able to make choices for technical designs that increase acceptability and incorporate the values defined in earlier research steps, the effects of technology under uncertain circumstances need to be assessed so that options are comparable. Technical designs need to be compared to identify which design is the least sensitive to changing circumstances and which designs increase acceptability. Further, favourable conditions need to be identified.

The goal of the Agent-Based Model is identifying favourable technical designs and conditions that cause high levels of acceptability.

5.2 Concept Formalisation

This section describes the elements of the model, the states an agent can have, the relations that are needed to generate patterns, the rules that lead to outcomes measured by performance indicators and the interaction of households with their environment. States indicate properties of households. Appendix E and F give an overview of the model elements, states and dynamics. The four capabilities that indicate the performance of the system:

- Autonomy;
- Welfare;
- Sustainability; and
- Acceptability.

Together they indicate the individual well-being.

There are three basic choices to be made when designing the hydrogen infrastructure:

- The source;
- The mixture; and
- The application in households.

There are two environmental factors:

- Income of the households; and
- Improvement of technology and end user equipment.

There are five conversion factors assigned to agents that are considered relevant for assessing capabilities related to hydrogen in the natural gas network. These five states are:

- Income;
- The social network;
- Attitude;
- Housing situation; and
- Energy label of the home.

5.2.1 Performance Indicators

As indicated by the system diagram the change of individual well-being indicates the acceptability of technical design choices. To be able to assess the performance of the system it is important to determine some performance parameters. These are the model outcomes. When running the model households come to certain conclusions. The CA suggests assessing the overall well-being of each individual agent. This is done by exploring individual capabilities. Therefore, it is distinguished between four different capabilities that sum up to an overall well-being. To not only get an average of all households the differences between individual households must also be considered. That improves the ability to interpret the performance of alternatives.

TABLE 7: PERFORMANCE INDICATORS

Model Parameter	Definition & Relevance	Data source
Autonomy	"The system allows for its users to make their own choices and choose their own goals" Autonomy is not equally distributed amongst residents. Assessing autonomy gives insights into the robustness of a system design.	(Ligtvoet, van de Kaa, et al., 2015) & Interviews

Sustainability	"The system does not burden ecosystems, so that the needs of current generations do burden not future generation" Sustainability, is strictly, seen not a capability according to the CA but rather a functioning as the infrastructure does not allow individual choices for the gas transported. However, it is assumed that it is not interesting for residents to be unsustainable.	(Ligtvoet, van de Kaa, et al., 2015)
Welfare	"The system promotes physical, psychological and material well-being" Welfare is determined by the options of residents to choose to change behaviour (electrical cooking) or chose not to change behaviour (cooking on gas). Furthermore, the times owners need to come into action to replace equipment matters. As long as there is no equipment available that is able to handle a variety of mixtures residents are (probably) forced to make two steps.	(Ligtvoet, van de Kaa, et al., 2015)
Acceptability	"The system allows its users to voluntarily make choices, based on arguments" This represents the capability to anticipate to a vision that is broadly shared in a community. So not only own interests are considered but it is also considered whether the solution creates enough capabilities for others.	(Barr & Gilg, 2016; de Vries, 2016; Ligtvoet, van de Kaa, et al., 2015; Morrison & Lodwick, 1981; Stephenson et al., 2010) & Interviews
Well-Being	"Effective opportunities to undertake the actions and activities that they want to engage in, and be whom they want to be" Well-being forms one global indicator for the performance of the system. Well-being is not cumulative.	(Robeyns, 2003 p.3)

5.2.1.1 Autonomy

Autonomy is an important aspect when it comes to changes. It is assumed that residents do not like authorities to make decisions without consulting the households. Households want to make own choices. Sustainability is the main reason for starting the project. However, it is unclear whether the households agree with the degree of importance of sustainability. It is indicated by some interviewees that residents chose economic benefits above sustainability.

5.2.1.2 Sustainability

"There will be a few who will do it for the environment but on the long term you probably want to make progress [in saving energy costs]." (Local Party 4)

To explore this statement sustainability is introduced. An important aspect of sustainability is that there is no such goal as being not sustainable. The model must explore to what extend individuals might be in favour of or against a technical design given the sustainability of the design and the assumed importance of sustainability for each individual.

5.2.1.3 Welfare

Welfare relates to comfort as it assesses the necessity of behavioural change. Even though comfort during the interviews have been indicated as being able to heat and having warm water in the model the attention is drawn to changes and initiative that must be taken by households because it has been indicated that people are only willing to spend money and take effort when there are benefits. It was hard to identify effects of the system that would be experienced as benefits besides savings and suitability (as long as savings are included). Therefore, it is assumed that the least change possible is most favourable which means that no behavioural change and no additional spending is needed.

5.2.1.4 Acceptability

Finally, acceptability is not a capability per se but indicates whether the households have the necessary knowledge to see their capabilities. In this case the facilitation of knowledge is based on the network. Even though the municipality and other parties put effort in the facilitation and information of households to an important extend the community opinion plays as role.

To some extend also the aspects of participation and democracy described by (Ligtvoet, van de Kaa, et al., 2015) are covered as the households adapt to other households.

5.2.2 Environment

The environment of the households describes external factors that cannot be influenced by the system. Even though there are many factors that are of importance three are introduced in the ABM as they are directly linked to performance indicators and agents' states. Income is clearly of influence and therefore possible changes in income are of influence. Also, the improvement of technology and energy costs matter according to the interviews.

The hopes are that prices for sustainable technology decrease quickly and technology improves to make investments more affordable. Also, the price for (green) hydrogen needs to drop. However, it is unclear whether this will happen and therefore also undesirable futures need to be explored.

5.2.3 Technical Design Choices

Based on insights from interviews and desk research some technical settings have been introduced to the model. Even though there might be broader than the once indicated, these are the alternatives that are mostly discussed and that have been indicated to be most realistic by the stakeholders. Even though these choices are concrete the model does not consider all details (e.g. The exact origin of hydrogen and the exact mixture). The purpose is to make some basic design choices comparable and eventually find ways to compensate for negative effects or cherish positive effects.

The three important choices are whether to require green hydrogen, whether to require pure hydrogen and whether to require full replacement of all functions of natural gas by hydrogen. Other alternatives as fuel cells, heating networks and heating with geothermic heat or surface water are not considered as the willingness to do a hydrogen trail has been mentioned when signing a covenant.

TABLE 8: DESIGN CHOICES

Design	Property
GreenH2	Hydrogen from any green recourse
Grey or Blue H2	Hydrogen from any source that is not sustainable electricity
Starting with mixing H2 and Natural Gas	Assumed that this causes stepwise transition from gas to pure hydrogen.
Just heating	To minimize the renovation of pipes in the house just heating might be an option.
Heating and cooking on H2	Requires no new habitual changes

5.2.4 Conversion Factors

The conversion factors are the boundaries of each individual agent. They describe the resources and physical or mental properties of the households that generate or inhibit capabilities. When technology incorporates values, conversion factors have to be respected. Table 11 gives and overview, definitions and data.

5.2.4.1 Income

There are four income classes. The social network consists of the agents within a certain reach. There are four different types of attitude: very conservative, a little conservative, a little progressive and very progressive. There are two types of housing situations. Either the households rent the house and are tenants or the households own their house and are owners. There are three different levels of energy labels. Appendix E System Elements shows the states that are included and Appendix F Data the values that have been chosen.

The income is assigned based on a distribution given by statistical research. The income changes each tick based on a trend and a random factor. The social network is determined in the beginning of the simulation. The size depends on the agents within a variable radius. The network is assigned based in a random factor and similarities in income. The network does not change over time. Only the information provided by the network changes. The attitude is assigned in relation to the income and based on research on lifestyle types. Attitude is stable over time. The housing situation is assigned also in relation to income and stable over time. The energy label is assigned due in relation to the housing situation and stable over time.

As shown in Appendix F, CBS considers four groups of incomes concerning households. The absolute income is used the get grip on the relative differences between the households to come to comparable results. Income here is used as an indicator for assessing whether households can bear the investments required to adjust to the energy system transition. Therefore, it is an important factor when analysing the acceptability of hydrogen in Stad. As there is no data available about all the individual incomes the data provided by CBS is used. However, this means that extreme differences between highest and lowest income might not be covered and the effects cannot be explored. However, it is assumed that the relative differences between the four income groups give enough insights into differences in individual well-being and capabilities as the ABM is supposed to measure overall patterns and predicting absolute values.

5.2.4.2 Social network

The position within the social network shapes the share of information and the ability to be aware that certain functions can be or cannot be realised. As residents exchange acceptability and information, it is of importance who is in reach to share these characteristics with. This means that households adapt their acceptability to the acceptability of the social network and to the information provided by other households that are part of the network.

The availability of information shapes the way residents see their capabilities and therefore the individual acceptability of the system. No extensive research has been done on the specific nature of the social network of Stad aan ´t Haringvliet as this is very time consuming and just one small piece of the whole system. During the interviews it has been stated that it is a close community. Furthermore, the choice has been made not to let the network change over time.

As the area is quite conservative ("bijbelbelt") structures change slowly. Furthermore, applying too many dynamics in the social system would make it hard to draw conclusions on the importance of the density of the network. The social clustering is based on the income as indicated by the lifestyle types (Friege, Holtz, & Chappin, 2016) there is a correlation between income and attitude.

Residents tend to live in an environment with other agents that share the same values this is how social networks and districts form. Residents value participations, democracy and mutual exchange of information. Studies of acceptability of technology have shown that framing and the party which is broadcasting information matters more than the content of the information (Poortinga & Pidgeon, 2004; White, Pahl, Buehner, & Haye, 2003). Therefore, the exchange of information is an important element of the model.

5.2.4.3 Attitude

One of the major challenges when modelling the social acceptability of households is indicating values and representing individual differences. The choice has been made to, in this case, consider attitude with respect to energy saving behaviour and insulation of households. A survey to assess the importance of values amongst households would have gained more detailed insights. However, from the interviews it became clear that households know too few about the effects of hydrogen infrastructure on their capabilities to translate these to concrete values. It was also concluded from doing interviews that it is hard to rate and compare values and to translate values into specific capabilities. Another reason not to ask the households to analyse their own values with regard to the changing energy system was the fact that this research should not influence opinions nor provide information that might affect the system as a whole.

Attitude is simplified and consists of two different aspects, namely conservativeness (resistance against change) and progressiveness (urge for change and sustainability). In Appendix F it is indicated how attitudes are exactly assigned. Research has shown (Friege et al., 2016) that there are differences in what people find important. Barr & Gilg, (2016); Morrison & Lodwick (1981 and Stephenson et al., (2010) give insights how attitudes are shared and influence energy related behaviour. The attitudes needed to be interpreted to be suitable to introduce into the Agent-Based Model. Attitude shapes the way households think about sustainability and the preservation of behaviour and comfort.

5.2.4.4 Housing situation

The housing situation describes how residents can either be tenant or owner of a house. This simplification addresses the most important difference between residents that are able to make choices on their own or are subject to choices of bigger institutions like in most cases housing corporations. The ratio of privately-owned buildings and collectively owned building clearly matters. These characteristics are most important as this represents whether households can make own choices or depend on the choices of a letter. It also determines who has to pay the investment costs. Other buildings (as schools, churches, shops, etc) are not specifically considered as there are no buildings with extremely high energy consumption or complex installations:

"There are some special buildings but outside the border of the village. You could leave them connected to the gas grid." (Local Party 4)

5.2.4.5 Energy labels

Energy labels of homes have an impact on the ability to insulate houses and therefore determine whether owners can choose to install a heat pump instead of consuming hydrogen as energy source for heating and/ or cooking. There are three different categories of energy labels as CBS provides data for this distribution. As the energy label determines the freedom to choose for all-electric. The energy label also influences future possibilities to insulate and to increase comfort or decrease costs. Affordability has been identified as important factor for acceptability during the interviews. Another indicator for the energy efficiency and possibility to insulate is the age of the houses. However, it is hard to draw conclusions about the recent state of the building by solely looking at the age. Therefore, the energy labels are considered, and assumptions are made for the building that do not have a label yet.

5.2.4.6 Enthusiasm & Scepticism

Some of the households are identified as enthusiasts or sceptics. Some households spread positive information that enable other households to increase their capabilities. Other households spread negative information and distrust which decreases well-being of households close in the social network.

5.3 Model Formalisation

This section describes the dynamic elements of the complex system and how they are introduced to the simulation model. The activities described in the system are:

- Time;
- Uncertainties;
- Assessment of capabilities; and
- Updating states by consulting other agents and environment.

The environment changes each timestep. The external states are relevant for determining the internal state (conversion factors and resources) of the agents each time step. Based on the changes of the environment and the conversion factors, all households evaluate their capabilities given the technical choice.

5.3.1 The role of time

Time is represented by ticks. The ticks indicate years. However, the preciseness of time is not important for the interpretation of the model. The most important function is the identification and representation of trends over time. The interpretation of the time horizon can be evaluated in a participatory way to validate the results and be able to come to the right decisions.

5.3.2 Uncertainties

During the interviews it has been stated that residents are hardly capable of getting grip of the situation and the consequences of changing the gas in the gas grid. This is due to a lack of information about choices and consequences. The uncertainties are aliments that clearly matter but where no answer could be found in any way. To be able to explore what assumptions might be correct ranges instead of single values are researched.

When introducing the conversion factors into the software the links between the elements were clear but there were uncertainties how strongly capabilities and conversion factors were linked. To come to sustained assumptions NetLogo and the exploratory modelling approach offer the opportunity to explore uncertain factors and assess the effects of assumptions. The uncertainties applied are:

- Importance of costs;
- Importance of comfort;
- Importance of information;
- Importance of sustainability;
- Radius;
- Number of enthusiasts; and
- Number of sceptics.

5.3.3 Assessment of technological design

Based on the conditions created by the technical design capabilities are evaluated and activities are executed to update states. Figure 6 gives an overview of the model implementation. The performance indicators are represented by ovals. The blue boxes are interactions between agents. The grey arrow indicates a loop. The white boxes are environmental factors and the black text indicates the activities linked to the loop. The blue factors are uncertainties and the red factors are individual conversion factors. The plus sign indicates that when one factor increases the other increases as well. A minus sign means that if one factor increases the other decreases. In this way causalities and decisions rules are presented.

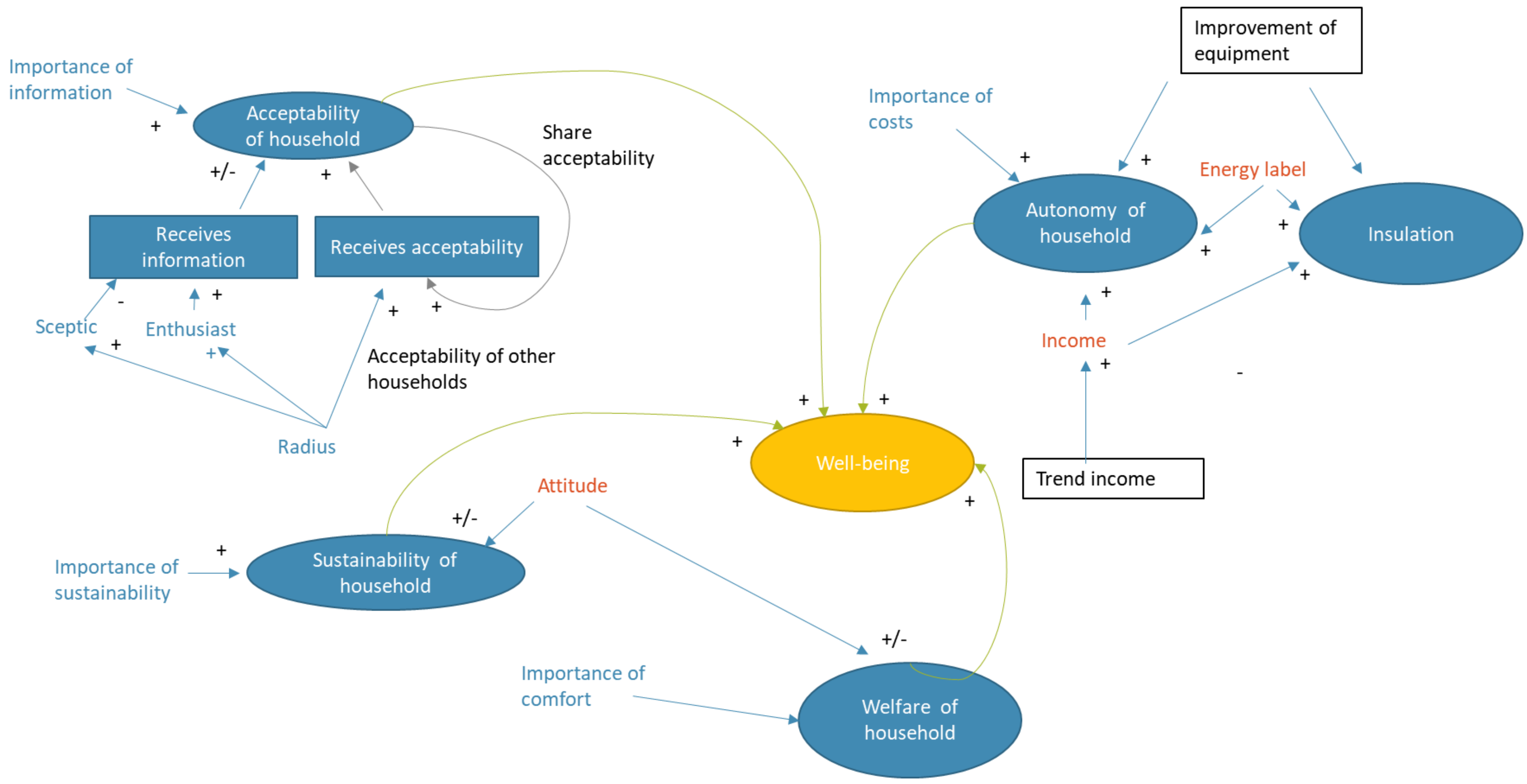


FIGURE 6: IMPLEMENTATION OF ASSESSMENT WELL-BEING

5.3.3.1 Insulate

Checks whether insulation is possible based on budget and costs for renovation, estimation that insulations becomes cheaper throughout time. Households with lower energy labels need higher incomes to insulate. The income needed decreases conform the improvement of technology throughout time.

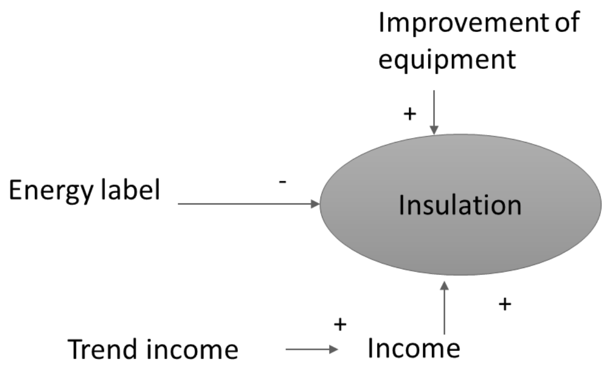


FIGURE 7: INSULATION

5.3.3.2 Evaluate acceptability

The acceptability assesses the effect of social interactions that causing spreading information. There is no cumulation because each timestep the values of acceptability are cleared. However, before clearing the values residents adapt to the acceptability they find around them. This can be interpreted as operationalisation of trust and democracy. Households share their enthusiasm and scepticism. The availability of positive or sceptic information determines whether any solution is considered acceptable. This function represents participation.

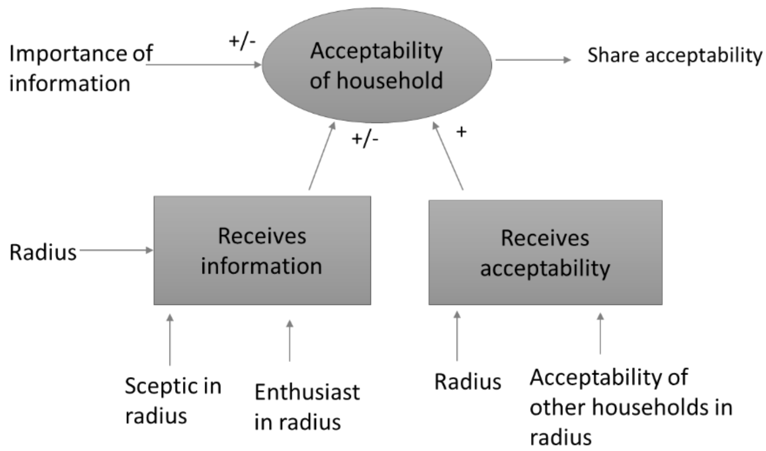


FIGURE 8: CALCULATION OF INDIVIDUAL ACCEPTABILITY

5.3.3.3 Evaluate Autonomy

As residents like choices the autonomy increase when the equipment reaches a certain improvement and the household has an income higher than a certain threshold.

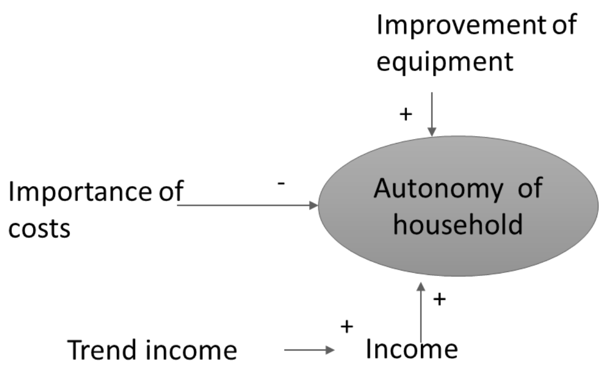


FIGURE 9: CALCULATION OF INDIVIDUAL AUTONOMY#

5.3.3.4 Evaluate Sustainability

Sustainability is determined by whether the source of the hydrogen is green or at least natural gas is mixed with hydrogen under consideration of the assigned attitude. Sustainability is multiplied with the importance of sustainability and the attitude.

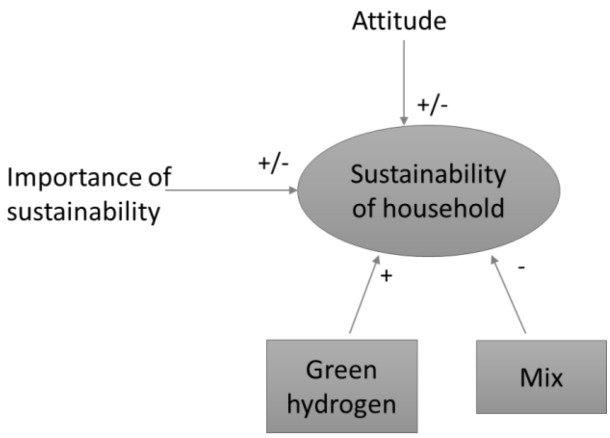


FIGURE 10: CALCULATION OF INDIVIDUAL SUSTAINABILITY

5.3.3.5 Evaluate welfare

Welfare is influenced by mixing natural gas and hydrogen. There is not yet equipment available that can handle mixes and pure hydrogen, so welfare decreases because equipment needs to be replaced two times. The comfort of gradual change is neglected. Welfare is also decreased when the stoves needs to be replaced and the projects permits juts heating with H_2.

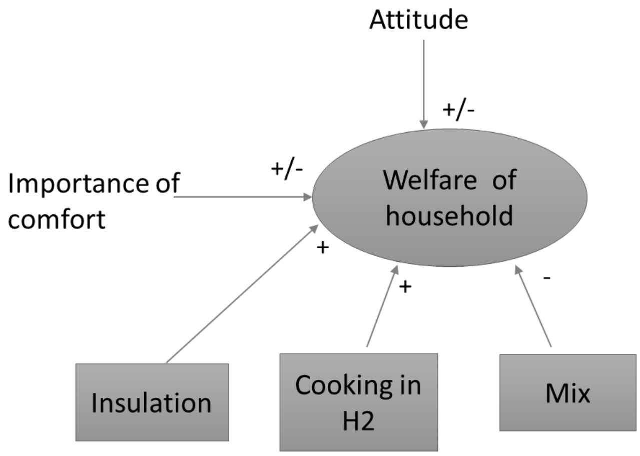


FIGURE 11: CALCULATION OF INDIVIDUAL WELFARE

TABLE 9: ACTIVITIES

Action	Calculation	Data Source
Capability to insulate	Insulation is equal to 1 when For energy label 1 the income > lowest income required For energy label 2 income > middle threshold of income For energy label 3 income > highest income required. Otherwise insulation equal to 0 which means no increase in comfort	Interviews
Exchange information	Enthusiasts increase the acceptability within their radius +1 Sceptics decrease acceptability in radius -1.	(Barr & Gilg, 2016; de Vries, 2016; Ligtvoet, van de Kaa, et al., 2015; Morrison & Lodwick, 1981; Stephenson et al., 2010) & Interviews
Evaluate acceptability	Find agents in radius with acceptability >1 adjust own acceptability +1	(Barr & Gilg, 2016; de Vries, 2016;

		Ligtvoet, van de Kaa, et al., 2015; Morrison & Lodwick, 1981; Stephenson et al., 2010) & Interviews
Evaluate autonomy	**All-electric and Insulation** If tenant autonomy -1 For owners with income 36 label A&B autonomy +1 otherwise -1. **Equipment** income <= 15 and equipment >= 11 income <= 25 and equipment >= 9 income <= 36 and equipment >= 7 income > 36 and equipment >= 5 Autonomy increases by 1. Otherwise it decreases by 1.	(Ligtvoet, van de Kaa, et al., 2015) & Interviews
Evaluate sustainability	**Attitude** Sustainability increases by 1 time the factor influenced by the attitude (between 0.5 and 1.5). Positive attitude leads to increased values of sustainability, negative decrease sustainability. **Mix** The sustainability is also determined by whether the hydrogen is mixed with natural gas. The assigned sustainability of an households is halved when mixing.	(Ligtvoet, van de Kaa, et al., 2015)
Evaluate welfare	**Mix** Welfare - 0.5. **Cooking** Welfare is decreased by 1 time a factor determined by attitude (between 0.5 and when no cooking on H2 is possible and stoves need to be replaced. Welfare is increased by 1 time a factor based on attitude when cooking is possible as the freedom to choose increases.	(Ligtvoet, van de Kaa, et al., 2015)
Evaluate well-being	Well-Being = Autonomy + Sustainability + Welfare + Acceptability	Based on CA

Development of income	Income = income + trend income	(ECN, 2017)
Improvement of technology	State of technology = state + improvement	Interview with technical experts

5.4 Model Specification

Having determined all elements and rules for actions and interactions the model now can be implemented into the NetLogo software (Appendix G). To be able to do so first a base case needs to be chosen that determined the standard settings of the ABM. Based on the Concept and the model formalisation the elements and rules can be filled with data. However, there are several important elements for which not enough or no reliable data is available. These elements are considered as uncertainties for which ranges have to be chosen.

As there are many choices possible, the most likely ones that have been sketched by the majority of stakeholders is chosen as base case. These setting forms the basis of the model and the experimentation. The base case means that the technical choices are green hydrogen, electrical cooking (just heating on H_2) and pure hydrogen. This case is chosen as it has been sketched as likely by many stokeholds but also has some advantages and disadvantages which makes it not an obvious solution to the problem. Disadvantages are that it is expensive as green hydrogen has higher costs than grey hydrogen, it causes behavioural change and to some extend fear as no gradual changes are possible. Advantages are that electric stoves already exist, that households might find it less caring to cook on electricity and that no extra nuisance is caused as no iterations are needed because it is a radical switch.

TABLE 10: IMPLEMENTATION OF DESIGN CHOICES

Design	Effect	Data Source
GreenH2	Increases sustainability Sustainability +1	Interviews
Grey or Blue H2	Decreases sustainability Sustainability -1	Interviews
Starting with mixing H2 and Natural Gas	Two transition steps are required which influences welfare in a negative way. Welfare / 2 & Sustainability /2	Interviews
Just heating	Just heating means that people with gas stove have to go for an electric stove. This decreases welfare. Welfare -1	Interviews

Heating and cooking on H2	Increases welfare. Welfare +1	Interviews

TABLE 11: DATA OF CONVERSION FACTORS

Factor	Definition	Properties	Data Source
Position within social network	Close to agents with the same income, depends in variable radius	Does not change over time	(Barr & Gilg, 2016; Kelman, 2017; Stephenson et al., 2010)
Income	Average spendable income per year	Income changes each step of time by a random number between 0 and the trend defined during the run. The starting values are House owners: 9 % 12,7 20,1 % 24,3 32,2 % 36,2 38,6 % 68,2 Tenants: 46,6 % 12,9 31,6 % 23,4 15,2 % 35 6,6 % 60,2	CBS
Attitude	Conservative or progressive	Attitude does not change over time. The values applied are (Appendix E System Elements)	(Friege et al., 2016)
Housing situation	Tenant or owner	60 % Owners 40 % Tenants	Interview local party 2
Energy label of home	3 levels. A&B, C&D or E & lower	10% good insulation (A&), 50% reasonable insulation (C&D) and 40% bad insulation (E & lower), does not change over time	CBS

Enthusiasm & Scepticism	Enthusiast or sceptic	Uncertain distribution	Interviews

TABLE 12: FORMALISATION OF UNCERTAINTIES

Uncertain factor	Range
Importance of costs	0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.
Importance of sustainability	0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.
Importance of information	0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.
Number of people that spread good or bad news	0-80
Radius	1-6

From the empirical research it seems that there is a big difference in capabilities of tenants and home owners. About 40% of the residents are home owners and 60% are tenants of in most cases the local housing corporation (Interview Local Party 1). As tenants are highly dependent on the choice of the corporation tenants need to have conversion factors that are different from house owner´s factors. From desk research it also seems that in general tenant have different characteristics as in terms of income and distribution of values (CBS, Conversation with resident during information event).

CBS distinguished between house owners and tenants. In general, more house owners seem to have a higher income than tenants. Even though Goeree Overflakkee is part of the province of Zuid-Holland the incomes given by CBS for Zeeland are used as in many ways (demographically, geographically and socially). Georee is more alike Zeeland than the Randstad.

As there is no scientific work done yet about the distribution of the values relevant for system transition on Goeree Overflakkee it has been decided to consider the importance of certain values as “uncertain” and to just differentiate in resources but give all residents the same values.

However, individual differences emerge through social interactions and are integrated during the modelling step by differences in attitude.

5.5 Implications for the verification and validation

Social simulation enables researchers and policymakers to analyse emergence due to heterogeneity of actors and downward causation within socio-technical systems. By representing the system, problems and possible solutions to these problems can be identified (Stefanelli & Seidl, 2017). Most important implications for the next step are:

- Uncertainties concerning the social interactions;
- Static parameters for sustainability and welfare; and
- The uncertainty of relative valuation of capabilities.

The strength of the ABM is that some important aspects (as heterogeneity and individual assessment) of the project in Stad that are conceptualised through the CA, can be implemented in the software. Theories on attitude and on exchange of information were considered additionally to the conceptual frame. The CA and the conceptual frame have given a useful support to grasp the complexity of the system and introduce it into NetLogo.

A limitation for the model at hand is that some states are still quite static. This diminishes complexity of the model and the results. The model could have been improved by more specific research on behaviour of the households of Stad. Dynamics would have been clearer and less assumptions would have been necessary. The conceptualisation and implementation of code is hard for this kind of social issues. Therefore, the model works thresholds and no absolute values to come to numerical code. This makes it important to carefully verify and validate the model. This mitigates the danger of coming to wrong conclusions. When interpreting the model results and bringing these results into practice this should be taken into consideration.

An important choice was which uncertainties to explore. The uncertainties are determined by the conceptualisation and the data available. Uncertainties are related to the importance of values and to the availability of information. This makes it possible to assess whether communication and engagement might be a successful strategy to support making technical choices. Influencing the importance of values might be hard as values are static. The abundance of information and the tightness of the social network might play a role for influencing the system.

5.6 Conclusion

What effects the acceptability of hydrogen distribution and domestic use for households?

The most important elements of the model that influence the acceptability of hydrogen are

- Conversion factors;
- Capabilities;
- Environment; and
- Technical design choices.

The performance of the hydrogen technology and different ways to realise technology is assessed by letting individual agents evaluate their

- Autonomy;
- Sustainability;
- Welfare;
- Social acceptability; and
- Well-being.

Autonomy represent the capability to choose for an alternative, sustainability assesses the possibility to reduce CO2 emissions, welfare covers comfort and preservation of habits, acceptability represents the public opinion and well-being measures the overall acceptance. The dynamics represented in the model are changes of the environment and changes of the states of individual households. The evaluation of capabilities allows to draw conclusions about the change in well-fare of individual households

Assumptions about the freedom of choice and the effect of information on the acceptability of technology can now be tested. Varying relations between external factors as changes in income and prices can be linked to resources of households. Crucial moments (turning points) in time can be identified when technology is cheap enough to create more autonomy. These turning points also depend on the trend of income. It is uncertain how much this matters for the increase in acceptability as ratios between or trade-offs of capabilities are uncertain. The model allows for testing the effects of different trade-offs and the effects of changes in external factors. So, if households value autonomy more than sustainability the effects on the acceptability of a certain design choice can be assessed. When effects are very negative or uncertain the deign might rather not be chosen.

6 Verification and validation

This section presents the results of the various steps executed to verify and validate the model. It contributes to answering: 'What affects the acceptability of hydrogen distribution and domestic use for households?' The aim of this chapter is to assess and demonstrate the value of the model for the case and the assessment of hydrogen in general.

Therefore, the verification and validation steps described by Augusiak et al. (2014) are presented. They suggest a complete and for decision makers comprehensible approach to investigate the model. The steps are:

- Data evaluation;
- Conceptual Model evaluation;
- Implementation Verification;
- Model Output Verification;
- Model Analysis; and
- Model Corroboration.

The data evaluation reviews the sources of data and the implementation of data. The evaluation of the conceptual model checks whether the conceptual model is suited to reach the model goal.

> The goal of the Agent-Based Model is identifying favourable technical designs and conditions that cause high levels of acceptability for developing an engaging activity with households.

The implementation verification erases bugs and errors that occur when implementing the model in the NetLogo software. The model output is verified by varying parameters and analysing behaviour. It is evaluated how the output contributes to solving the problem formulated in the problem statement.

> The problem is that the effect of hydrogen technology on the capabilities of households and resulting acceptability is unknown.

In the model analysis it is further evaluated whether the model meets its purpose. The model corroboration compares the model to new data.

6.1 Data evaluation

The goal of the data evaluation is to evaluate and especially prove the robustness of data used as input. Doing the data evaluation, the quality of data used to parameterise the model is evaluated by distinguishing between certain data and uncertain data. Sources of certain data are evaluated, and how to deal with uncertain data is discussed. A structured way to evaluate value is assessing a list of parameters used and eliminating questionable data from unreliable resources. The data used to specify the model is:

- Statistical data from resources as CBS;
- Theories and frames described in scientific literature; and
- Data from semi-structured interviews.

CBS is an organisation for statistical research that is part of the Dutch government. To guarantee their quality they apply international standards. Statistical data from CBS is used to specify incomes, numbers and energy labels. The data is directly implemented into the model. Because there is no specific data for Stad aan 't Haringvliet, the data for the region is used. This makes the model less specific, but still suffices to indicate tendencies and individual differences. As CBS uses four groups of income and three types of energy labels this has also been applied in the ABM. This decreases the real heterogeneity but suffices to create individual differences that cause diverging outcomes that indicate real world behaviour. CBS indicates that not all buildings have an energy label. The known labels are extrapolated to all buildings. A check whether this is a good choice has been done by considering the ages of houses in the region. Older houses are often more difficult to insulate and have a lower label. Even though there is no exact information available how the age of a house is related to the label, it is concluded that extrapolating the ratios indicated by CBS is a good indication.

As indicated in the chapter on the conceptual frame reviewed scientific literature is used to develop the conceptual frame that is basis of the model. Additional reviewed scientific research is used to indicate the link between values and attitudes (Barr & Gilg, 2016; Friege et al., 2016; Huijts et al., 2012; Morrison & Lodwick, 1981; Stephenson et al., 2010). Attitude is considered as part of the individual conversion factor of the households. This research is about behaviour related to sustainable energy, however it is not specifically about the introduction of hydrogen neither for the specific region. The data is used to specify individual differences in values. The ABM is specified in a way that does not ask for detailed data but for trends and abstract thresholds. Therefore the conclusions drawn and lifestyle types with regard to insulation described by (Friege et al., 2016) could be used in the model.

An important contribution of data is generated by the interviews. Technical characteristics of the changing energy system have been translated into concepts and could be introduced to the model. As the technology has not been fully explored yet some additional assumptions have been made about the severity of effects. To be able to explore these assumptions they have been introduced to the model in terms of uncertainties. The interviewing approach is suitable for providing data for the ABM as it indicates not only technical choices but also effects and the specific population. Especially the interviews with local stakeholders that regularly have contact with the households of Stad give a good indication of effects and social dynamics.

6.2 Conceptual Model evaluation

The conceptual model evaluation checks whether the conceptual model used for the model implementation is actually suitable for solving the problem at hand and able to represent the real world. It is hard to say something about the conceptual model as the ABM of Stad aan 't Haringvliet represents technical design choices that have not been made yet. So even though assumptions are made about the effect of these choices to conceptualise the model they cannot be compared to the real world. There are however two ways to generate insights that permit the evaluation of the conceptual model. The first is considering comparable existing ABMs and the second is identifying elements that are described by the conceptual frame as the conceptual frame is based on reliable scientific literature describing approaches that have been proven useful (CA and VSD).

As described in literature the CA is a good way to assess social well-being and justice. By evaluating whether the elements are implemented correctly, conclusions can be drawn about the conceptual model (Table 13). Even though, the ABM sticks to the concepts of the CA which has been proven useful, it is hard to judge whether this is the right way of introducing the problem of Stad into an agent-based simulation as there is only few evidence on the practical applicability of CA.

TABLE 13: EVALUATION OF THE CONCEPTS OF THE CA

Elements	Implementation
Capabilities	Set of choices according to the literature. In de model it is a sum that is based on the evaluation of conditions as for example the ability to pay for renovation and therefore have an all-electric energy consumption. Capabilities are independent of the actual choice made but only describe whether the agent can make any choice potentially interesting.
Functioning's	According to literature this is the choice that can actually be made. The sum of all functioning potentially available to be chosen is the capability. In the model the functioning's to heat are either all-electric or hydrogen. For cooking its either on hydrogen or with electricity.
Conversion Factors	The conversion factor describes the individual differences between household not only in terms of resources but also in terms of attitude. To some households certain capabilities are

	more important than others. In the model the conversion factors are represented by attitude and knowledge (scepticism and enthusiasm). Furthermore, the conversion factor is influenced by the surrounding.
Resources	The resources are actually part of the conversion factors. They describe the sources required to have certain capabilities (execute a functioning). In this model there is income as source but also insulation (the energy label). Another resource is the connectedness to the community described by the position within the social network.
Adaptative Preferences	The adaptive preference describes whether the household is aware of its opportunities or not. In the case of Stad aan 't Haringvliet this is represented by the ability to receive and distribute positive or negative information (enthusiasm and scepticism).

Other models have been published that integrate the CAS perspective with the perspective of the CA (Bloemhof, 2018; Veer, 2018). Both identify some complications when integrating CAS with the CA. The Agent-Based Model of the households in Stad aan´t Haringvliet is developed considering possible shortcomings. CAS is very dynamic, decisions are made every timestep, while the CA gives just one static moment in time, thus the interdependence of choices is not fully considered. The simulation of Stad aan 't Haringvliet also does not force households to make decisions or to spend money. The capabilities that are simulated are mainly influenced by different resources or resources that do not exhaust as information for example. This makes that in most cases the resource of one capability does not take away the resource for another. In this way the effects of decisions and adaptivity are integrated without actually simulating decisions.

6.3 Implementation Verification

The Implementation verification assesses whether the formulated concept has correctly been translated into a computer model. In the case of ABM following single agents and assessing the correct calculation of variables makes it possible to check the model implementation. The checks that have been executed and confirmed are

- ✓ Check whether households correctly distinguished between owners and tenants
- ✓ Check whether energy label and income are correctly assigned
- ✓ Check whether neighbours are found
- ✓ Check whether key performance indicator is correctly assigned
- ✓ Check evaluation of own well-being

✓ Check parameters over time

Appendix I shows how individual agents assign their initial values (income, energy label, housing situation, attitude) and how their values change over time given certain circumstances. This check can be done for most dynamics, but some values are difficult to assess as whether the right agent is chosen as closest agent or from which agent information and which kind of information is received. Nevertheless, based on the visualisations on the NetLogo interface it can be concluded that the social clustering works in the expected way. The analysis can be found in Appendix H. Still, it is difficult to evaluate these variables as these are part of the emergence of the system. However, doing the next verification steps also help to identify bugs in the software implementation when looking at overall patterns.

It is concluded that that the agents assign the correct values to the variables that can be checked. The output verification and model analysis as follow-up are also checking the overall behavioural patterns and variables that are more difficult to check.

6.4 Model Output Verification

The model output verification is a step to evaluate the correspondence of the model and the real world. So, besides checking whether the concept has been introduced in the right way, the outcomes of the model have to be compared to the reality. This is done by comparing findings from the interviews to the output of the model.

The base case is used to compare the mode behaviour to the real-world behaviour that has been observed in the interviews. The model input is changed to assess how the model reacts to these changes and whether the reaction is realistic. The model is not able to grasp all the complexity of the real world but in this step, it is tested whether the model is able to say something useful that can be applied in decision making. In this verification step the parameters that should cause a known pattern are changed. In this verification step one parameter at a time is changed. The corresponding KPI´s are assessed in the next step and the interaction between changing patterns are analysed. The patterns used to test the model are described during the interviews.

The most important conclusions regarding the real-world system that could be drawn from the interviews are:

- Costs are more important than all other aspects, the higher the costs the less acceptable;
- People do not want anything to change unless it causes an improvement, the more changes the less acceptable;
- People do not have an opinion because they know nothing about the technology, the more information the more acceptable; and
- Situations as given in Groningen increase the interest for sustainability.

Based on these findings some expectations are formulated in Table 14. To analyse whether the model is able to represent these findings in a correct way changes of parameters are evaluated to better understand how the model responds to changes. Ranges of uncertain parameters are applied and analysed based on:

- Function and effect in the real-world system
- Chosen range and effect of the range
- Shape of the curve (well-being)
- Explanation how this shape is caused (by analysing other KPI´s) and
- Giving context of the real world /Implication for experimentation and interpretation.

The ranges are not absolute but chose based on some playing with the model. The ranges suitable for showing the desired effects applied are given in Table 14. The table furthermore gives the expected behaviour that may either be confirmed by the simulation or be rejected due to the model output.

The curves and shapes analysed are outputs from the NetLogo interface and Python (EMA). The graphs are analysed by

- Explaining the axis
- Describing the graph
- Interpretation of the graph

TABLE 14: PARAMETERS CHANGED TO VERIFY THE MODEL OUTPUT

Change of parameters	Values single run	Values multiple runs	Base Case	Expected behaviour
Radius	1, 15	1-6	3	When the radius is increased, more residents receive information faster but also acceptability changes faster.
Trend Income	-2, 4	-2-6	2	Increased autonomy as more people can buy equipment and choose for all-electric.
Improvement of technology	0, 15	0-4	1	This effectively means decreasing costs.
Importance of sustainability	0.1, 20	0-3	1	Choosing for green H2 becomes more appealing
Importance of costs	0.1 ,20	0-3	1	The overall well-being increases
Importance of comfort	0.1 ,20	0-3	1	The heat only alternative becomes less interesting
Enthusiasts	-	0-80	20	Enthusiasts increase acceptability

Sceptics	-	0-80	20	Sceptics decrease acceptability
Replications		10	-	-
Run Length	30	50	-	-
Experiments	1	50	-	-

6.4.1 Radius

- **Assumption based on the real-world:** People do not have an opinion because they know nothing about the technology, the more information the more acceptable
- **Conclusion based in the model:** A small social network causes lower acceptability A highly abundant network also has an undesirable effect on the acceptability.

The radius determines the abundance of the interactions within the community. The greater the radius the more households are reached when sharing information and acceptability. When positive information is spread more households will adapt their capabilities due to the new insights gained. When households surrounded by other households with high acceptability they anticipate. The radius determines the reach in which households are looking for information.

The range chosen to model the radius is 1-15 for the single run. This means that households can receive information from almost any other households. Thus results of very abundant interactions can be detected. The visualisation of single run shown (Figure 129) does not allow for drawing general conclusion but visualises how the dynamics of higher number of runs can be explained and arise.

Conclusions cannot be drawn from a single run. Therefore the effects of variations in the abundance of the community is explored using EMA and by running the simulation 50 times with a smaller range. Figure 41 shows that a radius between 2 and 4 leads to high acceptability (Appendix J). This needs to be interpreted as the radius does neither given any insight into the number of neighbouring households not the number of interactions per time unit (tick).

TABLE 15: NUMBER OF INTERACTIONS DUE TO THE RADIUS

Radius	1	2	3	4	5	6	10
Neighbours	3	7	12	18	28	40	109

NetLogo allows for calculating the average number of neighbours for different runs. Few interactions (3) cause low acceptability. Many interactions (more than 18) facilitate spreading negative information in Stad aan ‘t Haringvliet.

Figure 12 presents the acceptability on the y-axis in relation to the time (x-axis) for a radius of 1, 3 and 15 patches of the NetLogo interface. The first graph shows that after a short period of time acceptability increases. After a first jump it increases stepwise. In the Second graph acceptability directly increases to a comparably high level (ca. 400) and afterwards increases slowly. Septs are less obvious than in the first graph. The last graph shows different behaviour. Initially acceptability increases but fewer than in than with a smaller radius. Over time acceptability increases and decreases. A small radius causes lower acceptability than the radius of the base case. A very high radius also has an undesirable effect on the acceptability. Acceptability increases fast but decreases throughout time. When developing a communication strategy this should be kept in mind.

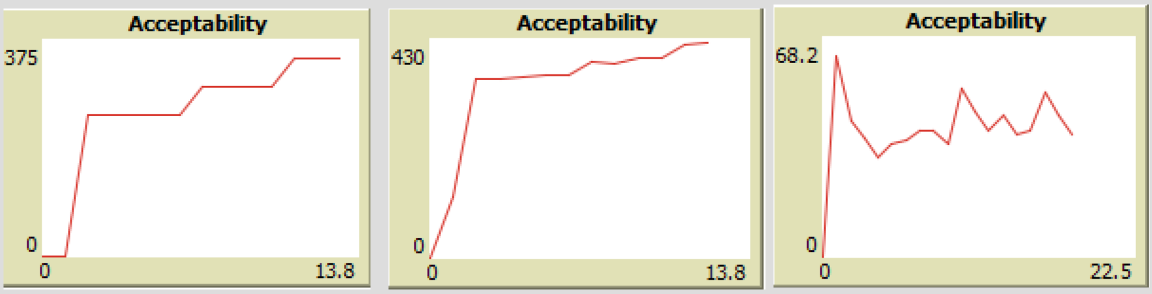
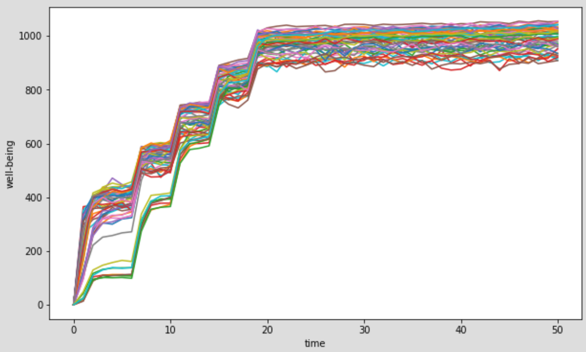


FIGURE 12: ACCEPTABILITY WITH RADIUS =1, RADIUS = 3, RADIUS = 15



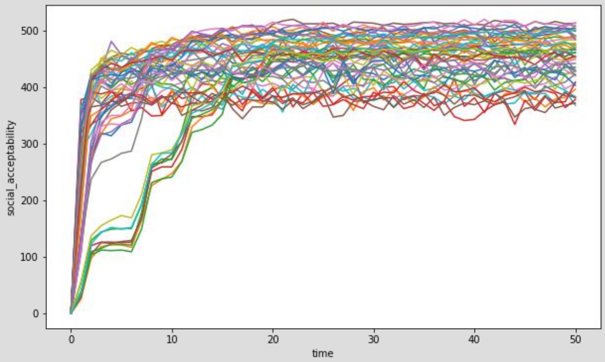


FIGURE 13: WELL-BEING WHEN CHANGING THE RADIUS 1-6

FIGURE 14: ACCEPTABILITY WHEN VARIATING RADIUS

Figure 13 presents the well-being on the y-axis with the time on the x-axis. 50 experiments with changing radiuses are executed over a period of 50 ticks. The graph shows a splitted set of data. This split in the data can also be detected in Figure 14 where the acceptability is plotted against the time. While in most cases acceptability directly increases, in some cases it takes longer for acceptability to increase. This can possibly be explained by the delay found in the first graph of Figure 12. When there is very low interaction acceptability takes long to arise.

Acceptability and well-being are analysed because these KPI´s are influenced by the change of the radius. The other KPI´s are determined by other factors, thus not effected. Figure 13 and

Figure 14 show that a bigger radius especially facilitates spreading negative information. And that the more information is available the more people change their minds.

6.4.2 Trend Income

- **Assumption from the real world:** Costs are more important than all other aspects, the higher the costs the less acceptable
- **Conclusion based on the model:** A stable income causes long-term acceptability. Decreasing incomes decrease autonomy over time. When there is a mismatch between costs and resources acceptability declines, thus costs are important.

The change of income influences the freedom of choice of households because the spendable income is a resource that determines whether households:

- Can buy new equipment suitable for hydrogen consumption; and
- Insulate and install a heat pump.

If the income is too low, households have no choice what to buy and autonomy remains low. The range chosen to explore the effect of income goes from negative to positive. This simulates the basic development from a rising or declining economy. The values are low as the average income is expected to change slowly.

Analysing a single run, assumptions can be made how income and autonomy are related and how autonomy in the end affects well—being. Autonomy is analysed because it is shaped by financial aspects. The other KPI´s are influenced by other variables.

Figure 15 plots autonomy (y-axis) against the number of ticks, thus time (x-axis) for changes in trend of income from -2, 2, and 4. Negative trend of income means that incomes decrease, positive trends determine the extent to which incomes increase. The first graph shows a negative trend. At first autonomy increases step-by-step but after serval ticks the autonomy starts to decrease. In the second graph autonomy increases step by step and stabilises after a certain time. In the third graph autonomy stabilises after a shorter period and it only takes 3 steps to stabilise. From Figure 15 is concluded that the higher, the income the faster autonomy increases. Decreasing income (-2) seems to become a limiting factor even though technology increases. The stepwise increasing autonomy is due to the improvement of technology. Increasing income fosters autonomy but appears to be not the most important driver of autonomy.

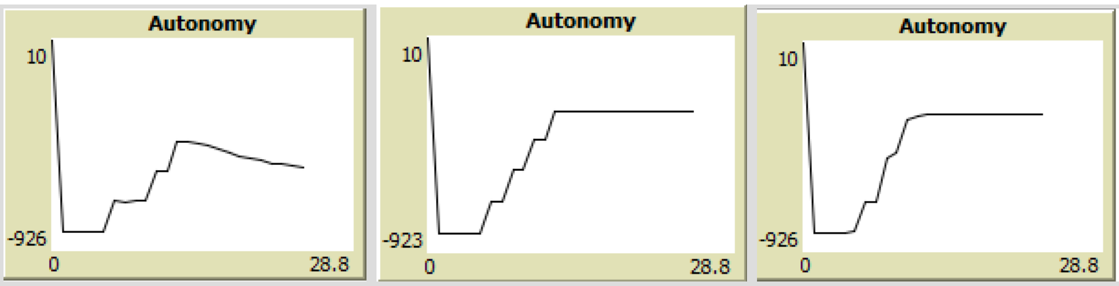
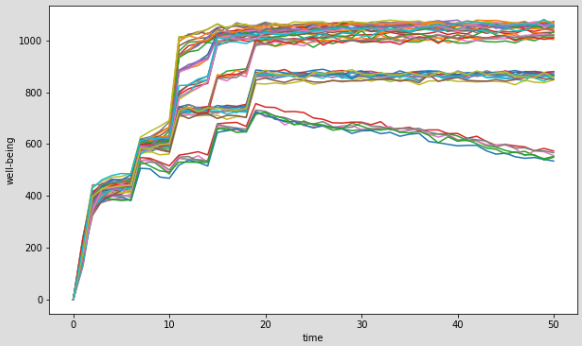


FIGURE 15:TREND INCOME -2, 2 AND 4



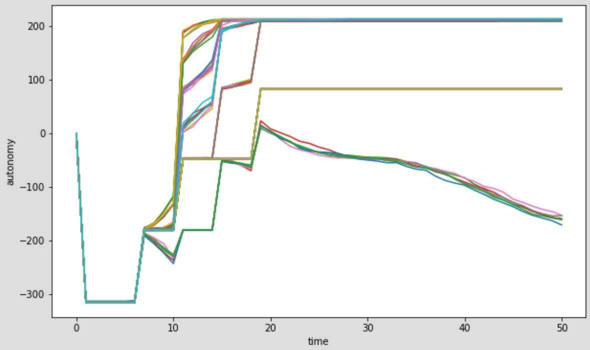


FIGURE 16: TREND INCOME VARIATES BETWEEN -2 AND 6

FIGURE 17: AUTONOMY WHEN VARIATING TREND OF INCOME

From Figure 16 and Figure 17 is retrieved that a differentiation can be made between stagnating autonomy and decreasing autonomy. There are two levels where autonomy stabilises. Increasing income causes high outcomes of autonomy. A stable income causes stabilisation at a relatively high level. Decreasing income causes decreasing autonomy and therefore decreasing well-being. For the real-world system this is an external uncertainty. The project managers must be aware of the effects of changes in income. Based on the recent trend the decision might be taken to delay the project or to compensate for decreasing incomes. When incomes increase quickly it may be the right time to execute the project.

6.4.3 Improvement

- **Assumption from the real world:** Costs are more important than all other aspects, the higher the costs the less acceptable
- **Conclusion based on the model:** Increasing the speed of acceptance can be done by fostering the innovation process because the improvement determines the speed in which autonomy increases. Quickly decreasing costs, increase short-term acceptability.

The improvement of technology represents the speed of innovation, economies of scale and the market. As the model has not been developed to analyse the market but the acceptability for households due to capabilities the assumptions are quite simple. Conclusions can be drawn for scenarios in which technology improves slowly or very fast. The effects lead to strategies that support innovation or compensate for a lack of improvement.

The range chosen to analyse the improvement in the single run is very broad to generate visuals that are as clear as possible. The range of the analysis of multiple run is smaller as the single run indicates that autonomy stabilizes at a fixed level.

The graphs of autonomy generated by a single run (Figure 18) indicate interesting behaviour that can also be detected in the overall model behaviour when looking at different scenarios of well-being in. The single run exactly explains how autonomy increases step-wise in different speeds depending on the improvement. When autonomy increases very fast no steps can are generated but the effects of increasing income become apparent. Autonomy stabilises independently of the improvement at the same level. This means that independently of the speed of innovation autonomy in the end is maximised. Increasing the speed of acceptance can be done by fostering the innovation process.

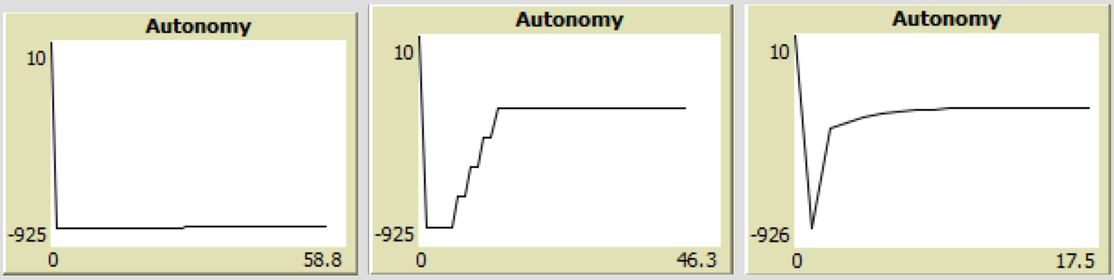
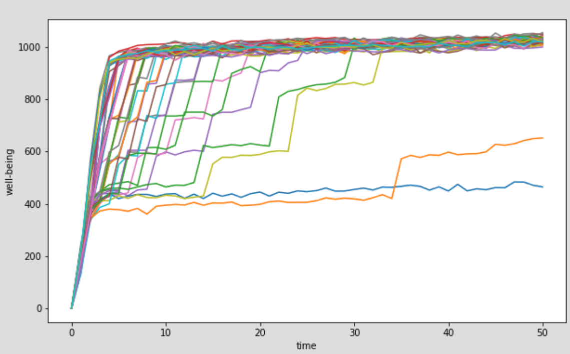


FIGURE 18: IMPROVEMENT 0, 1, 15

Running the model serval times leads to the same results. Well-being stabilises at the (almost) the same maximum level, but the speed of reaching this level differs (Figure 19 & Figure 20. The runs show two outliers that are caused by very low improvement (Appendix J). Without improvement there is no autonomy as most households are not able to pay for insulation, heat pumps or equipment suited for hydrogen.



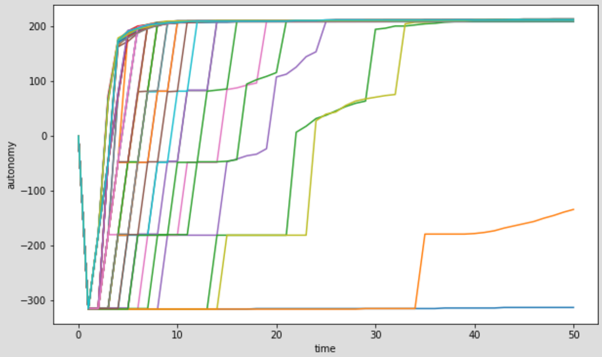


FIGURE 19: CHANGES IN WELL-BEING DUE TO VARIATIONS IN IMPROVEMENT (0-4)

FIGURE 20: CHANGES IN AUTONOMY BASED IN CHANGES IN IMPROVEMENT (0-4)

Improvement of technology is responsible for the step-by-step increment of well-being and therefore an important contributor to the overall shape of the resulting curve (Figure 18).

6.4.4 Relative importance of capabilities

- **Assumption from the real world:** Situations as given in Groningen increase the interest for sustainability
- **Conclusion based on the model:** The model is able to explore effects of differences in the valuation of capabilities but is not able to determine which is most important.

The importance of sustainability represents the uncertainty in how far households value the fact that the introduction of hydrogen is capable of reducing CO2 emissions. The higher the interest of households for reducing the environmental impact of their energy system the more sustainability contributes to well-being. So this parameter determines the ratio of the contribution of each of the four capabilities to well-being. In the single run extreme diverging values are tested. A value of 10 means that sustainability is ten times more important than costs or comfort e.g. Multiple runs are compared for a range between 0 and 3. 0,1 in this case means that the other capabilities are ten times more important than sustainability.

The importance of costs and the importance of comfort are modelled in the same way as the importance of sustainability. The importance of comfort indicates the uncertainty with regard to how much households want to stick to existing patterns and how difficult habituation to new technology is. On the short-term low importance of costs is desirable, on the long-term higher importance of costs lead to higher well-being because technology becomes affordable. There is a turning point after 20 ticks caused by a change in affordability of technology.

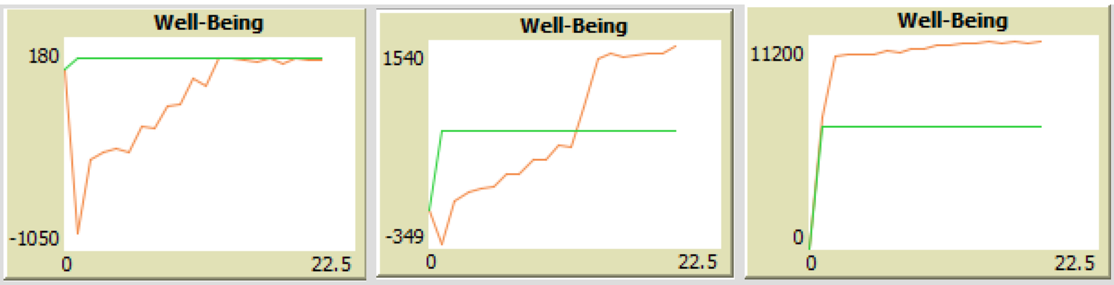
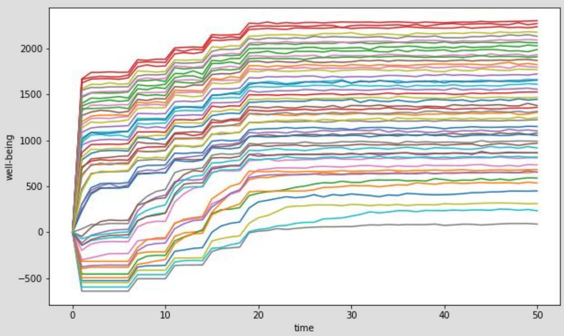


FIGURE 21: IMPORTANCE OF SUSTAINABILITY 0.1, 1, 10

The red line indicates well-being while the green line shows the satisfaction caused by sustainability (the capability of being sustainable). The importance of sustainability has an important impact on the overall well-being when choosing for green hydrogen as Figure 21 indicates. Figure 22 confirms that the initial interest for sustainability is determining for the final outcome of well-being over time. The importance of sustainability not changes over time. An important addition to the model would be exploring what effects changes in interest over time might have. However, here a point of discussion is identified that can only be solved by engaging households. The curves of well-being change in a different way when changing the importance of costs (Figure 23). Figure 24 comparing autonomy and well-being helps to understand the pattern presented in Figure 23 and the interaction of income and improvement. The higher the importance of costs the lower the starting values of the scenarios as the freedom to choose is low. When the importance is low it does not matter so much for the overall well-being that there is few choice. However, high values after 20 ticks are due to high importance of costs. The crossing area of the lines in Figure 23 is the turning point were high importance leads to desirable outcomes (Appendix J).



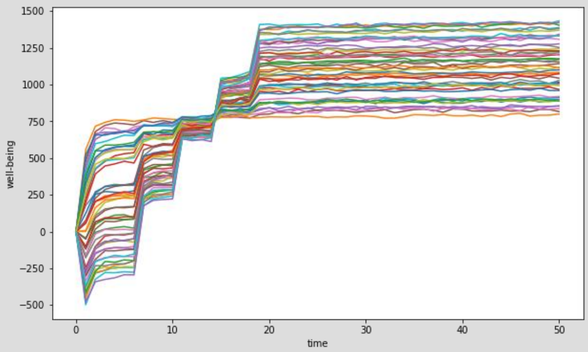


FIGURE 22: WELL-BEING DUE TO CHANGES IN IMPORTANCE OF SUSTAINABILITY

FIGURE 23: WELL-BEING WHEN CHANGING THE IMPORTANCE OF COSTS

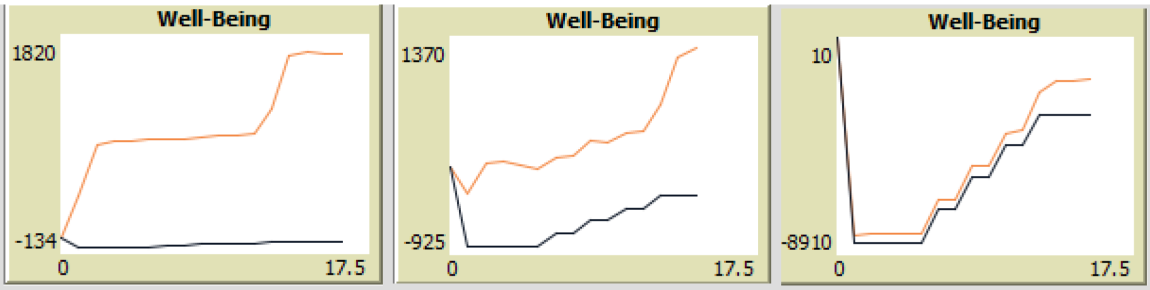


FIGURE 24: IMPORTANCE OF COSTS, 0.1, 1, 10

The red line represents well-being while the black line plots autonomy. When the importance of costs increases the autonomy decreases because autonomy depends on costs and income available. However, as soon as autonomy increases well-being rises.

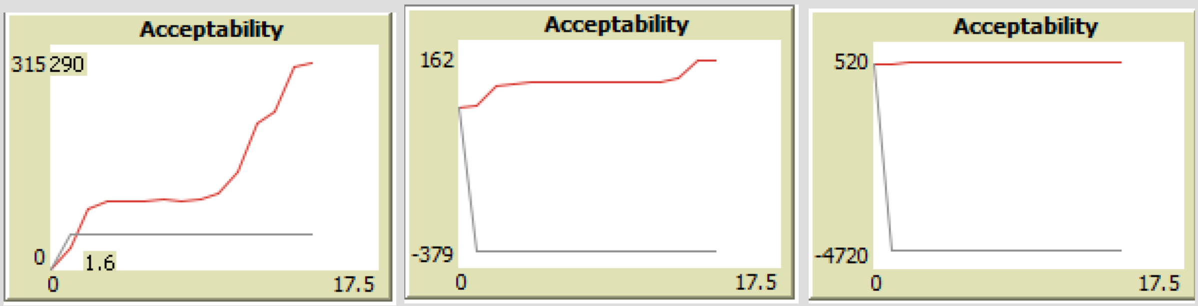
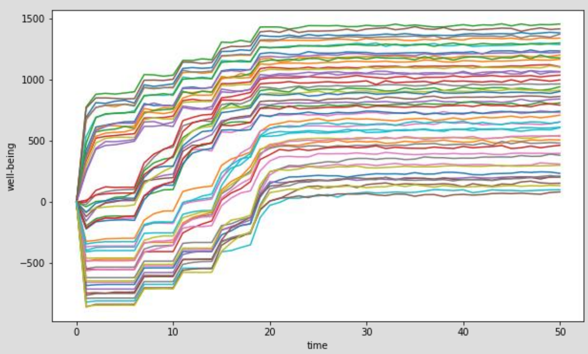


FIGURE 25: IMPORTANCE OF COMFORT 0.1, 1, 10

The red line indicates acceptability and the blue line welfare. Welfare does not change over time (Figure 25 & Figure 27). However, it has an important impact on the information spread and therefore the acceptability of the system (Figure 26). The initial values of welfare are determining for the level were well-being stabilises after 20 ticks.



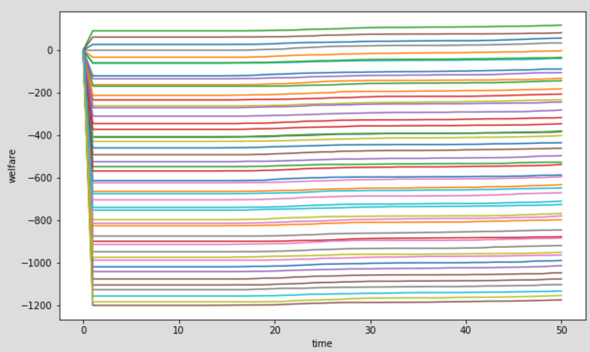


FIGURE 26: WELL-BEING WHEN VARIATING IMPORTANCE OF COMFORT

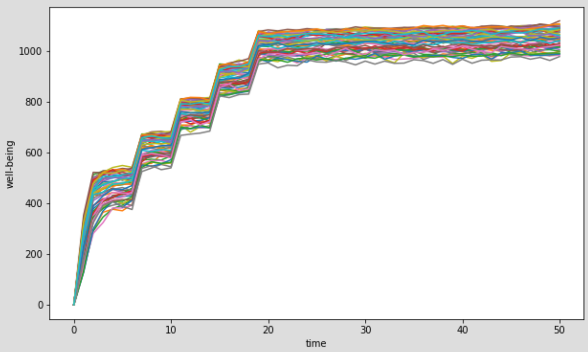
FIGURE 27: WELFARE WHEN CHANGING THE IMPORTANCE OF COMFORT

6.4.5 Enthusiasm and Scepticism

- **Assumption from the real world:** Situations as given in Groningen increase the interest for sustainability
- **Conclusion based on the model:** The model is able to explore increased sense of urgency. It indicates that more supporters cannot outweigh opponents. A higher sense of urgency decreases the number of opponents and therefore the acceptability of hydrogen.

The model represents enthusiasm households and sceptic households and their effect on the overall wellbeing. Information and the direction of information shapes the way households interpret their conversion factors. E.g. when households assume, due to the information received, that technology is too expensive they might not even have a look at the technology available thus experience a lack of capability to participate in the project. This decreases well-being and acceptability. This example might also work the other way around. When households assume that technology generates benefits they probably feel a higher need to find ways to adapt to technology.

The range that is explored in Figure 28 and Figure 29 is between 0 and 80 out of 525 households being enthusiast or sceptic. The range might have been a little broader, but it can be assumed that only few households actively spread information and effectively influence their environment. The figures clearing show the step-by-step effect of improvement. Additionally, a small divergence of values of values is identified when simulating a high number of enthusiasts. The range of possible results increases when varying the number of sceptics. Acceptability is shared anyway, thus the additional number of enthusiasts does not have much effect. Thus, the outcomes are determined by the eel of negativity of information. The conclusion can be drawn that high number of sceptics generates greater negative impact than a lack of enthusiasts.



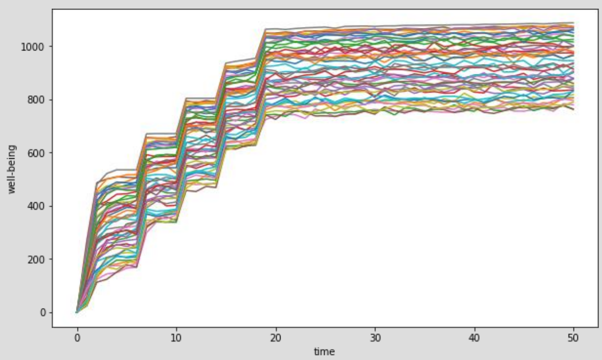


FIGURE 28: WELL-BEING CAUSED BY A HIGH NUMBER OF ENTHUSIASTS

FIGURE 29: WELL-BEING CAUSED BY A HIGH NUMBER OF SCEPTICS

6.5 Model Analysis

In the model output verification, the patterns of the model output are analysed. 6.4 presents a profound analysis of patterns and behaviour due to changes in parameters Conclusions can now be drawn about the sensitivity of the model, but also the real-world, to changes in external and internal factors. The purpose of the model analysis is to better understand and illustrate found patterns and to further explore the model. The model analysis goes one step further than the model output verification because it analysis the reasons for emergence. However the analysis is based on the checks executed in 6.4. Stochastic uncertainty arises due to:

- Randomly assigning a position on the model interface to agents;
- Asking agents in a random order to apply the rules; and
- Randomly assigning increase in income.

This causes emergence for certain aspects and explains the observed patterns. An important capability causing emergence of well-being is acceptability due to exchange of communication. This capability is hardly predictable and caused by interactions that cannot easily be traced due to stochastic uncertainty (Figure 13 and Figure 14). A high number of sceptics generates greater negative impact than a lack of enthusiasts because households that experience capabilities and acceptability share their experience anyway.

6.6 Model Output Corroboration

A scenario workshop is executed to generate new data for validating the model but also for the purpose of engaging households. The design of the workshop is described in detail in the methodology 2.2.5 and results are presented in Appendix Q.

Some important conclusions about the assumptions made when developing the ABM are retrieved from the first part of the brainstorm session. The answers given by the participants indicate that the effects of the alternatives the conclusions are:

- Sustainability is not the foremost effect determining acceptability;
- Cooking on electricity but also cooking on hydrogen are potential barriers; and
- That there is a trade-off between gradual change and clear long-term decisions.

Evaluation of modelling output

Green hydrogen is desirable. However, other issues are addressed in a more extensive way. It remains questionable whether green hydrogen does not necessarily increase acceptability but grey decreases acceptability. Further it is remarked that for some households sustainability possibly is not of importance at all.

When comparing the effects of electric cooking to cooking on hydrogen gas it is ascertained that the freedom of choice increases acceptability. The households afraid of hydrogen can choose to cook on electricity. The ones that want to preserve their habits can choose for cooking on gas. Certainly, some households will not like to give up cooking on natural gas. Cooking on hydrogen might be a comparable and therefore acceptable alternative. The main concerns though, are related to safety when talking about cooking on hydrogen gas. It seems that households rather tend to trust hydrogen in their boilers than in their kitchens.

It is ambiguous whether a switch to fully pure hydrogen or slowing increasing the ratio of hydrogen in the natural gas grid is more acceptable for households. On the one hand a gradual transition brings advantages and tranquilises residents as also slowly experience is built up. On the other hand, it is an important disadvantage to make adjustments in households twice in a short period of time. Furthermore, uncertainty about the future might cause scepticism and doubt. For residents it is hard to anticipate under uncertainty. Timing is an important factor that has not explicitly been addressed in the ABM. On participants also indicated that the quality and origin of the gas distributed might not even matter to most residents.

6.7 Implications for experimentation and participation

The implications to be considered in the next steps and when interpreting or using the model are the need to:

- Translate abstract concepts; and
- Translate numerical outcomes into nuanced directions for solutions.

The methodology to evaluate the model has been proven useful and accurate. It carefully considers a broad range of the assumptions and potential flaws. The model output verification has shown that the model generates behaviour that could be expected from the data received during interviews. The model corroboration must show whether this data was suitable for building and verifying the model.

The model outcomes should not be directly communicated, but it requires interpretation and context to be of value. Generating values above and below zero can cause confusion. Zero is not a specific point of reference. The data only gives direction without hard thresholds when something is acceptable or not. This must not be interpreted in the wrong way.

The model analysis shows that there are many possible ranges of outcomes of the model due to uncertainty. This has been expected. In the model analysis the most important factors driving acceptability when researching the base case are identified. More profound research of the factors and how exactly they influence well-being increases the value of the model. All in all, the methods suggested by Augusiak et al. (2014) is very thorough and shows the shortcomings and limitations of the model.

6.8 Conclusion

From this chapter serval conclusions with regard to the use of the model for the problem of Stad aan 't Haringvliet could be drawn.

What effects the acceptability of hydrogen distribution and domestic use for households?

A very high frequency of communication within the community has undesirable effect on the acceptability because a high number of sceptics generates greater negative impact than a lack of enthusiasts. Additional enthusiasts do not have a positive effect and therefore should not necessarily be part of a communication strategy. Decreasing the spread of negative and demotivating information on the other hand is a problem that needs to be tackled. A communication strategy needs to anticipate to this findings.

Autonomy to install a heat pump is only for a small number of households relevant. This makes increasing autonomy for all a difficult issue that certainly should be discussed with households. Changes in income are too little to have significant meaning for autonomy and well-being. The improvement of technology, thus decreasing costs and increasing choice is more important.

The role of timing the project has been identified. Based on the recent trend the decision might be taken to delay the project or to compensate for decreasing incomes. When incomes increase quickly it may be the right time to execute the project. Increasing the speed of acceptance can be done by fostering the innovation process. When technology is affordable a high interest for saving money increases the acceptability of the technology. When technology is not affordable yet, the acceptability is low. There is a turning point after a certain amount of time.

With regard to the model corroboration it is concluded that model assumptions about the trade-offs of sustainability, comfort and affordability are appropriate. The model indicates the topics cooking and the discussion of gradual changed. Assumptions on the importance of autonomy and freedom of choice need iteration. The residents additionally highlight the importance of independent experts. Experts can give the information on which final decisions should be based according to residents. It must, according to the participants, not fully be based on the public opinion.

The simplicity of the current conceptual model allows for starting up discussions with stakeholders that are not familiar with neither the CA nor modelling and simulation. It is easily communicated to stakeholders that have few knowledge of the philosophy of the CA and the technical requirements of hydrogen. Simplicity of the concepts enables for communication about the model and use of the model for engaging households.

Translating the conceptual frame into a conceptual model leads to some more strengths and weaknesses, with regard to the analysis of the system of Stad aan ‘t Haringvliet. The model allows for tracing acceptability and exchange of information throughout time. A frame that focusses on choices and how they influence each would be a valuable addition to the model. In the current situation the actual decisions and how making a decisions possibly restricts capabilities are outside of scope. Increasing the number of loops and interactions will uncover more mechanisms and links (Veer, 2018).

7 Experimentation

This chapter evaluates the performance of three combinations of technical design choices given uncertainties and different scenarios. The chapter provides an answer to 'What are the effects of different designs on capabilities of households given uncertain valuation of capabilities and social structures?' by experimentation.

At first the problem and goal for the experimentation are formalised. Designs are formulated that can be tested. Subsequently the experimental set-up is argued. Ranges of uncertainties are defined for the valuation of the capabilities, for external factors and social structures.

It is explored how uncertainties influence the performance of technology in terms of creating capabilities for households. Conclusions are drawn on which topics to discuss with households and eventually other stakeholders.

7.1 Purpose of the experimentation

The purpose of this research step is exploring the system to prepare for an engaging activity. This means that turning points, uncertainties with high impacts and unanswered questions need to be identified in order to be discussed with households and stakeholders. One problem that occurs when modelling the case of Stad aan 't Haringvliet is that the reciprocal or mutual relation of capabilities remain unclear. This problem has been addressed earlier in 2.1.2. In literature it is mentioned as *'value incommensurability'* (Hsieh, 2007; Martinez-Alier, Munda, & O'Neill, 1998). This research step needs to give insights into the relation of the valuation of capabilities and the designs in order to, in the next step, identify under which circumstances designs may be accepted.

Thus, a discussion with households is prepared which provides for fruitful conclusions about which designs to choose and how to support the designs. The ultimate goal is to come to insights that can form the basis of a communication and participation strategy. Therefore, also the role of information within the social structure needs to be explored. The insights that lack to have a discussion about the designs are:

- hypothesis about the complex role of information;
- what information is of influence;
- how it spreads; and
- circumstances that support certain designs.

The designs are not directly compared per capability because this allows for going into detail and structuring the analysis. In this way it can be explained how well-being is constructed and with respect to value incommensurability how to interpret well-being.

7.2 Technical Designs

Based on the interviews a choice is made which setting and combinations of technical choices to explore. The different technical design choices are

- The base case, which is most likely to be chosen
- A comfortable and sustainable solution
- A slow transition towards hydrogen infrastructure that allows habituation.

The choice to compare these results allows for comparing a progressive and a conservative scenario (Appendix K). The base case can possibly be a reasonable compromise between the two extremes.

The base case called *electric cooking* includes:

- Green H2;
- Just heating with H2 and cooking just on electricity; and
- Pure H2 in the pipes.

The second design is called *cooking on green H2* because it includes:

- Green H2;
- Cooking and heating with H2; and
- Pure H2 in the pipes.

The third design is called mix of grey hydrogen and consists of:

- Grey or blue hydrogen; and
- Just heating, thus only electric stoves.

7.3 Experimental Set-up

The run length, the number of experiments and the number of replications have to be chosen carefully. To assure that the right settings are chosen some tests are executed. This ensures for not missing any relevant results nor drawing invalid conclusions. This section discusses the experimental set-up by:

- Choosing a run length,
- Determining the number of replications per scenario,
- Choosing scenarios to be explored through determining ranges of uncertainties and
- Assigning initial settings to model parameters.

The figures analysed in the model output verification 6.4 show that well-being stabilises after a certain amount of ticks. In most runs the final level is reached after roughly 20 ticks. Run with longer runtimes, up to 200 showed no additional changes. A run length of 50 is chosen to make sure no important results are missed without spending too much time on experimentation and generating data. Other run lengths have been tested in Appendix L.

7.3.1 Replications and Experiments

A balance has to be found between spending run time on replications and experiments. As there are random variables that play a role in the model no conclusions can be drawn from a single run. Therefore, the different experiments (same scenario´s) are run several times. This assure that conclusions are not drawn on a random outlier. Comparing 10 and 100 replications a balance has to be found between long run times and sufficient data to solve the problem. Appendix L shows why 10 replications are chosen.

The number of experiments is 200 because a number of 1200 experiments does not give any new insights and 50 experiments are too few to draw conclusions from (Appendix L). A high number of experiments is desirable as it leads to more robust and detailed results when analysing the data. However, many experiments need lots of capacity to be executed. A balance between time for running the experiments and generating enough data to come to purposeful conclusions has to be found.

7.3.2 Uncertainties

In the previous chapter a number of uncertainties are identified. To explore the effects of uncertainties on different design choices ranges need to be chosen. The ranges are chosen based on the insights from the model output verification and model analysis. In this analysis step conclusions were drawn on how factors influence overall patterns and how these patterns are related to the real world. The ranges are chosen in a way that serves for drawing realistic conclusions. The ranges are presented in Table 16 and substantiated in Appendix L.

Improvement and trends income are external factors that are uncertain in the future. Weight of costs, importance of information, importance of comfort and weight of sustainability are representing the ratio of valuation. When the value of weight of costs is three and the other uncertainties are equal to one this means that costs are three times more important than the other aspects (which are equally important). In this way the incommensurability of valuing different capabilities (e.g. being sustainable, affordability that leads to autonomy) can be explored.

The number of enthusiastic households, the number of sceptic households and the reach of social interaction (radius) determine the social structure. The interactions due to the radius are indicated by

Table 17. As there is no research done on the current public opinion nor the information households have at the moment, it is uncertain whether information spreads within the network. Further, the frequency of households sharing information about the hydrogen project is uncertain. Exploring the radius means exploring the frequency of interactions.

TABLE 16: SETTINGS DURING THE EXPERIMENTS

Parameter	Range [unit]
Improvement	0, 4 [decreasing costs per time unit]
Trend income	-2, 6 [1000 € per time unit]
Weight of costs	0, 3 [ratio]
Importance of information	0, 3 [ratio]
Importance of comfort	0, 3 [ratio]
Weight of sustainability	0, 3 [ratio]
Enthusiasts	0, 80 [households]
Sceptics	0, 80 [households]
Radius	1, 6 [patches]
Run length	50 [time units]
Replications	10 [#]
Experiments	200 [scenario's]

TABLE 17: NUMBER OF INTERACTIONS DUE TO THE RADIUS

Radius	1	2	3	4	5	6	10
Neighbours	3	7	12	18	28	40	109

7.4 Valuation of Capabilities

The score of the designs identified on the capabilities under varying valuation are analysed. Therefore the results of the experiments are analysed based on the outcomes of the key performance indicators:

- Social acceptability;
- Fairness
- Autonomy;
- Welfare;
- Sustainability; and
- Well-being.

The results of the experiments are analysed following these steps:

- Interpretation of the parameter in the real-world system;
- Chosen range and effect of the range;
- Pattern of the outcome and effect on capability;
- Explanation how this effect is caused; and
- Giving context of the real world.

The graphs of the results presented in this chapter are outputs from the EMA workbench (Python). They are analysed by:

- Explaining the axis;
- Describing the graph; and
- Interpreting the shape.

7.4.1 Social acceptability

The social acceptability represents the ability to realise capabilities due to social interactions and insights gained by interactions. There are two ways in which households may influence each other:

- Spreading enabling information; and
- Spreading disabling information.

The households that provide others with enabling information are enthusiasts or front runners. The households providing disabling information to others are sceptics.

The graphs that plot acceptability for households over time show comparable patterns for all scenarios (Appendix M). Stable levels of acceptability with small but capricious fluctuations over time as presented in Figure 30. Very few cases show bigger fluctuations. This indicates that even though a stable level of social acceptability is reached there remain some differences between individuals and fluctuations over time. As experts during the interviews indicated it is hard to make everyone happy. Maybe the strategy to be developed should rather focus on the overall social acceptability instead of taking this small fluctuations away. Therefore it is not so interesting to analyse how exactly fluctuations arise but to identify factors that cause high levels of social acceptability for the majority of households.

The PRIM (Patient Rule Induction Method) analysis presented in Appendix M is summarised in Table 18. When gathering data for the model it remains unclear how exactly information influences households. The simulation shows that if information actually is an influential factor the levels of social acceptability increases and contribute to overall well-being. Thus the question how important social acceptability and community values as e.g. democracy needs to be addressed when developing a strategy as it is essential for deciding how to design for acceptability. This also determines how much effort should be done on increasing the number of enthusiasts and decreasing the number of sceptics.

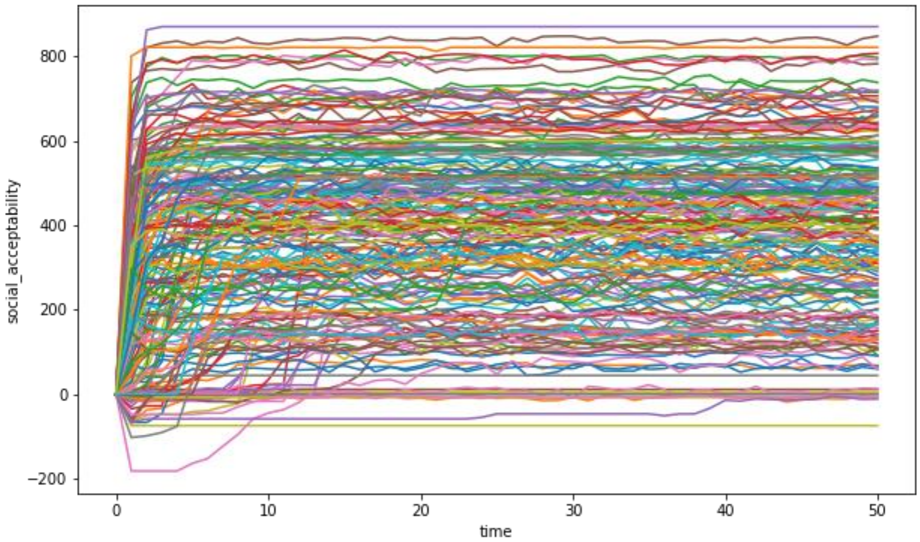


FIGURE 30: SOCIAL ACCEPTABILITY FOR HOUSEHOLDS FOR THE BASE CASE

From the summary of results in Table 18 is concluded that the same factors, independently of the designs cause high levels of social acceptability, even though the design cause different outcomes of social acceptability. This insight needs to be further explored when actually engaging households.

TABLE 18: SUMMARY OF RESULTS FOR ACCEPTABILITY

Technical configuration	High levels	Low levels	Score
Base Case	High importance of information, few sceptics, many enthusiasts	-	High
Cooking on green hydrogen	High importance of information, few sceptics, many enthusiasts	Great radius, many sceptics	High
Mixing grey hydrogen	High importance of information, many enthusiasts	-	Low

No conclusions can be drawn on which factors cause low levels of acceptability for grey mixing and the base case. The PRIM analysis is not able to identify significant factors in this case as presented in Appendix M.

7.4.2 Fairness

Researching the individual comparison allows drawing conclusions about the fairness and the equity created by the different designs. There are two indicators that allow for analysing differences between individual households:

- Colour of the agent in NetLogo; and
- Minimum and maximum values of capabilities of a run.

NetLogo assigns colours depending of the value of well-being of each households. Thus the number of green, yellow and red households indicates for how many households a design is acceptable or not acceptable throughout time. The graphs presenting the differences of numbers of coloured agents indicate the effects of the designs on individual differences.

- Many agents change their colour given the base case, even though overall well-being stabilises, for a number of agents the acceptability changes due to the social network.
- Green cooking the design is acceptable for most agents within a short period of time, thus equity is high.
- For grey mixing at fist the design is not acceptable but throughout time the number of green agents increases. Changes between acceptable and not acceptable are less frequent than in the base case but in general it is less acceptable for a high number of household.

It can be concluded that the base case causes insecurity as the acceptability is very sensitive to the social network and the information spread. The green cooking design is less sensible as it is more acceptable in general. Other capabilities seem to outweigh the effects of social interactions. This assumptions needs to be discussed when developing a strategy given the problem of value incommensurability described in the introduction of this chapter. The relation of different capabilities needs to be specified by further exploring valuation of capabilities.

NetLogo also reports the household with the lowest and highest value of each capability. Comparing the lowest and highest values in the system throughout time allows for drawing conclusions whether some designs create bigger or smaller differences between households. In Appendix M the results for comparing the effects of the designs on differences between individuals are presented. The graphs show no significant differences in minimum and maximum values between the scenarios.

7.4.3 Autonomy

Autonomy indicates whether a design is affordable and offers the households freedom of choice. Autonomy depends on the ability to choose for all electric and to replace equipment. There is a big difference in autonomy between households that rent and households that own their homes.

As housing corporations take the decisions which systems are used for heating and cooking, tenants only get to decide which stoves and pans to buy. So tenants have autonomy to some extent but less than owners.

The development of autonomy is independent of the design that is chosen as autonomy mainly depends on the weight of costs, trend of income and to a small extent to the improvement of technology (Table 19). The results of comparing the curves of the different scenarios and the analysis with PRIM are presented in Appendix M.

Figure 31 plots the outcomes for autonomy of 200 experiments over time given the design of the base case. The other design show very comparable results. The graph indicates that initially there is a drop in autonomy as households are not able to afford the new technology. In many scenario´s autonomy increases within a few time units and stables on a certain level. This level depends on how much autonomy or costs are valued by households. The higher the interest for a cheap solution the lower the score of hydrogen infrastructure in creating autonomy. The graph in Figure 31 shows some cases where autonomy increases slowly. According to the results of the PRIM analysis this is probably caused by a low trend of income. However, as indicated in Appendix M the coverage and density of the analysis are too low to certainly draw this conclusion. The drop of autonomy that can be detected in the graph after 30 ticks has already been explained in 6.4.2 and 6.5. It can be concluded that high interest for costs and increasing incomes increase autonomy.

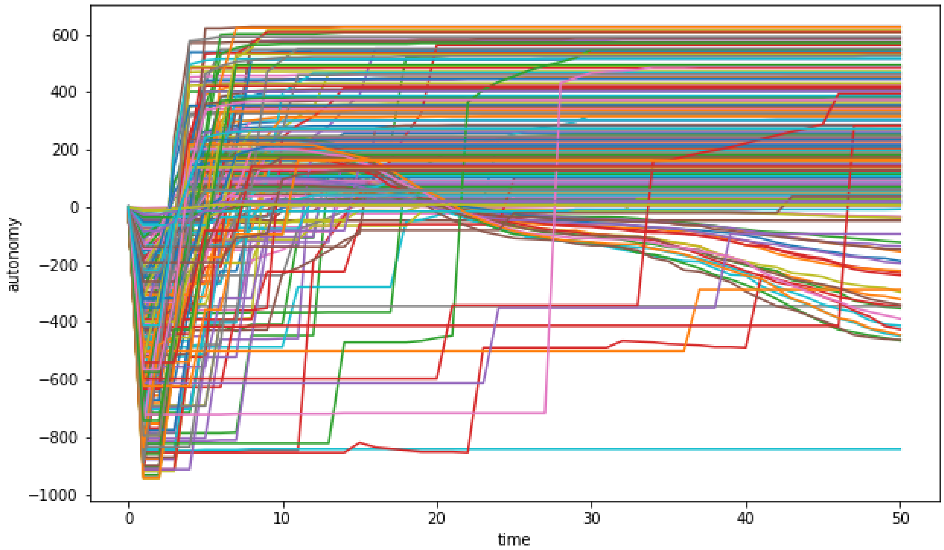


FIGURE 31: AUTONOMY OF THE BASE CASE

Because the weight of costs seems to play an important role the interest of households for costs, especially in comparison with other capabilities, must be further explored in engaging activities.

Thus a strategy to design a solution for Stad needs to consider the spendable money of households, but also the trade-off households make between affordability and other values. Households need to decide what are good ways to address this possible barrier for the acceptability of hydrogen infrastructure. Autonomy may be increased by letting households decide how to increase autonomy and affordability.

TABLE 19: SUMMARY OF RESULTS FOR AUTONOMY

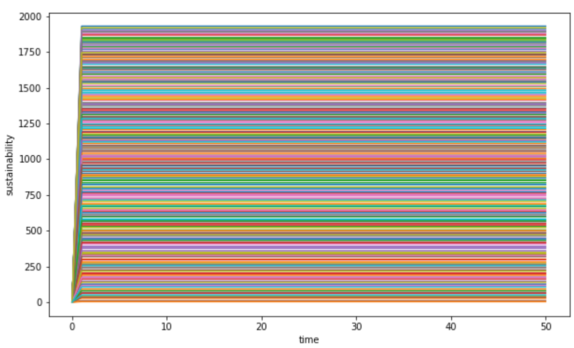
Technical configuration	High Autonomy
All Designs	High weight of costs, high trend of income, high improvement

7.4.4 Sustainability & Welfare

Sustainability is a performance indicator for the ability of a design to enable households to reduce their CO2 emission. Welfare indicates the ability to choose daily patterns and habits. Both parameters have not been fully researched yet and offer an opportunity to deepen and improve the model. Currently the key performance indicators are static over time as indicated in Figure 32 and

Figure 33. The graphs plot sustainability and welfare over time.

A design either causes or not causes sustainability and welfare. The valuation of the capability determines in how far the sustainability and welfare influence the overall well-being.



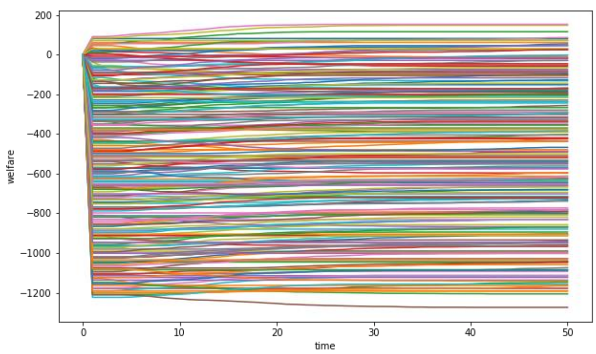


FIGURE 32: SUSTAINABILITY OF BASE CASE

FIGURE 33: WELFARE OF BASE CASE

The graph presenting sustainability shows straight lines. The small variations of welfare throughout time can be explained by increasing welfare when insulation becomes affordable. However, these variations are very small and do not have an impact on well-being.

TABLE 20: SUMMARY OF RESULTS FOR SUSTAINABILITY

Technical configuration	Score on Sustainability	Score on Welfare
Base Case	High	Low
Cooking on green hydrogen	High	High
Mixing gey hydrogen	Low	Low

7.4.5 Well-being

Well-Being is a very general performance indicator. It indicates the acceptability of the designs. Both well-being and acceptability are ambiguous measures. To be able to interpret the measures it is assumed that increasing capabilities increase the acceptability. Thus, the more well-being increases the more acceptable a solution. To interpret the results, the current situation is chosen as starting point. This is not necessarily true but allows for an interpretation that helps to engage stakeholders. It makes it easier for stakeholders and households to understand the abstract concepts applied in the model.

Assessing overall well-being makes it possible to compare designs in terms of morality. However, results really need to be interpreted carefully as actually the capabilities cannot easily be summed up to one overall performance indicator as well-being. However, well-being here is used to do a first exploration of the potential acceptability of the designs and to explore the effects of uncertain valuation of different capabilities. The analysis of the graphs can be found in Appendix M. PRIM analysis helps to determine factors that cause a high or low level of outcomes. The results presented in Table 21 retrieved from the graphs (score of designs) and the results from the PRIM analysis (factors causing high levels of well-being). There is a major drop of well-being in the beginning of the runs. For most cases the initial drop or raise is the most influential factor. The runs can be mainly distinguished is the range of the drop which is determining for the final level of well-being in most scenarios.

For the real-world the results mean that the uncertainty of how comfort and the urge to reduce sustainability is determining for the acceptability of the design. When a strategy succeeds in decreasing the urge to continue cooking on gas the design is more acceptable. Increasing the urge for reducing CO2 emissions also fosters the acceptability.

Even though values remain stable, information and facilitation of change may change the effect of designs on capabilities. How to inform and to facilitate needs to be further explored in collaboration with households. The conclusions that can be drawn about well-being from the experiments is the following step must address how to increase comfort and valuation of sustainable designs.

TABLE 21: SUMMARY OF RESULTS FOR WELL-BEING

Technical Design	Results of PRIM Analysis	Score of designs
Base Case	Low importance of comfort, high weight of sustainability, high trend income and great radius	Big differences between scenarios
Cooking on green hydrogen	High importance of comfort, high weight of sustainability, high trend income and great radius	High
Mixing gey hydrogen	Low weight of sustainability and importance of comfort	Low

7.5 Conclusion

The problem that occurs when modelling the case of Stad aan 't Haringvliet is that the reciprocal or mutual relation of capabilities remains unclear. This problem is clarified by analysing the effects of designs on the capabilities of households.

What are the effects of different designs on capabilities of households given uncertain valuation of capabilities?

This chapter questions whether well-being can easily be interpreted as the valuation of capabilities is uncertain and values cannot easily be compared. Questions that have been identified and need to be answered are:

- The trade-off between costs and sustainability remains unclear;
- The valuation of cooking on gas remains unclear; and
- The effects of gradual change are ambiguous, therefore timing is important.

The second aspect that is researched is the complex role of information and of the social cluster. The statements to be discussed in the next chapter are:

- Enthusiasts cannot outweigh sceptics has negative information has more impact than positive information;
- Frontrunners can improve acceptability when sharing experiences; and
- The frequency of interactions influences acceptability.

Results for the individual capabilities and well-being are analysed separately to respect the potential incomparability of capabilities. From the PRIM analysis it is concluded that the relative importance of the capabilities matters most when determining the effects of designs on the acceptability of a technology. The input of households is needed to interpret the outcomes and find out how to create favourable circumstances for the designs. However also sceptics, enthusiasts and the radius (frequency of interactions) play a role for some designs.

When analysing the designs and scenarios it can be retrieved from the data that the initial settings are mostly determining for the final levels of the key performance indicators. For the case of Stad this means that initial choices are very important for long term results, thus acceptance. Patience is needed as in most scenarios well-being initially decreases, mainly because autonomy is very low. Over time many of the scenarios with initially negative values increase due to a turning point in autonomy. This indicates that timing is an important issue to be addressed when discussing with households.

The scenario electric cooking (base case) causes a wide range of possible outcomes for well-being, the outcomes of cooking on green hydrogen are mainly positive. When households care less about comfort than about sustainability, cooking on electricity is acceptable. High interest for sustainability in combination with high importance for comfort increase the acceptability of cooking on green hydrogen. Mixing grey hydrogen with natural gas causes mainly negative results in terms of well-being even when there is low interest for comfort and for sustainability.

The analysis of results indicate that the base case is possibly acceptable under certain circumstances, that green cooking potentially does not cause barriers, thus is accepted and that grey mixing is not acceptable. Grey mixing asks for additional measure to compensate for a lack of acceptability. These assumptions need to be checked with stakeholders and households. A question to be answered is whether the importance for capabilities can be influenced and what are other possible ways to increase the performance of designs.

The analysis shows that there is an opportunity to create new information by further exploring data for sustainability. In the current simulation it is indicated that sustainability and welfare play a role for acceptability. However, dynamics might have important additional effects.

8 Engagement Workshop

This chapter describes the practical use of the qualitative data analysis and modelling results. The last sub-question 'How to improve the acceptability of designs together with households in the realisation of hydrogen distribution and domestic use in Stad aan ´t Haringvliet?' is answered.

This chapter has four goals. These goals are leading for the structure of this chapter:

- Evaluating the importance of the capabilities that are analysed based on the experiments;
- Identifying the role of information;
- Improving the designs identified in section 7.2 and tested in section 7.4 by letting stakeholders think about measures to increase capabilities; and
- Evaluating the value of a workshop as engaging activity.

The workshop consists of three parts that generate data for reaching the goals and answering the question. These parts are:

- A questionnaire;
- A brainstorm session; and
- An evaluation of the workshop.

The details of the workshop design are described in section 2.2.5 and the workshop forms used to gather information can be found in the Appendix O. Based on the notes during the workshops and on the evaluation form filled by the participants, it is discussed whether the scenario workshop helped engaging stakeholders. Conclusions are drawn considering what can be improved when repeating the workshop.

8.1 Importance of capabilities

Some important conclusions on how to interpret the results of the experimentation are retrieved from the questionnaire. Asking participants to indicate the importance of values possibly embedded in designs leads to the conclusions that:

- Information plays an important role for accomplishing capabilities;
- The importance of autonomy is ambiguous; and
- The importance of sustainability, affordability and safety needs to be stressed.

From the questionnaire it is concluded that comfort, sustainability and affordability are the most important values within the set of values provided. The results of the first question are presented in Appendix Q. Freedom of choice and fairness are less important according to participants.

The public opinion in the community of Stad is, according to the participants, not only influenced by external experts, but also formed within the social network. Residents tend to repeat what they hear from others. They are sensitive to negative as well as positive information and opinions that are shared.

The importance of autonomy and freedom is ambiguous. One of the participants states that there should not be a choice for households as it can cause anxiety and concerns. People want to make a thought-out choice but are not capable of gathering or understanding the needed information. Residents and users would want experts to make the right choices. Another participant thinks that residents do not like to be confronted with accomplished facts but want to understand the argumentation and want to take part in the discussion.

From the discussion is concluded that paying more for sustainable energy is only acceptable when this increases comfort and it means for example decreasing energy consumption and saving costs elsewhere. It is indicated by participants that hydrogen is acceptable when it is affordable, sustainable and safe. Especially safety is highlighted.

8.2 Improvement of the Design

The participants choose to evaluate and brainstorm about the design that scores lowest. The design is a combination of gradually mixing grey or blue hydrogen with natural gas and obligatory changing to electric stoves in all households.

Strengths identified are:

- Opportunities for good timing;
- Learning; and
- Affordability

Weaknesses identified are:

- A lack of sustainability;
- A lack of clarity to base decisions on

Improvements that follow form the brainstorm and discussion are:

- Providing information;
- Letting households experience designs;

8.2.1 Discussion of strength and Weaknesses

The positive psychological effect of gradual change and habituation is stressed. Timing is an advantage of the design because it allows for gaining experiences with technology and developing innovations. Better timing also increases freedom of choice as more technology becomes available and learning is possible.

"The design is a compromise and that's what people (households) appreciate." (Participant)

A strength is that this solution in the first place is possibly cheaper than the others. On the other hand, it is also argued that this option on the long term might be expensive. When the price for natural gas increases and a mixture of hydrogen and expensive gas in distributed.

A problem identified by participants is a lack of sustainability. Residents might think that it is not worth the effort when the solution is not sustainable. As only electric cooking is granted, dissatisfaction about the fact that cooking on gas is not possible, arises. It is also assumed that there are possibly higher investments as there are at least two moments of change. Again, uncertainty about future developments might harass some households as investments cannot be planned.

8.2.2 Discussion of measures for improvement

A solution is choosing for green hydrogen (or blue) instead of grey hydrogen and mixing it with natural gas in the first instance.

"Improving this scenario actually means choosing for one of the other scenarios". (Participant)

Information is crucial for households. When information and support suffice, the benefit of gradual change is not needed. That clears the road for radical change. Offering the possibility to try out a new technology or participate in seminars might increase acceptability. More concretely, it is suggested to organise free workshops on how to cook on an electrical stove. The way in which electric cooking is presented (as obligatory and predetermined or a free choice but with a strong advice to cook electrically matters for the acceptance of this design choice.

Another way to provide information to households is to inform or motivate front runners and sharing their stories of trial and error. Subsidies for induction stoves could improve the scenario as well as donations of pots and pans. Subsidies on insulation increase sustainability and therefore may compensate the shortcoming of a design with grey hydrogen. Another suggestion made by one of the participants is supporting the financing process by loans and services.

"For the other scenario's we would probably have come to the same measures to improve performance."(Participant)

This insights are valuable outcome because they indicate general measure to increase acceptability. The average score of the improved design increased by almost 80% as presented in Appendix Q.

8.3 Evaluation of the Workshop

The evaluation of the workshop brings forward some remarks of doing a workshop with stakeholders and households as engaging activity. The conclusions that emerged are:

- Project leaders gained more new insights than representatives of households during the workshop;
- The workshop is in line with the knowledge level op participants; and
- Brainstorming is a valuable tool to generate data.

The analysis also leads to some suggestions how to improve the workshop. Conclusions are that the work may be improved by:

- Better framing of the goals and ambitions of the workshop;
- Increasing the amount of interaction between participants; and
- Improving the clarity of designs.

The participants are especially motivated when being able to share their own views and discuss those with the group. Participation during the workshop is balanced and all participants contributed. There is space for opinions and sharing those. However, three participants are not fully satisfied about the amount of information they are able to share during the. More interactions during the workshop might increase the value of the workshop and the data generated.

The atmosphere during the session is positive because all participants agree that the energy system has to change either way. New insights about technology, the role of choices and the opinion of the community are gained by most participants but especially project leaders. Two representatives state that there are no new insights, as not enough attention is payed to public support from the community. Better framing might improve the effectiveness of the workshop.

It is suggested that the designs are good but not complete. The explanation needs to be clearer. It is possibly better to have bigger differences between scenarios and fill them with concrete examples. They are too abstract to easily describe during the workshop. Also, language should be simpler (less jargon, easier phrases that connects with the worldview of the participants). The forms fitted their purpose as they were not too long /short. One of the biggest difficulties was to bridge between theory and practice, thus connect the concepts applied in the research to what the participants experience in their daily life.

The workshop fitted well with the background of all participants because all participants were already involved in the project. Still, for residents with less knowledge, the content should be changed. From the reaction of the participants can be drawn that answering the questionnaire was more difficult than the brainstorm. The brainstorm was most interesting and interactive to stakeholders, and led to important new insights.

Considering the different stages of engagement described in literature, the workshop covers the aspects of informing, consulting and involving. It also creates the potential to take a step towards collaboration in a future step (Helbig, Dawes, Dzhusupova, Klievink, & Mkude, 2015). A description of the stages and a profound analysis is provided in Appendix R.

8.4 Conclusion

How to improve the acceptability of designs together with households in the realisation of hydrogen distribution and domestic use in Stad aan ´t Haringvliet?

The acceptability of design can be improved by engaging stakeholders and households by making use of a workshop. A workshop for discussing and improving different design is concluded to lead to:

- Mutual Learning of participants through providing and receiving new insights;
- Identifying bottlenecks of the designs provided;
- Identifying measures to mitigate for short-comings; and
- Providing a basis for a long-term strategy for engagement and communication.

The workshop provides for discussing the results of the ABM without going into detail about the model. The questions that came forth from the experimentation are discussed with the participants:

- The trade-off between costs and sustainability remains unclear
- The valuation of cooking on gas remains unclear
- The effects of gradual change are ambiguous, therefore timing is important

The importance of autonomy and freedom is ambiguous. Paying more for sustainable energy is considered by the participants as only acceptable when this increases comfort and it means for example decreasing energy consumption and saving costs elsewhere. The question whether cooking should be electrical or on hydrogen is a topic that actually bothers households and needs to be discussed with households. The decision to cook electrically or on hydrogen should be made by the households, not by force. Finally, the discussion whether a gradual transition or a radical change is desired must be continued by project leaders and stakeholders. One of the strengths of providing a workshop to the residents is that even though one specific design has been discussed, conclusions could be drawn for the other designs as well.

The benefits of scenario workshops with stakeholders are mutual learning and together develop broader designs (Mulder et al., 2012). The main limitations are that scenarios are too abstract to come to useful conclusions. However, the workshop held is suitable as small-scale study to gain some experience in bringing the results of ABM into practice. A workshop succeeds in engaging stakeholders and households because different stages of engagement are reached and the basis for further engaging activities and increasing the influence of households on the decision is facilitated. Concrete actions to improve the performance of the designs developed by participants are free pans and workshops when switching to cooking on electricity. Other suggestions are financial support and information given by experts. It is suggested to identify and support front runners that gain experience and share it with the other households. These insights have the potential to form a basis for a participatory strategy developed by households for households.

In summary, this chapter shows that there is no clear agreement on which design is the best. However, the results of simulation clearly serve for having a lively and fruitful discussion about the different technical considerations and measures to support the acceptability of a chosen technology.

9 Conclusion & Recommendations

This chapter collects all sub-conclusions and insights on their implications. It uses them to formulate a clear answer to the main research question. The conclusion results in recommendations for the project leaders of the hydrogen pilot, households and policy makers of Stad aan 't Haringvliet. Finally it is reflected in the context of the whole research project. This chapter includes:

- The answer to the main research question,
- The interpretation of results,
- The practical implication,
- The added value of the research for literature; and
- Limitations and suggestions for further research.

9.1 Acceptable technology

This section answers the main research question based on the answers of the subquestions. First the answer to the subquestions are summarized and corelated to each other, then the main research question is answered.

Which aspects related to the acceptability of replacing natural gas by hydrogen in households can be used for the conceptualisation of the problem?

The conceptual frame combines the elements of VSD, the CA with a complex system perspective. The elements of the conceptual frame are values, capabilities, acceptability, conversion factors, heterogeneity and interactions. This allows for assessing well-being and making assumptions about acceptability even under changing circumstances and for longer time periods. Acceptability is assessed in terms of well-being due to individual capabilities of households. Getting to know more about levels of well-being and changes in well-being allows for making assumptions about acceptability of technology. The recent technology is taken as reference point because it has been proven acceptable for a majority of households.

Which capabilities cause acceptability for households when assessing potential technical designs of hydrogen infrastructure for Stad aan 't Haringvliet?

The capabilities that can be retrieved from values, conversion factors and effects of technical alternatives are: the choice for alternative ways of heating; the choice for quality and price of replacing equipment; the the possibility to insulate; the ability to reduce CO2 reduction and choosing own daily patterns in terms of cooking and heating.

These capabilities form the basis of the assessment of a set of technical designs as they indicate the freedoms that households currently have. In the future, these freedoms and choices should be sustained. As long as the freedom of choice does not change, the new technology will be evenly accepted as the current one.

What effects the acceptability of hydrogen distribution and domestic use for households?

A very high frequency of communication within the community has undesirable effect on the acceptability. A high number of sceptics generates greater negative impact than a lack of enthusiasts. The autonomy to install a heat pump is only for a small number of households relevant. This makes equally increasing autonomy for all households a difficult issue. The choice when to realise the technology, thus the timing of the project phases, influences the acceptability. When realising the project too early acceptability might be too low.

What are the effects of different designs on capabilities of households given uncertain valuation of capabilities?

The choices for a design, influence the long-term acceptability because infrastructure creates a lock-in effect. Decisions cannot easily be undone. When to choose a design and when to actually transform the energy system, is an important issue. Time influences the affordability and information available, thus the acceptability of system change. Furthermore, relative importance of the capabilities matters when determining the effects of designs on the acceptability of a technology. The relation of sustainability, comfort, distrust and affordability needs should be clear, in order to determine which role cooking on hydrogen, CO2 reduction and a gradual transition can play.

How to improve the acceptability of designs together with households in the realisation of hydrogen distribution and domestic use in Stad aan ´t Haringvliet?

There is no clear consensus on which option is the best. Additional measures as workshops, information and financial support to make the designs acceptable are required. There are some general measures and also design specific measures. Sustainable and often more expensive designs are only acceptable when saving costs elsewhere. For example, by increasing comfort and decreasing energy consumption. The decisions on how to design cooking, whether electrical or on hydrogen, is a topic that actually matters for households. It should be discussed with a broad range of households. Acceptability can further be improved by letting households decide whether or not to introduce a design that fosters smooth transition or a radical change.

Technology alone is not able to fulfil all values identified in literature, during the interviews and during the workshop. Additional measures are required. Empirical research shows that technology needs to be supported by institutions, communication and information. Adapting technology to local needs and involving households in decision making increase trust and acceptance.

Which technical choices provide for an acceptable design of hydrogen distribution and domestic use to households in Stad aan ´t Haringvliet?

Hydrogen infrastructure is acceptable if:

- Having a small impact, thus when offering the same comfort and security against the same costs as the current system;
- Improving the current situation in terms of comfort, sustainability, safety and costs;
- Being implemented supported by additional institutional measures that mitigate for costs and distrust; and
- The timing is right.

Acceptability depends on the freedom of choice a technology is able to create. It also depends on the characteristics of users. Formulated the other way around new technology must not cause more restrictions than the current technology. It should create more opportunities. Engaging stakeholders showed the properties of new technology were often compared to the current system. It is hardly possible to say something about the acceptability of a future system without looking at the current system. Technical choices must be adapted to the local context as soon as possible. The concept of acceptability allows for engaging stakeholders and households even when decisions have not been made yet. Even though acceptability is a concept that is too complex to directly discuss with stakeholders and end users, examples linked to the current system allow for having a fruitful discussion about design requirements and what technology should enable.

Advantages and disadvantages of different designs of hydrogen infrastructure are identified. Even though the aim of the project is local and sustainable energy production and consumption due to financial and technical challenges options are considered that are not renewable. Thus hydrogen has a green image but is not necessarily a sustainable solution. The most obvious design of a hydrogen infrastructure offers the same capabilities as the current natural gas supply. However, with respect to other applications (in mobility, for storage, decentral production) innovative applications also need to be explored. This also stresses the importance of timing and identifying the right moment to switch. So even though a deadline is agreed upon, criteria need to be formulated when it is the right moment to switch regarding readiness of technology and affordability of end-user equipment.

Information plays a central role when it comes to assessing acceptability. In this research especially information spread amongst households is considered but there are more ways in which information and communication matters. There can be distinguished between technical information and public opinion. Both affect trust in technology and in project leaders. The acceptability of designs is improved in collaboration with households by adding institutional components. Purely technology is not able to incorporate all relevant values.

9.2 Reflection on the conceptual frame

This section presents interpretation of results It is a step-by-step guide. Further, the conceptual frame as guideline for the research is discussed and reviewed. The conceptual frame enables discussing the results from the research steps and analysing the relations between results.

Answers to the sub question illustrate the variety of aspects addressed by the main research question and how to fill the frame with specific content as presented in Figure 34. Transparent elements are mainly related to the complex system perspective, blue ovals are related to the CA, yellow ovals are retrieved from literature on VSD and grey elements are added based on the research.

The conceptualisation of the problem serves for defining acceptability of technology. Technology is acceptable when it *increases individual well-being, thus the number of capabilities to realise important or valuable actions*. This asks for more aspects to be defined and also for explanation of the implications for the case of Stad aan 't Haringvliet.

The conceptual frame indicates the core concepts of this research and the relations between those concepts. Well-being is a state of individuals caused by the number of capabilities they have. The capabilities researched for the hydrogen infrastructure of Stad aan 't Haringvliet are presented in Figure 34). Technology is responsible for creating capabilities but also decreasing capabilities thus has an impact on individual well-being. The functionality and properties of hydrogen infrastructure determine whether households are capable of reducing CO2 emissions and choose how to heat and to cook. Based on these capabilities further specifications may be defined for hydrogen equipment.

Heterogeneity is specified by looking at income classes, housing situation and attitude of households and making those conversion factors. This is only a small set of conversion factors that potentially matter, so the oval is moved more outside of the system border. Additionally, there is a lack of insights on how interactions influence conversion factors over time. Due to practical experience and literature it is sensible that interactions influence e.g. attitudes over time. However, these influences have not yet been researched and would be an improvement of the simulation model. Currently, the relation described in the conceptual frame between interactions and heterogeneity is not filled yet.

In this research it is assumed that well-being increases acceptability and acceptability takes away barriers for the acceptance of hydrogen technology. Therefore the aspect of acceptance is added outside the scope of the research. No research has been done on the effect of acceptability on acceptance. However, it is assumed that acceptability positively affects acceptance. Another new aspect that is more important than initially expected in the role of value incommensurability and uncertainty. As it is a major challenge to gather data about values and relevant capabilities in a consistent and unambiguous way, the experiments mainly gave insights into the uncertain contribution of different capabilities to well-being. Capabilities cannot easily be summed up, and households should be involved when translating capabilities into effects of designs on acceptability.

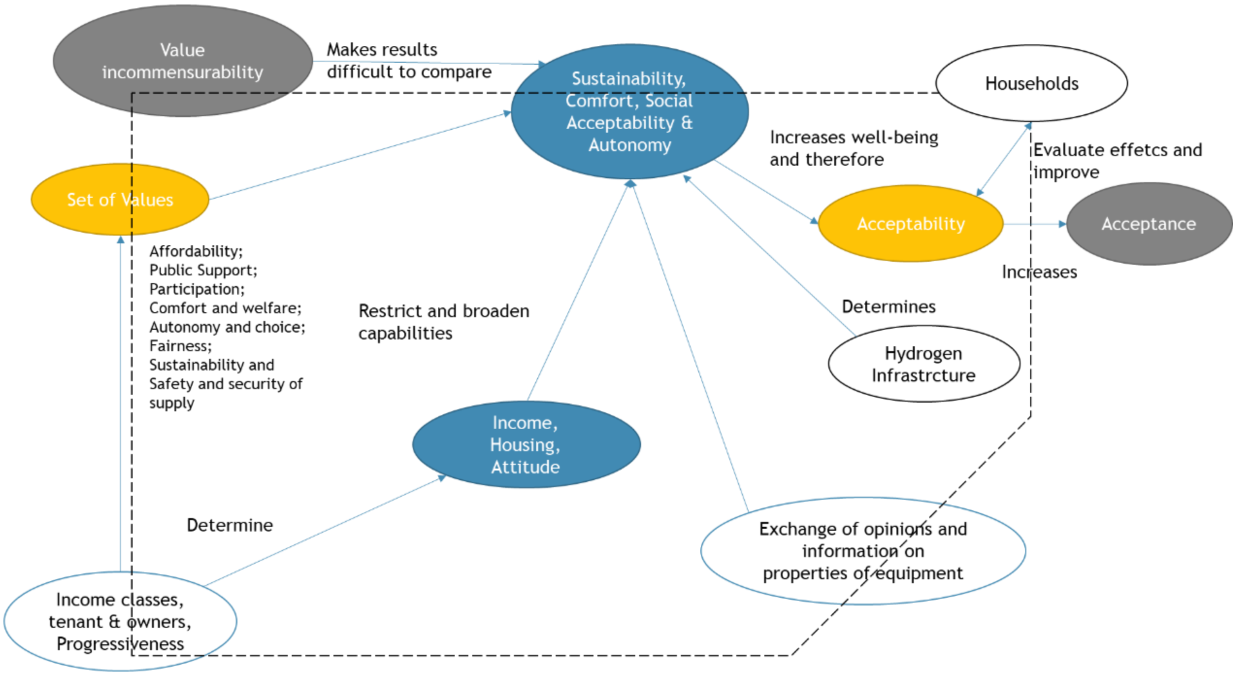


FIGURE 34: CONCEPTUAL FRAME APPLIED TO THE CASE AND REVIEWED

9.3 Recommendations

Practical implications lead to some recommendations and starting points for a communication strategy and further participatory approaches.

9.3.1 For the project leaders and stakeholders

As basis for a communication strategy and a participatory approach to continue the hydrogen project in Stad aan 't Haringvliet some recommendations for the project leaders are formulated. The most important recommendations are:

- Make acceptance measurable;
- Create certainty by making decisions;
- Do more research on technical components; and
- Involving manufacturer and installers of end user equipment.

All parties agree that public support or what in Dutch is called ‘draagvlak’ is the most important factor for a successful project. However, no clear measures, assessment methods or strategies to foster draagvlak or acceptance have been developed yet. Residents are informed but no attempt is done to actually get grip on the public opinion. At this moment mostly technical and financial issues are discussed. To define acceptance an indicator should be developed. The analysis of the interviews showed that stakeholders involved have different ideas about the scope of the project and basic decisions have not been made yet. The benefit is that residents do not get the feeling that decisions have been made already. The drawback is that it is hard to start a conversation when the project is still abstract and uncertain. This may be a source of distrust and confusion.

Currently, there is no green hydrogen available. The project for conversion of locally produced green electricity into green hydrogen stagnates. There is an initiative to install a wind turbine that directly produces hydrogen. However, people are sceptical when it comes to installing additional wind turbines as this is already a touchy topic. No other options to retrieve green hydrogen have been considered yet. So before offering the option of green hydrogen, it must become clear where the hydrogen is coming from and against which costs. Insights are needed in what way the source of electricity matters when producing (green) hydrogen with it.

Uncertainties make it difficult to conclude on the acceptability of a system. Also, uncertainty generates anxiety. Besides looking for subsidies, a next step in this project is defining the concrete district where to start the pilot. Possibly even identifying specific front runners. It is now up to project leaders to contact households more specifically, gathering information and map for which households it would be interesting or to be part a front runner. It is especially important to involve a broad range of households in this process. Residents need to know what to expect so they can make their own choices (e.g. renovate now or later). Additionally, there is now a sense of urgency given the earthquakes in Groningen. This urgency is a window of opportunity and for a pilot on the changes of hydrogen for Stad aan ‘t Haringvliet.

Furthermore, some stakeholders are missing in the process. One is the party producing hydrogen. The other would be a manufacturers of end user equipment or installers that are directly in contact with clients and end users. The manufacturers usually play an important role in providing information about innovation of equipment. In this case the manufacturers might add important insights and might be able to speed up the process.

9.3.2 Recommendations for the households

Households are the most important stakeholders in relation to this research subject. The following recommendations are done:

- Inform rather than simply adapt to the general opinion;
- Give feedback; and
- Don´t be afraid of not understanding all details.

It is understandable that some households do not want to be engaged. Obviously not everyone needs to know everything about hydrogen. However, when receiving very positive or very negative opinions further information may be consulted. The households then take responsibility for the whole community. Furthermore, the stakeholders need feedback in to be able to anticipate not only technology but also the process. Especially when there has no channel for communication been fond yet, proactive households are needed to give feedback about the public opinion and how to improve the project. Finally, for most households it is not so obvious that project leaders and experts also don´t know everything. Households should not be afraid of not knowing or understanding every detail of the complicated technology but should dare to ask questions, especially about parts that are relevant for them personally.

9.3.3 Recommendations for policy makers

- Create trust in institution before providing information;
- Be aware of emotions;
- Make information manageable and accessible

It appears that households struggle to deal with abstract concepts and a lack of imagination what changes possible mean for them personally. On the other hand, distrust and anxiety also arise when decisions have been taken without informing or involving households. Thus policy makers have to deal with a thin line that is hard to identify. However, households in Stad seem to make it easier than other residents in the Netherlands for the local project leaders in Stad aan 't Haringvliet. Households actively participate and engage which creates a bottom process. However not all households are involved and sufficiently informed yet. The mood may still change due to sceptics sharing negative opinions and experiences with project leaders. Mostly opposition arises due to distrust in institutions rather than distrust in technology. Uncertainty of technology reinforces the struggle. The reactions of households to controversial projects are not malicious. Policy Makers should be aware of the emotions that are caused by creating uncertainty, unfair costs and benefits and the feeling to of being excluded from decisions. Policy makers must not get frustrated by the reaction of residents and local parties but should rather show understanding and mediate.

In order to prevent conflicts and the formation of opposition policy makers should provide a platform with information that up-to-date, discusses different perspectives and is understandable and of interest for a great variety of publics. This advice is not only applicable for the case of hydrogen but for all kinds of complex and potentially controversial technology and infrastructure.

9.4 Reflection on the research project

This section assesses the quality and implications of the research project. By reflecting on

- The social and scientific relevance;
- The limitations of this work; and
- The research process.

Different perspectives are integrated. Acceptability of hydrogen is not only an issue of framing nor of designing the right technology but of doing both to the right extend.

4.1.1 Societal and scientific relevance

The social and scientific relevance reflect on practical implications and the contribution of this work on the scientific field.

Novel energy systems cause diverging interests, unknown risks and often controversial distribution of (social) costs and benefits (Cass & Walker, 2009; Devine-Wright, 2007). Local opposition is one of the main barriers when it comes to reaching climate goals in the Netherlands (Breukers & Wolsink, 2007). Therefore, this research develops a novel approach for preventing social opposition and resistance amongst residents. The way of addressing the problem makes it possible to assesses values and moral frames that play a role and identify who benefits before talking about technological change (Sovacool, 2014) and evaluating a system even before it exists.

The research provides new scientific insights with regard to capability sensitive design described by Oosterlaken. The difficulty of truly assessing the effects of ethical concerns is addressed in literature. One of the scientific goals reached with this work is a contributing to practical experiences and empirical substantiation. It diminishes the gap between literature and the practice of project management and decision-making.

Letting stakeholders and households shape and reflect on the results of the research makes it responsible research.

The results of the modelling approach are hard to grasp for stakeholders. Therefore, an engaging workshop has been developed. The workshop shows that relevant insights for stakeholders are created by discussing unambiguous examples and impact of technology and institutions. Based on these insights, the process of engaging households and making strategies bottom up is continued.

General conclusions about potential barriers and good design choices are drawn. This research is not only relevant for case owners. It shows how the broader problem of unacceptable transitions can be addressed. Applying the conceptual frame and formalising a simulation model facilitate structuring any problem. Being able to incorporate values beforehand fosters the energy transition. Societal implementation might become easier and faster.

The aim of this CoSEM and SEC master thesis project is designing a solution for a large and complex socio technical project by considering technical institutional, economic and societal knowledge. It is a multidisciplinary work, since methods from different fields (social research methods and a modelling approach) are integrated to address a socio-technical problem.

4.1.2 Limitations & Further research

An important limitations of the research are that the link between acceptability and acceptance has not specifically addressed. It remains unclear how acceptable technology influences acceptance and to what extend the organisation of the project process matters. Further a sustained selection is made what capabilities and dynamics to include. However, there may be other important capabilities that did not pop up in neither the interviews nor the workshop. Therefore more information about the specific needs of households should be gathered. It may be explored which households need financial support and in which way this is implemented (leasing, subsidies, sponsoring, corporations).

To prove the value of the conceptual frame it must be applied in other contexts. Now the frame has not sufficiently been tested. The goal of the research was mainly practical and not conceptual. Improvements for translating vague and abstract concepts into something than can be used for a workshop session. Further research might also show how to develop a workshop for a bigger public.

A limited set of choices is evaluated by simulation and consulting households. The modelling approach highlights the problem of comparing values and specifying weights of values. However, the model makes it possible to explore the effects and identify issues that need to be further discussed. Possible barriers to acceptability as sceptics, a lack of front runners sharing experiences, a lack of willingness to change habits and a lack of urgency for sustainability can be addressed by project leaders. The aim of the issues identified is to let local stakeholders develop designs, strategies and measures together with households. Inherently this facilitates for embedding local values. The great benefit of Agent-Based Modelling for the problem of Stad is that ABM structures and conceptualises the system and therefore succeeds in identifying issues that ask for attention in the next project phase. The benefit of ABM in the case of Stad is that a system that does not exist yet can be explored and possible interventions are simulated. Further it causes low costs and creates a guideline for a participatory process and leads to discussion. A limitation of the results of the modelling approach is e.g. time because it is a vague and it remains unclear on which terms technology and acceptability improves. Another suggestion for improvement is that agents should make choices. Currently, the model is not able to grasp full complexity of the system. It is quite simple and does not include all the possible interactions, choices and values that are relevant. The added benefit is that it is easy to communicate. The model generates easy presentable and evaluable outputs.

The technological choices discussed, are not the only choices possible. During the workshops it is indicated that there are some more applications of natural gas that may cause challenges when replacing gas. Furthermore, it considers high level technology. In this research some very basic choices concerning the infrastructure are assessed. More specifics design requirements are needed to embed values I end user equipment. Further, a limited set of capabilities is discussed. There are more capabilities that may be relevant; they are excluded from the research. Doing a workshop to engage stakeholders has advantages and disadvantages. It is an appropriate way to reflect on the work and ask for new input. The content of the workshop of this project was too abstract to be easily evaluated. Terminology needs to be clearer and simpler to make participants feel comfortable and generate the desired data. The number and composition of participants was suitable to execute the workshop as a pilot. In order to make the workshop applicable for a broader public, the forms and formulations of questions need to be revised. Additionally, the workshop could be more active and interactive. Now participants mainly were filling in forms individually. The made results easier to interpret during analysis. A structured discussion would lead to additional valuable insights through mutual learning. More interaction increases the perceived engagement and the quality of results (Mulder et al., 2012).

4.1.3 Research Process

Especially the interviews and the workshop asked for long term planning. The interviews were an exciting way to get in touch with the field. I got to new places and spoke to interesting people I otherwise wouldn´t have met. I also participated in local events as the festive signing the covenant in Sommelsdijk, the first information session of households and the progress meeting with local stakeholders and project leaders. I was pleased by the way I was treated. People actually cared about my research, wanted to help and were interested in the results. That was really a great motivation.

The modelling approach had to start before finishing transcribing and coding all interviews. The iterations between coding and modelling might have caused bias as one might code in a way that supports existing assumptions that are already part of the model conceptualisation. A benefit is that the process made the conceptualisation and analysis of interviews more comprehensible. It also took away the biases as the research steps had to be closing for both methods.

The overlap of the different research steps made the modelling process difficult and unstructured. Also, because the CA does not explicitly address interactions it was hard to make the connection between the CA and the strength of ABM given the research question. A choice that was taken late in the process was to focus on households instead on all stakeholders. Operationalising capabilities and values for all stakeholders was even more difficult than just going through the process for households.

Installing and learning Python for the exploratory modelling approach was quite a challenge. Code and programming are not my strengths, but I was happy to improve my skills and proud that I actually succeeded in using, even though not mastering, the programmes. I was glad I was supported by my supervisors, Jan but also by Marc. I think it is a very important skill to at least understand how Python and the Workbench work as this is not something I have gotten in touch with earlier. In future I will face more situations where I have to get comfortable with tackling difficult tasks that are outside my comfort zone.

The organisation of the workshop was very short terms and during a period everyone was on holidays. However, the local parties really supported me in organising the workshop. The workshop was a success and will hopefully be followed by another bigger workshop at a later phase of the pilot.

In the end, all the research ingredients needed to be assembled. As the process was so capricious, it was challenging to make on coherent report of the notes of all intermediate results and trails with the simulation. However, after long and some painful hours a story started to grow. A story that is based on a research with great potential. In the future, this potential can be redeemed with the commitment of relevant stakeholders.

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Appendix

A. Conceptual Frame

TABLE 22: AREAS OF APPLICATION OF THE CAPABILITY APPROACH(ILSE OOSTERLAKEN, 2009)

Areas of application of the Capability Approach
general assessments of human development of countries,
assessing small-scale development projects
identifying the poor in developing countries
poverty and well-being assessment in advanced economies
deprivation of disabled people
assessing gender inequalities
debating policies
critiquing and assessing social norms, practices, and discourses
functionings and capabilities as concepts in non-normative research

TABLE 23: CENTRAL HUMAN CAPABILITIES (MARTHA, 2006)

central human capabilities
life
bodily health
bodily integrity
senses, imagination and thought
emotions
practical reason
affiliation
other species
play
control over one's environment

TABLE 24: LIST OF KEYWORDS FOR LITERATURE REVIEW

List of keyworks			
Values Sensitive Design	Values embedded in technology	Responsible Research and Innovation	Social Acceptability of Hydrogen
Capability Approach	Values in energy system transition	Value assessment	Public Acceptance of technology
Complex System Design	Value conflicts	Incommensurability	Barriers for energy transition

B. Interview Protocol

The structure of the interview protocols consists of two parts. The first part consists of some general questions exploring the role of a party within the project exploring interests and considerations when participating in the projects. The interviewees are asked to share their view on the feasibility (financial, technical and social) of the project to get a general view of the projects. Also, some general challenges are addressed as availability of subsidies, public support, technical feasibility and the lack of experience. They are asked to describe the process of the project so far, possible benefits and barriers and what is needed in future. Benefits and drawback of certain technical and institutional designs are identified, but also key stakeholders. This part of the interview is hardly comparable but leads to important insights for understanding the system as a whole and the roles that stakeholders and households play.

The second part of the interview protocol has is developed based on the literature review and helps operationalising the values. The questions are meant to identify capabilities and assess which capabilities might cause barriers or even be opportunities to increase acceptability. Capabilities that seem to be less important can be identified and removed from the list. The list with the values proposed to the interviewees can be found in Table 25. A pilot was done with the first interviewee to identify new issues and revise the interview guide. Questions were adjusted and another conceptual frame that was initially presented to the interviewees was removed because it was too abstract.

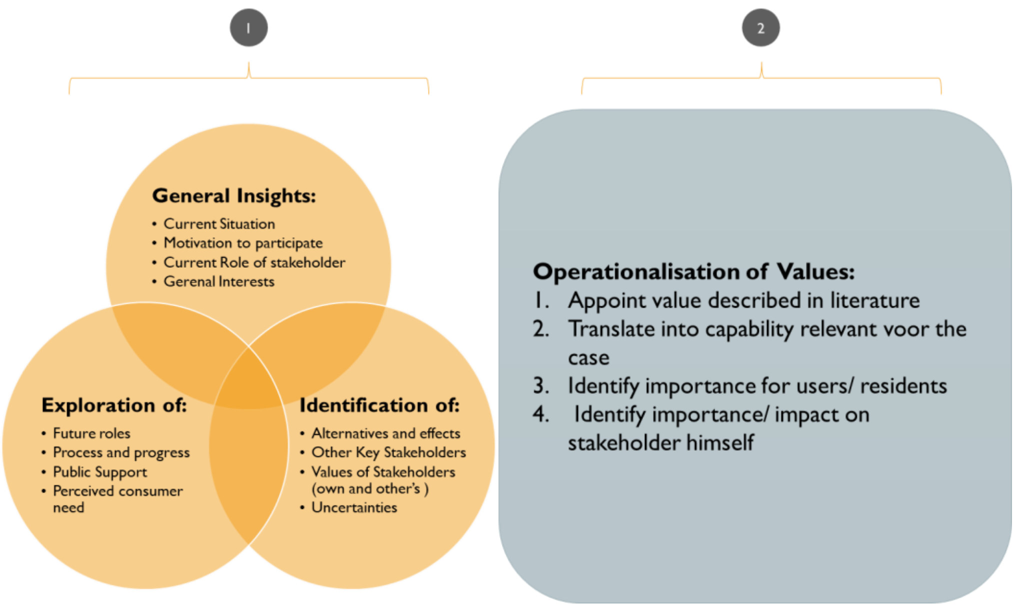


Figure 35: Structure of the interview protocol

The interview protocol gives insight into the general questions asked However, as many different participants of the covenant and other related parties were interviewed also some specific questions for each interviewee were prepared. An example can be found in Appendix 0.

1. What is the specific role of the party for the covenant? Why did the party decide to participate and what is the nature of the participation?
2. What knowledge is there already and what knowledge lacks?
3. What are technical alternatives to realise hydrogen in the distribution grid?
4. How does that effect households and users?
5. What are good solutions?
6. What are legal barriers and how can they be solved?
7. What are financial barriers and how can they be solved?

8. What should be the next steps?
9. In what way can play the values mentioned in Table 25 play a role for users and for other parties?

TABLE 25: VALUES PROPOSED TO THE INTERVIEWEES (LIGTVOET, VAN DE KAA, ET AL., 2015)

Value	Description
Accountability	The system allows for tracing the activities of individuals or institutions
Autonomy	The system allows for its users to make their own choices and choose their own goals
Calmness	The system promotes a peaceful and quiet state
Cooperation	The system allows for its users to work together with others
Correctness & Tractability	The system processes the right information and performs the right actions & the functioning of the system can be traced
Courtesy	The system promotes treating people with politeness and consideration
Democracy	The system promotes the input of stakeholders
Economic Development	The system is beneficial to the economic status/ finances of its users
Efficiency	The system is effective given the input
Environmental Sustainability	The system does not burden ecosystems, so that the needs of current generations does not future generation
Freedom from bias	The system does not promote a select group of users at the cost of others
Identity	The system allows its users to maintain their identity
Informed Consent	The system allows its users to voluntarily make choices, based on arguments
Legitimacy	The system is deployed on legal basis or broad support
Ownership	The system facilitates ownership of an object or of information an allows its owners to derive income from it
Participation	The system promotes active participation from its users
Privacy	The system allows users to determine which information about them is used and communicated
Reliability	The system fulfils its purpose without the need to control or maintain it
Safety and health	The system does not harm people
Trust	The system promotes trust in itself and its users
Universal Usability	The system can be easily used by all (foreseen) users
Welfare	The system promotes physical, psychological and material well-being

The interviews are mostly held in person at the office of the stakeholders. Two were held on the phone for practical reasons. The interviews took between half an hour and one and a half hours. Especially in the beginning some more time was needed to get better grip on technical characteristics of the systems and the interest of key stakeholders. The interviews were recorded by using a mobile phone and transcribed into word files.

The order of the interviews is from basically from broad to narrow which means that in the first interviews more attention was payed to the broader playing field and later on more attention the concrete situation in Stad aan 't Haringvliet. While two technical experts could give insights into the technological state of the art, but also technical uncertainties and financial challenges, two policy makers gave more insights into institutional opportunities and barriers, possible subsidies and legislation. Both groups of interviewees gave insights into the key stakeholders involved, general challenges of those kind of projects and public opinion in general terms. Four local parties gave insights into specific characteristics of the region, into roles of local actors, opinions so far and lessons learned about change in the past. All stakeholders were asked to give some insights into what they thought residents and users want from the system.

With most stakeholders it was easy to arouse interest and make an appointment. Some stakeholders were more difficult to get in touch with but in the end, this did not have effect on the research. During the interviews the stakeholders spoke in an open way willing to share information but also to receive new insights. There was much interest for social acceptability and obvious awareness for the need of public support. However, most evaluations seemed to base on technical, legal and financial aspects and acceptability of consumers was mostly expected to be very rational.

Example Protocol

The interviews were held in Dutch as all the parties involved are Dutch and it was more comfortable and easier to speak Dutch. Additional to the general questions these actor specific questions were asked.

- Waarom hebben de woningcorporaties het convenant getekend?
- Hoe is de verhouding huurwoningen van coöperaties en particuliere eigenaren in Stad aan ´t Haringvliet? Hoe onderscheidt zich Goeree Overflakkee van andere gemeentes in Nederland? Hoe kijkt de bevolking na het convenant?
- Welke veranderingen komen er op woning coöperaties af? Welke kosten zijn hieraan verbonden? Welke kosten zijn er voor andere partijen? Op welke termijn ontstaan deze kosten? Hoe worden kosten verdeeld?
- Wat moet er aan de gebouwen aangepast worden? Is er sprake van overlast? Op welke manier? Wat is het verschil ten opzichte van normale onderhoudswerkzaamheden? Wat verandert er voor bewoners? Welke veranderingen zijn aanvaardbaar? Welke rol speelt isolatie?
- Op welke manier worden bewoners betrokken? Wanneer en op welke manier worden bewoners geïnformeerd?
- Is de woningcorporatie wettelijk gebonden aan het akkoord van de bewoners? Zou er iets aan wet een regelgeving moeten veranderen om het project dadelijk te kunnen realiseren? Welke rol spelen vergunningen? Hoe woorden andere partijen (niet-gebruikers) beïnvloedt?
- Wat zijn belangrijker partners en waarom? Welke andere stakeholders zijn er en wat voor belang hebben deze? Op welke manier wordt er samen gewerkt? Wat zijn de eerste stappen die nu gezet moeten worden? Wat zal er in toekomst gebeuren?
- Wat vinden bewoners belangrijk op korte en op lange termijn? Hoe kan dit gewaarborgd worden?
- Wat is het verschil tussen Woongoed GO en andere woningcorporaties?
- Welke rol speelt een woningcorporatie nu voor de energietransitie en welke rol zouden woningcoöperaties kunnen spelen? Wie moet initiatief nemen?
- Is het mogelijk om met een installateur te spreken die regelmatig in contact komt met klanten/ in de huizen van klanten komt?

C. Coding Approach

A combination of listed and free coding was applied to analyse the interviews and sustain the choices made in the model.

TABLE 26: APPLICATION OF CODES

	Technical Expert 1	Technical Expert 2	Local Party 1	Policy Maker 1	Local Party 4	Local Party 3	Local Party 2	Technical Expert 2	Totals
affordability	10	3	4	2	5	2	2	1	29
All-electric	4	1	1	1	3	1	0	0	11
Attitude	0	0	0	0	0	0	3	0	3
Autonomy	2	0	2	3	1	1	0	0	9
Characteristics	1	0	0	0	2	3	4	1	11
Comfort	9	4	4	1	1	1	0	0	20
Cooking	2	1	1	2	2	1	1	1	11
End User Equipment	0	0	0	0	0	0	0	2	2
Enthusiasm	2	0	1	0	1	0	3	0	7
Equality	6	1	1	0	1	0	0	1	10
Green Hydrogen	1	3	0	0	1	1	0	1	7
Heating	6	1	1	0	3	1	1	1	14
Housing Situation	2	0	0	0	2	2	0	1	7
Importance of comfort	0	0	0	0	0	0	0	0	0
Improvement of Technology	0	2	0	0	0	0	0	1	3
Information	8	1	3	0	6	1	1	3	23
Insulation	1	0	4	0	2	1	0	0	8
Interaction	0	0	0	0	0	1	0	0	1
Mix	0	1	1	4	2	3	1	3	15
Need for renovation	6	1	2	1	1	1	0	1	13
Options	0	1	0	0	1	4	2	0	8
Privacy	2	0	0	0	0	0	1	0	3
Process Participation	0	0	3	2	1	0	1	1	8
Public Opinion	3	2	1	3	5	2	2	1	19
Safety	4	1	3	1	4	0	0	2	15
Scope	0	0	0	0	0	0	1	0	1
Security of supply	2	0	1	2	1	0	0	2	8
Strategy	6	2	4	1	1	0	3	1	18
Sustainability	3	2	2	1	3	0	2	0	13
Timing	4	0	0	0	0	0	1	0	5
Totals	84	27	39	24	49	26	29	24	302

Code Group	**Code**
Technical Choices	All-electric Cooking End User Equipment Green Hydrogen Heating Insulation Mix Need for renovation Options Safety Security of supply
Policies	Affordability Information Interaction Process Participation Strategy Timing
Functional Values	Affordability Safety Security of supply Sustainability
Social Values	Comfort Equality Privacy Process Participation Public Opinion Sustainability
Capabilities	Affordability Autonomy Comfort Cooking Heating Insulation Process Participation Safety Security of supply Sustainability Timing

Effect of Hydrogen Technology	Comfort Equality Need for renovation Privacy Process Participation Public Opinion Safety Security of supply Sustainability
Uncertainties	Affordability Attitude Enthusiasm Importance of comfort Information Interaction
Conversion Factors and Resources	Affordability Attitude End User Equipment Enthusiasm Housing Situation Importance of comfort Improvement of Technology Information Insulation Strategy

TABLE 27: CODE GROUPS AND CODES PER GROUP

D. Results Qualitative Data Analysis

Perspectives

Policy Perspective

The interviews with stakeholders that have a policy perspective give insights into the broader context of the study. This perspective helps to decide whether the options and capabilities identified by other interviewees fit into the broader context or face any legal or financial barriers. It seemed that the project as a whole yes cannot be realised due to legal barriers.

"Knowledge development, but also existing laws and regulations sometimes stand in the way of hydrogen. I think it is stated in the Gas Act that you can only transport natural gas but no hydrogen through the existing pipes." (Policy Maker 2)

Technical Perspective

When looking at alternatives the technical perspective is predominant as local stakeholders are often not well-informed about technical alternatives. Opinions and perspectives differ as for example about mixing hydrogen and natural gas. The local stakeholders have picked up some information that seems not have the same relevance for the technical experts. Another local party does not mention the challenges and drawbacks of an intermediate step.

*"What I understand, I am not an expert of the whole process though, what you make with electrolysis is pure hydrogen and actually that is too high quality to be burned." (*Local Party 3)

"*From the perspective of end user equipment, the easiest way to make one choice. The device is suitable for one or the other. From the technical point of view, it would be nicer not to want to embrace the entire range of gas and hydrogen, which in the future might be possible, but at the moment it is still too early." (*Technical Expert 2)

"But it will have to be done in steps and we will have to learn from it and once again have to remove the fear from the residents. Probably an intermediate step will be the necessary." (Local Party 4)

Local Perspective

While identifying the relevant or valuable capabilities the opinion of local parties is important as parties that are further away can only guess what plays locally. Technical experts know about end users and their capabilities but are mostly talking about costs and functional considerations while local parties try to empathize with residents.

"And a hydrogen flame, I do not know if you've ever seen him probably not because you cannot see them. So, I always think about cooking we simply have to do it on electricity." (Technical Expert 1)

"Wat de grootste belemmering is in het kader van verduurzaming is het van koken op gas af moeten." (Local Party 3)

"If you ask me I prefer that they [residents] switch to electricity. That is up to the residents themselves." (Local Party 1)

The analysis focusses on domestic use not on use of grid. Technical changes of the grid, legal issues are explored during interviews outside the scope of this analysis as this will not be element of the Agent-Based Model.

Values

Affordability

Residents need to be able to pay energy costs, rent, equipment to consume hydrogen, the net operator needs to be able to earn back investments and the corporation has to be able to justify investment costs. There is few information available about what the costs of the network, the costs for producing hydrogen and the costs for adjusting households are. However, high investments are required.

"Hydrogen requires quite substantial investments" (Policy Maker 1)

Nevertheless, energy must stay affordable.

"Security of supply at an acceptable price" (Policy Maker 2)

Affordability plays an important role for comparing alternatives as heat pumps and heat networks, also timing plays a role for investments. It seems to be more desirable to be able to influence the timing.

"Short-term changes have a lot of impact, changes that can be announced in the long term are less. It can be noiseless." (Technical Expert 2)

Benefits are mainly measured in terms of costs but also in sustainability.

*"They only have it [benefits] as hydrogen is cheaper [than current sources of energy] and [environmentally] friendlier. And then it comes out on the wallet again." (*Local Party)

Public Support

There must be some kind of consensus within the community that the solution proposed is a good solution. In some way the public opinion should be considered in the model. As there is *"no innovation without acceptance"* (Technical expert 1). However, there is a lack of strategy when it comes to creating acceptance. The parties are aware of the need for information but do not mention any concrete plans.

"Communication will be needed. It is the future but with good information I do not expect heavy problems" (Local Party 2)

Public opinion is related to trust. The local parties mention that residents especially trust experts,

"Someone who comes in [to install end user equipment] must have knowledge. And one must be able to communicate with the customer in a good way. Then they have faith." (Local Party 4)

There seems to be enthusiasm about sustainability on the island. Again, this enthusiasm is limited by the affordability.

"Because our island also distinguishes itself with sustainability. Many parties are very positive about it."; "I think it [enthusiasm] is mainly related to the cost" (Local Party 2)

Process Participation

Especially given the specific characteristics of the community of Stad aan 't Haringvliet the choice should not be taken without the residents. However, it is still unclear how participation should be shaped in order to comply with the value of the households. Process participation is hard to conceptualise. However, the effects of proving the community with information can and should be considered.

"I think it is very important for residents to involved. I also think it is good that the residents get their own group of representatives." (Local Party 4)

Comfort and welfare

Comfort according to the interviewees means minimizing change and the need for residents to be informed, having a warm house without doing something different. This is about the ease of use and should be considered as different options identified seem to have different effects, but comfort must be handled as important condition for acceptability.

"Comfort is important." (Local Party 1)

"Nothing should change in use and comfort compared to the recent system." (Policy Maker 1)

But, it seems quite difficult to increase the comfort compared to the current energy supply.

"Nothing is going to change about the product heat in terms of comfort related to hydrogen installations. If you get insulation, then you feel an improvement of comfort but just changing the energy source does not cause improvement of comfort." (Local Party 4)

Autonomy or choice

This value is mainly determined by financial resources of the residents. There is few information available about the costs and benefits. However, even though this value was hard to conceptualise during the interviews, it should play a role in the next step. Some examples of situations (capabilities) where autonomy plays a role are given but no evaluation is given how this is related to acceptability. The parties do not seem to have any ideas about this relation.

"I do not think that one can use hydrogen in the long term when other does not. I do not think it is an option. Everyone has to do it to make it profitable." (Local Party 4)

Not only profitability of the project but also the housing situation seems to matter when considering autonomy.

"I think that a tenant cannot when we are going towards supply of hydrogen. In case of renovation, you can have the same situation that one tenant refuses he is obliged to cooperate, otherwise the rest will be stagnated. That will also be the case here." (Local Party 3)

Fairness

Fairness or equality seems not to be an issue yet. However, effects and the importance of fairness remain unclear and it is assumed that there are few. Therefore, in the next step the individual differences might be researched in order to conclude whether this is a potential barrier in the future.

"I do not see that people are clearly deteriorating or moving forward. The result is warm water and the heating remains the same." (Local Party 4)

Again, money seems to be an important factor influencing this value as is stated by the technical experts.

"*I see that people with money can change [pay the transition], and people without will be lagging behind."; "Compensations for unfair distribution of costs may be necessary."* (Technical expert 1)

"The idea is that we choose the cheapest solution for each location. To what extent it is difficult for some people to pay, I find it very difficult to give an answer. Look, there will always be people who have trouble with that for whatever reason." (Technical expert 2)

Sustainability

The role of sustainability in the project is clear. However, it remains unclear how much sustainability matters especially in relation to other values. The next research step must explore this. However, the interviewees gave some ideas for basic assumptions.

Sustainability in most cases seems not to weigh out costs.

"There will be a few who will do it for the environment but on the long term you probably want to make progress [in saving energy costs]." (Local Party 4)

Local parties agree on that.

"When it comes to sustainability, they [residents] expect to rent a home with low energy costs" Local Party 1)

It can also be concluded that effects are less tangible that for example less comfort or lower costs.

"Zero-emission is the big environmental benefit, the reason why we do it [introducing hydrogen to households], but you do not notice that much in your home." (Policy Maker 1)

Safety & Security of supply

There is not much know about the safety and security of supply, but it is stated poorer performance then the recent system is not acceptable. Therefore, this value can be excluded as the recent system is accepted. Rather the information about and perception of safety play a role then safety itself.

"The system simply has to work always." (Local Party2)

Neither the local parties nor the technical experts have an exact idea of how to realise security of supply.

"If I have understood correctly, there is still a great deal of uncertainty about how the network should be set up and what needs to be changed in order to achieve the current security of supply of gas." (Technical Expert 2)

Safety is important to residents. And there seems to be the urge to take existing negative associations away by providing the right information and the right way.

"People also care about safety" (Local Party 1)

It is important that uncertainties [about hydrogen] are removed. That one does not think we will get bombs. These are things that must be discouraged." (Local Party 4)

Conversion Factors

Attitude

For the next research steps assumptions need to be made in what way people are conservative or progressive. While the CA disregards attitudes and choices the individuals in the end take but just assesses the number of functions people can chose from, this research takes a slightly more practical view and considers in what way the CA is suitable and what the added insights of taking attitude into account could be. It is clearly mentioned by several stakeholders.

"There will be a few who will do it for the environment but on the long term you probably want to make progress [in saving energy costs]." (Local Party 4)

The number of people willing to actively participate and taking a proactive role in thinking about alternatives is unknown. However, there is a village council and small group representing residents that is actively participating in thinking about the future of the project. It is unclear how attitudes are distributed and the role they play.

"It is a relatively small village of 1500 inhabitants with a close community." (Local Party 3)

"It is a bit inherent to island residents to be careful." (Local Party 3)

Information

Another factor that might influence the capability to realise desired functions is the capability to process information and detect options and choices. The information given to households it essential for being able to realise capabilities. However, it is only mentioned that many residents are not engaged in transitions and rather want it to be fixed than taking actions themselves. This indicate that the proactiveness of residents differs, but it is unclear in what way. There is a lack of information and understanding of technical alternatives and the individual effects amongst residents and households.

"I have no idea what the perception of hydrogen is. Frankly, I think that the average resident in the Netherlands does not really know much about hydrogen and only knows the idea of the burning Hindenburg." (Technical Expert 2)

Money

Stakeholders stated that some residents are concerned about costs and financial risks, some are more concerned about the environmental impact and sustainability of the island. However, security of supply must be given.

"Security of supply at an acceptable price." (Policymaker 2)

Financing and costs seem to be important uncertainties of the project as there is neither a calculation nor any experience yet. There are differences in the capabilities of residents to pay for renovation and new equipment. It is assumed that the available income of households determines the willingness to accept the project.

"Our estimate is that a part of the population could do it [renovation] but we have a large part of the population living in the older homes that simply do not have the money to adjust housing." (Local Party 2)

There is almost nothing known about investments in the grid or the households, about the costs for equipment and the costs of green hydrogen. No statistics are available about the exact state of the houses. However, the interviewees indicated that there are many buildings that are hard and expensive to insulate.

"Which materials for pipes are suitable or not, what needs to be adjusted and very important, which price card is placed in that, there is still uncertainty." (Technical experts 1)

Housing Situation and Insulation

"There are two types of residents. Private homeowners and the tenant of the housing association" (Local Party 4)

It is assumed that some of the residents owning a house are able to pay for the renovation needed but that there are also households that have problems with spontaneous or high investments. The housing situation is determining for the capabilities as tenants have less freedom of choice. The housing corporation pays the investments for the end user equipment. The owners have to pay the investments by themselves, which means they might encounter a barrier.

*"I think that a tenant cannot refuse if it is said we are going from then and then supply hydrogen." (*Local Party 3)

"I think that individual homeowners can choose, but if you live in a block where you rent from a corporation, you will collectively decide" (Technical Expert 1)

"And if the CV has to be replaced, that is a major investment" (Local Party 2)

The insulation of a high number of houses is poor because in Stad there is "*relatively old property."* (Local expert 2).

Alternatives

All-electric

Four out of five parties mention all-electric as likely alterative for gas. However, it is also stated that this is not an option for all households as the house has to be sufficiently insulated to be able to heat with a heat pump. As insulation of old buildings is very costly, only a limited number of households (very rich households or households living in already well-insulated houses).

"Heat-pumps heat with low temperature. Then it is important to insulate the house. These are quite high costs." (Technical Expert 4).

What matters for these alternatives are the existing insulation, the housing situation and the budget available for insulation.

"If there were only houses owned by housing corporations, you would come a long way in my opinion. I believe that 60% is a private owner, and then you have to deal with a lot of parties." (Technical Experts 2)

The choice of tenants is very limited as the corporation takes decisions on in what way to renovate buildings. However, it is an advantage for the whole systems corporations are one central party that owns 40% of the buildings. It is especially hard to involve private house owners as there are differences in resources available as investments are payed by the house owners. Tenants have the advantage that they do not have to pay one big amount all at once but that the corporation bares the investment. Nevertheless, rents increase.

100% Hydrogen or a mix of methane and H2

Opinions on impact of the mix of natural gas differ. Some parties do not consider it as a solution and other do not see it as option as there does not exist equipment yet that is suitable for mixes and pure hydrogen.

"From the end user equipment point view it is easiest to make one choice. The device is suitable for one or the other." (Technical Expert 2).

From the societal point of view a gradual change must be considered.

"It will have to be done in steps. We will have to learn from it. We have to remove the fear from the residents. Probably it will be the necessary intermediate step." (Local party 4)

This alternative has an effect on the CO2 emitted, the investment costs for households and the number of times renovation and adaptation of equipment is needed. On the other hand, change might have a positive effect as better timing would be possible.

Green Hydrogen

Even though it is unclear on what term green hydrogen can locally be produced it is assumed that it will possible. Plans are made to build a conversion station or a wind turbine that directly produces H2. The exact source is out of scope. Not only the prediction but also the costs of green hydrogen are uncertain. At this moment natural gas is profitable. Hydrogen produced from natural gas is still cheaper than green hydrogen.

"Most hydrogen is currently from natural gas. Methane reforming. It is also the cheapest way at the moment." (Technical Expert 1)

"Green hydrogen is generally more expensive than grey hydrogen." (Policy Maker 1)

An alternative for green hydrogen in Stad would be retrieving grey or blue hydrogen from the industrial area of Rotterdam. This might be considered as short-term solution. It proves the availability of using hydrogen in households when the production of green hydrogen is not ready yet. Another reason to choose for this option would be a lack of subsidy for green hydrogen. There are clear doubts about this option.

"When you put the CO_2 under the ground you call it blue hydrogen because it does have a low CO_2 footprint. But the question is, is that what we want?" (Policy Maker 1)

Heat network

The opinions about the heat network were divided. Most interviewees agreed that different locations ask for different solutions.

"In places where it is wise to apply hydrogen, do it. In places where it is not sensible, don´t do it." (Technical Expert1)

"The idea is that you choose the cheapest solution for each location.", (Technical Expert 2).

As the costs for the use of hydrogen are unknown it is hard to judge which of the alternatives is cheapest under which circumstances. The heat network should not be considered in the next research step. From the interviews it seemed that there are few opportunities to retrieve heat. There is more interest in gaining experience in bringing hydrogen into individual households.

"There are no industries that produce heat, so surface water would be the only alternative for a heat grid" (Local Party 3).

It also seemed that parties were convinced that a heat network caused higher costs due to complicated renovations and a completely new infrastructure. The purpose of the project is reusing the existing distribution grid.

*"We also do not want a heat network. This means large pipes and return pipes and very high losses. That is far too expensive." (*Technical Expert1).

"No heat grid is not talked about in this case" (Local Party 2)

Cooking

A decision whether cooking on hydrogen should be possible must be taken. There are examples where households cook in hydrogen as in Leeds (Leeds City Gate, 2016).

However, local parties indicate that it might be more desirable to just heat with hydrogen. Fear seems to play a role here. On the other hand, not being able to cook in gas is also identified as a barrier for change. One interviewee suggests leaving that decisions to households themselves.

"A big barrier of sustainable transition is that people cannot cook on gas anymore" (Local Party 3)

*"If you ask me I prefer that they switch to electricity. That is up to the residents themselves." (*Local Party 2)

"It seems to me more important that one has fear of hydrogen. When it is well explained a closed boiler for heating is causing less anxiety than a hydrogen mixture for cooking. I think that is an even higher barrier." (Local Party 4)

E. System Elements

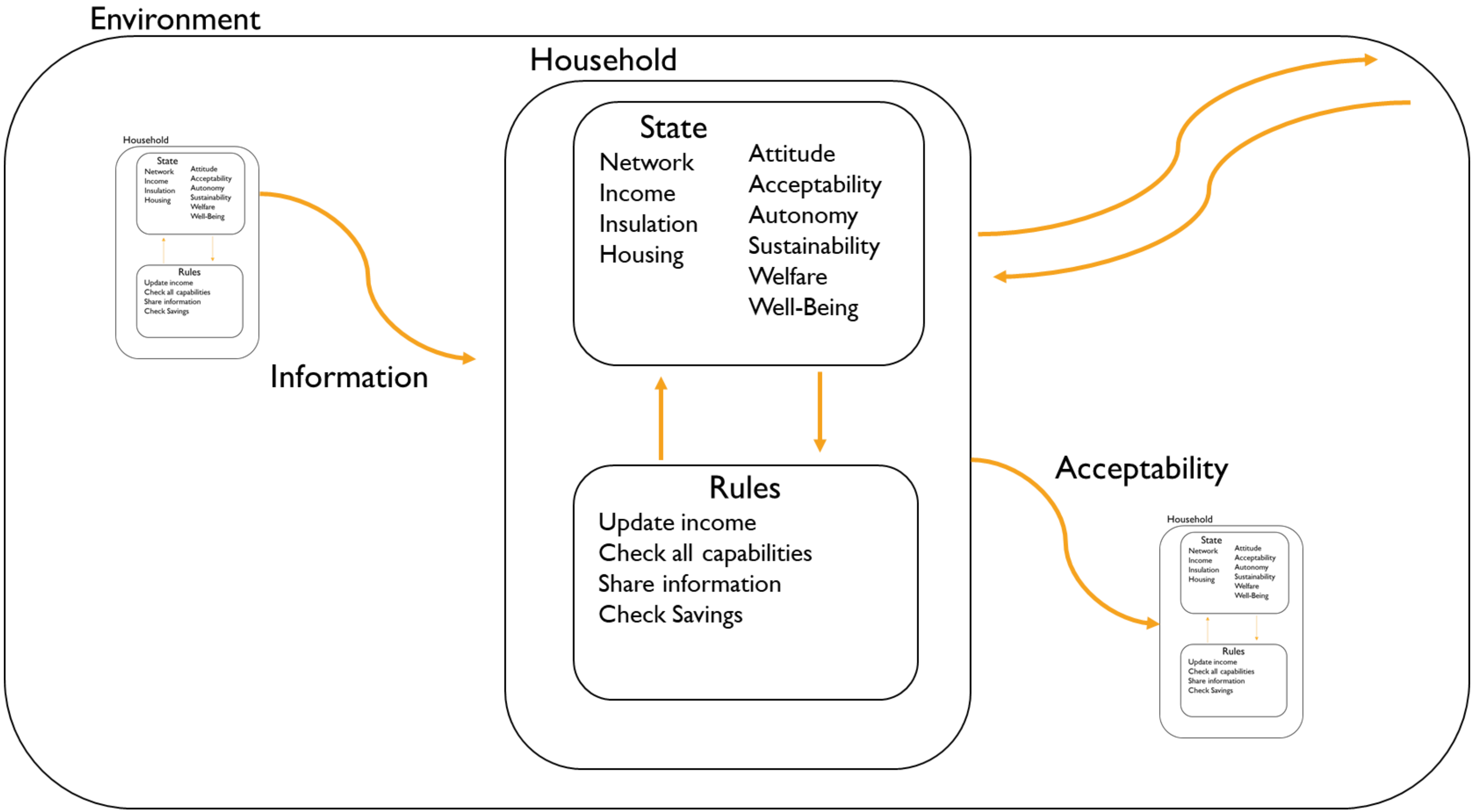


FIGURE 36: VISUALISATION OF CONCEPTUAL MODEL FROM AN AGENT PERSPECTIVE

F. Data

TABLE 28: FORMALISATION AND IMPLEMENTATION OF PARAMETERS

Model Parameter	Definition & Relevance	Data, Rule & Formula	Data source
Autonomy	"The system allows for its users to make their own choices and choose their own goals" Autonomy is not equally distributed amongst residents. Assessing autonomy gives insights into the robustness of a system design.	Autonomy is determined by two different capabilities. The first is choosing to go for an all-electric solution and the second is preparing the house for the introduction of hydrogen (buying new stoves and pans e.g.). **All-electric and Insulation** Tenants have no choice. The autonomy decreases by 1. Owners can only choose if the house is well-insulated (label A&B) and the income is above 36 or the house has already been improved in earlier runs. The autonomy increases by 1. **Equipment** As residents like choices the autonomy increase when the equipment reaches a certain improvement and the household has an income higher than a certain threshold. Autonomy increases by 1. Otherwise it decreases by 1. income <= 15 and equipment >= 11 income <= 25 and equipment >= 9 income <= 36 and equipment >= 7 income > 36 and equipment >= 5	(Ligtvoet, van de Kaa, et al., 2015) & Interviews
Sustainability	"The system does not burden ecosystems, so that the needs of current generations do not affect future generation" Sustainability is strictly seen not a capability according to the CA but rather a functioning as the infrastructure does not allow individual choices for the gas	Sustainability is determined by whether the source of the hydrogen is green or at least natural gas is mixed with hydrogen under consideration of the assigned attitude. **Attitude** Sustainability increases by 1 time the factor influenced by the attitude (between 0.5 and 1.5). Positive attitude leads to increased values of sustainability, negative decrease sustainability.	(Ligtvoet, van de Kaa, et al., 2015)

	transported. However, it is assumed that it is not interesting for residents to be unsustainable.	**Mix** The sustainability is also determined by whether the hydrogen is mixed with natural gas. The assigned sustainability of an households is halved when mixing.	
Welfare	"The system promotes physical, psychological and material well-being" Welfare is determined by the options of residents to choose to change behaviour (electrical cooking) or chose not to change behaviour (cooking on gas). Furthermore, the times owners need to come into action to replace equipment matters. As long as there is no equipment available that is able to handle a variety of mixtures residents are (probably) forced to make two steps.	Welfare is influenced by mixing natural gas and hydrogen. There is not yet equipment available that can handle mixes and pure hydrogen, so welfare decreases because two times equipment neds to be replaced. The comfort of gradual change is neglected. Welfare is also decreased when the stoves needs to be replaced and the projects permits juts heating with H2. **Mix** Welfare is decreased by 0.5. **Cooking** Welfare is decreased by 1 time a factor determined by attitude (between 0.5 and when no cooking on H2 is possible and stoves need to be replaced. Welfare is increased by 1 time a factor based on attitude when cooking is possible as the freedom to choose increases.	(Ligtvoet, van de Kaa, et al., 2015)
Acceptability	"The system allows its users to voluntarily make choices, based on arguments" This represents the capability to anticipate to a vision that is broadly shared in a community. So not only own interests are considered but it is also considered whether the solution creates enough capabilities for others.	Effect of social interactions based on spreading information. **Share of acceptability** Each timestep the values are cleared. There is no cumulation. However, before clearing the values residents adapt to the acceptability they find around them. This can be interpreted as operationalisation of trust and democracy. **Share of enthusiasm / scepticism** The availability of positive or sceptic information determines whether any solution is considered acceptable. This function represents participation.	(Barr & Gilg, 2016; de Vries, 2016; Ligtvoet, van de Kaa, et al., 2015; Morrison & Lodwick, 1981; Stephenson et al., 2010) & Interviews

<table>
<tr><td>Well-Being</td><td>“effective opportunities to undertake the actions and activities that they want to engage in, and be whom they want to be”

Well-being forms one global indicator for the performance of the system. Well-being is not cumulative.</td><td>Well-Being is the sum of all capabilities.
Well-Being = Autonomy + Sustainability + Welfare + Acceptability</td><td>(Robeyns, 2003 p.3)</td></tr>
<tr><td>Individual Comparison</td><td>“The system does not promote a select group of users at the cost of others”
Fairness is one of the values indicated in literature that has not directly been introduced to the model but can be assessed in this alternative way.</td><td>As all the other indicators give insights into overall performance of the system this indicator considers differences between individuals and therefore equality.</td><td>(Ligtvoet, van de Kaa, et al., 2015)</td></tr>
<tr><td>Position within social network (clustering)</td><td>Close to agents with the same income, depends in variable radius</td><td>Static</td><td>(Barr & Gilg, 2016; Kelman, 2017; Stephenson et al., 2010)</td></tr>
<tr><td>Income</td><td>Average spendable income of household in1 000 euros per year</td><td>Income changes each step of time by a random number between 0 and the trend defined during the run. The starting values are
<table>
<tr><td>House owners</td><td>9 %</td><td>12,7</td></tr>
<tr><td></td><td>20,1 %</td><td>24,3</td></tr>
<tr><td></td><td>32,2 %</td><td>36,2</td></tr>
<tr><td></td><td>38,6 %</td><td>68,2</td></tr>
<tr><td>Tenants</td><td>46,6 %</td><td>12,9</td></tr>
<tr><td></td><td>31,6 %</td><td>23,4</td></tr>
<tr><td></td><td>15,2 %</td><td>35</td></tr>
<tr><td></td><td>6,6 %</td><td>60,2</td></tr>
</table></td><td>CBS</td></tr>
<tr><td>Attitude</td><td>Conservative or progressive</td><td>Attitude does not change over time. The values applied are:</td><td>(Friege et al., 2016)</td></tr>
</table>

<table>
<tr><td></td><td></td><td>
<table>
<tr><td></td><td>Established Conservatives</td><td>Established Liberals</td><td>Reflectives</td></tr>
<tr><td>Age</td><td>50-65</td><td>50-65</td><td>30-65</td></tr>
<tr><td>Income per month</td><td>>3000</td><td>>3000</td><td>>3000</td></tr>
<tr><td>Attitude towards insulation</td><td>-0.25</td><td>+0.5</td><td>+0.25</td></tr>
<tr><td></td><td>Conventionals</td><td>Adaptive Mainstream</td><td>Hedoninsts</td></tr>
<tr><td>Age</td><td>50-65</td><td>30-49</td><td><29-65</td></tr>
<tr><td>Income per month</td><td>2000-3000</td><td>2000-3000</td><td>1000 - >3000</td></tr>
<tr><td>Attitude towards insulation</td><td>+0.25</td><td>+0.25</td><td>+0.25</td></tr>
<tr><td></td><td>Traditional Workers</td><td>Domestically Centred</td><td>Entertainment Seekers</td></tr>
<tr><td>Age</td><td>>65</td><td><29</td><td><29</td></tr>
<tr><td>Income per month</td><td>1000-2000</td><td>1000-2000</td><td>1000-2000</td></tr>
<tr><td>Attitude towards insulation</td><td>+0.25</td><td>-0.25</td><td>-0.5</td></tr>
</table>
</td><td></td></tr>
<tr><td>Housing situation</td><td>Tenant or owner</td><td>60 % Owners
40 % Tenants</td><td>Interview local party 2</td></tr>
<tr><td>Energy label of home</td><td>3 levels. A&B, C&D or E & lower
Static, only insulation might change</td><td>10% good insulation (A&), 50% reasonable insulation (C&D) and 40% bad insulation (E & lower)</td><td>CBS</td></tr>
<tr><td>Development of income</td><td>The income of residents determines whether residents can realise capabilities (all-electric alternate, buy equipment to anticipate to hydrogen in network).</td><td>It seems that the Netherlands is still recovering, and incomes are increasing, however making concrete assumptions for Stad is difficult.

Determined by the trend of income fixed throughout time.</td><td>Centraal Planbureau</td></tr>
<tr><td>Improvement of technology</td><td>Technology improves in different ways, most importantly the price decreases which throughout time enables new capabilities for residents, secondly the choice</td><td>A comparable development as for solar panels and wind turbines is expected. The bigger the scope and the more experience the lower the costs for technology.</td><td>(ECN, 2017)</td></tr>
</table>

	increases which has a positive impact on the autonomy of residents, finally the efficiency and therefore the sustainability increases.	The equipment improves every timestep by the factor ‘improvement’ which is also fixed through time	
GreenH2	Hydrogen from any green recourse	Increases sustainability Sustainability +1	Interviews
Grey or Blue H2	Hydrogen from any source that is not sustainable electricity	Decreases sustainability Sustainability -1	Interviews
Starting with mixing H2 and Natural Gas	Assumed that this causes stepwise transition from gas to pure hydrogen.	Two transition steps are required which influences welfare in a negative way. Welfare / 2 & Sustainability /2	Interviews
Just heating	To minimize the renovation of pipes in the house just heating might be an option.	Just heating means that people with gas stove have to go for an electric stove. This decreases welfare. Welfare -1	Interviews
Heating and cooking on H2	Requires no new habitual changes	Increases welfare. Welfare +1	Interviews
Importance of costs	Assumed to be higher than sustainability	0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.	Model Output Verification
Importance of sustainability		0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.	Model Output Verification
Importance of information		0.1-3 Where 0.1 indicates that it is 3 times less important and 3 that it is 3 times more important than others.	Model Output Verification
Role of attitude		Is either neglected or considered.	Model Output Verification
Number of people that spread good or bad news		0-80	Model Output Verification
Radius		Between 1 and 6	Model Output Verification

Capability to insulate	Opportunity to increase welfare by insulation when price has improved sufficiently for the income available	Checks whether insulation is possible based on budget and costs for renovation, estimation that insulations becomes cheaper throughout time. Households with lower energy labels need higher incomes to insulate. The income needed decreases conform the improvement of technology throughout time. Insulation is equal to 1 when For energy label 1 the income > lowest income required For energy label 2 income > middle threshold of income For energy label 3 income > highest income required. Otherwise insulation equal to 0 which means no increase in comfort	Interviews

G. Use of the model

This sections describes how to use the model and what the model does when running it. The section gives an explanation of the interface and the different functions introduced but also identifies some shortcomings and suggestions to improve the model.

Set-up

The set-up button and function create residents and assigns characteristics as for example whether they are tenants or owners, defines incomes, attitudes, position within the social cluster and identifies whether there are residents that are enthusiast or sceptic. Using the set-up button also resets al parameters to their starting values. Furthermore, the shape of the agents and the colours on the interface are defined.

Go

When pressing go stepwise some functions are called. The order is important for the results. The code and elaboration of calculations are represented in

TABLE 29: MAIN FUNCTIONS OF THE MODEL

Name function	Action
Share acceptability	Each timestep the values are cleared. There is no cumulation. However, before clearing the values residents adapt to the acceptability they find around them. This is the operationalisation of trust and democracy.
Share information	The availability of positive or sceptic information determines whether any solution is considered acceptable. This function represents participation.
Update variable characteristics and global variables	This is where residents get to know their new income and where trends cause new values of external factors (improvement of technology).
Checks whether saving is possible by insulation	Insulation becomes cheaper each step. It is checked whether the insulation is cheap enough to insulate a house with a certain label and income.
Evaluate autonomy	Checking whether the combination of characteristics (income) and other factors (price) allow the resident to buy ne needed equipment (eq. electric stove, new boiler) and whether the resident can choose to go for all-electric (owner, income and insulation of the house). This function represents autonomy, freedom from bias and fairness.
Evaluate sustainability	By checking whether the hydrogen is green or at least mixed. This indicates whether people have the choice to reduce their CO_2 emission.
Evaluate welfare	Assess behavioural change needed (cooking possible) and whether this is iterative (mix) or not (100%H2). This functions covers economic and behavioural welfare.
Calculate well-being	Sum of autonomy, sustainability, acceptability and welfare
Insulation	Opportunity to increase welfare by insulation when price has improved sufficiently for the income available

Interface

This section explains the interface and how to run the model and make use of the different options NetLogo offers. Figure 37 shows the interface and indicates the different elements. The interface is important for the next step of the research, tracking agent behaviour for verification of the model implementation.

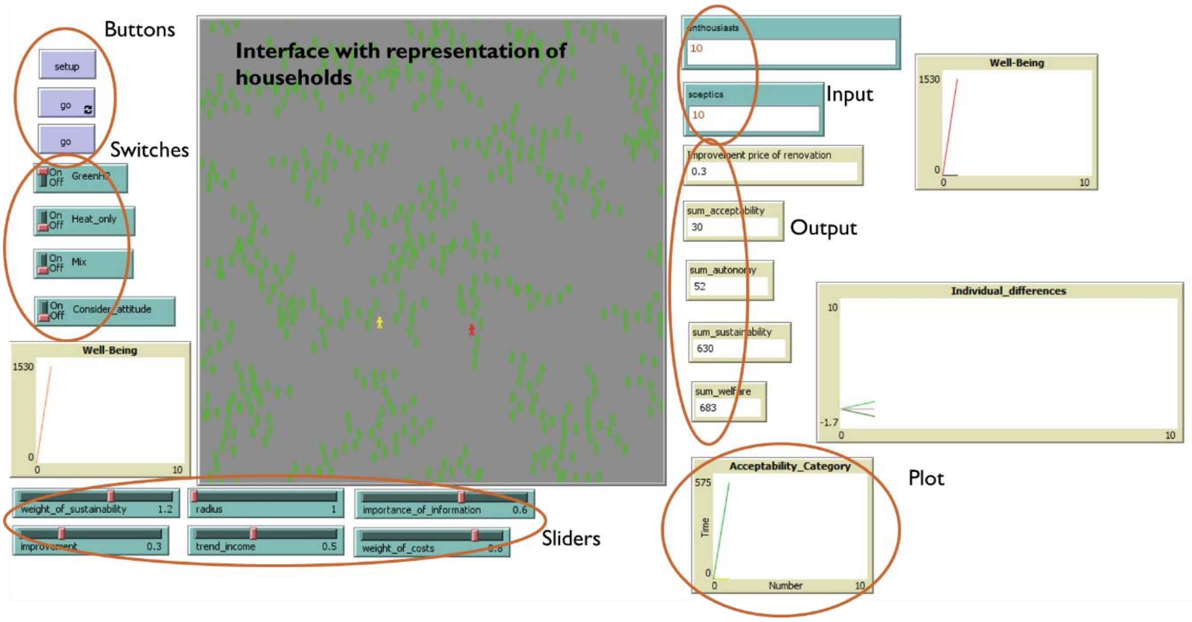


FIGURE 37: INTERFACE OF THE NETLOGO MODEL

Interface

The interface shows the residents where each person represents a household. To visualize the outcomes three colours have been chosen. Red indicates that the so

Buttons

The buttons can be used to call the function described in the section above (set-up and go). The first go button calls a continuous function that runs go until it is manually stopped. The second button runs go just once.

Switches

The switches are used to turn on and of different known (technical) design choices. The choices influence the evaluation of capabilities executed by the go-function.

- GreenH2 on means that the H2 is produced in a sustainable way, off means that CO2 is emitted for producing H2.
- Mix on means that there is not 100% H2 in the grid but that it is mixed with natural gas and therefore CO2 is emitted
- Heat only stand for just heating with H2 and changing to electrical cooking while the other option would be also cooking on gas)

The last switch represents an uncertainty. It determines the importance of individual differences between agents, thus attitudes. Depending on the results it indicates whether the municipality need to find out more specifically how attitudes differ and what attitudes are in the concrete situation.

Sliders

The sliders also indicate uncertain factors. Two factors are external factors and unknown because we do not know the future (improvement and trend income). The other factors are internal uncertainties.

- Radius: Indicates the reach in which acceptability is shared
- Importance of sustainability: Is the factor that indicates the importance of sustainability for an individual
- Importance of costs: Is the factors that indicate the importance of costs for an individual

The interviews and desk research have not given enough insights to determine the values. Therefore, the model offers the possibility to explore during the next research step what the effects are and under which circumstances which design performance well. The goal is to identify a design that is not sensitive to this internal uncertainties. When it seems that one of uncertainties plays an important role, this can indicate that the municipality should put effort in further researching this factor.

Input

The input represents values that can be filled in manually. In this case the number of enthusiast and sceptic residents that are part of the social network . It gives a possibility for the municipality to interact with the network from within the network by providing the right people with the right information.

Plots

The plots show different outcomes the model provides. The plots show how certain results develop during time.

- Well-being is the overall well-being calculated by summing up all capabilities
- Individual Differences shows the differences between the agents with the highest and lowest value of the capabilities
- Acceptability Category shows the number of green, yellow and red agents and how they change over time

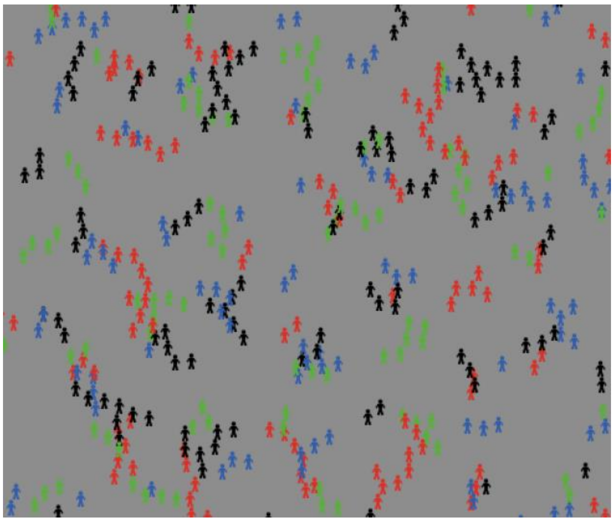
Monitors

Monitors give output values of the current state of time. They help to verify the model and explain agent behaviour.

H. Agent Behaviour

The model is supposed to show a how agents cluster. This is visualised. A visual tool to see whether the set up actually cerates the pattern it is supposed to is letting tenants be black and house owners blue. To check whether this is true the residents can be inspected. The interface of the NetLogo model clearing shows that some kind of clustering takes place. As owners often have higher incomes that tenants it can also be seen that clusters of tenants and clusters of owners form next to each other. The cluster is further evaluated by checking the actions of individual agents.

Figure 39 shows the distribution of attitudes across the network. The red households have a negative attitude, while the yellow agents have a positive attitude. As defined earlier negative means conservative and positive means progressive. As the agents are randomly spread and clustered when pushing set up NetLogo does not allow show whether the relations of income and attitude are correctly implemented,



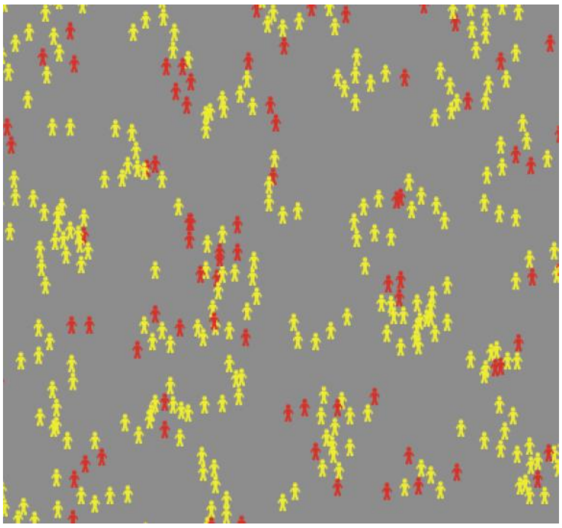


FIGURE 38: CLUSTERING OF INCOMES (LOWEST: BLUE, GREEN, RED, BLACK IS HIGHEST)

FIGURE 39: DISTRIBUTION OF ATTITUDE (RED BELOW 0, YELLOW GREATER THAN 0)

I. Single Agent Testing

The residents have some characteristics called turtles-own. In order to check an agents behaviour these individual values can be traced for a single agents. Some checks are executed to confirm that the concepts are implemented correctly and that there are no bugs. Initial settings but also the first steps in time (ticks) are traced.

- ✓ Check whether owners correctly distinguished between owners and tenants

When doing the set-up each agents gets a number that identifies the individual agents. A colour is assigned. 105 stands for blue. The right colour is assigned as agent 35 is an owner.

- ✓ Check whether energy label and income are correctly assigned

The energy label is assigned by checking the category. The lowest 10% get the best energy label. As the category of this resident is 85, energy label 3 is assigned, correctly as programmed. The income is 24 as all owners with who number between 28 and 92 have an income of 24. Finally, all other factors do not have a value, yet which is also correct. Analysing the set-up of agent 35 several times shows that the incomes always stays the same but that the category and therefore the energy label can variate. Resident 35 is always an owner.

- ✓ Check whether neighbours are found

Resident 35 has identified 52 as closest neighbour and knows 52 pf the other households.

- ✓ Check evaluation of own well-being

When pushing “go” *once* the characteristics of the agents change. The colour changes, as a threshold of well-being has been introduced that visualises wither a solution might be acceptable or not. This threshold is 0 for the colour red. As this agents have an individual well-being calculated as the sum of all capabilities (0.5 + 0.5 -1,5 + 0) of -0.5 this is correct. The first characters until income are stable. There agent does not seem to be assigned enthusiast neither sceptic.

- ✓ Check whether key performance indicator is correctly assigned

Sustainability is 0.5 as the alternative offers mixing green H2 with natural gas. The acceptability is 0 as the other agents around seem also not to spread positive nor negative information. The possibility to insulate is given and equal to 0.

- ✓ Check parameters for several ticks

Pushing “go” the second time shows how the income increases as the trend of income is positive. Following the agent throughout time shows that some parameters change over time but that others stay the same (welfare and sustainability).

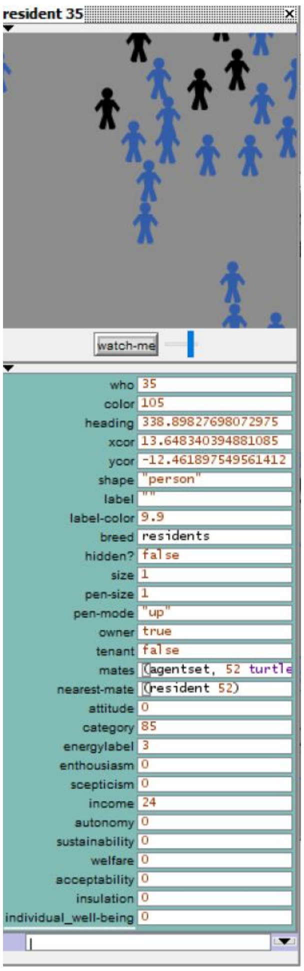


FIGURE 40: TRACING A SINGLE AGENT

J. Model Output Verification

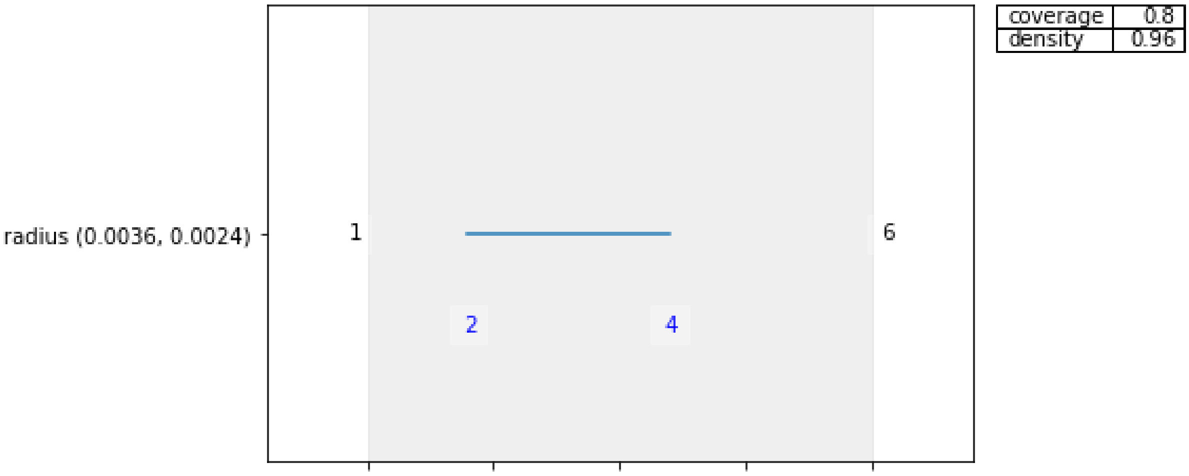


FIGURE 41: EFFECTIVE RADIUS FOR HIGH LEVELS OF WELL-BEING

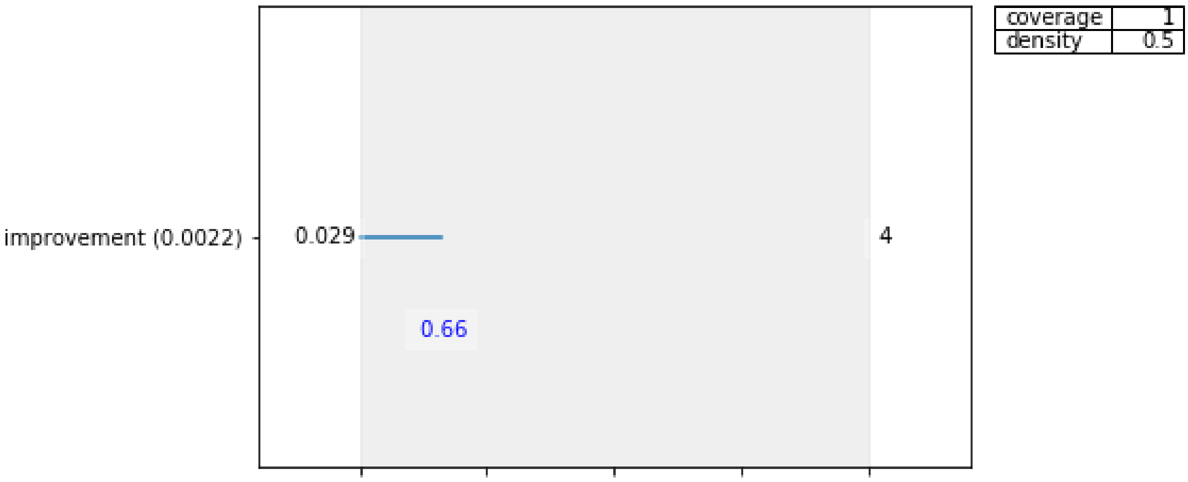


FIGURE 42: ANALYSIS OF OUTLIERS

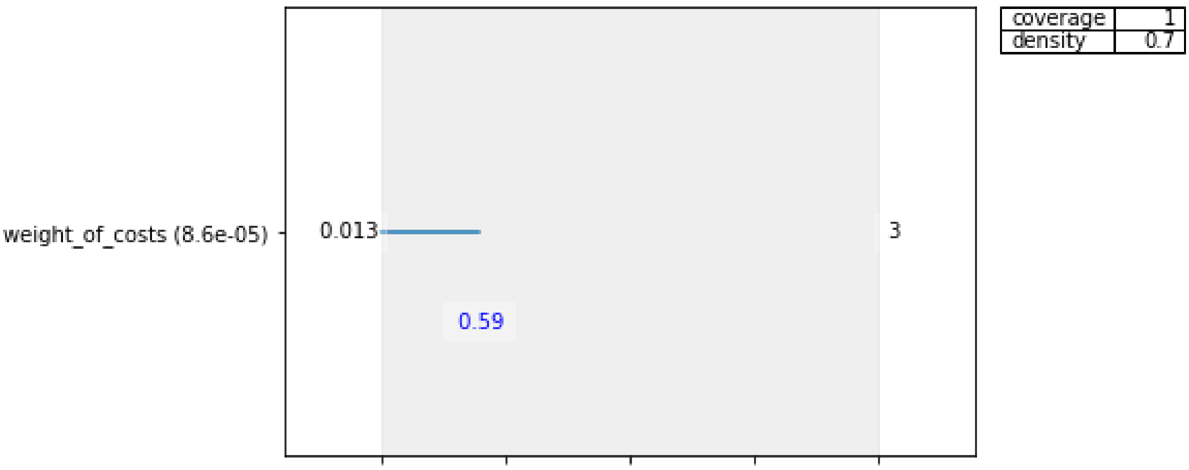


FIGURE 43: LOW LEVELS OF WELL-BEING WHEN VARYING IMPORTANCE OF COSTS

K. Identification of design combinations

All possible combinations of technical design choices are explored (Figure 44). The graph does not yet indicate which combinations in general cause high levels of well-being and which combination perform poorly. A PRIM analysis is executed to identify subspaces with high levels of well-being (Figure 45).

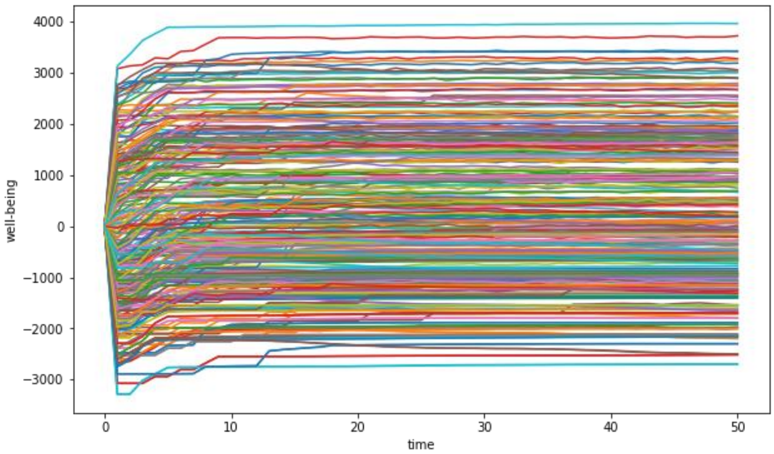


Figure 45

FIGURE 44: WELL-BEING UNDER MULTIPLE UNCERTAINTIES

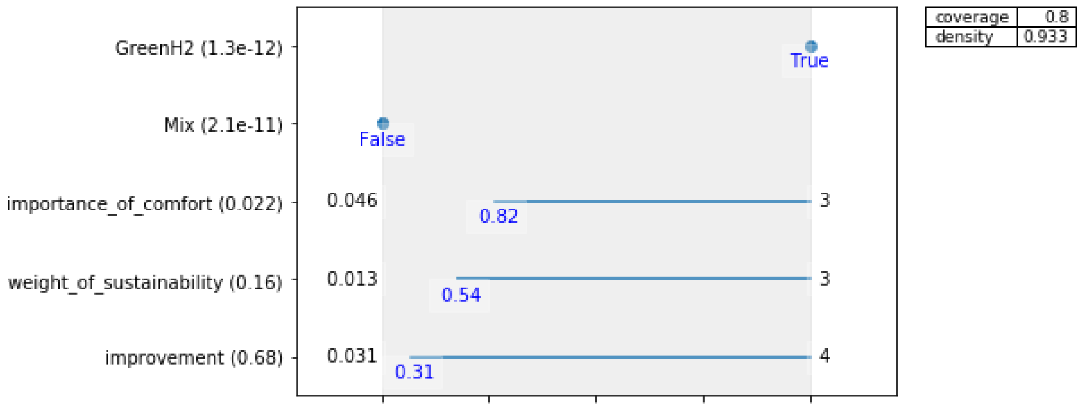


FIGURE 45: PRIM ANALYSIS OF TECHNICAL DESIGN CHOICES

Besides the base case the two scenarios are choses that are expected to that perform in very different ways. This allows for a broad exploration. Green hydrogen and pure hydrogen are according to the analysis a 'good' combination of technical design choices. However, more detailed results and interpretations are needed to be able to compare the scenarios. This is just a first sketch. Table 30 gives an overview of the design chosen to be analysed based on the results from Figure 45.

TABLE 30: OVERVIEW OF DESIGN VARIATIONS

Scenario	Configuration
Electric Cooking	Green hydrogen, Electric Cooking, Pure Hydrogen
Cooking on green hydrogen	Green Hydrogen, Cooking on H2, Pure Hydrogen
Mixing grey hydrogen	Grey hydrogen, Electric Cooking, Mixing

L. Experimental Set-up

Several tests are executed to argue the choice for the experimental set-up. The goal described in the chapter is leading.

Run Length

A run length of 50 ticks is sufficient to come to relevant conclusions. Most scenarios have a stable level of well-being after 25 ticks.

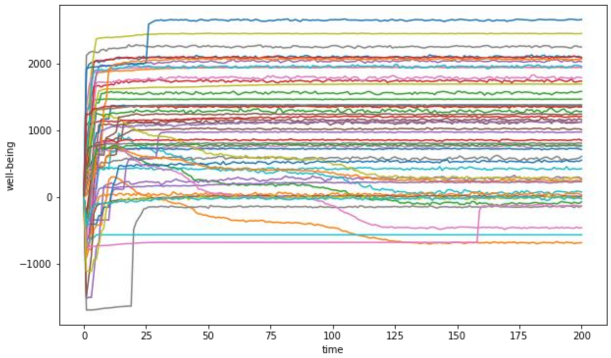


FIGURE 46: RUN LENGTH OF 200

Number of replications

The time needed to execute 3 experiments with 500 is very long. Too be able to execute sufficient experiments to come to reliable and clear outcomes the number of replications should be lower than 500. There is stochastics uncertainty due to:

- Random choosing agents,
- Trend of income uncertain and
- Position is uncertain.

Choosing the right number of replications mitigates for drawing potentially wrong conclusions based on random differences in data. 10 and 100 experiments with a dummy parameter are compared. The graphs comparing single runs, with dummy variable are presented by Figure 47. There are small differences, but 10 replications seem to be good enough for the purpose of the experimentation in this research.

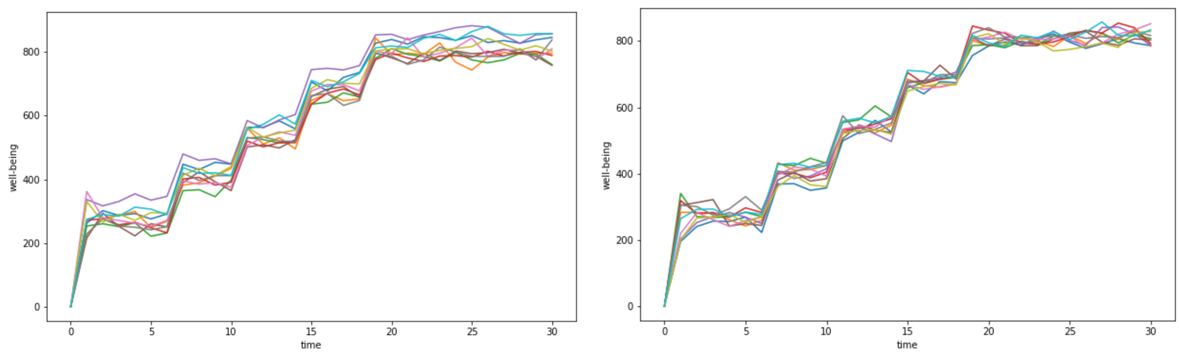


FIGURE 47: 10 EXPERIMENTS WITH DUMMY VARIABLE 100 AND 10 REPLICATIONS

The processing time to do 10 replications per scenario is acceptable and provides for being able to run enough experiments in an appropriate timeframe.

Number of experiments

A number of 200 scenario is sufficient to come to the necessary insights as 1200 experiments do not show any interesting outliers or a completely different pattern.

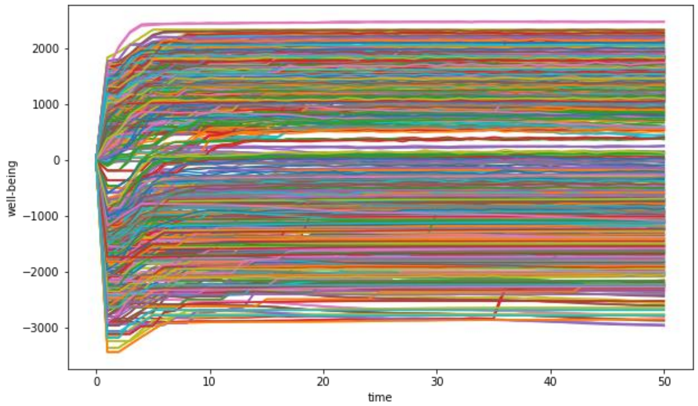


FIGURE 48: 1200 EXPERIMENTS

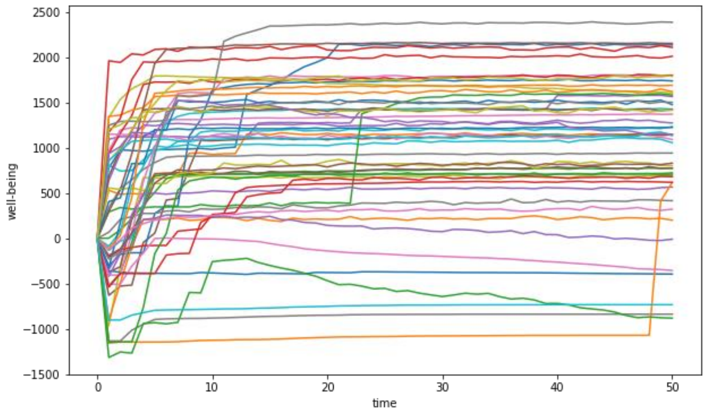


FIGURE 49: 50 EXPERIMENTS

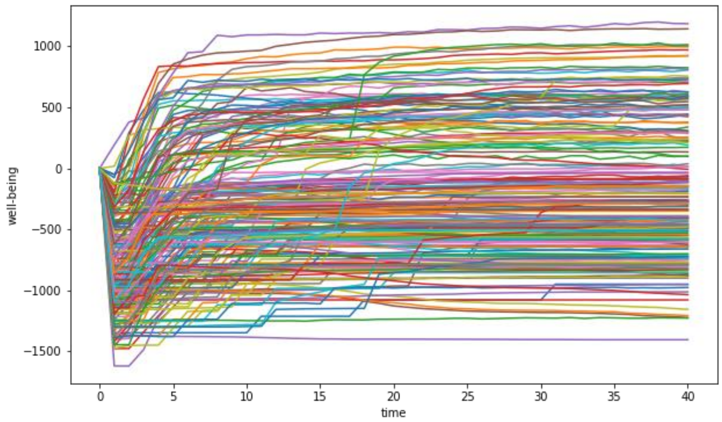


FIGURE 50: 200 EXPERIMENTS

Substantiation of settings

Certain ranges are chosen for exploration of the effects of designs on capabilities. These are chosen based on the insights form the verification and validation.

It has been proven useful to look at a range between 0 and 4 for improvement as broader ranges to not give any new insights as smaller ranges might neglect the interactions between improvement and other parameters as increase of income and their common effect on autonomy. For the trend income a range chosen small enough to say something about small changes and broad enough to not mis any global effects. The four parameters comparing the importance of weight of the key performance indicators, the capabilities can be small or bigger than one. Between 0 and 1 means that a capability can be 10 times smaller (0.1) than another (with the value of 1). This allows for clearing distinguishing between desirable and undesirable effects of designs. Between 1 and 3 means that a capability is up to 3 times more important than another (with the value of 1).

The number of enthusiasts is chosen in relation to the cluster and the total number of households. It is assumed that only a small number of households can be actively involved in supporting or opposing the project. Therefore a range between 0 and 80 is chosen. In this way also effects can be measured when there are either no enthusiast, no sceptics or none of any.

TABLE 31: SETTINGS DURING THE EXPERIMENTS

Parameter	Range [unit]
Improvement	0, 4 [decreasing costs per time unit]
Trend income	-2, 6 [1000 € per time unit]
Weight of costs	0, 3 [ratio]
Importance of information	0, 3 [ratio]
Importance of comfort	0, 3 [ratio]
Weight of sustainability	0, 3 [ratio]
Enthusiasts	0, 80 [households]
Sceptics	0, 80 [households]
Radius	1, 6 [patches]
Run length	50 [time units]
Replications	10 [#]
Experiments	200 [scenario's]

M. Experimental Results

Social acceptability

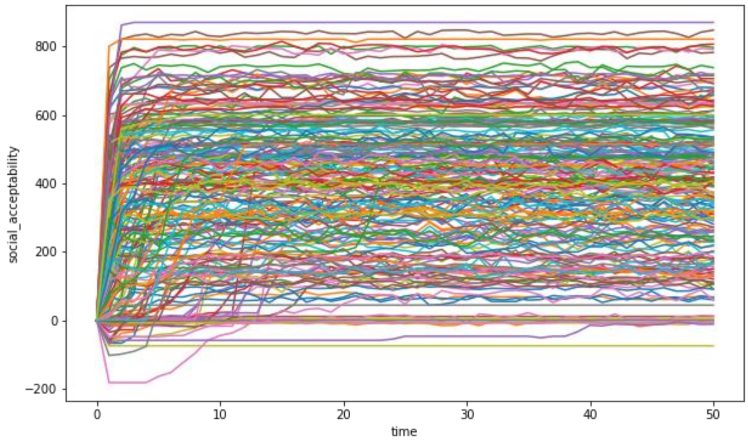


FIGURE 51: ACCEPTABILITY FOR THE BASE CASE

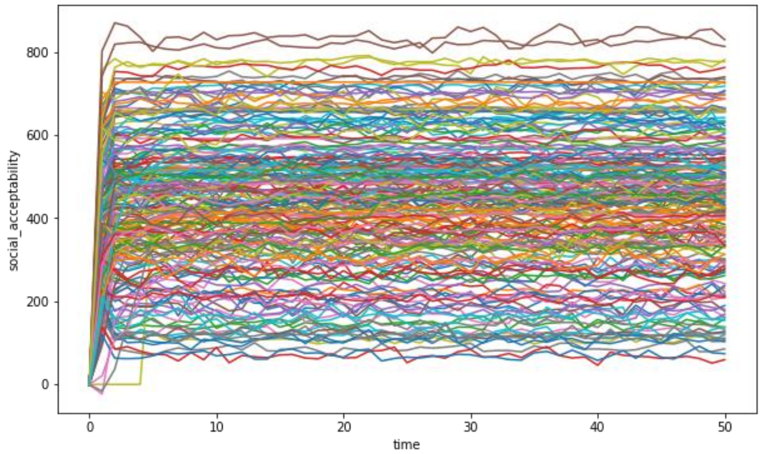


FIGURE 52: ACCEPTABILITY FOR GREEN COOKING

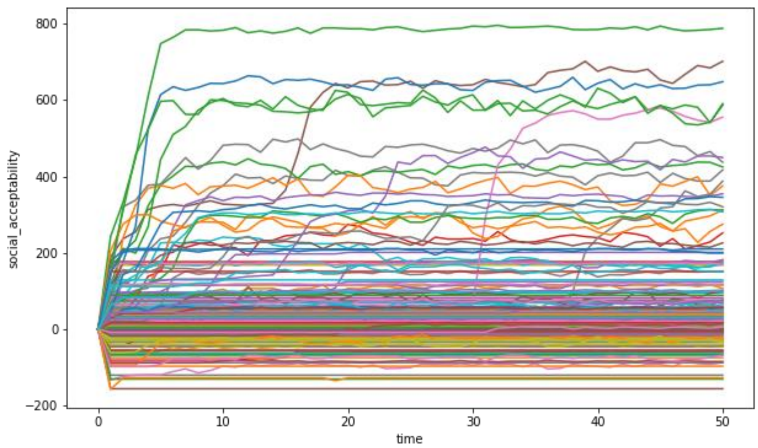


FIGURE 53: ACCEPTABILITY FOR GREY MIXING

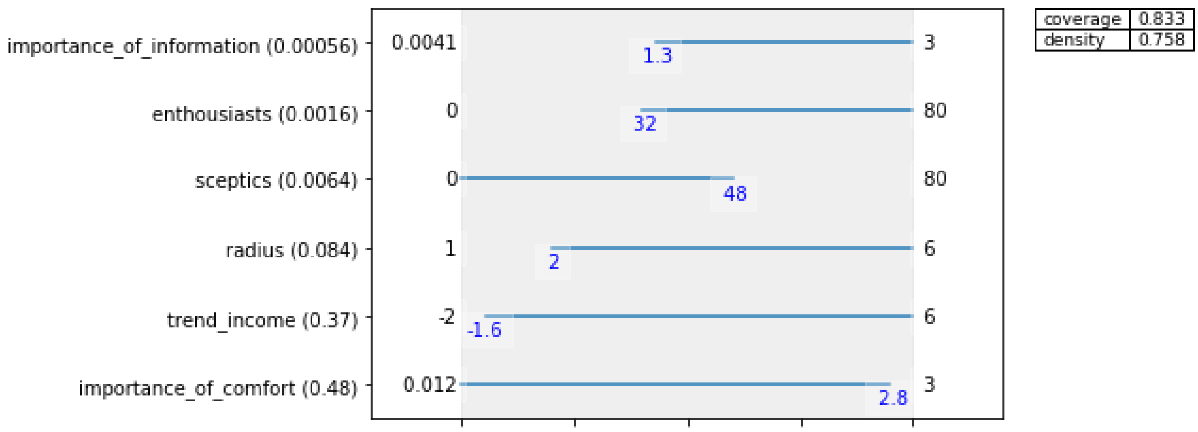


FIGURE 54: FACTORS CAUSING HIGH ACCEPTABILITY FOR THE BASE CASE

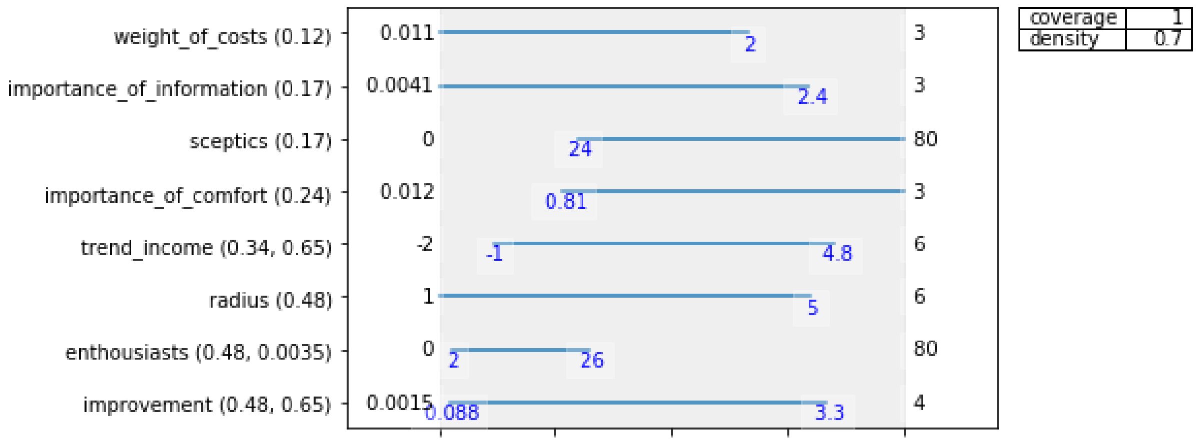


FIGURE 55: FACTORS CAUSING LOW VALUES OF SOCIAL ACCEPTABILITY

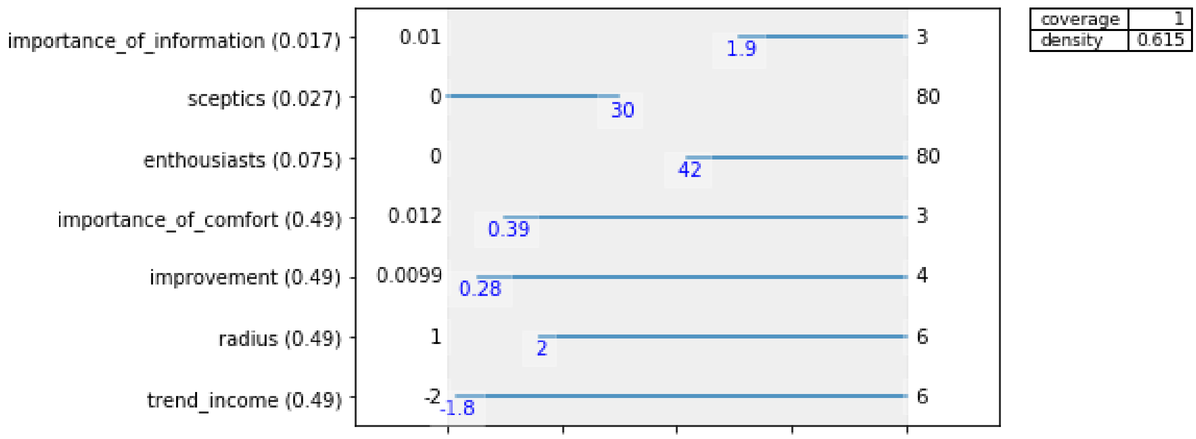


FIGURE 56FACTORS CAUSING HIGH ACCEPTABILITY FOR GREEN COOKING

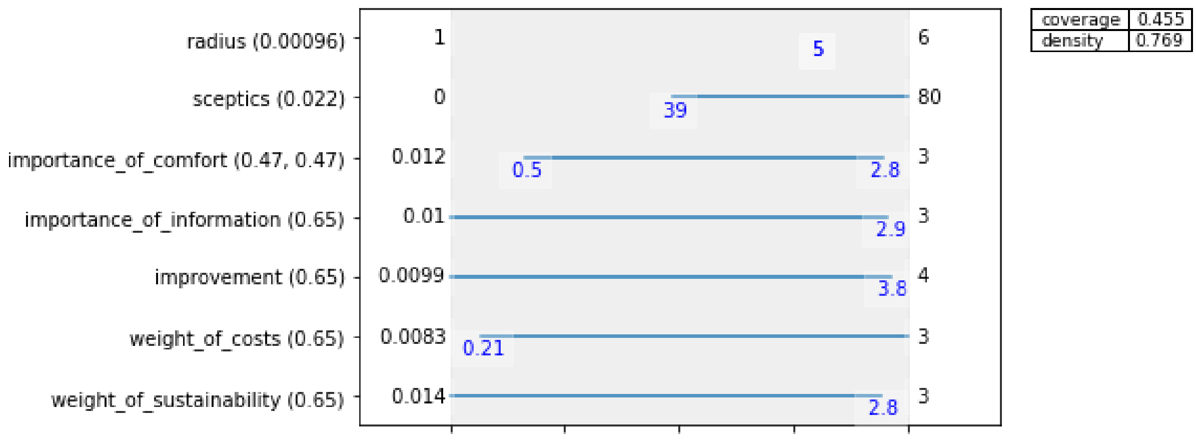


FIGURE 57: FACTORS CAUSING LOW LEVELS OF SOCIAL ACCEPTABILITY

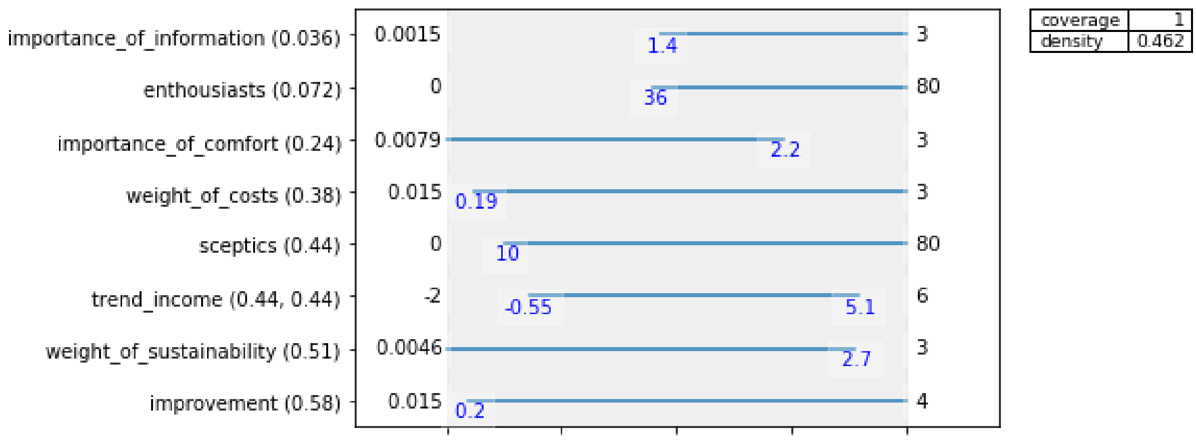


FIGURE 58: FACTORS CAUSING HIGH SOCIAL ACCEPTABILITY FOR GREY MIXING

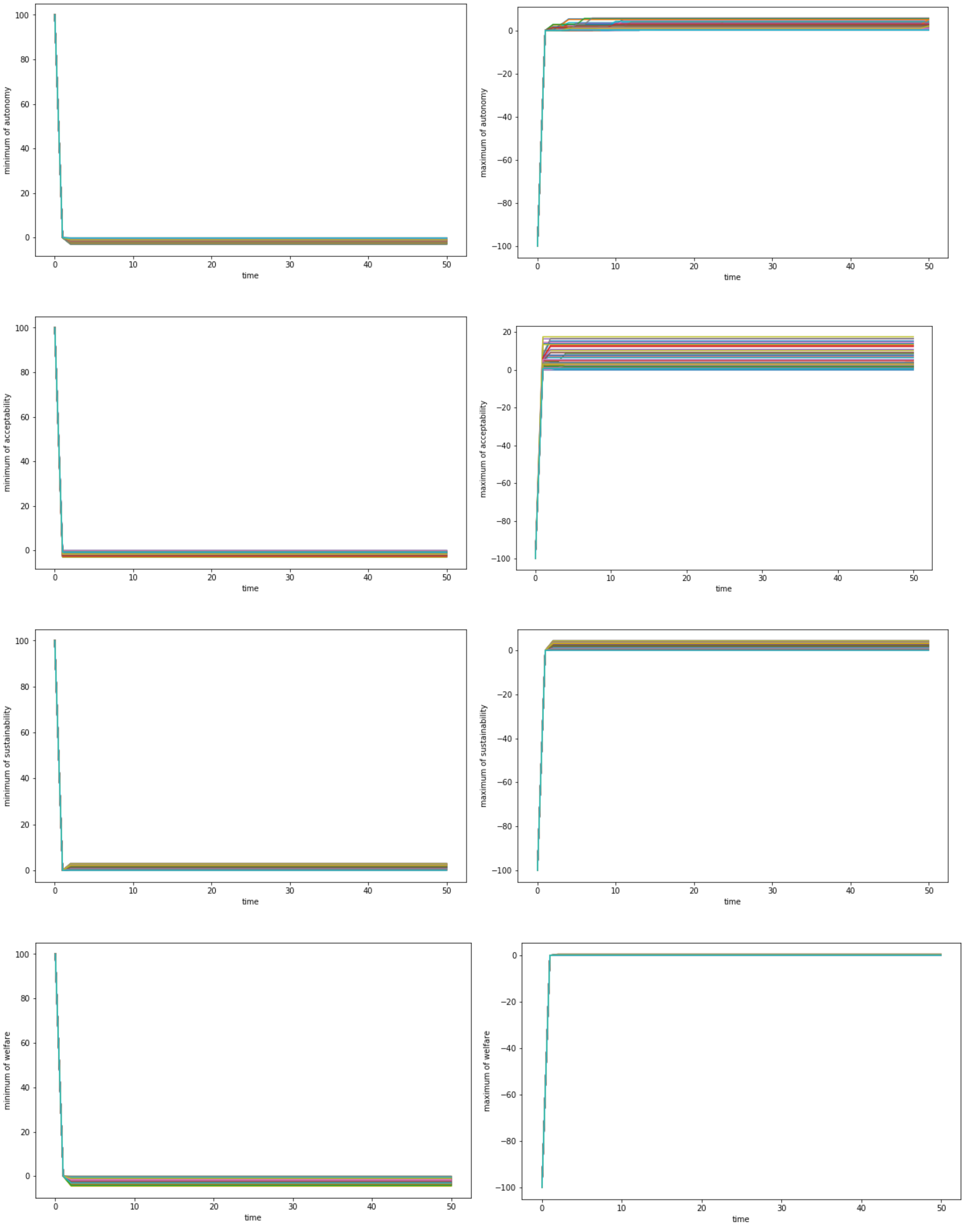
Fairness

For the analysis of the individual comparison the minimum and maximum values of each run per capability are plotted over time. The starting values of minimum and maximum are 100 / -100. The graphs for each of the designs presents:

- The minimum values of autonomy
- The maximum values of autonomy
- The minimum values of acceptability
- The maximum values of acceptability
- The minimum values of sustainability
- The maximum values of sustainability
- The minimum values of welfare
- The maximum values of welfare

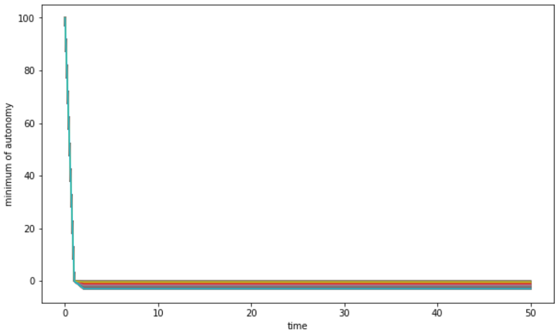
There seems to be almost no difference between the effects of the designs. One difference appears when analysing at the differences in values of welfare. For the base case and green cooking there are no differences in minimum values. There are some small differences for grey mixing. For the base case and green cooking there are small differences in maximum values but for grey cooking there are no differences. The of grey mixing in some cases is lower than for the others designs. The maximum value of welfare for the base case and green cooking in most cases is higher than for grey mixing. It can be concluded that the variation of values is equal but that the values for welfare are generally lower for the grey mixing design.

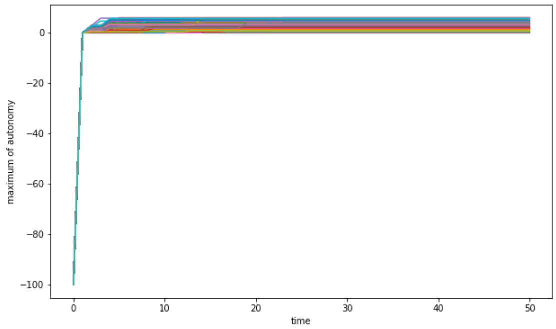
Base Case

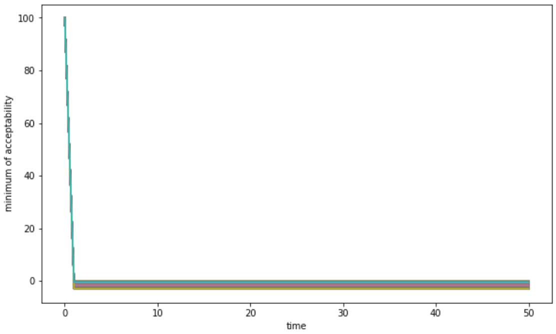


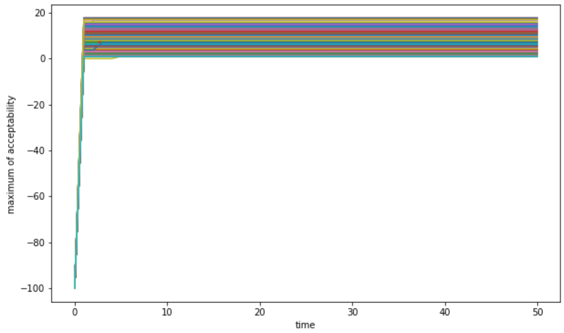
minimum of autonomy
maximum of autonomy
minimum of acceptability
maximum of acceptability
minimum of sustainability
maximum of sustainability
minimum of welfare
maximum of welfare
time

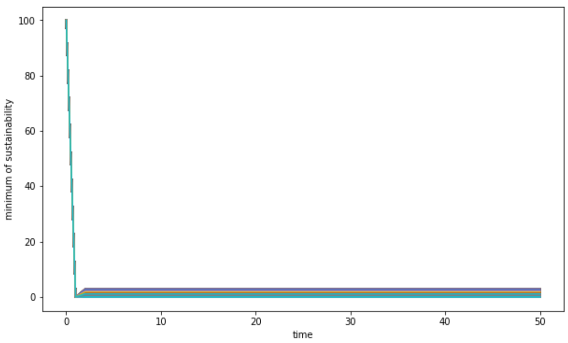
Green Cooking

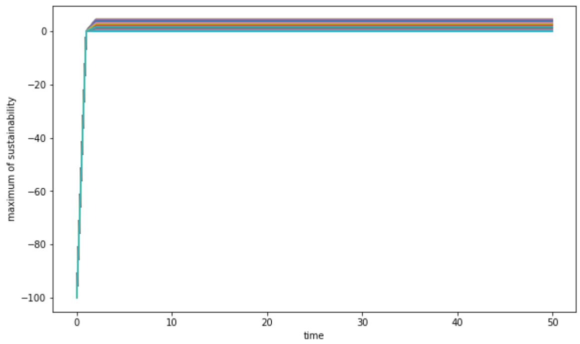


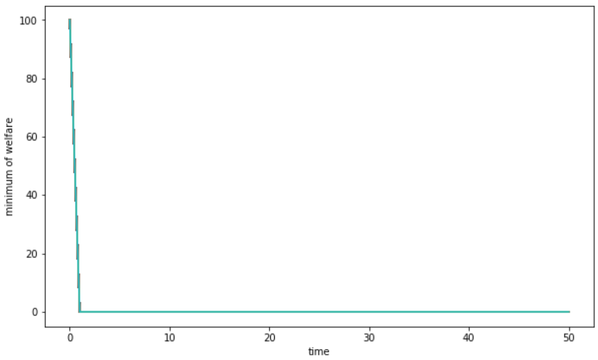


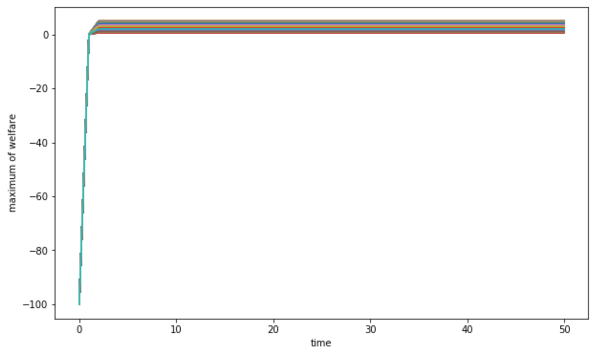




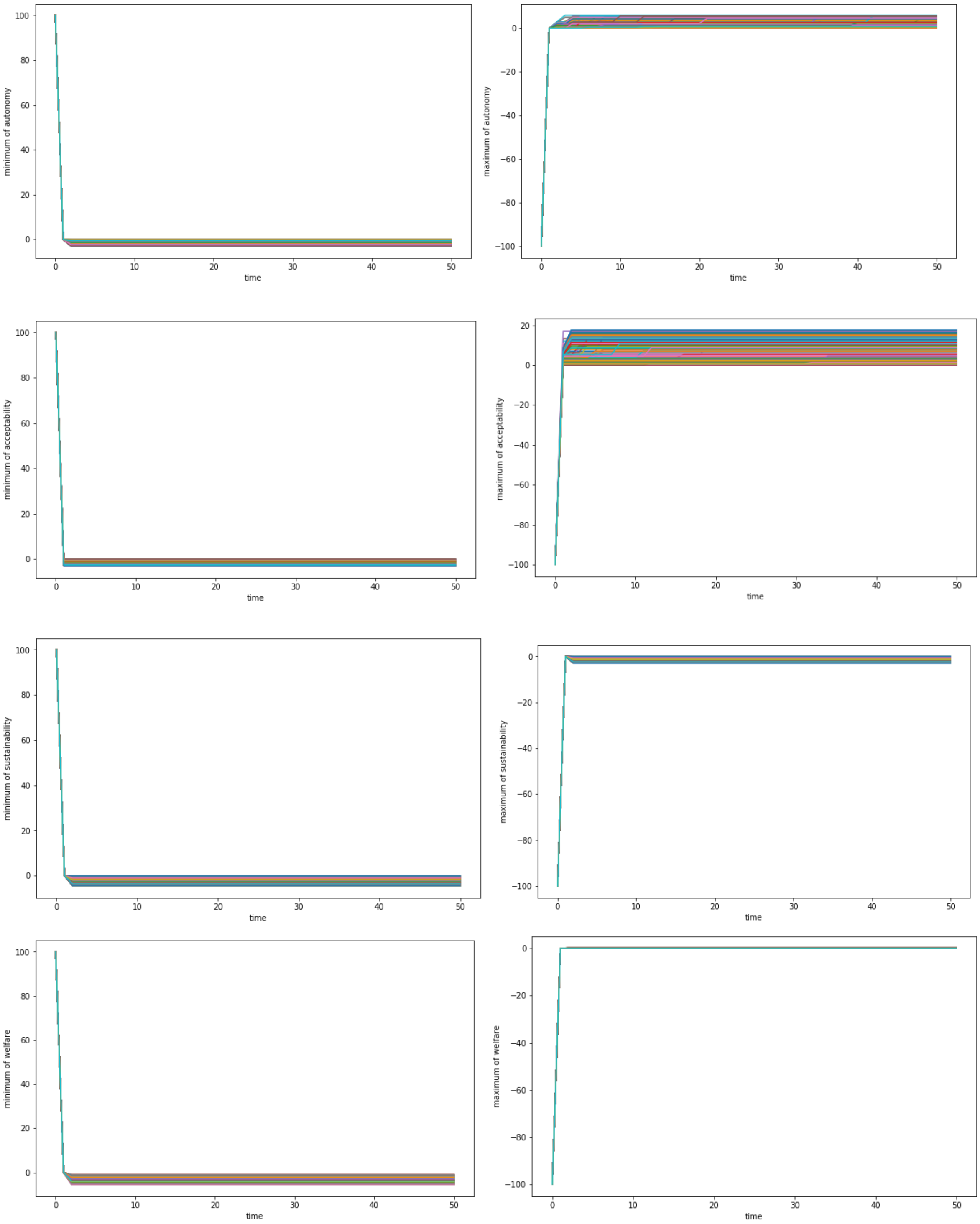








Grey Mix


minimum of autonomy
time
maximum of autonomy
time
minimum of acceptability
time
maximum of acceptability
time
minimum of sustainability
time
maximum of sustainability
time
minimum of welfare
time
maximum of welfare
time

Green

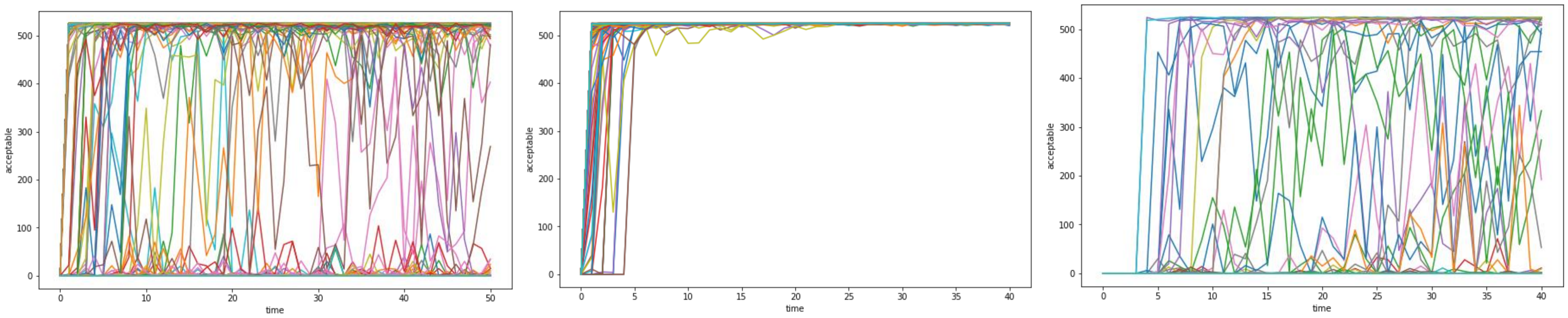


FIGURE 59: NUMBER OF GREEN HOUSEHOLDS (BASE CASE, GREEN COOKING, GREY MIX)

Yellow

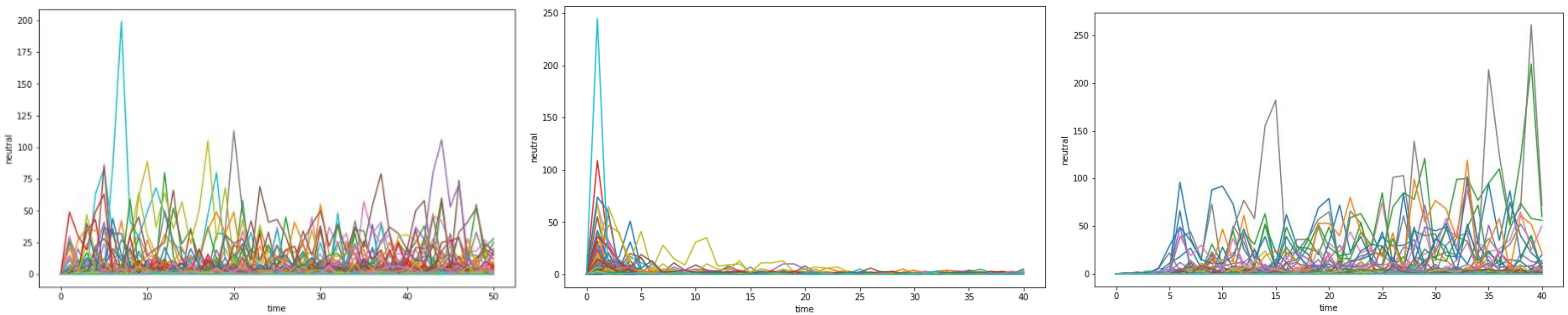


FIGURE 60: NUMBER OF YELLOW HOUSEHOLDS (BASE CASE, GREEN COOKING, GREY MIX)

Red

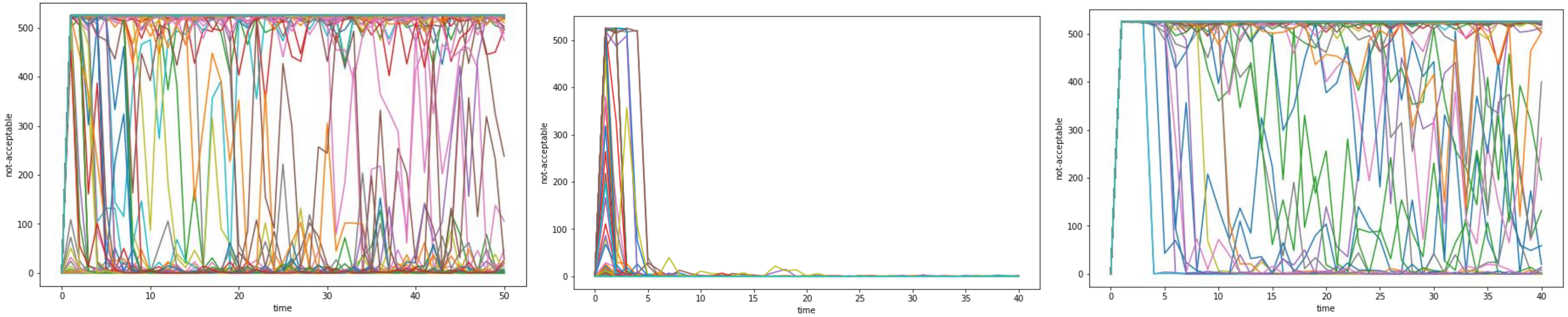


FIGURE 61: NUMBER OF RED HOUSEHOLDS (BASE CASE, GREEN COOKING, GREY MIX)

Many agents change their colour given the base case, even though overall well-being stabilises, for a number of agents the acceptability changes due to the social network. Green cooking the design is acceptable for most agents within a short period of time. For grey mixing at fist the design is not acceptable but throughout time the number of green agents increases, changes between acceptable and not acceptable are less frequent than in the base case

Autonomy

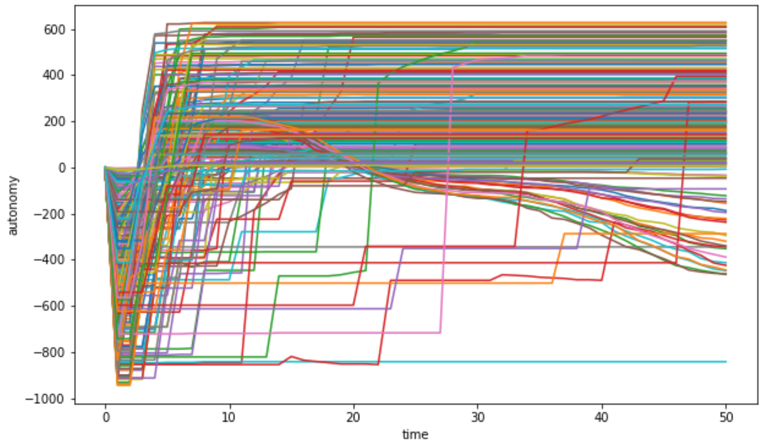


FIGURE 62: AUTONOMY OF THE BASE CASE

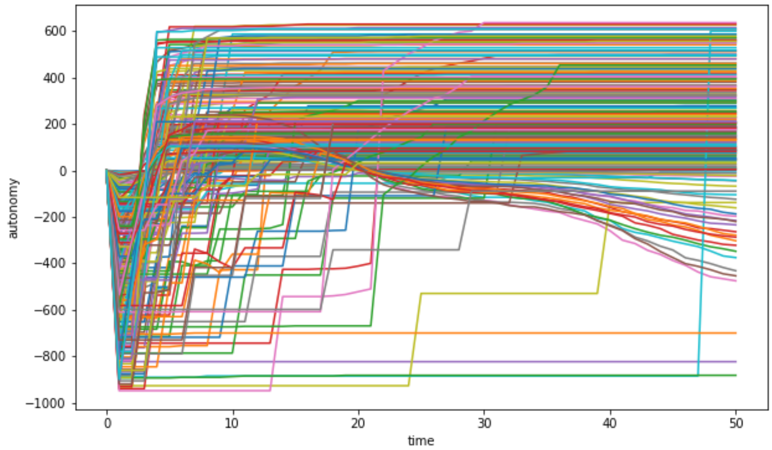


FIGURE 63: AUTONOMY OF GREEN COOKING

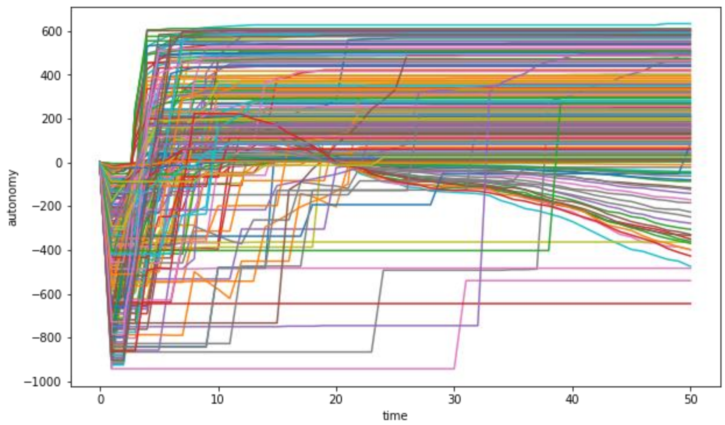


FIGURE 64: AUTONOMY OF GREY COOKING

The PRIM analysis shows that there is similar behaviour concerning factors causing high levels of autonomy. However, it is difficult to say something about low levels of autonomy as the coverage and density are quite low. As shown in the plots the shape of the curves of the three designs are very much alike as the designs do not influence autonomy in different ways. It is assumed that the same factors would cause low levels of autonomy. One factor that certainly causes low autonomy is low trend income. The others that are identified by PRIM (radius in the case of green cooking and sceptics in the case of grey mixing Figure 67 & Figure 68) probably do not play a role.

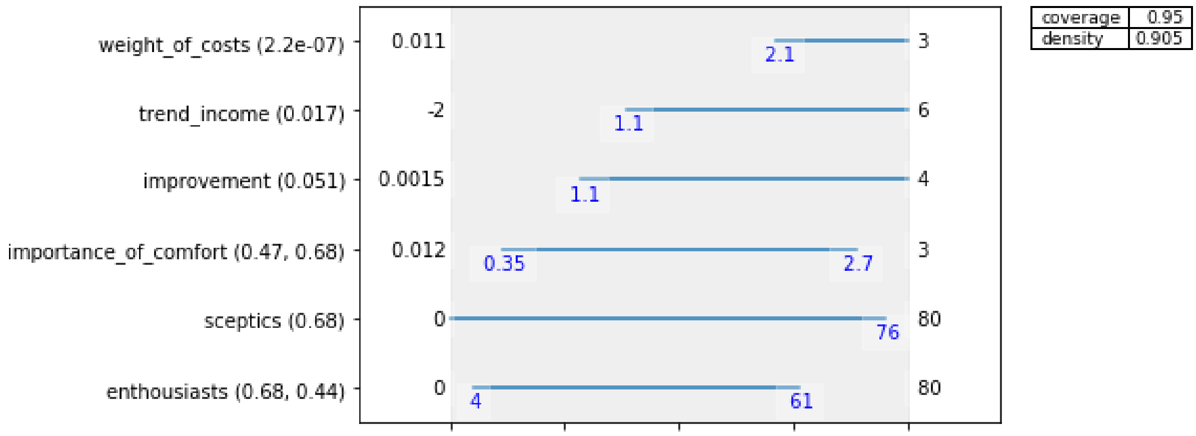


FIGURE 65: FACTORS CAUSING HIGH AUTONOMY FOR THE BASE CASE

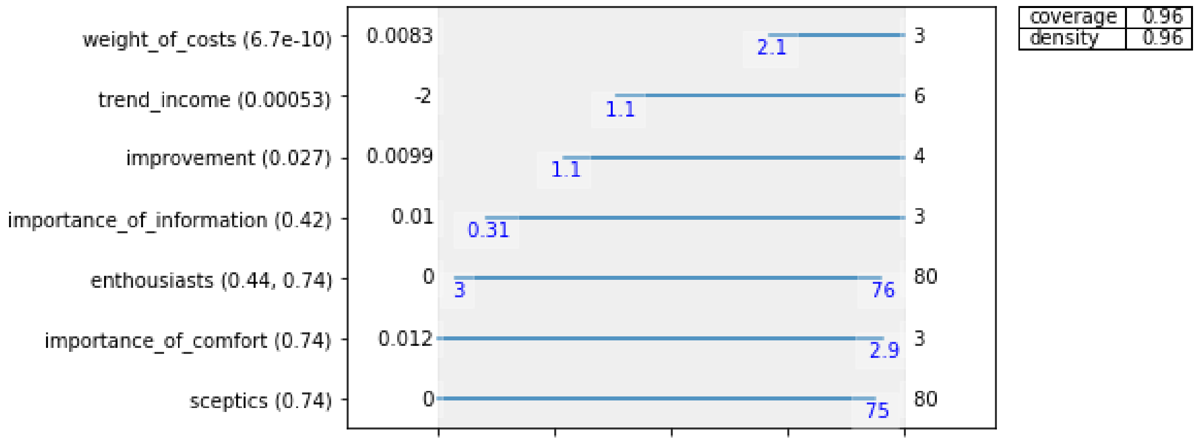


FIGURE 66: FACTORS CAUSING HIGH LEVELS OF AUTONOMY WHEN COOKING GREEN

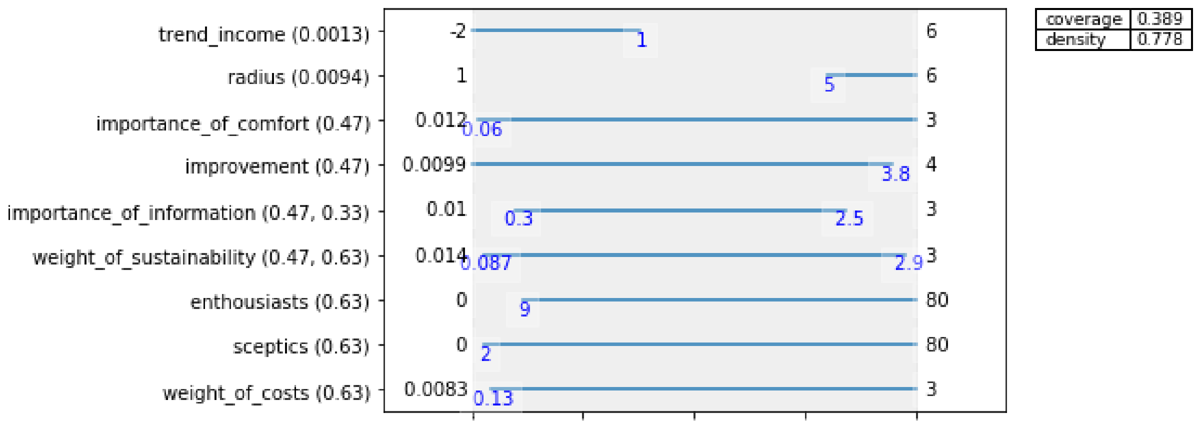


FIGURE 67: FACTORS CAUSING LOW LEVELS OF AUTONOMY

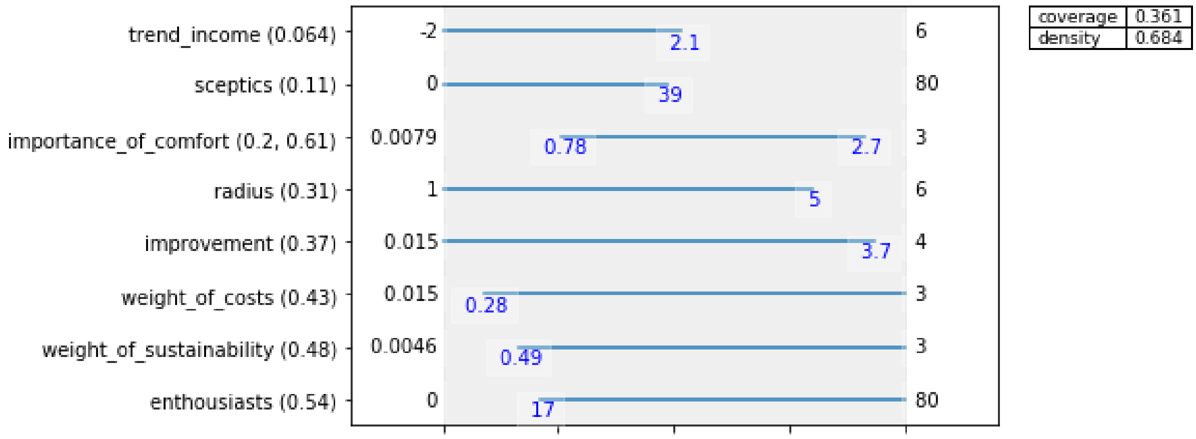


FIGURE 68: FACTORS CAUSING LOW AUTONOMY FOR GREY MIXING

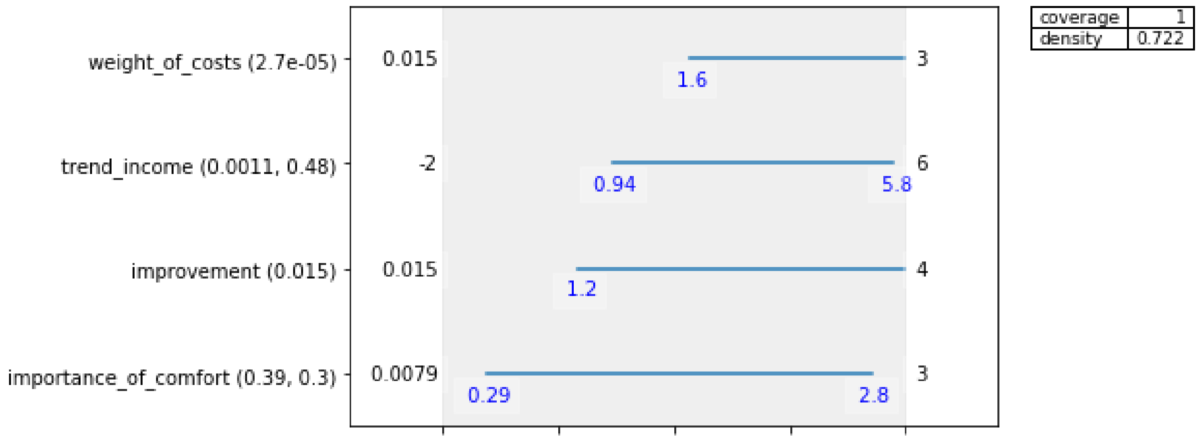


FIGURE 69:FACTORS CAUSING HIGH AUTONOMY FOR GREY COOKING

Sustainability and Welfare

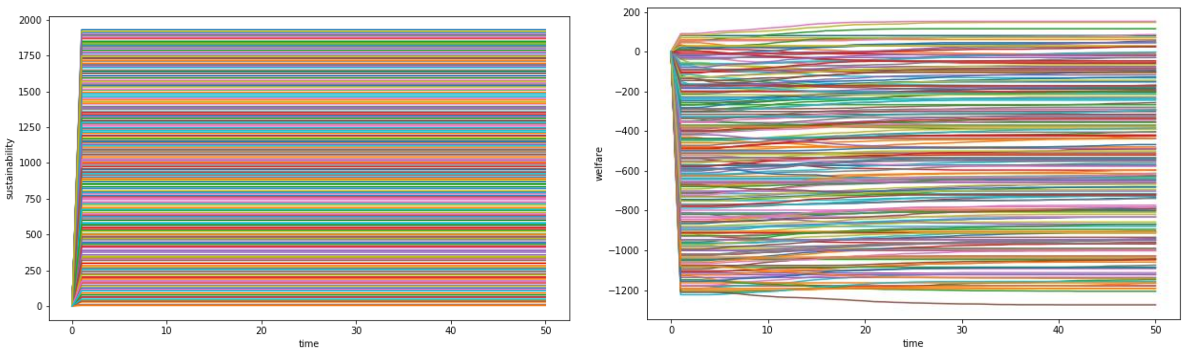


FIGURE 70: SUSTAINABILITY AND WELFARE OF THE BASE CASE

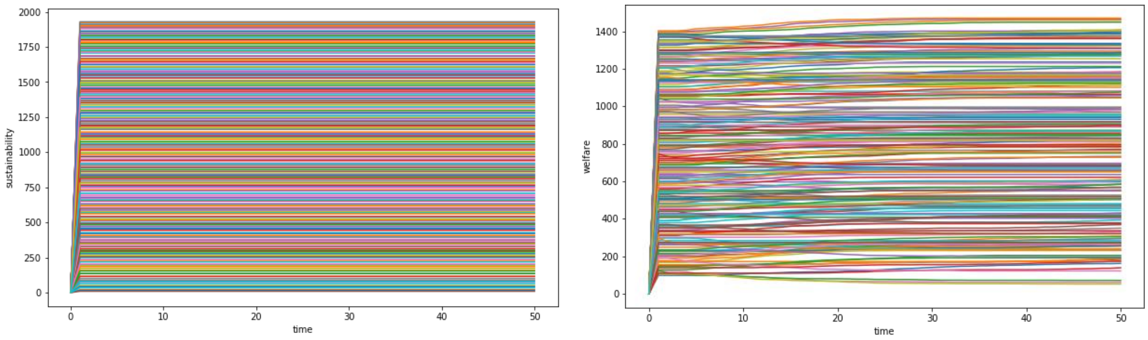


FIGURE 71: SUSTAINABILITY AND WELFARE OF GREEN COOKING

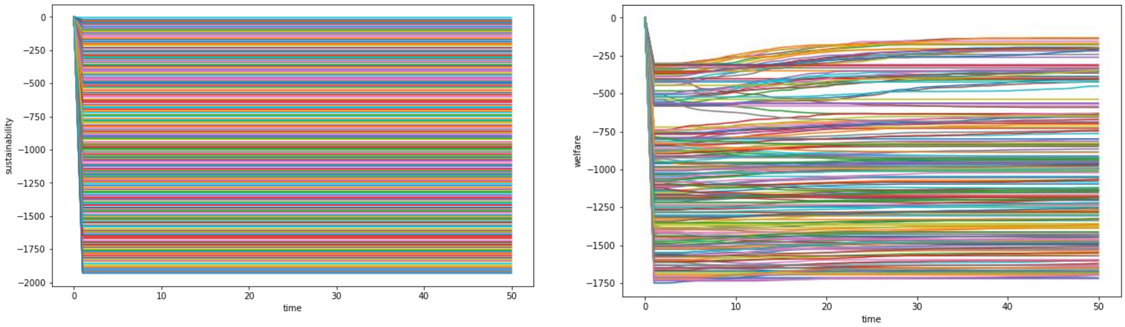


FIGURE 72: SUSTAINABILITY AND WELFARE FOR GREY MIXING

Well-being

The graphs show the well-being of 200 different experiments (10 replications) with a run length of 50 ticks.

Figure 73 Figure 74 & Figure 75 show the well-being over time for the different designs. The first graph shows a drop in the beginning and an increase of well-being over time. Most scenarios stabilise fast, some increase stepwise over a longer period. The majority of the scenarios remains below 0 which means that there is no increase in acceptability. Acceptance may become an issue I these cases. In the second graph the value of well-being directly increases. Most scenarios stabilise quickly, very few slowly increase over time. All scenarios case an increase I well-being. The acceptability of the technology may be such that acceptance will not be a barrier. In the final design in all scenarios well-being is decreased. This does not necessarily mean that there will be a lack of acceptance, but more research is needed on how to compensate for the restricting properties of the technologies for households.

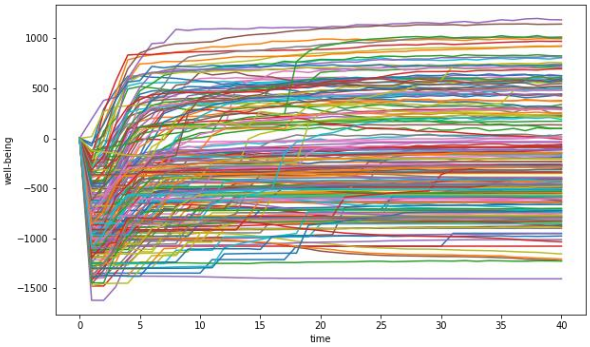


FIGURE 73: WELL-BEING OF BASE CASE

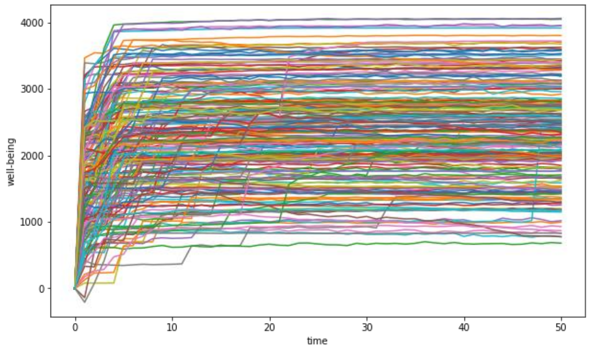


FIGURE 74: WELL-BEING OF GREEN COOKING

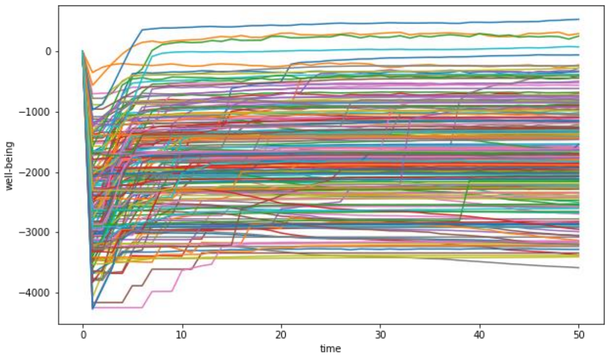


FIGURE 75: WELL-BEING OF MIXING GREY HYDROGEN

The analysis with PRIM shows that in this scenario the most important factors for generating high levels of well-being at the end of the runtime are importance of comfort, weight of sustainability, trend income and radius. The higher these parameters are (see the range given by Prim) the better the scenario performs. Importance of information, the number of sceptics and enthusiasts and the improvement of technology not cause specifically high levels of well-being. In further research the causes of negative outcomes might be explored to determine whether one of these factors has an especially negative effect.

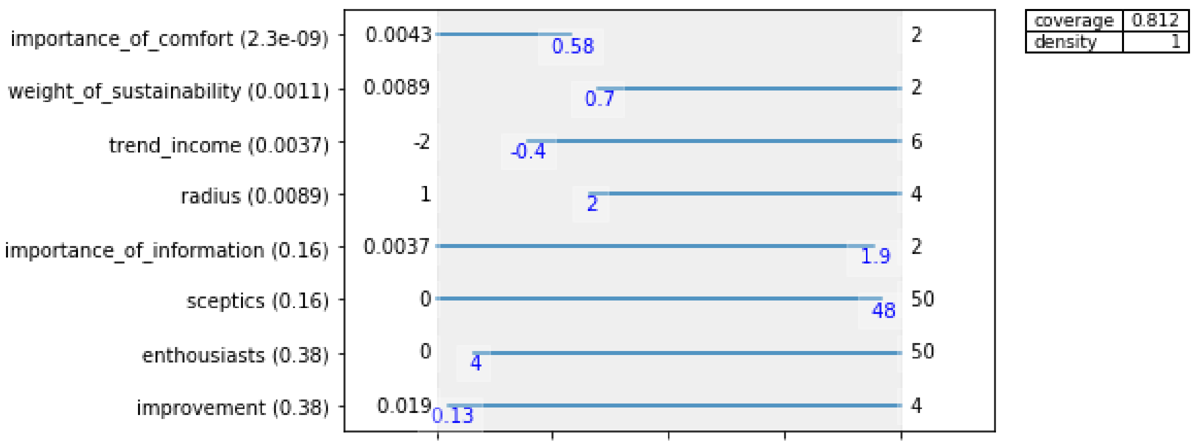


FIGURE 76: PRIM ANALYSIS OF THE BASE CASE

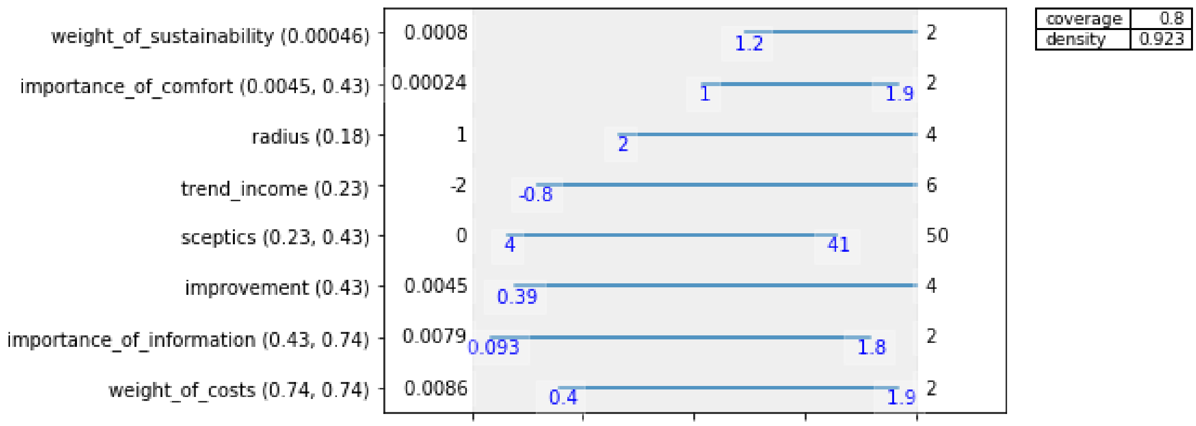


FIGURE 77: FACTORS CAUSING HIGH LEVELS OF WELL-BEING

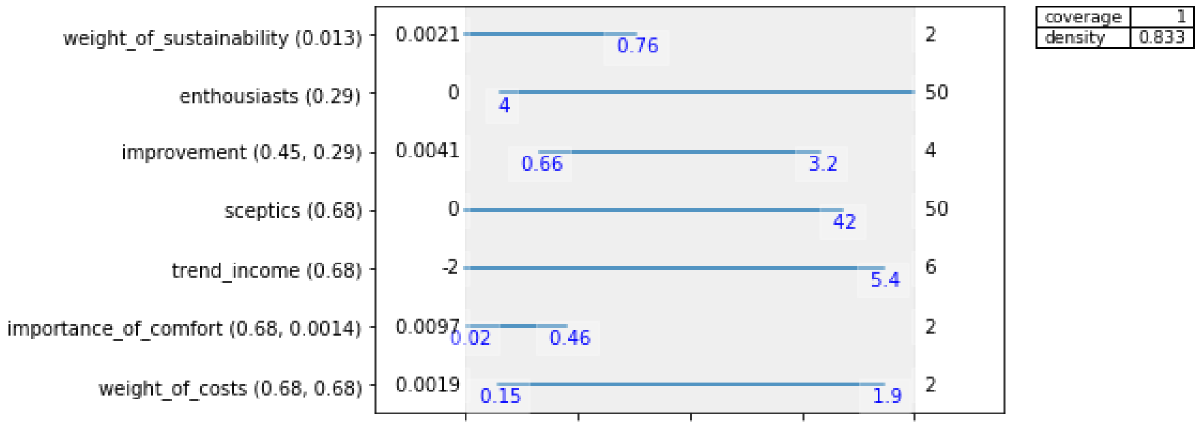


FIGURE 78: FACTORS CAUSING HIGH LEVELS OF WELL-BEING

N. Form Informed Consent (Dutch)

Toestemmingsverklaring Workshop Aardgasvrij Stad aan 't Haringvliet

Deze workshop is onderdeel van een onderzoek over acceptatie van waterstof in het bestaande aardgasnet. Er wordt in het onderzoek gekeken naar technische ontwerpen die rekening houden met sociale waarden. Er wordt onderzocht op welke manier dit toegepast kan worden in Stad aan ´t Haringvliet. Het doel van de workshop is het om de effecten van mogelijke oplossingen te evalueren. Hiernaast wordt er een poging gedaan om bestaande oplossingen dusdanig aan te passen dat ze beter aansluiten bij de waarden van bewoners.

De workshop wordt opgenomen maar de opnames worden uitsluitend gebruikt om de resultaten te analyseren. Daarna worden de opnames verwijderd. De gegevens en data van de deelnemers worden volledig geanonimiseerd in het onderzoek. Persoonlijke gegevens worden niet opgeslagen en u kunt de workshop op elk moment verlaten. Quotes worden alleen met uitdrukkelijke toestemming gebruikt.

Voor vragen kunt u ten alle tijden met mij contact opnemen.

	Ja	Nee
Deelname aan de workshop		

Ik heb de informatie over de workshop gelezen en begrepen.	☐	☐
Ik heb de mogelijkheid gekregen om vragen te stellen over de workshop en deze zijn tot mijn tevredenheid beantwoord.	☐	☐
Ik stem er vrijwillig mee in om deel te nemen aan deze workshop en begrijp dat ik kan weigeren vragen te beantwoorden en dat ik me op elk moment kan terugtrekken uit de studie, zonder een reden te hoeven geven.	☐	☐
Ik begrijp dat mijn deelname aan de workshop gefilmd wordt en dat de opnames na afloop van de analyse vernietigd zullen worden.	☐	☐
Gebruik van data		
Ik begrijp dat de informatie die ik geef zal worden gebruikt voor een onderzoeksrapport over acceptatie van energiesystemen.	☐	☐
Ik begrijp dat de persoonlijke gegevens die over mij worden verzameld en het mogelijk maken mij te identificeren, niet gedeeld worden met het onderzoeksteam.	☐	☐
Ik ben het ermee eens dat de informatie die ik gedurende de workshop geef kan worden aangehaald in citaten in het onderzoek.	☐	☐

__________________	______________________	_________
Naam deelnemer	Handtekening	Datum

Ik heb het informatieblad nauwkeurig toegelicht voor de deelnemers en zo goed mogelijk ervoor gezorgd dat de deelnemers begrijpen waar ze volstrekt vrijwillig toestemming aan geven.

Vera de Jong	___________________	_________
Student en onderzoeker	Handtekening	Datum

O. Workshop Form (Dutch)

Beantwoordt de vragen hieronder vanuit uw eigen perspectief als bewoner of als vertegenwoordiger van uw organisatie.

Op een schaal van 1 tot 10 (1 = niet belangrijk, 10 = zeer belangrijk), hoe belangrijk zijn onderstaande waarden als het gaat om het vervangen van aardgas?

Comfort ☐

Keuzevrijheid ☐

Duurzaamheid ☐

Overeensteming ☐

Gelijkheid ☐

Betaalbaarheid ☐

Wat of wie beïnvloedt de publieke opinie over het project Aardgasvrij Stad voornamelijk?

Onder welke omstandigheden bent u bereid/ is er bereidheid om over te stappen naar een elektrisch kooktoestel (mits u dat niet al heeft)?

Onder welke omstandigheden bent u bereid/ is er bereidheid om meer te betalen voor een duurzame energievoorziening?

Onder welke omstandigheden is het acceptabel om over te stappen naar waterstof?

Is het belangrijk dat er een alternatief geboden wordt naast waterstof? Wanneer is er sprake van een *goed* alternatief?

Opties voor Waterstof in Stad aan ´t Haringvliet

In het onderzoek wordt het concept *aanvaardbaarheid* gebruikt om keuzes te beoordelen. Met aanvaardbaarheid wordt de keuzeruimte bedoeld die bewoners en gebruikers hebben. Deze keuzeruimte is onafhankelijk van de persoonlijke voorkeur. Er wordt onderzocht in hoeverre de realisatie van waterstof de keuzeruimte beperkt of vergroot gegeven individuele eigenschappen van bewoners. Het doel is om een technisch ontwerp te kiezen dat zo veel mogelijke ruimte biedt. Een voorbeeld zou kunnen zijn of bewoners gegeven hun huidige apparatuur in staat zijn om aanpassingen te betalen.

Vul hier uw eerste indruk van de opties in. Is de optie volgens u aanvaardbaar?

Bij het beantwoorden van de vraag kunt u denken aan het beoordelen van de consequenties, u kunt aangeven of het een goede of een slechte keuze is en in hoeverre bewoners met verschillende middelen dezelfde kansen hebben. Hiernaast kunt u ook de kans beoordelen dat er voor een bepaalde optie gekozen wordt.

OPTIE 1: ELEKTRISCH KOKEN

- DUURZAME ENERGIE VOORZIENING
- KOKEN OP EEN ELEKTRISCHE PLAAT OF INDUCTIE
- ÉÉN DUIDELIJKE OVERSTAP NAAR WATERSTOF

OPTIE 2: KOKEN OP GROENE WATERSTOF

- DUURZAME ENERGIE VOORZIENING
- KOKEN OP EEN AANGEPAST GASSTEL
- ÉÉN DUIDELIJKE OVERSTAP NAAR WATERSTOF

OPTIE 3: MIX VAN GRIJZE WATERSTOF

- WATERSTOF VAN EEN NIET-DUURZAME BRON
- KOKEN OP EEN ELEKTRISCHE PLAAT OF INDUCTIE
- GELEIDELIJKE OVERSTAP

Brainstorm

De volgende stap is een brainstormsessie. Omdat de tijd beperkt is zullen we slechts één scenario behandelen. Vul in de tabel hieronder uw inschatting in over hoe aanvaardbaar de scenario's zijn. Geef door middel van een cijfer aan (1 voor niet aanvaardbaar, 10 voor zeer aanvaardbaar) hoe u de scenario's inschat. Op basis hiervan wordt een keuze gemaakt welk scenario gezamenlijk besproken wordt. Het vervolg zal een brainstormsessie zijn waarin het probleem naar boven gebracht wordt en verbetervoorstellen worden aangedragen om uiteindelijk een nieuw cijfer te geven.

	Mate van aanvaardbaarheid (cijfer 1 -10)	Sterkte / probleem	Verbetervoorstel	Nieuw cijfer
Scenario A: Elektrisch koken Duurzame energie voorziening Koken op een elektrische plaat of inductie Één Duidelijke overstap naar waterstof				
Scenario B: Koken op groene waterstof Duurzame energie voorziening Koken op een aangepast gasstel Één Duidelijke overstap naar waterstof				
Scenario C: Mix van grijze waterstof Waterstof van een niet-duurzame bron Koken op een elektrische plaat of inductie Geleidelijke overstap				

Evaluatie

Heeft u nieuwe inzichten opgedaan tijdens deze workshop? Welke? Wat had beter gekund?

Heeft u informatie kunnen geven aan andere?

Vindt u deze scenario's een geschikte manier om betrokken te worden bij het ontwerp van Aardgasvrij Stad? Waarom?

Andere opmerkingen, tips of vragen?

P. Designs

ELECTRIC COOKING

This scenario is used as basis to compare to the other possible choices. In this scenario there is green hydrogen from either a conversion station or a local wind turbine directly producing hydrogen. The scenario does not explicitly consider the source of the green hydrogen. The benefits of green hydrogen and especially locally produced hydrogen are that CO2 emissions are actually prevented and locally produced green energy is used by local households with few losses due to distribution. It is acceptable for residents that hydrogen is green. It is preferable to grey or blue sources and therefore increases acceptability.

It has been determined that boilers can use hydrogen as fuel but that the hydrogen is not brought into the kitchens. This means that all stoves have to be replaced that are not electric yet and that, when replacing it by induction new pans need to be bought. Households do not find it acceptable that stoves have to be replaced and pans need to be bought. They prefer having the choice to either keep the old equipment and replace parts of it to adjust it for hydrogen or to cook on electricity. The acceptability decreases when choices are made in advance.

Hydrogen is pure which means that are needed but there is no need to switch twice (natural gas to mix to pure H2) so only once boilers have to be replaced. Just one renovation is considered more acceptable than two as it saves time and costs of changing equipment. Even though gradual changes might have the advantage to provide habituation it is concluded that households prefer a radical switch.

As opinions are dispersed about the issue there are households that do not find it acceptable then others. It seems that there are more households that find the solution acceptable and therefore spread positive information. This influences the other households that adapt to this opinion. So, there are doubts but in general there is a rising line.

COOKING ON GREEN HYDROGEN

In this scenario the hydrogen is also from a green source which makes it acceptable to households that find sustainability important. To those who find it not important it is not necessarily unacceptable (as long as costs stay the same). In all scenarios households find extra costs unacceptable. The attitude that has been introduced in the simulation determines in how far acceptability is influenced by the urge for sustainability or the urge to save costs. This scenario also provides for hydrogen in the kitchens of Stad aan ´t Haringvliet. It is very acceptable as it leaves the choice to the consumer in what way to cook and when to switch to all-electric if that is desired. The acceptability therefore increases. This scenario also includes pure hydrogen and skips the step of first mixing for trial which increases acceptability .

It seems that this scenario causes a more rapid conclusion that the system provided is acceptable. However, there are still some small doubts. The overall result of the scenario seems to be comparable to the first scenario. However, when looking at the individual differences acceptability and autonomy have the same shape, but welfare diverges. Even though, the minimum and maximum values are both positive there is a difference. The question therefore is whether a scenario is more desirable that causes unequal benefits or no benefits for all.

MIXING GREY HYDROGEN

This Scenario sketches the opposite to the second scenario. The hydrogen comes from a grey source which means because it is a pilot it is still made of natural gas. There are possibilities to store the carbon in the ground but still CO2 is produced to make hydrogen. Currently it is more expensive to retrieve hydrogen from green sources than from grey sourced. The hydrogen furthermore cannot be produced locally but probably will come from the Rotterdam Industrial Area. Households in the model are not happy with this. However, because mixing at least has the intend to learn about how to introduce hydrogen as sustainable replacement of natural gas some residents acknowledge mixing to be sustainable to a small extend and their satisfaction decreases just a little.

As in the first scenario the hydrogen is only brought to the boilers which means that there is no choice but cooking electric. Finally, the choice is made to the natural gas in the grid with a certain amount of hydrogen as this causes smaller technical adjustments and properties that are more alike natural gas. Probably the adjustments are less far-reaching and less expensive as adjustments made for pure hydrogen. However, mixing probably means that in several years another step and more renovations will be needed to make the full switch to pure hydrogen. The effect of this choice is that households have to renovate two times which costs time and extra money. A possible advantage is that there is some more time for habituation and learning. However, comfort decreases.

Q. Workshop Results

TABLE 32: ASSESSMENT OF IMPORTANCE OF VALUES

Value/ score									Total
Comfort	6	7	8	8	8	8	9	7	54
Freedom of choice	7	6	5	6	7	8	4	7	43
Sustainability	7	9	6	10	5	8	10	9	55
Consensus	7	8	7	8	5	7	7	7	49
Equality/ Fairness	7	8	6	6	5	7	7	8	46
Affordability	7	8	7	8	8	8	9	9	55

TABLE 33: SCORES OF SCENARIOS

Scenario/ Score									Total
Scenario 1	6	7	8	8	2	9	3	6	49
Scenario 2	8	8	6	6	8	1	3	7	47
Scenario 3	1	5	5	2	2	2	6	4	27

TABLE 34: SCORES AFTER IMPROVING THE THIRD SCENARIO

Original	1	5	5	2	2	2	6	4	27
New Score	8	8	7	4	5	2	7	7	48

R. Evaluation of the Workshop

The participants needed a while to understand the concept of acceptability and consider this perspective when assessing the scenarios. The forms used during the interviews were very useful to give the session structure and to generate comparable results. However, some questions needed more explanation. It was for example not directly clear what the values equally and consensus meant in the context of the workshop. Some questions were too specific for resident. This caused confusion. On the spot we decided that they were filled in as if they were residents. Crucial for the workshop was that the language used during the workshop connected with the participants. Given the feedback of the participants this might be improved.

When giving the workshop, it became clear that the Capability Approach is quite a difficult approach to discuss without really explaining it in detail. While the questionnaire was easy to fil in and a very good starting point to war-up the participants, the second part of the workshop was a little more difficult. Decided not to go into detail about the model, the assumptions and the conceptual frame it was hard to explain were the scenarios came from and from what perspective they should be answered. Choosing the right participants for the workshop is essential but difficult. The choice of participants was limited. This caused that the content of the scenario did not fully align with all participants.
Helbig, Dawes, Dzhusupova, Klievink, & Mkude, (2015) describe different stages of engagement of public in policy making. These stages are takes as starting point for answering the sub question and actually taking a practical step in engagement.

The workshop has covered informing as most participants indicated that they received new insights or perspectives for approaching the problem. However, informing will not be enough as residents are no stakeholders with low urgency. Also, the next step has been reached as the member of the city council got the change to share their opinion on the technical design choices with the project leaders and the municipality.

TABLE 35: FORMS OF ENGAGEMENT DESCRIBED BY (HELBIG ET AL., 2015)

Form of engagement	Definition and effect
Informing	This measure has the effects that stakeholders are merely informed, for example, via websites, fact sheets, newsletters, or allowing visitors to observe policy discussions. It is suitable only to engage those stakeholders with low urgency, influence, importance, or interest.
Consulting	This includes conducting interviews, administering surveys to gather information or opening up draft policy documents for public comments. The main goal of this form of engagement is to elicit the views and interests, as

	well as the salient information that stakeholders have with regard to the policy concern
Involving	The methods ask for stakeholders working together during the policy development process, scenario building, engaging panels of experts such as the Delphi method, group model building that includes simulating policy choices, games, or role playing. Models, simulations, or scenarios can be used as boundary objects to enable diverse sets of stakeholders to have a shared experience and exchange knowledge.
Collaboration	Collaboration means that stakeholders' advice and recommendations will be incorporated in the final decisions to a maximum extent.
Empowerment	Empowerment means that the final decision making is actually in the hands of the public, consensus building within legal parameters, citizen juries, stakeholder boards, living labs