Untangling Scenario Components with Agent Based Modelling:

an Example of Social Simulations of Water Demand Forecasts

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This research undertaken initially as part of the FIRMA project used the model developed to represent existing scenarios. The aims are:

- To develop a model of household water demand
    - using integrated assessment
    - based solely on ownership, frequency of use and volume per use of appliances
    - composed of qualitative and quantitative elements
- To investigate the consistency of the scenarios represented
- To show that Multi Agent Based Simulations can be a descriptive method allowing partial validation of model components
- To demonstrate that computer simulations can be used to explore causal relationships behind scenarios
- To provide supporting evidence of the importance of new technology uptake

1 Introduction

In these days of modern technologies and simultaneous scientific progress in many fields, social challenges such as understanding the reasons for emerging phenomena can be difficult to address. Bigger and more complicated formal problems can be solved thanks to transistors excelling at replicating binary decisions, which has resulted in a significant increase in the use of computer models over the last few decades. However, it is possible that in devising analytical or computer-based representations one could be relying on modelling techniques that are unsuitable for the intended purpose. For example, the ease with which data processing techniques can be used to extract statistical properties and /or links can lead modellers to forget that obtaining a meaningful output requires careful assessment of whether all relevant aspects of the phenomenon are taken into account. This means that flaws, such as non-compliance (or lack of verification for compliance) with assumed properties or limits of significance of a model's results, can be overlooked. As a consequence, a description, however complicated, might not capture all aspects of a phenomenon or process. Using the example of water demand scenarios, this research demonstrates that Multi Agent Systems (MAS) not only provide an alternative to these techniques, but represent an improvement: they can be used on a wider variety of representations, and their components can be more easily related to actual entities or processes.

The use of models is common in science and its practical applications, for example to inform us or provide us with services. Often the techniques involved in the modelling process are not rigorously assessed, either on their own or in comparison with potential equivalent methods. This can be an issue when the technique involved has limitations or drawbacks that impact on the validity (or its extent) of the conclusions it reaches. In particular, when dealing with a social phenomenon, the way it is observed can matter. The observations upon which a model is based could be restricted, and the framework used for representing restricted observations could influence the aspects of the phenomenon that are considered. Thus it is possible to imagine that observing a phenomenon could lead to capturing only a part of the aspects of the phenomenon. The selection of a framework to analyse these observations might not consider the missing aspects since their presence has not been part of the selection process. It is for reasons such as these that the tools used in the construction of a framework are critical and as such can impact on the result obtained, from a descriptive or a forecasting point of view.

There are many reasons why modelling techniques might not be applicable to some specific phenomenon. The principles behind a technique can mean that the modelling techniques have mathematical or conceptual limitations that make it unfit for its intended purpose. An example of this is where one wants to apply statistical methods to a sample that is too small. Critical mathematical properties only hold with large enough datasets. With too small a sample, these properties do not hold, and consequently the result does not hold either.

Another possibility is that a particular modelling tool cannot capture some crucial aspect(s) of the problem / situation. In game theory, tools that were used for representing and solving static situations had to be modified to deal with repeated games where players can draw information from history, and change their behaviour accordingly. This is a particular case of a changing environment that may influence the player's choice. The potential evolution of a physical environment might invalidate the results of any modelling technique unable to take this into account.

Similarly, there can be issues with modelling tools that are unable to represent and link aspects with different natures, for example quantitative and qualitative. This variation in nature results in existing techniques not being very good at relating quantitative and qualitative variables.

There are many cases where tools and techniques are used at times when they should not. An example of this is in econometrics and statistics. Econometric or statistical models can describe or infer links between variables that are assumed fit for the purpose. But all the important variables might not be included, and even if they are, it can be difficult to find out which way the causality goes. For example, the sale of umbrellas is statistically linked with rainfall, but only our knowledge of the underlying behaviour provides the information as to which provokes which. Analytical / statistical models can help identify possible causal links. But this is only possible with simple models (with simple and / or few relations between variables), while their main use tends to be for inference / forecasting with complicated models. One of the consequences of dealing with unknown links is that the missing information could lead to erroneous conclusions.

These issues were addressed in a project entitled Freshwater Integrated Resource Management with Agents (or FIRMA). Supported by European Union's Framework 5 Programme for Research and Development, and by the European Commission, it intended to “produce the knowledge and technologies needed for the rational management of water resources for domestic needs and those of industry and agriculture”.

The FIRMA project aimed to help improve water resource planning by “developing and applying agent-based modelling to integrate physical, hydrological, social and economic aspects of water resource management” (FIRMA (2003)). Its members used recent developments in modelling techniques to investigate some specific problems faced by the participating countries. Faster computers have enabled the development of tools, including object-oriented programming and Multi Agent Systems, that were applicable for addressing these problems.

In England, the issue was to understand the changes in behaviour occurring regarding domestic water demand. It is a model addressing this latter problem that is the focus of this study.

More specifically, it is a model that is devised to be used by stakeholders in different situations. Typically, the water companies should be able to infer from the simulated behaviour some possible future patterns of water consumption in the presence of climate change.

This model was initially devised solely in accordance to the aims of FIRMA. Developed in cooperation with Scott Moss, and built as part of an integrated assessment framework, the code of the original model has been checked and reviewed, while the model itself was refined with the addition of population characteristics, and the adoption process was improved. That version of the model has then been used to generate simulations analysed in the CCDEW project, and presented in the report for that project.

Further enhancements have been implemented into the model so it could tackle issues that were raised in attempting to represent scenarios from the Environment Agency. As well as emergence and adoption of new technologies, there can be substitutable technologies, as well as disappearing technologies, which were necessary to represent for example changes in regulation with stricter requirements on water efficiency performances.

Understanding behavioural changes is also the remit of the Environment Agency, and particularly its Water Resources department. The role of the Environment Agency is to protect and improve the environment as a whole, with specialists working on all areas of this wide scope - from nuclear issues to flood warning and building flood defences; from research on forest development to assessment of manufacturing processes.

For obvious human reasons, as well as for economic ones, (e.g. due to the strict regulations put in place by OFWAT), it is necessary to make sure that the balance between water supply and water demand is not negative, either now or in the future. Anticipating the evolution of water demand is hence compulsory.

The anticipation and prevention of insufficient supply with respect to the associated demand is one of the reasons for the generation of forecasts. The Environment Agency researches what the future might hold regarding the evolution of water demand as part of its strategy. These forecasts are based on scenarios, and are developed in its document “A scenario approach to water demand forecasting” (Environment Agency (2001)). In this, every scenario represents a set of assumptions that is regarded as plausible. These assumptions lead to a forecast of water demand levels and their evolution up to 2020 via a consistent reflection. The tools used for these calculations are basic, consisting of a complicated system of linked functions and spreadsheets.

Due to the practical limitations at the time, these scenarios have not been reassessed or re-implemented in order to question their consistency.

One of the issues regarding the testing of scenarios is that standard statistics cannot be used. It is not possible to analyse the previous data (which is by nature unique) and to infer different scenarios with their own specific assumptions. Moreover, the few studies including statistical inference of levels of demand have been proved inconclusive, if not invalid (Herrington (1996)).

Recognising that the difference between scenarios is based on differences in household behaviour can be understood as a necessity for including qualitative components into any model of the problem. One could attempt to use purely qualitative methods to assess the scenarios, but this would prevent any quantitative results from being obtained (and therefore quantitative techniques being used for testing the results of the research).

This thesis will demonstrate that Multi Agent Systems (MAS) is a modelling technique that can go a long way towards avoiding these issues. MAS have no underlying theory other than the one the modeller chooses to use, and therefore have (in general) no intrinsic limitations on their expressive power. MAS can represent static or dynamic systems, quantitative or qualitative links and variables. MAS can tackle information of different natures. MAS allows a modeller: to keep equation-based relations; to make the modeller's subjective assumptions explicit; and to minimise the necessity of such assumptions.

The representation and analysis of the scenarios used by the Environment Agency for future projections provides an example of how MAS can be used successfully where other modelling techniques cannot.

In recent years, research on MAS has enabled the development of the tools that were used for constructing and testing the model described herein. Social simulations in general have benefited from this important progress in computing, both in terms of interface and processing power. While they have dealt with various kinds of data before, the difficulties of representing an artificial society with the interactions amongst its members have benefited significantly from improvements of hardware and software capabilities.

Social simulations and Multi Agent Systems can be used in order to model the Environment Agency's forecasts. Such a model will then help address the question of whether the forecasts are consistent, demonstrating at the same time the capabilities of MAS.

This research was undertaken according to the following steps.

Chapter 2 contains a description of the modelling target and the justification for the self-imposed limitations over the model, in particular the economic aspect of the water demand. It states that in this work, water management is considered as equivalent to water conservation, defined by Baumann, Boland et al. (1998) as "any beneficial reduction in water use or water losses". It also explains that the pricing aspect is not included in the model developed because the effects of metering upon a household's water use are not yet known well enough. This chapter also includes a presentation of the context and the current state of the literature regarding water demand management. The literature review shows that strictly qualitative and strictly quantitative methods have been used with little success: when all models have been run with data that were more recent than those in the original sample (which was used to generate the model), models originally providing the best results have been providing the worst ones. Finally, this chapter also presents the two main actors in England and Wales for water demand management, the Office of Water Services (OFWAT) and the Environment Agency, accompanied by the details of the four scenarios used in the Agency's forecasts.

Chapter 3 describes methods and tools used to evaluate scenarios. It demonstrates via an analysis of real data that the underlying distribution is highly non-normal. The presence of leptokurtosis, together with additional knowledge about the process, point towards the possibility that the distribution has no defined second moments. As this is a requirement for the use of many statistical techniques, it can be a reason for the failure of quantitative models presented in chapter two. Moreover, the properties of the system analysed and the fact that it generates power law distributed data lead to the conclusion that there is a phenomenon of self organised criticality present.

After the detailed presentation of Multi Agent Systems, chapter three describes the modelling stages. It presents the links between the observations of the target system, devising a conceptual model, and a computer model, to help understand how the use of MAS and object orientated programming minimises the loss of information and the inclusion of implicit assumptions. This chapter concludes with a presentation of the language used in this research. SDML (Strictly Declarative Modelling Language) is based upon the Strongly Grounded Autoepistemic Logic, which provides an internal consistency to the model. Decisions made by agents can be analysed and their sources found via the database kept throughout the simulation.

Chapter 4 presents the different scenarios, detailing their similarities and differences. As households are represented in a MAS, their characteristics and the way they interact with the other households depends on the governance system and the social values, which are the drivers for each scenario. This chapter also specifies the definition and representation of innovators in the context of water demand and appliance adoption. While most representations use the traditional Bass model (Bass (1969)), the necessity to know the size of the market in order to compute the adoption of innovation prevents its use with this MAS. This results in a different approach based on the agent's endorsements, *i.e.* the agent's personal and subjective beliefs with which they will get to know new products, include them in their list of choices, and make a choice within that list. It is followed by the explanation that governance and social values are represented through endorsements, and the data used as a reference in the model (climate data) or for the assessment of the model (water consumption estimates). Then is a description of the components and processes of the model, categorised according to the main object each relates to: the Agent, the Environment, the Interactions (within the model), and the Organisation (in the model). An overview of the model structure and sequence concludes the chapter.

Chapter 5 describes the generation of scenarios, and provides results on their sensitivity to changing parameters. Scenarios are distinct according to the governance system and the values in the society. The governance system and social values have consequences on different aspects of the model, the four drivers put forward by the Environment Agency: the water policy, the technology, the behaviour, and the economics, which are all included in the model. Making assumptions on these aspects generates consequences used as statements that, together with endorsement values, characterise each scenario. Running the simulations for every scenario provides a first opportunity to test the generated data, and demonstrates that the kurtosis (a measure of the peakedness for a distribution) is far from a normal distribution indicating that the underlying data-generating process may not have defined second moments. The undertaking of sensitivity analysis that follows begins with assessing the impact of the structure, leading to the conclusion that overall patterns observed did not seem significantly influenced by the grid structure. The density of agents is more significant, as it requires a minimum density for the processes to take place, but further variations do not lead to changes in the underlying distribution of the water use data generated. On the other hand, the visibility for every agent is an important parameter. As the vision range increases, so does the information available to the agent. With more information comes an increased choice of actions, and as a consequence, potentially different outputs. The specific analysis of innovation diffusion concludes this chapter, showing that the simulated results are in accordance to standard theory and observations.

Finally, chapter 6 presents the conclusions comparing the data obtained from the different scenarios. Direct comparison with the data and assumptions provided in the Environment Agency's "Water Resources for the Future – A Scenario Approach to Water Demand Forecasting" is not possible, mainly because of the difficulty in representing miscellaneous use, and also because population growth is not included in this research. Simulation results have been presented and discussed with Rob Westcott, Policy and Process Advisor for Water Demand Management, who took part in the writing of the Agency's reference publication mentioned above.

To sum up, this document presents in turn the background to the problem (chapter 2), the limitations of standard techniques and the principles of Multi Agent Systems (chapter 3), the assumptions and processes of the model (chapter 4), the details of scenario implementation and sensitivity analysis (chapter 5), and the discussion of these results together with comments from the Environment Agency (chapter 6).

It is now time to introduce the original purpose of the scenarios, water demand management in England and Wales.

2 Context and literature

2.1 Introduction

This chapter introduces the concept of water demand management and describes the institutions involved and the origin of the scenarios they use for their forecast. The argument presented is that water demand management is necessary in many developed countries but the dynamics of water demand are not yet well understood.

Many important decisions have been taken in order to adjust the policies and capacities of the water supply industry to both the changing needs of the consumers and the environment. Due to the fact that some of these decisions will involve projects that would take a long time to be implemented, they must rely on a sound analysis of what the situation will be. But predicting the evolution of demand is not obvious. Predicting consumer behaviour in general has been the focus point of marketing and policy research. The present research endeavours to assess the forecast via scenarios in the particular case of water demand.

The interactions amongst agents, the institutional environment, and the diffusion of innovative appliances are the driving components of water demand. They will be specifically addressed later, but have an immediate impact upon the form of this work. The analysis required to deal with this subject is consequently multi-disciplinary, as it involves knowledge of environment sciences, marketing, and sociology. This makes the issue interesting, but also less likely to be adequately addressed through only one of these multiple aspects. A presentation of how the literature can treat this kind of issue is provided below.

The first section presents the details of the various definitions and underlying consequences of management. It is followed by a description of the particular side of management that is involved in this work and a brief list of the various approaches that can be used. An introduction of the different actors in the question follows, providing further information on the particular institution which is the Environment Agency.

2.2 Water management

This section presents the different views of water management, and the definition that will be used follows, explaining why some water management methods or issues are not developed in this work (such as water supply management, pricing policies, and water quality).

2.2.1 Definitions of management

To define management is quite difficult. The Webster dictionary defines it as:

1. the act or art of managing: the conducting or supervising of something (as a business)

2. judicious use of means to accomplish an end

3. the collective body of those who manage or direct an enterprise

Management is a vague concept to apprehend. It requires the accurate definition of the end, and the knowledge of available means. The means will be discussed further, focusing here on the “ends”.

Essentially, this is where the differences in the literature appear. The definition loses here some objectivity, as defining the “ends” of management requires taking into account economic theories or philosophical concepts. Amongst these concepts are sustainability and social welfare. The introduction of these two concepts, as well as the balance between the two poses problems because of the challenges in measuring such outcomes. Taking into account social components can drive the problem into an ideological debate. In the present case, management in a context such as natural resources is mostly understood as a reduction of the ratio of costs to benefits for the society. From then on, the different measures of costs and benefits for a society could lead to other possibly similar debates of definition, measurement and representation. As one can see, the careful definition of management is not easy.

There are several common uses of “management” in this context and that is why trying to give a global definition of it is probably ambitious. These uses mainly refer to the way water is provided.

In developing countries, water management refers to methods of allocation or repartition. The aim is basically to provide enough water to everyone. It is a huge task, and any progress is marginal on a global scale, but very significant at the scale of the user.

In developed countries, water management refers more to these complicated definitions, including welfare and social components in the reflection, rather than the single issue of providing water to those whom are deprived of it. What matters then is how water is used, its supply, repartition, and waste. When a critical level of available water is reached, a fear of depletion arises. That is when the management starts involving sustainability and when reducing the demand matters most. In the following work, it is considered that water management is equivalent to water conservation, since there are already ways of distributing it, and “water conservation is any beneficial reduction in water use or in water losses” (Baumann, Boland et al. (1998)).

In the following section the two possibilities of water management are presented, and the opportunity is seized to describe a simple presentation of the meaning of management throughout this work.

2.2.2 Managing Water demand or managing water supply

The reasons for focusing on a particular side of water management need to be expressed.

Firstly, the original issue is the impact of climate change in some European countries, and specifically in a region of the UK (Downing, Moss et al. (2000)). The consumers have the central role in the questioning. Looking at their behaviour and its changes in the event of climate change, the possibility of changes that could have some impact on the demand is not considered, and the demand is unconstrained[1], apart from specific occasions and actions taken by the institutional body. This allows a focus on the demand itself. It is mainly validated by historical events.

Also, without the climate change issue in mind, one could realise that water supply management is generally driven by the necessity of improving the supply of water. It is then either an improvement on quality, or quantity, or both (Twort, Law et al. (1985)). It is assumed in this research that the quality requirements for water from the appropriate institutions are met. This is driven by the fact that although a failure in meeting these requirements would impact on consumers, it is up to institutional bodies to solve this problem. Hence, water supply is widely treated in the literature on developing countries and sustainable development. Again, it is not the case here, even though sustainability is clearly becoming a concern for everyone.

The needs for water on a worldwide scale are growing. And the last decades showed increased concerns over natural resources scarcity. The examples are numerous, from the Malthusian approach and the simple ratio population / natural resources, to the Club of Rome and its equivalents, adding the different options of production and pollution.

The only common part amongst these is that water is seen as an economic good. But one must distinguish between the necessity of water and public water supply. Different uses have different elasticity, hence the tendencies to use water-pricing policies to influence the level of water demand[2] as shown further.

2.2.3 The context of water demand management

The current literature in water demand management in England and Wales is frequently the result of research undertaken by the institutions involved in the field, mostly the water companies and the regulators. See Butler and Memon (2005), the Environment Agency's report on variable flush

[1] In other words, it is considered that the demand for water is the actual consumption of water.

[2] As some water uses have an elasticity with respect to price greater than one, *e.g.* for lawn and garden areas, an appropriate pricing policy could reduce the expenditure.

retrofitting (Environment Agency (2005)), OFWAT's report on “security of supply, leakage and the efficient use of water” (OFWAT (2005)), WRc’s Sustainability of Water Efficiency Measures project (WRc Plc (2005)).

Regulators expect the companies to have sufficient knowledge to make sound assumptions in their forecasts, but they also need this knowledge to be in a position to assess the current situation and the other stakeholders’ positions and actions. Companies need to increase their knowledge. That is why for example they try and quantify the effects of simple measures over water demand, and how they might evolve over time.

One of the main challenges with demand management is that it is a soft approach. A hard approach would consist in building structures such as dams or reservoirs. This would help with securing the water supply, and can be relied upon as it reacts to various constraints or situations in a predictable way that engineers can describe. The soft approach, based on changing behaviours and enabling water efficiency by promoting different appliances, is more sensitive to everyday variations and there is little certainty about how it might change over time. For that reason, water companies and regulators undertake research projects, trying to understand future trends in water demand.

For example, a promotion campaign for cistern displacement devices, or a trial of retrofitting variable flush mechanisms to existing toilets might be reasonably affordable to a water company, but the uptake of the method, while the campaign is ongoing and after, will vary. How much water tools like these would save on average, and for how long, is the subject of many projects over the past few years, and every actor in the field recognises the need for more investigation.

Butler and Memon (2005) provide an exhaustive view of the current demand management knowledge and challenges. The Environment Agency (Environment Agency (2004)) assesses water companies resources plans, particularly the main aspect of their duties, the security of their water supply.

This has to take into account the evolution of water demand following the companies' actions. The model developed in this work relates to that forecast.

Other techniques have been used for representing natural resources management:

For example, Howitt, Reynaud et al. (2002) have applied a set of calibrated stochastic models to North California water supplies. However, their research does not differentiate between decision makers and customers, although they seem to obtain significant conclusions on the importance of some components of the model rather than others (namely intertemporal substitution preferences rather than risk aversion or the discount factor).

On a larger scale the SORTIE model by Landcare Research (2002) developed to investigate forest dynamics is based on probabilities. It attempts to quantify the natural processes of forest recruitment, growth, and mortality, adding into this the effects of herbivory by exotic pests.

In addition to approaches such as probabilities or system dynamics, agent based models seem reasonably suitable to tackle the different aspects involved.

Natural resources and environmental issues in general have been the subject of multiple research using modelling techniques based on Multi Agent Systems. Bousquet, Lifran et al. (2001) present an overview of the different uses of game theory and agent-based modelling in management of natural resources. Barreteau, Bousquet et al. (2001) suggests that agent based modelling together with role playing games can provide a way to explain the contents of the model, validate it, and communicate around it. Another example of such a mix is in Etienne (2003), where vegetation dynamics and agent's behaviour have been implemented to assess negotiation process in sylvopastoral management planning.

The sole use of Multi Agent Systems is also present, for example in Etienne, Le Page et al. (2003), where the authors describe how MABS can be integrated into a step by step approach to build land management scenarios. Another example of land management can be found in Polhill, Gotts et al. (2001), where the authors compare agents' strategies and their results on land selection.

Scenarios as such are not the only option to try and represent uncertainties. There are other methods available.

The use of scenarios, as pioneered by Shell, is growing. They are best used when they are devised while remaining aware of the reason for their creation, keeping in mind their goal assists in ensuring the robustness of the approach (Schwartz (1997)).

As expressed in Fahey and Randall (1997), the most important steps in scenario planning are:

- Decide on the key question to be answered by the analysis
- Set the time and scope of the analysis
- Identify major stakeholders / objects involved
- Find key uncertainties
- Define the scenarios and identify extremes
- Write out the scenarios
- Assess the scenarios, developing appropriate methods if required.

Other possible approaches for dealing with uncertainties include contingency planning and sensitivity analysis. While the former tends to focus on a single (often major) issue or uncertainty, the latter tends to assess how a model reacts to changes in the variables or parameters.

Sensitivity analysis frequently involves a large amount of work, trying to cover many combinations of values, but the usefulness comes mainly when expected changes remain simple. When the importance (and possible number) of variables increase, sensitivity analysis becomes more difficult, and less meaningful. In more complex environments or models, a scenario will, from a set of assumptions, provide a result from major changes in the dynamics of the model.

2.2.4 The pricing aspect

This research will not focus on the financial point of view. This part presents the main ideas and explains why they are not considered. The financial side of water management is theoretically the easiest to change, and also a very efficient one, as the different international experiences show.

A point to be made is that the definition of water management adopted is (purposely) not appropriate for social or economics debate. Despite the existence of successful examples of financial policies, it is not a substitute for demand management, since they differ not only in their application, but also in their meaning. The second one is that economically, the results depend very much on the specificities of the water uses, and probably even more on the characteristics of the households themselves (Rees, Williams et al. (1993)).

Financial pressure can be easily (at least in many countries other than the UK) applied onto households. As an economic good, water demands will react to water prices. They rely on monetary incentives and disincentives to relay accurate information to the households about the value of water, to promote better water use practice (OECD (1999), Pezzey and Mill (1998)).

The basic economic theory argues that the more expensive a product gets the less the demand. This implies several assumptions on the underlying characteristics of that good.

First the concept of elasticity must be introduced. It refers to the extent to which the demand will vary according to variations of some other economic indicator. There are different variables generally linked with the demand of a product: its price, and the available income. They respectively qualify the substitution effect and the income effect. The former is for most goods positive, since as their price rises, other equivalent products can replace them. The latter is also generally positive, although there are several distinct situations then. Either it is less than 1 and the proportion of the income used to buy this product is diminishing, or it is more than 1 and the demand proportionally increases with the income. The last possibility is a steady demand with respect to the income.

This concept of elasticity is very important, since different uses of water will not have the same elasticity. For example it is easier to reduce the water use for gardening purposes than it is to reduce the water for hygiene purposes.

Second, using that concept, it must be expressed that the good is an ordinary good. There are specific ones that can see their demand vary in different ways with respect to the variations of its price, depending generally on the income.

Also, the appropriate values of elasticity must be known for every use, in order to find the specific pricing policy that will give the expected results. It is hence necessary to know the household income[3], and the part devoted to some specific water use. This difficult task would need knowledge of the characteristics of the relevant area that could well be out of reach from the current classifications like ACORN.

Finally, in the UK the water prices for domestic use cannot be changed easily. There is a regulator for the water companies, since they need to have the OFWAT authorise them to have their prices changed. One must keep in mind the fact that the economics of the “market for water”, due to the nature of the good, that is common, fragile and necessary, cannot be taken independently of other matters. For example, they depend on the political regime, and the choices made by the government. It is extremely difficult to debate about strictly economical matters, since these have extensions (causes and consequences) into other fields. They are therefore limited not

[3] If the households are not rich enough, water might become a Giffen good, *i.e.* a good showing an increase in demand as its own price rises, and this kind of policy would become useless, and inequitable.

only by their feasibility, but also by the acceptance of the ideas or theories they rely on.

Consequently, the focus on pricing issues for water demand is not only relying on other assumptions about the good involved, it also requires assumptions, appropriate research and estimation of the elasticity of that good. In addition, the representation of the various levels of demand relative to the price would be themselves relying upon economic theory and a most likely debatable statistical analysis. Therefore, it is not going to be one of the aspects involved in this work. Although the income levels can play an important role in the demand for water, they will be represented later by the adjustment of parameters in the different cases.

2.3 Demand side management

In developed countries, a lot of effort is now turned towards the management of water. The concern is that the water demand has been increasing, while the available quantity of water is limited. As water supply must meet that demand it is the whole water system that is endangered. This research is aiming at the demand for water not as a way to help reducing actual demand as such, but more generally in order to improve our understanding, and then being able to use that understanding to better adapt the policies to the demand, or find the appropriate policy for a specific aim, and use that understanding to debate possible future situations in various cases of climate change (Hulme and Jenkins (1998)).

In many cases, the increasing interest in demand side management is due to its relative low cost and flexibility (Barnett, Morse et al. (1963)). This section presents the main differences between demand and supply management, as well as giving examples of the former in the literature.

2.3.1 Characteristics of demand management and supply management

Water demand management and water supply management have the same target (as a product). But they are different approaches and as such have different means and ways to influence it. It is important to note that they are not competing against each other, but are complementary to each other, both in terms of supply meeting the demand, and in terms of adapting the structures for the evolution of the system.

Because they are on opposite sides of the market, their components (quality and quantity), structure (*e.g.* the timescale they deal with), situations (active or reactive) and tools differ.

In the current study, the quality of water provided is not a priority. It is assumed as meeting the minimal requirements from the regulators, but no more, since water quality is not really influencing the demand. Apart from the exceptional case where the water would not be drinkable and hence the appropriate demand would be null, there is no real influence of the quality upon the demand itself. Also, there is no competition amongst water companies in terms of market shares. One company will not become the provider of a specific household just because they provide better water. For water supply, the quality of water is quite an important factor. Being analysed from the company's side, it has a direct impact upon the deliverable quantities. In that sense, water demand management does not have to deal with water quality issues, while water supply has to.

Being in a developed country, the quantity of water that is used is set by the demand, rather than by the supply (apart from rare occasions). It would be logical to start acting on what sets the demand instead of reacting to a phenomenon. Moreover, the relevant structures involved are on different scales, both financially and in terms of time. For example, generalising metering for households is a prerequisite for many demand management policies, as well as a tool to better forecast the supply for the water companies themselves. Where a demand side policy would use metering and pricing, being flexible, a supply side policy would build or remove additional dams and reservoirs, being permanent.

Since there is a sequence in the system, from demand to supply, succeeding in understanding and eventually influencing demand is being active. The water companies are trying to forecast the demand in order not to remain reactive, being able to plan for their own development.

For short-term management, the financial angle is certainly the most effective on households, although it has its limits. Raising the price of water helped reduce the demand in most cases. It is not the most appreciated or the most equitable approach and there are surely alternatives. Actions and influences must be evaluated in order to influence them in due time.

In the medium term, demand management would educate, raise the importance of knowledge and responsibility.

It is actually in the long term that the knowledge brought by demand management can have the most impact. Because it leads to questioning the behaviour of households, and tries to find influences, patterns, and explanation, it reduces the uncertainty the water companies face when devising future important investments.

The current knowledge in water demand management is relatively centred upon the different pricing policies available and their impacts.

2.3.2 Partial approaches

The water demand management literature in UK in particular, and in Europe in general is quite sparse. In the existing literature, two different approaches are used to deal with water demand management: a qualitative one (used in surveys or interviews), and a quantitative one mainly based on econometric studies.

2.3.2.1 Qualitative approaches

Qualitative research relies on the collection of qualitative data via techniques such as interviews, notes, or observations. These methods often produce very descriptive data, intending to describe a phenomenon in textual or spoken form.

Recent research projects (for example Water cycle in New Developments[4], or preliminary work from Lancaster University) are investigating the reasons for which people use water. Going further than how the water was used, their aim is to improve the understanding of why it was used in such a way, and is therefore addressing the issue of the perception of water by its users. In this interpretive process, the researchers use interviews with customers from a specific water company to obtain the information required.

Carefully selected customers are contacted by their water company to ask if they would be ready to discuss water use. When they accept, they are later contacted by an interviewer to agree a meeting date at their house. During the meeting, the interviewer will questions to guide the conversation, while taking notes / recording it, in order to capture and synthesise the perception and the underlying reasons for using water. This often leads to assessing what do people think is the purpose of a bath (which is often seen as a way to relax), of a shower (similarly, a fast way to get clean), sometimes even what does clean / dirty mean, or when are clothes “clean” or “dirty”.

The data accumulated is valuable and informative, but comparisons between different households are rarely possible, as they have different beliefs that cannot be measured (literally) against one another.

The qualitative approach is mainly dealt with in surveys. It is trying to link water consumption ex-post to qualitative characteristics, like the socio-cultural patterns, or income levels, but also the influence of the area, such as the urban / rural characteristics.

One can distinguish two different steps in surveys. While the first one is trying to understand the consumption structure and patterns, the second is more focused on trying to devise and evaluate policies related to water demand. In the late 80s, several studies were undertaken in the UK, for many of which the issue of metering was central. In order to evaluate its potential effects upon consumption, this consumption had to be analysed and its

[4] Cf. http://www.wand.uk.net/

drivers understood. The SODCON is a comprehensive survey launched in 1994 of domestic water consumption in the East Anglian region. Its goals were to provide notably an explanation of the factors that determine unmeasured demand, details of the patterns of water consumption, estimates of demand responses to various tariffs structures, and detailed cost of metering. The descriptive statistical analysis provided an important database of information and constituted a starting point for an analysis on a household level (Edwards (1996)).

In 1990, Tate published an in-depth review of water demand management in Canada for four water use sectors: municipal, industrial, agricultural, and non-withdrawal uses (Tate and Canada Inland Waters Directorate (1990)). Their review gives a global idea of water demand management, dealing with implementation techniques and evaluation criteria of the result.

The implementation can be achieved through different methods, such as:

1. Economic techniques: monetary incentives (rebates, tax credits...) and disincentives (higher prices, penalties, fines...) to relay to users accurate information about the value of water. Prices send signals to both consumers and producers about the economic value of the resource use.

2. Structural and operational techniques: structural techniques are those that alter existing structures to achieve better control over water demand (metering, recycling...), whereas operational techniques are actions by water users to modify existing water procedures to control demand patterns more effectively. They recommend water saving devices, and even increased prices to push towards maintenance in the household. They also evoke a dual water system, with grey water for secondary use, and then save some chemical pollution.

3. Socio-political techniques: it refers to policy and related measures that can be taken by public agencies to encourage water conservation. They mainly focus on water pricing, public education, and privatisation.

Of course, any policy has to be evaluated. Several criteria can be used for that purpose.

1. Technical evaluation: it may involve “engineering efficiency”, basically measuring the ratio water pumped into a system / water delivered to consumers or end uses, but also economic and environment factors.

2. Economic evaluation: engineering efficiency cannot address the value of any specific use of water (residential use / industrial use). Economic efficiency in resource use is for them a major economic policy aim (maximum productivity).

3. Financial evaluation: the rate of return should be greater than the cost of the capital.

4. Environmental evaluation: quality of life, decreasing wildlife populations, aesthetics, etc.

5. Social / political / institutional evaluation: according to Tate (Tate and Canada Environment (1989)) political acceptability was probably the most important criterion in the setting of water rates. Equity of the payments is also a concern. Though they have not found yet the absolute criteria, the authors argue that equity should drive demand management measures.

These ideas raise new problems about the evaluation of a policy, and although it might be easier to assess a policy purely in terms of water use, it is harder to evaluate its level of equity or environmental effects. For all that, water demand management is looked at for some given purposes. In Canada, its essential feature is the attempt to make water development funds cover as many initiatives as possible (Brooks, Peters et al. (1988)).

The recommendation of a cost-benefit analysis is of course difficult when it deals with economic and financial problems (*e.g.* the cost of improving the water-related part of municipal infrastructures). This may be due to the uncertainty on both the final cost of necessary investments (as well as the fact that they are not always paid by the same part), and the evaluation problem of the results above.

Consequently, as one can see, the pricing policy and the way to implement the appropriate measures are the main issues here. It is a more static view than mathematical modelling in that it is looking at the relations between parameters or characteristics of the participants. It is trying to build a theory, or at least make assumptions on these links, but it is most of the time unable to validate them and their eventual evolutions.

2.3.2.2 Quantitative approaches

Econometrics is the main type of quantitative model of water demand management. This consists in linking "external" data to a particular water demand (average, highest, etc.). Most of these are weather effects. Those commonly used are:

- Temperature: average daily maximum, average daily mean temp, average daily temperature 7 days before the peak 7 days, average daily temperature during the summer 6 months, highest daily temperature during the peak 7 days, average daily maximum temperature during the peak 7 days (Males, Turton et al. (1979), Herrington (1996)).

- Rainfall: total monthly rainfall, total rainfall during the peak 7 days, average monthly summer rainfall, number of days since 2 mm of rainfall or more, weighted rainfall measure 7 days before peak, weighted rainfall measure 10 days before peak

- Sunshine: average daily hours of sunshine, average daily hours of sunshine during the 7 days before peak, average daily hours of sunshine during the peak 7 days, average daily hours of sunshine during the summer 6 months (Herrington (1996))

- Other weather characteristics: frost, soil moisture deficit (Males, Turton et al. (1979), Herrington (1996))

The type of data that will be used in a model will depend on the time horizon involved (months, weeks, seasons, etc.).

The Herrington report (Herrington (1996)), investigates which climate variables seem to be more closely related to water demand, and the quantitative responsiveness of the latter to climatic changes. However the water shortages observed might have several explanations. It can be a “wrong” estimate of water consumption, not being an unrestricted demand. That is why some extreme data are removed from the study. This is not without consequences though[5]. In the UK, despite the importance of the climatic effects upon the demand, no data are available. Hence the reference to some studies and their treatment, making use of annual average data, selective or consecutive weekly consumption data under different forms, and series of peak seven days ratios. Unfortunately, the UK led studies seem to have statistical problems, from suspected multicolinearity to the inadequacy of the methods used (*e.g.* non-stationarity in Smith, Turton et al. (1978; Smith Robert, Turton et al. (1978)). Still the conclusion from every study is that sunshine seems to be the least useful variable (although it is also the least tried), whereas both rainfall and temperature are often significant.

Temperature and moisture deficit vary a lot in the studies, which is not very surprising due to their very different natures. But as for rainfall, except for some specific classification, those that can be compared show some similarities: for 21 of the 22 elasticities taken into account, they are symmetrically distributed within a range from –0.013 to –0.110, centred around –0.075 for US and –0.047 for Australia. Note that this is the same order of magnitude as the UK rainfall elasticities also quoted (-0.04 and –0.06).

[5] The removal of extreme data, as indicated later, might change the whole nature of the analysis, and reveals moreover the choice of adapting the data to the technique, or the technique to the problem.

Some other noticeable factors, on top of rainfall itself, are the number of rain days and the number of days since the last significant rainfall.

Unfortunately there are flaws in this approach which result from the forecasting limits of econometrics.

In econometrics, the explanatory value of an estimation is expressed by the “goodness of fit” function. This is because it compares the data generated with the original ones; it is *the* most important indicator for the econometric model. The issue being that there are many different goodness-of-fit testing procedures producing different results. Hence the choice of the function is difficult and certainly of high importance.

Also, amongst the multiple econometric models used by then, Mayer (1975) showed that the results of several econometric models were highly specific to the period they were computed. This issue probably arises because no behaviour or interaction itself is taken into account by an econometrics model. The lack of interactions in the long run between components of different scale is certainly an issue, as shown below.

Herrington (1996) reached the same conclusion, noting that the best estimations for the period from 1960 to 1980 “gave poor results for that part of the 1980s decade where the absence of supply restrictions allowed the exercise to take place”. The conclusion was even stronger, noting that “in general, the better the original forecasting, the worse the prediction” (p.78).

Attempting to describe the numerical relationships between key economic forces such as capital, interest rates, and labour, econometrics is not necessary appropriate for every case. Econometrics has great difficulties dealing with the issues of interest here, while a modelling approach can be successful with a Multi Agent System.

The distinction made in the literature is based on the fact that that while most of the necessary analysis of the consumer behaviour is qualitative, relying mostly on in depth interviews, when it comes to water consumption, most of the existing studies are empirical and quantitative. The extent to which a different kind of modelling offers the possibility to overcome this cleavage between qualitative and quantitative issues is one of the purposes of this work.

These approaches are only dealing with some aspects of the problem. The current issue is not single faceted though, and that is why each of these methods can only bring a partial view of it. Hence the point to demonstrate here is that water demand management based on understanding the social influences is a viable and complementary approach.

2.3.3 Examples of water demand management

In North America, several different techniques of water demand management have been used.

The economic techniques rely solely on prices and have been presented earlier. It is working partially because water is very cheap, and immediately available, unlike other liquid beverages like cola (1500 times more expensive), milk (1900 times) and so on. Some structural changes are necessary, such as the installation of generalised metering, and leakage detectors, and improving sprinkling requirements.

Socio political techniques refer to the measures and policies taken by the regulating institutions, which are generally public agencies.

They do not represent a single answer to a problem, but a range of answers, since they can be viewed and used as an interrelationship of techniques, as described by Postel and Worldwatch (1985): “Successful efforts to curb per capita demand invariably include some combination of water saving technologies, economic incentives, regulations and consumer education. These measures are mutually reinforcing and they are more effective when implemented jointly”.

In Canada, where these techniques have been applied, the inelasticity of the fixed costs of providing water has created a strange phenomenon. While households were reducing their demand, the water companies could not reduce the corresponding bills, due to the presence of these costs. The implementation of a dual pricing structure solved the issue, having one block pay for the fixed costs of system operation, and the second block being a constant unit commodity charge.

To some extend, many of the developed countries already have a kind of demand management policy in place. It generally is under the form of metering and the associated price scheme. This policy is adopted by some developing countries, while some like Belgium, Greece, Italy, Japan, Portugal and Switzerland are using increasing charges[6] to apply the same equity principle that the rich use more water than the poor.

2.4 Actors and purposes

The current situation for the water supply in the UK involves different actors. From the consuming households to the regulators, there is a hierarchy in the water supply process, with regulation parties and executive parties. The executive parties are the water companies providing water, while the regulative parties include the various institutions that are imposing necessary requirements.

2.4.1 The different actors in water demand management in England and Wales

In this work the word stakeholder is used as a generic term. It covers the households as well as the different institutions, including the water companies. It is necessary to specify here their nature and aims.

The Environment Agency is the central body with responsibility for long-term water resources planning in England and Wales. Part of its duty is "*to conserve, augment, redistribute and secure the proper use of water resources in England and Wales*" (Environment Agency (2001)). It involves different aspects of water, such as navigation on some rivers, flood defence, waste minimisation, and water quality. Its aims are multiple. Introduced by the water resource act in 1963, its powers and role strengthened with the water resources act in 1991. In 1995, its duties were extended under the

[6] Variable charges are often encountered as part of an increased block tariff scheme, where the volume charge per unit increases as consumption rises

Environment Act to “contribute to sustainable development and to promote the conservation and enhancement of the natural environment”, as well as to “(…) take account of costs and benefits in exercise of its functions, and to have regard to the economic and social well-being of rural communities” (Environment Agency (2000)).

It is responsible, amongst other things, for setting up drought plans, the review of water companies’ water resources plan and drought plans, and setting out the Agency’s vision for the long-term management of water resources in each region as well as globally for England and Wales.

Because of its institutional status, it has additional responsibilities, expressed through three principles (Environment Agency (2000)). The first two principles are the recognition of the need for development of new water resources as well as the value of water in the environment. The result is that increasing effort must be applied to the efficient use of water, as more resources development is required. The robustness to uncertainty and change means that it is necessary to identify a way forward that is both flexible and robust to a range of possible futures. Finally, the precautionary principle states that when there is uncertainty about the consequences of an action, decisions should be taken cautiously and the source of the uncertainty should be clarified.

The Office of Water Services (OFWAT) is the economic regulator for England and Wales. The water companies produce plans of how they intend to develop and manage their supply system. The OFWAT determines prices to customer so companies have sufficient income for the parts of the plan that are considered justified.

Water companies provide the public water supply. Each of them must develop and maintain an efficient and economical water system for water supply in its area. They “*make decisions about the way they want to manage their supply-demand balance according to the values of the company and their understanding of the needs of their customers*” (Environment Agency (2001)).

It is not unlikely that institutions and water companies themselves use scenario approaches in order to assess the impact and/or evolution of specific variations of driving components on their respective objectives. The Environment Agency has taken some scenarios from governmental studies to devise various likely environmental futures for England and Wales. It is on these likely futures that some important decisions can be taken and they therefore need to be as sound as possible.

2.4.2 Scenarios and environment

2.4.2.1 History of Scenarios

The user of scenarios for planning is quite common. Used by industries, nations, shop chains, technologies, they are a specific approach. While dealing with uncertainties, one can either consider the whole (frequently continuous) range of alternatives, or specify particular cases that would capture key properties of this range.

From their appearance in the literature in the 40s, scenarios have been more and more frequently used. Past data and previous assumed relationships were extrapolated to generate scenarios till the 80s, when the studies in innovation and diffusion showed that the future is dependent on changes in social and economic systems where paths are multiple, and indeed not fixed, but evolving themselves. The goal of scenarios then became the analysis of some trends within a “possibility space”, and eventually the reduction of that space finding potential discontinuities in order to improve the decision making process.

The first example of the use of scenarios for forecasting purposes is from Shell in the 1970s. A major international company mainly focused on petrochemicals, they needed guidelines in order to constrain the uncertainties, and therefore plan in accordance to a specific evolution of the world.

They needed a view that could be used specifically, although being devised on a more global point of view. They started developing scenarios that would present a consistent situation regarding sustainability and emissions. Scenarios were then “*carefully crafted stories about the future* *embodying a wide variety of ideas and integrating them in a way that is communicable and useful*"[7].

Not dissimilar to game theory, a scenario approach consists in weighting the eventualities, providing more than a mono-disciplinary insight, to achieve a synthetic, plausible description of a future.

Scenarios take into account a wide range of phenomena and ideas. Due to the number of aspects included, the analysis undertaken is hence different to game theory, which is composed of an in-depth analysis of an often simple problem.

The process of devising scenarios has a focus point on the moment the uncertainty is defined, and different paths can be identified. These paths, or branching points, will constitute the basis of the scenarios. In the case of Shell, the selection of the paths investigated was made "*on the basis that they help […] to examine the risks and opportunities for policies and strategies*" (Shell (2003)).

Based on a sensible definition, scenarios would provide the description of a plausible situation and be the ground of a discussion regarding the policies, actions, reflections and commitments that it raises.

As expressed by Ged Davis, "*scenarios are particularly useful in situations where there is a desire to put challenges on the agenda proactively (for example when there are leadership changes and major impending decisions) and where changes in the global business environment are recognised but not well understood (such as major political changes and new emerging technologies)*" (Davis (2002)).

The benefits of scenarios are even more visible when one begins to imagine the many aspects of a problem involving natural resources, and society. As expressed earlier, the interconnections between the components of the system studied can lead to increasing difficulty, should one try to take

[7] Cf www.shell.com/scenarios

into account the many influences upon what would become the structural of one's representation.

Scenarios can be refined and tuned with respect to their purpose.

It is the case for climate change and social behaviour through time. Scenarios are used because the future is uncertain, and the ability to adapt to these future changes might have effects upon the longer term (*e.g.* technological changes).

2.4.2.2 Scenarios for the Environment

Scenarios have already been used for climate change issues. For example the ECLAT international project[8] is focusing on the environmental impacts of climate change and climate change modelling. Artificially created scenarios integrate uncertainties at different levels: the theories they are using (*e.g.* marketing or sociological), the data (through collection and treatment), the assumptions that are made in order to generate the scenarios, and consequently, the scenario itself, that puts these components together, and for which some options are chosen while others are discarded.

[8] This Concerted Action Initiative has two specific objectives: to improve the understanding and application of results from climate model experiments, and to monitor the availability of results from new climate change experiments performed in Europe and worldwide. For more information see http://www.cru.uea.ac.uk/eclat/

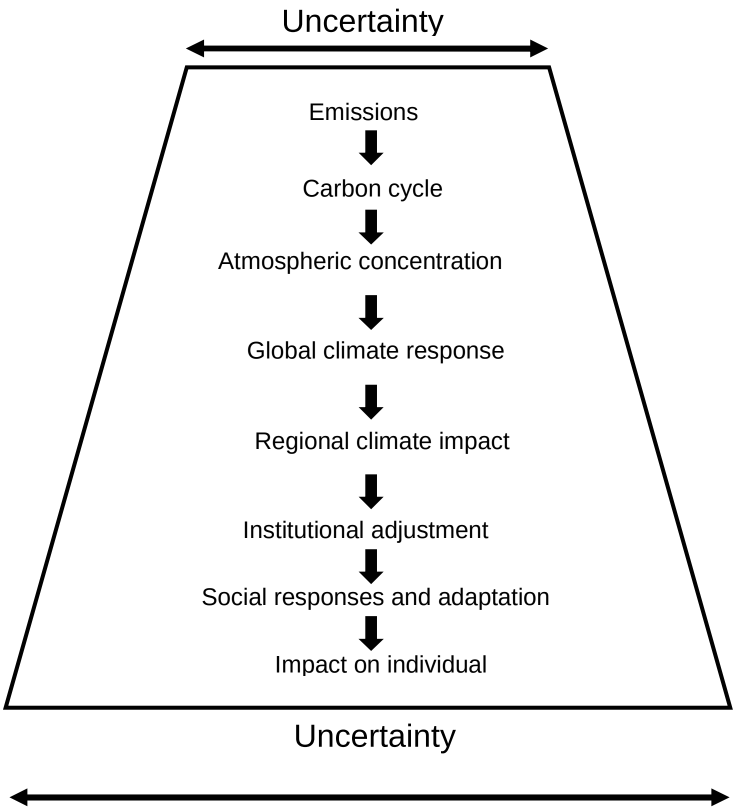

Figure 1: Addition of uncertain phenomenon

This diagram from the CCDEW report by Downing, Butterfield et al. (2003) shows the increasing uncertainty as the different components are integrated into a model.

Multiple scenario frameworks are built on the Environmental Futures scenarios from the UK Foresight programme (Berkhout and Hertin (2002),Berkhout, Eames et al. (1998), Department of Trade and Industry (1999)). This programme tries to look beyond normal commercial horizons to identify potential opportunities from new science and technologies.

The Foresight Future scenarios have been created for the UK Foresights programme, and the project was funded by the Department of Trade and Industry, as well as the Department of Environment, Transport and the Regions. The research was led by the Science and Technology Research Policy for the UK Foresight Programme (SPRU) from the University of

Sussex. These scenarios represent a tool for forecasting, enabling institutions, businesses, and more generally users, to apprehend possible futures in order to improve their decision making.

Generated via an iterative participatory process, the scenario framework also draws on pre-existing work such as the scenarios developed by the Intergovernmental Panel on Climate Change (2000) that is trying to estimate future greenhouse gas emissions (Zinyowera, Watson et al. (1996)).

The UK Climate Impacts Programme (UKCIP[9]) scenarios use computer estimations of climate change, and are attempting to assess their impact upon the UK's socio-economic structure (UKCIP (2000)). They differ from the Foresight scenarios by being specifically designed for the timescale of the associated climate scenario provided, and by providing details likely to be of use for regional and sectoral studies. For example, they give greater emphasis to the possible changes to regions and to certain types of geographical domain. Classified according to governance system and social values, their denomination is equivalent to the Foresight scenarios apart from the Provincial Enterprise, renamed National Enterprise. Every scenario describes a plausible future, and the shape of water demand, agricultural trends, future transport, and economic development.

The scenarios presented by the Environment Agency are based upon the UKCIP scenarios, themselves based on the Foresight scenarios. The Foresight scenarios were devised taking into account various sectors of the economy. The UKCIP focused on the climate change impact, and the EA focused further on water resources.

[9] The UK Climate Impacts Programme (UKCIP) provides scenarios that show how climate might change and co-ordinates research on dealing with our future climate. It provides free information to organisations in the commercial and public sectors to help them prepare for the impacts of climate change.

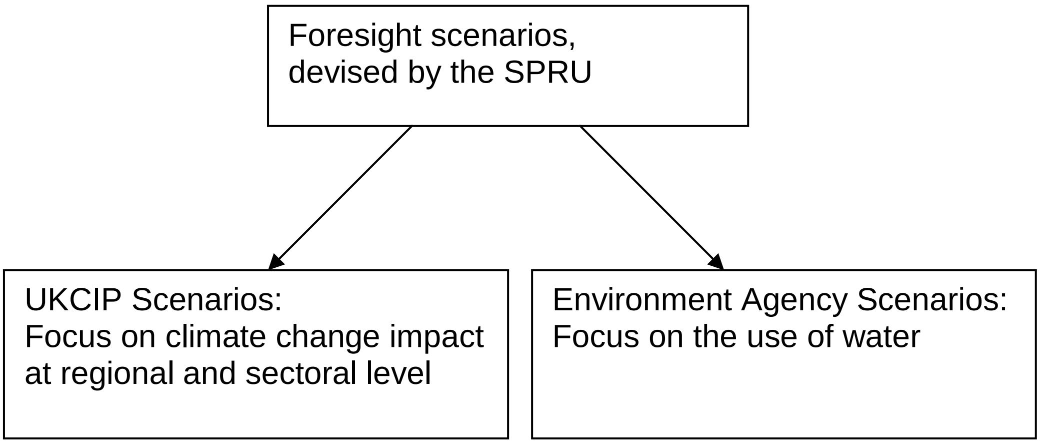

Figure 2: Origin of scenarios

Four distinct Foresight scenarios were retained as archetypical cases. They are classified according to a couple of main indicators or drivers of change: the social values of the individuals and the governance structure in place.

Social values go from individualistic to more community oriented, while the system of governance, dealing with the structures of the government and the decision making process go from autonomy (power remaining to national level) to interdependence (power moves to institutions, *e.g.* from the EU to regional government).

Values / Governance	Individual	Community
Interdependence / Globalisation	World Markets (B)	Global Sustainability (C)
Autonomy / Regionalisation	Provincial Enterprise (A)	Local Stewardship (D)

Table 1: The four scenarios

The scenarios have specific general characteristics, presenting the general trends, and more details regarding economic and sectoral trends, employment and social trends, regional development, health, welfare and education, and the environment.

The Department of Trade and Industry, which originated the Foresight scenarios, characterises them as follow. Each is described in terms of a short qualitative description which is supposed to be indicative of that scenario.

World Markets

This is characterised by individualism and globalisation.

In this scenario, people aspire to personal interdependence, material wealth and mobility to the exclusion of wider social goals. Integrated global markets are presumed to be the best way to deliver this. Internationally co-ordinated policy sets framework conditions for the efficient functioning of markets. The provision of goods and services is privatised wherever possible under a principle a 'minimal government'. Rights of individuals to personal freedoms are enshrined in law.

Provincial Enterprise (National Enterprise for the UKCIP framework)

This is characterised by individualism and regionalisation.

In this scenario, people aspire to personal independence and material wealth within a nationally rooted cultural identity. Liberalised markets together with a commitment to build capabilities and resources to secure a high degree of national self-reliance and security are believed to best deliver these goals. Political and cultural institutions are strengthened to buttress national autonomy in a more fragmented world.

Global responsibility

This is characterised by community and globalisation.

In this scenario, people aspire to high levels of welfare within communities with shared values, more equally distributed opportunities and a sound environment. There is a belief that these objectives are best achieved through active public policies and international co-operation within the European Union and at a global level. Social objectives are met through public provision, increasingly at an international level. Markets are regulated to encourage competition amongst national players. Personal and social behaviour is shaped by commonly held beliefs and customs.

Local Stewardship

This is characterised by community and regionalisation.

In this scenario, people aspire to sustainable levels of welfare in federal and networked communities. Markets are subject to social regulations to ensure more equally distributed opportunities and a high quality local environment. Active public policy aims to promote economic activities that are small scale and regional in scope, and acts to constrain large-scale markets and technologies. Local communities are strengthened to ensure participative and transparent governance in a complex world.

Every scenario is based on different assumptions, and this results in different numerical indicators such as the UK GDP growth (Department of Trade and Industry (1999)). From these indicators and the assumptions behind them, the Environment Agency has provided a detailed description of the scenarios in terms of economic and social situations as well as the more direct drivers. These are presented in the tables below.

Scenario	Drivers		
	Social values	Governance structures	Role of policy
World Markets	internationalist libertarian	weak, dispersed, consultative	minimal, enabling markets
National enterprise	nationalist, individualist	weak, national, closed	state centred, market regulations to protect key sectors
Global responsibility	internationalist, communitarian	strong, coordinated, consultative	corporatist, political, social and environmental goals
Local Stewardship	localist, cooperative	strong, local, participative	interventionist, social and environmental

Table 2: Global view of UKCIP scenarios' drivers

Scenario	Economic trends			
	Economic development	Structural change	Fast growing sectors	Declining sectors
World Markets	high growth, high innovation, capital productivity	rapid, towards services	Health and leisure, media and information, financial services, biotechnology, nanotechnology	manufacturing, agriculture
National enterprise	medium-low growth, low innovation, maintenance economy	more stable economic structure	private health and education, domestic and personal services, tourism, retailing, defence	public services, civil engineering
Global responsibility	medium-high growth, high innovation, resource productivity	fast, towards services	education and training, large systems engineering, new and renewable energy, information services	fossil fuel energy, traditional manufacturing
Local Stewardship	low growth, low innovation, modular and sustainable	moderate towards regional systems	small scale manufacturing, food and organics farming, local services	retailing, tourism, financial services

Table 3: UKCIP scenarios and underlying economic trends

Scenario	Social trends			
	Unemployment	Income	Equity	Areas of conflict
World Markets	medium-low	high	strong decline	social exclusion, immigration / emigration, political accountability
National enterprise	medium-high	medium low	decline	unemployment, poor public services, inequality
Global responsibility	Low	medium-high	Improvement	structural change, change of skills, political accountability, institutional rigidity
Local Stewardship	medium-low (larger voluntary sector)	low	strong improvement	land use, under investment, environmental restrictions

Table 4: UKCIP scenarios and underlying social trends

Assumptions upon the events happening in each scenario are inferred from the global drivers and trends. These assumptions refer to the formal parameters that permit to distinguish between scenarios. Referring to this more formal level, the scenarios vary depending on:

- Market penetration of devices (rhythm of diffusion)

- Ownership and volumes (frequency generally supposed stable)

- Absence or presence of future saving technologies regulations

- Proportion of metered households

The effects of the latter are still not clear. Studies are in progress to provide a robust answer, but are still unavailable at the present time. This is developed further in section 4.2.4.

The Environment Agency has used the Foresight scenarios as a starting point to develop specific water demand scenarios. As they are not officially part of the foresight scenarios, they changed their names into

Provincial Enterprise	A
World Markets	B
Global Sustainability	C
Local Stewardship	D

Building a scenario requires the preliminary analysis of the system or phenomenon, its drivers and the relationships between its components. In the case of water demand management, assuming particular (maybe extreme) measures or policies, they could result, when combined, in a socio-economic environment that was not previously considered. As a consequence of this possibility, specific and original paths can be devised, hence expanding the range of possible outcomes. Considering this multiplicity, the strategy devised or considered after studying these outcomes, even if not directly involved in the main question, could become if not more robust, possibly more thought out.

It is important to know how correct these scenarios are. As a basis for decision making, and often the reason for policy choices, they should be as sound as possible. It is difficult to have the knowledge of what the future will be, and hence to recognise for sure the evolution of a society. Since it is not possible to validate a prediction till the moment in time it is supposed to happen, it is not possible to validate a scenario describing what a future socio-economic situation will be. Qualifying a society and its water use is subject to debate even ex-post, when statistics and observations are available. Without an ex-ante validation of a scenario for the future, the other reasonable way is to assess the method with which the scenario is produced.

Therefore, a reflection must be engaged during the scenario creation that will evolve during its process. The Environment Agency is aware of the potential and limitations from these scenarios, as demonstrated by the reasons for their development.

2.4.2.3 The history of Environment Agency scenarios

The scenarios used in this research have been developed by UK Foresight, and then tailored by the Environment Agency. This is in order to represent how general tendencies regarding social values and governance could be reflected in overall principles of daily behaviour for households, and consequently their characteristics.

To assess the reasons why the Agency has used scenarios and what their expectations were, it was necessary to ask them directly This would also be an opportunity to discuss what future scenarios forecasting might have, as well as the evolution in their methods.

To answer these questions, a meeting was organised with Rob Westcott, Policy and Process Advisor for Water Demand Management, who took part in the previous forecast project, as well as the writing of the reference publication, "Water Demand Forecasting, a Scenario Approach for England and Wales".

They developed scenarios in order to obtain consistent sets of assumptions, and observe their interactions in the long run.

The Environment Agency "*consciously developed scenarios of possible futures, as the Foresight programme intended its framework scenarios to be used, to help policy makers think about changes not only in the obvious sectoral drivers but also how perceived "givens" (governance and society) might change over the long term. Basically our scenarios are possible future outcomes. The way in which we evolve to get there was not our primary objective. For us "what could ultimately happen" was the key question to be addressed. Then we wanted to explore "what can we do about it?" That is, what needs to be done and by whom to ensure sustainable (read that as our "desired") outcomes might be achieved. Where possible these became specific actions required in order to deliver our strategy.*"

The expectations from scenarios were "*not predictions as such. We know that any one of the four scenarios will not be universally applicable to the […] situation [in England and Wales]. The future will include elements from all of the scenarios with a net effect somewhere within the envelope we suggested.*"

An important use of scenarios is the fact that they are flexible both in size and timescale. The Environment Agency had the desire to select the best approach for their purposes, and hence decided to improve upon their previous work on forecasts since "*previous forecasts we had developed/were developed by water companies were not suitable. The National Rivers Authority (NRA) forecasts were limited by generalised assumptions that were little more than sensitivity testing of key parameters (metering, leakage, demand growth) and climate change. The water company forecasts could not be compiled on any reliably consistent basis (assumptions varied, were not transparent, reflected company policies/business aspirations, and commonly influenced by revenue forecast aspirations). Also some issues over data protection and confidentiality limited explicit use of their forecasts.*"

The Environment Agency wanted to use assumptions consistently reflecting regional/local variations where possible. The objective was "*to access all water uses not just public water supply, thus the issue of scale and representativeness raised its head early on. We wanted explicitly to explore impacts of metering, changing occupancy, innovation and changes in appliance use, behavioural aspects, changes by sector in water consumed by non-households, potential leakage levels, and opportunities for efficiency across these sectors*".

The set of Foresight scenarios "*gave […] a framework from which to build a set of alternative futures. But to reflect the impact of some of the drivers in the scenarios it was clear that the level of disaggregation of demand components had to be extensive. This meant micro-component for households, sectoral characterisation for non-household, spray irrigation defined by crop and alternative methods of leakage control*".

To generate these scenarios, they tried to make an example of best practice, and incorporated the latest tendencies and tools in their assumptions, according to practical limitations.

The methods and techniques were limited by data and ability to define assumptions at a reliable scale (anything other than global).

This "*resulted in some components not taken into account for every effect they might have. For example, climate change was not considered internally within the household forecasts but the spray irrigation forecasts were able to test the effects.*"

But for the Environment Agency, scenarios are simply a means to achieve their aim.

"*The Environment Agency needs to secure the proper use of water resources. A long-term (+25 year) view is necessary due to the nature of water resources planning and time to implement resource options. In order to promote sustainable solutions our strategies need to consider all significant demands on the water environment and how these may change. Operating at a macro-scale, Agency planning benefits from the use of scenarios to test implications of changes to key demand drivers and also assumptions about their future significance. Their limitation is that they can only generalise and do not easily translate to the local level.*"

2.5 Conclusion

This chapter introduces the concept of water demand management and describes the institutions involved and the origin of the scenarios they use for their forecast.

Section 2.2 presented water management. It defined management as equivalent to water conservation, or "any beneficial reduction in water use or in water losses". It explained that for developed countries supply is not the only aspect of water that can be influenced. Amongst other reasons, the concern of climate change and the decreasing relative availability of natural resources have resulted in a recent focus on water demand.

Section 2.3 distinguished the soft approach of water demand management from the hard approach of water supply management. While the former focuses on behaviours and uses, and remains immaterial, the latter consists of supplying more resources via new structures such as dams or reservoirs. The section also describes exclusively qualitative and exclusively quantitative approaches that can be used to address water demand, and provides examples where they have been used.

Section 2.4 presented the regulators involved in the management of water resources. It explains that as a regulator, the Environment Agency must set out its vision for the long-term management of water resources in each region as well as globally for England and Wales. Uncertainty regarding the future must be taken into account when forecasting. In order to achieve this, the Agency has defined four scenarios characterised according to social values and governance structure, and where the driving components of the water demand are: the environment, the interactions within agents, and the diffusion of new devices.

It is necessary to put the consistency of the scenarios the Environment Agency has generated to the test. Some traditional well-known and well-developed tools are available. Unfortunately, as it will be shown in the next chapter, they focus on one aspect of the problem only. It is here necessary to represent multiple facets of the issue and a review of the existing methods shows that Multi Agent Systems could provide a more appropriate and more exhaustive tool for such an analysis.

3 Methodology and tools

3.1 Introduction

The previous chapter presented the context of the research. Providing a simple definition of management and presenting demand side management, the chapter also detailed the approaches traditionally used, exclusively qualitative or quantitative. The description of the actors involved in water management in England and Wales, and the scenarios for the environment present the sketch of the target system, what we will attempt to represent.

This chapter presents the various methods to address the issue of scenario evaluation and the associated tools. Following a reflection on the way to represent the issue, it is argued that modelling is an appropriate method. Describing the nature, advantages and limits of the different modelling techniques, it is argued that the properties of the target system lead to a unique choice of modelling tool. It provides the description of the different stages for the research, which starts with two stages. First devising the model / adjusting the parameters, and then evaluating the scenarios and their assumptions.

3.2 Problem representation

The aim here is to assess the various scenarios of water management for households. It is then necessary to define more precisely the possibilities that can be used to represent the object of the study, as well as justifying the selected tool, and describing the resulting model.

In order to communicate the various questions we want to investigate, a representation, or model, is needed. According to the Oxford English Dictionary, a model is “*the representation of a structure*”, while modelling is “*the devising or use of abstract or mathematical models*”. Therefore, as soon as one tries to communicate about the object of an analysis, or a structure, the representation used is a model. Sometimes fairly accurate, as is the current representation of the orbits of planets, it can also be more vague, as could be an oral description of a landscape for example. Both are descriptions and representations, but the precision and objectivity of the language used are different.

Modelling can be descriptive or analytic. The latter intends to infer some general truth from the representation, while the former generally does not allow that. It could be for example because of the lack of information about the structure that is represented, or the lack of objectivity of the language itself.

Often modelling has been understood as mathematical modelling. The reason is most likely that historically mathematics is the most commonly used form of formal language. Formal languages give precision. Although they are not the only ones in the analytic class of models, they are the most used, for the reasons stated above

3.3 Modelling techniques and model properties

The purpose of the enquiry must drive the selection of the tools involved, as some can be more suitable than others. A model is the representation of a system. As such, it can be devised using common language, for example in surveys, or using more formal languages, such as mathematics, or programming languages. Selecting formal modelling for a research means using formal tools for analysis of the system involved rather than surveys to describe it. They are not exclusive (rather interactive even), as will be shown later.

The reasons for modelling are in general (Kwasnicki (1999)) an attempt to:

- Understand and explain a given phenomenon
- Forecasting (more widely prediction and retrodiction)
- Supporting decisions to achieve well-defined goals
- Design a system with optimal performances

As seen in the water management literature, the most common modelling techniques are qualitative or quantitative. Examples were given in the literature review, mainly with surveys and econometrics. I will now describe the use of these approaches in the case of a formal model and in which measure they are appropriate.

The quantitative class of models is composed of analytical models. Typically using algebra, they offer the possibility to achieve a generality of results. It is also used to find optimal solutions to systems, should they exist. Disadvantages of quantitative models are that they might need to use extreme simplifications or very high level formalism, which is consequently difficult to follow for anybody else than the modeller. In our case, it is also the fact that they refer to ideal systems. Ideal systems are not common in social sciences. Our knowledge of the components and interactions accounting for a phenomenon is often imperfect. Including in a model assumptions that are thought to hold, or assuming that a model is complete when the knowledge it is built upon is not, can only lead to results with a limited validity (if any).

If it is possible there is no better representation of a system than the system itself. The advantage is an unbeatable realism and a straightforward verification. Still, its strength is also its problem. Many systems cannot be studied individually and easily. They might not be replicable, or the timescales involved might be too different from the modeller's, and the parameters for the system could also prove very difficult to tune / constrain.

The simulation approach is the third way. Computer simulations can use expert knowledge from various sources. The experiments are repeatable and controllable. Timescale is easy to set up, although it can generate issues with some computational capabilities. The major inconveniences of simulations are the necessity of running many simulations, the lack of generality, and the derived time constraint.

More importantly simulations are an iterative process. Unlike analytical methods that start from the properties of a state to express a solution, when simulating there is a starting point and rules of evolution that result in a situation with unplanned characteristics. Both approaches can be used, but the former is only suitable if the purpose is to find a (potentially optimal) solution (here a state of the world) with known characteristics. Simulations on the other hand are appropriate when investigating a process and undertaking a dynamical analysis. In cases where cognition and subjectivity play a significant role, the generality of results expected from analytical models can not be achieved. Among other reasons, the presence of cognition makes path-dependency appear in the model.

There is an open question about the validity of modelling and simulating itself. Due to the capacities of today's resources (be they human brains or microchips and memory), a trade-off is necessary. If one wants to represent a society, the agents composing it could be in a continuum from numerous and simple to few and complex.

With simple, numerous agents, absence of sophisticated behaviour could turn the whole set of results into useless numbers, the system obtained being too different from the one observed.

Another option is to create a system with fewer agents, but more elaborate behaviour. Thus the modeller has less data to analyse, which makes the treatment easier. The challenge is to define 'fewer' agents, as there is obviously a limit on how much fewer. When attempting to solve problems with 1, 2 or 3 dimensions, a scientific approach is likely to find the/a solution(s). Increasing the number of aspects or dimensions of the problem could make it too complicated (or not practical) to find these solutions. In some fields of research, objective solutions or equilibrium/a could become difficult to find as the space of possible expands with the dimensions / aspects of the problem. There is also the possibility that a problem becomes too constrained to be solved, and a solution might not exist. In game theory for example, any successful negotiation model is with two players only. The type of model developed in this research is not as basic, and does not have a small, limited set of possibilities.

From the range of methods that could be used, the analytical one is too idealistic for social purposes, and the more qualitative one would involve building a system upon which the modeller would not have enough control.

The conclusion is that to investigate modern socio economic processes, computer simulations seem to be the most promising tool.

Modelling is about representing a system. It is hence reasonable to expect that the outputs of the model are comparable to the observed data. Consequently, if the latter present some statistical properties, one would expect a faithful model to generate data in accordance. Of course, it is not a sufficient condition for validation, although it seems a necessary one.

Social phenomena can present the characteristics of complexity.

Pavard and Dugdale (2000) define a complex system as "*a system for which it is difficult, if not impossible to restrict its description to a limited number of parameters or characterising variables without losing its essential global functional properties*." The properties of such complex systems are: non-determinism, limited functional decomposability, distributed nature of information and representation, emergence, and self-organisation.

It is commonly assumed that the behaviour of a system can be foreseen. But as complexity generates non-straightforward behaviour (Edmonds (2000)), if a system is recognised as complex, this assumption cannot hold. In the present case, the resulting data will be analysed further below and some statistical tests undertaken, to demonstrate that the data does not seem to have the commonly assumed property of normality.

Natural and social systems generate data characterised by the presence of occasional and unpredictable events.

The characterisation of an event in the case of social systems can be done through the changes that occur. The time series or cross-sectional analysis of a specific indicator will reveal changes between two situations, referenced by the stage, or object studied, or location (commonly shown for the number of references in a paper, the values of stocks in finance, the number of links pointing to or originating from a web page web links, or town size distribution).

For example, in the case of modelling water demand, one can consider water consumption as a random variable, and treat these data via some statistical method in order to know more about the eventual underlying distribution. Software like SPSS can ease this task. It can apply a test like the Kolmogorov-Smirnov to a set of data, and assess whether the sample observed could have come from a set with a particular (known) distribution. This includes a test for normality. When putting the water consumption data from the Fairlight region to this test, the results are non-ambiguous. The probability that it is part of a normal sample is very close to zero.

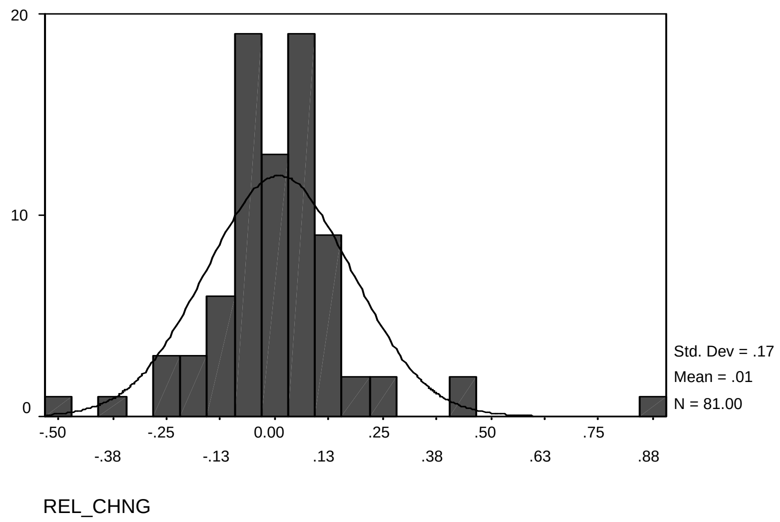

Figure 3: Comparison of distributions for a given sample

Figure 3 displays two distributions. The bar chart is the actual distribution of observed relative changes in a simulation run, while the curve represents the theoretical distribution for such values should the sample be normally distributed. The standard deviation and mean used to generate the theoretical distribution are taken from the sample of observed data. Although this is a standard limitation of the KS test, it results in overestimating the chances that the underlying distribution is found to be normal. This only tends to make the opposite assumption more difficult to prove with this method, which therefore retains its validity in this particular case.

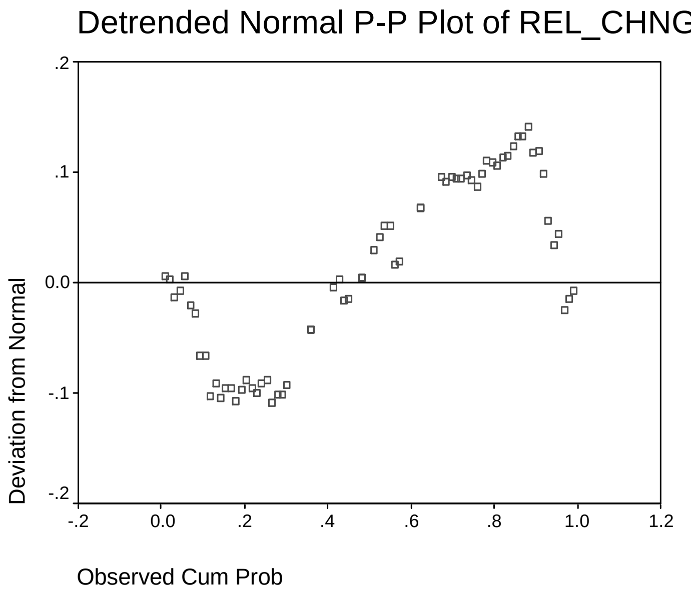

Figure 4: Comparison of de-trended cumulative probability with normal

Figure 4 is a probability-probability (P-P) plot, used to see if a given set of data follows some specified distribution. It is constructed using the theoretical cumulative distribution function of the specified model, and it should be approximately linear if this specified distribution (here normal) is the correct model. As this particular graph is corrected for trends, if the model is correct, the dots would be aligned with the horizontal line.

Not surprisingly the tests tend to confirm the assumption that this sample does not fit a normal pattern. The property shown, a relatively fat tail and thin peak, is known as leptokurtosis. This means that there is in the sample an excess of data values near the mean, and far from it.

Instead of normal distributions, even with time-dependent mean and variance considered by economists, physicists like Per Bak (1997) used the power law devised by Pareto in 1893. If the data observed fit this kind of distribution, the consequences are important. The probability density function of the Pareto distribution has two parameters, α as the "peakedness" parameter, in the interval (0,2], and β as the "skewness" parameter, in the interval [-1,1]. The issue is that these parameters have critical values. When α is equal to 2, the characteristic function of the paretian distribution reduces to that of the normal distribution. But for $\alpha < 2$, there is no finite variance for the distribution, and for α less or equal to 1, there is no finite mean.

Moss (2001) has investigated some different means of generating such a distribution. Three explanations are: a normal distribution with predictable time varying parameters, a stable Pareto distribution with infinite variance generated by self organised critical social process, or a non stable distribution generated by a self organised critical social process.

Because the model self-organises around the critical state and remains around that state thereby to produce power law distributed data of extreme events, this phenomenon was called self-organised criticality[10]. Some necessary conditions in which self-organised criticality (SOC) emerges were summarised by Jensen (1998) as those where:

- Model components (cells, agents, etc.) are metastable in the sense that they do not change their behaviour until some level of stimulus has been reached.
- Interaction among the model components is a dominant feature of the model dynamics.
- The model is a dissipative system.
- The system is slowly driven so that most components are below their threshold (or critical) states most of the time.

The social embeddedness is coined in Granovetter (1985) and defined by Edmonds (1999), as “the extent to which modelling the behaviour of an agent requires the inclusion of other agents as individuals rather than an undifferentiated whole”. It means that formally, it is more relevant to model an agent as a part of the total system of agents and their interactions as opposed to modelling it as a single agent that is interacting with an essentially unitary environment.

[10] Because the model self-organises into the critical state and remain in that state thereby to produce power law distributed data of extreme events.

The model devised must then be able to capture qualitative behaviour, allow quantitative results to be tested against the Environment Agency's own, and describe households' characteristics and behaviour while generating aggregated data that can be tested against commonly accepted theories or observation. All this without being based on paradigms / theories that are not validated.

System dynamics, interviews, surveys, cellular automata amongst other techniques fail on one or more of these aspects. Two methodologies might be able to match these requirements: microsimulations (or microanalytical simulation models), and Multi Agent Systems.

Microsimulations are frequently used to analyse the effects of financial and social policy interventions. In microsimulation, a sample is generated with characteristics similar to those observed, generally using probability distribution, or statistical relationships. The microsimulation model then uses probabilities of transition for individuals from one state to another and then generates aggregate changes in the artificial society.

Individual behaviours are not based upon rules, but upon probabilities. Individuals change because they are "told to", not because of a specific reason. There is no explicit decision-making process. As put by Boman and Holm (2004), "[t]he whole purpose of such models is to represent observables and facilitate policy experiments, sometimes with the help of theory and theoretical concepts; and if the model fails in prediction (as they normally do), there is no other excuse for its construction."

In essence, one could argue that microsimulation is the methodology used by the Environment Agency: a model built upon statistical relationships with careful characterisation of initial population, and transition states.

On the other hand, Multi Agent Systems are based around interactions. Agents represent entities that interact with other agents and with their environment. Decisions they make can be justified from their knowledge and beliefs. Major benefits of this approach are the fact that they have no underlying assumptions and it is possible to validate parts of the model (provided an appropriate indicator can be used), which can make a model useful, even if its “fails” its predictions.

That is why simulation experiments are so far the only way to understand self organised criticality. The SOC literature acknowledges that there is not yet an analytical method to create models that generate the appropriate processes.

3.4 Presentation of Multi Agent Systems

The multi-agent approach originates from Distributed Artificial Intelligence research, where multiple heterogeneous components of a system should interact in order to reach a global goal. The use of entities at the micro level then starts in the ‘70s, with the work of Hewitt, who defined actors, which are interactive, as self contained object that can execute tasks simultaneously with others.

Nowadays, there are different approaches to Multi Agent Systems. One is led by Wooldridge and Jennings, and considers a Multi Agent System a closed one, where the components / agents must strictly behave in a controllable and predictable way (Wooldridge and Jennings (1998)).

Another one consists in representing a system and observing the emerging behaviour at macro level.

While both approaches are bottom-up, *i.e.* start with representing the micro entities of the system in order to represent / generate a bigger one, the kind of systems they can deal with are not equivalent. As expressed in Moss (2000), the former is focused on “tidy” systems, while the latter is used for “messy” systems. The author characterises a system as tidy if its boundaries and the relationships represented are clear and well understood, as well as their carefully monitored development. They are systems that software engineer devise and use, as they allow total control of the process, by limiting for example the interactions, communications or information for the agents involved. The so-called messy systems on the contrary have fuzzy boundaries, and components whose relationships are difficult to represent.

The latter is a more appropriate idea for representing a society, while the former is perfectly suitable for devising Multi Agent Systems that must achieve a specific task.

Having shown that the system that must be represented can not be considered as tidy, due to the presence of interactions, social embeddedness and complexity, one could argue that the development of Multi Agent System would be able to tackle these issues.

The basic element of a Multi Agent System is the agent. It is defined as “a physical or virtual entity

1. which is capable of acting in an environment,
2. which can communicate directly with other agents,
3. which is driven by a set of tendencies (in the form of individual objectives or of a satisfaction/survival function which it tries to optimise),
4. which possesses resources of its own,
5. which is capable of perceiving its environment (but to a limited extent),
6. which has only a partial representation of this environment (and perhaps none at all),
7. which possesses skills and can offer services,
8. which may be able to reproduce itself,

whose behaviour tends towards satisfying its objectives, taking account of the resources and skills available to it and depending on its perception, its representations and the communications it receives” (Ferber (1998)).

A classical opposition was drawn between reactive and cognitive agents: cognitive agents can form plans for their behaviours, whereas the reactive are classically those that just have reflexes. Through the use of endorsement, the agent we are dealing can be considered as cognitive, although Ferber (1998) tries to show how both approaches can converge, while emphasising different aspects: one focuses on the building of individual intelligence whose communication is organised, whereas the other imagines very simple entities whose co-ordination emerges in time without them being conscious of it.

From that broad definition, a Multi Agent System (MAS) is a system comprising the following elements:

1. an environment, that is a space which generally has a volume
2. a set of passive objects (*i.e.* can be perceived, created, destroyed and modified by the agents)
3. a set of agents, which are specific objects and represent the active entities of the system
4. a set of relations linking agents to each other
5. a set of operations making it possible for active agents to perceive, produce, consume, transform and manipulate passive objects
6. operators with the task of representing the application of these operations and the reactions of the world to this attempt at modification.

According to Ferber (1998), the main application of Multi Agent Systems of the moment can be seen as problem solving (as an alternative to centralised problem solving), multi-agent simulation (widely used to enhance knowledge in biology or in social sciences), construction of synthetic world (used to describe some specific interaction mechanisms, and analyse their impact at a global level in the system), collective robotics (defining the robots as a Multi Agent System where each subsystem has a specific goal and deals with this goal only), and kenetic program design (a very efficient modular way to program)

In Artificial Intelligence, the agents are in general characterised as reactive, cognitive, proactive, situated, or communicating for example. In social simulations, the choices are determined by the system that must be represented, together with the choices of the modeller and the experts that have analysed it. Therefore, the agents in this project are only qualified within the standard Multi Agent categorisation when they need to be.

The MAS framework is considered as in between a strict Object oriented approach and a strong agent approach like an AI agents based framework, and a good balance between generality and ease of agent-based application development (Silva, Romao et al. (2001)).

The recent literature has seen a proliferation of Multi Agent-based research. Yet, the current trend among modellers is not a reason to choose a method. It is nevertheless the case that a Multi Agent System has properties that are appropriate to the issues this research is dealing with. First, it allows representing a system in a way that is compatible with the complexity conditions. Second, it is possible to observe emerging patterns of behaviour, via for example an indicator on a macro level. Finally, generation of the model, as a representation of a system, can be done using a participative approach ensuring that smaller elements of the model, as well as interactions amongst them, are devised properly (Barthélémy, Moss et al. (2001), Edmonds, Barthélémy et al. (2002)).

Consequently, using MAS simulations allows a focus on processes, which is a necessity in the study that is presently developed, as information diffusion and behaviour emergence are of high importance in the assumptions involved. That is why a Multi Agent System is used in this work.

The appropriateness of a method does not mean that the modelling process cannot fail, or be biased. The modeller has to ensure that the modelling method itself, *i.e.* the various modelling stages, is as sound as possible.

3.5 Representation of subjective values

In the model developed, agents will make decisions according to their perception of the current situation. For increased realism, this perception must be subjective. Because the underlying logic for decision can be seen as a maximisation of satisfaction, or utility, it has often been represented via a utility function with specific properties, or preferences. But there are other ways to implement such an evaluation process. One of them is endorsements.

One of the strength of endorsements is that the information an agent obtains is not only evaluated according to its nature, but also according to its origin.

While it might be possible to create a utility function that would have all these attributes, it will certainly be complicated. Endorsements are simple.

Information, as well as its origin, is stored in the agent's memory. When the agent needs to make a decision, it weighs up the information using its personal endorsement weights. This set can be personal or common with other agents, or possibly follow a given distribution.

By combining the origins of the information with the weights representing how important or reliable that source is, an agent can then compute a subjective value for this information. If the information is itself (or triggers) an action, then the agent decides to select the action associated with the highest value (maybe from a combined set of endorsements).

3.6 Modelling stages

Verification and validation of that model will be crucial issues when building a model for social simulations. They must be present at every stage of the modelling process. It is then necessary to express that process and the relevant steps with respect to the targeted purposes of that representation.

3.6.1 Modelling theory

Because there can be some implicit references to the modelling process in the model structure, this is a description of the different stages and the explicit and implicit parts in them.

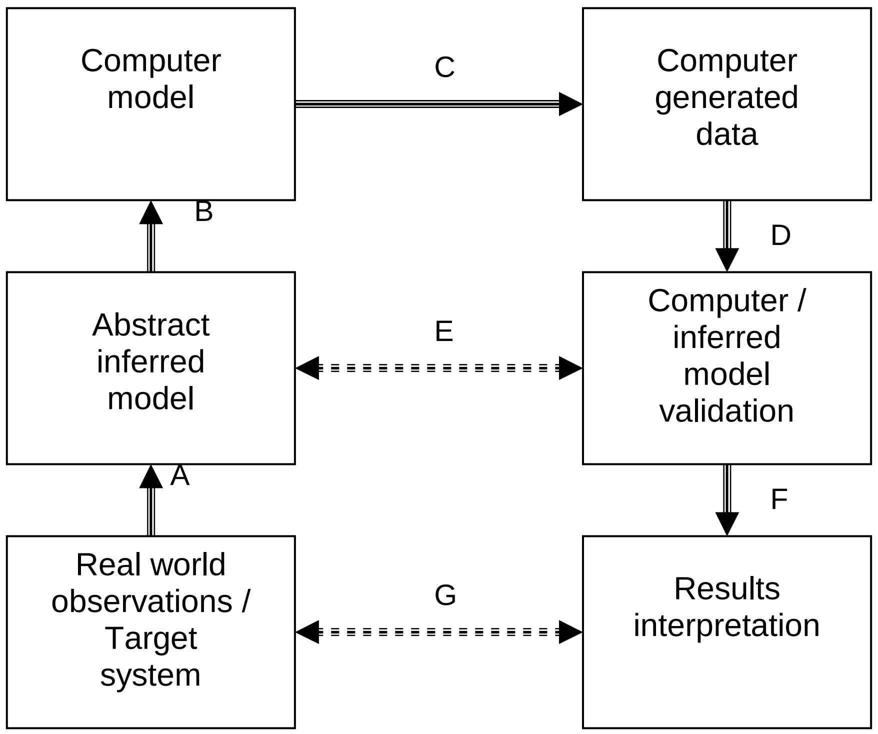

Figure 5: The modelling stages

The different links are named A - G for easier visualisation. Each relates to a modelling step.

Link A is the creation of an abstract model that will represent the parts of interest. Link B is the translation of that abstraction into a computer model (*i.e.* lines of code). Link C is the running of the computer model in order to generate data. Link D is then the analysis of these data eventually with respect to some indicator. Link E represents the validation of these data against the abstract model, and link F is the interpretation for the real world of the conclusion. Link G is the comparison of the generated assumptions, including the potential effects of the results on the "Idea" of the target system.

Some guidance was given by Edmonds (2000) on how to ensure that the complete modelling cycle is as strong as possible. He proposes several criteria in order to help evaluate the rigour of the modelling.

Abstraction, referring to the link A, has to be correctly specified .The parts or aspects of the target system that are supposed to be represented must be explicitly defined, and of course the abstract model must remain relevant.

Design, referring to link B, is the process of writing up the formal model. It has to clearly remain linked to the abstract model, since it is its translation into a more formal representation. Specially, the parts derived from the abstraction and those necessitated by some logical or computational constraints ought to be explicit.

Inference, referring to link D, is in our case the transformation of computer-generated data into a more generic rule, or phenomenon. Caution is here necessary. One must check that the expressed outcomes are effectively a necessary result of the model specification and design. Dependence upon particular parameters or settings has to be looked at.

Analysis, referring to link E, has to be clear. The eventual limitations of the technique should be expressed here, as well as the set up for further testing and replications.

Interpretation, referring to link F, must be justified and relevant.

Application, referring to link G, must verify whether the conclusions applied to the target system are justified, and whether the rest of the steps are sound enough to justify the conclusion itself.

One of the key points to bear in mind is that a model must be thought of as a representation of reality. It is necessary to bring the attention to the fact that it is not *the* representation, but more a way to focus on some parts of it.

This should help the modeller to devise a representation with a method allowing keeping a close (scientific) eye on the different stages.

Simulations are used on many occasions, from hard sciences like physics to software applications in finance, or the game industry. The aims can be very different though, and not only because of the various application fields. In the present case, the model represents an artificial society. Amongst the different uses of simulation in the case of artificial societies described in Hales (2001), two of them are involved in this work: theory building and reverse engineering.

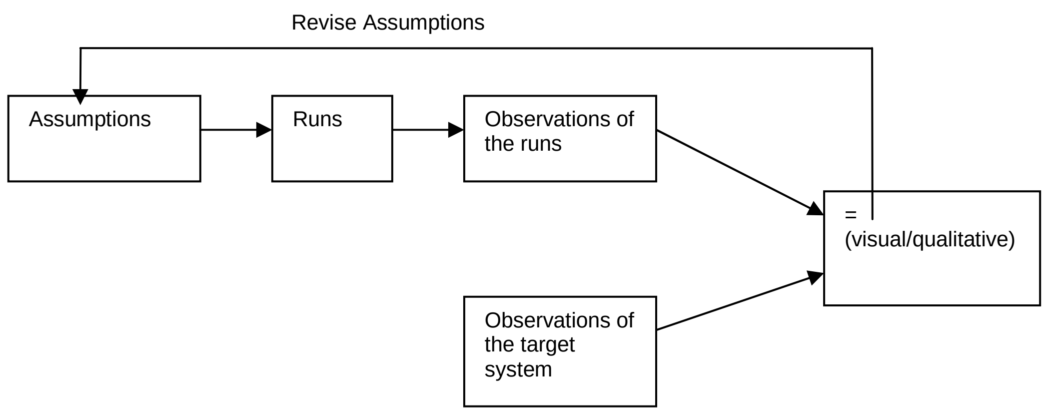

Figure 6: Reverse engineering[11]

[11] Courtesy of Dr D. Hales, original in Hales (2001)

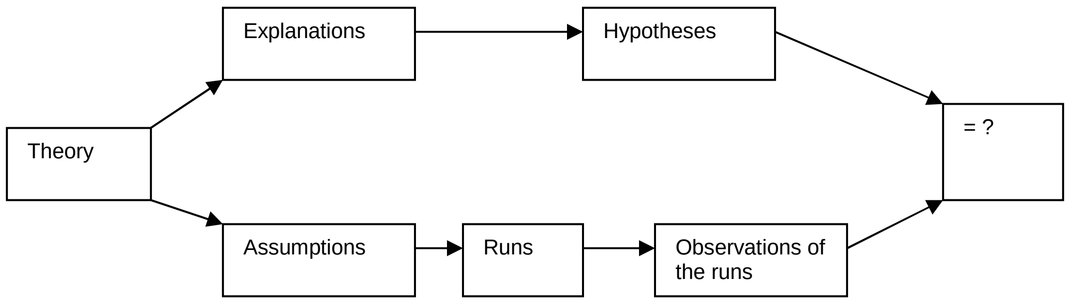

Figure 7: Theory building / testing[12]

The above figures refer to artificial society experimentation, defined as "a set of assumptions used to construct the society; a set of runs produced by execution of a computer program which embodies it; a set of measurements of observations of the runs; a set of explanations (a theory) which attempts to link the assumptions and the observations and a set of hypotheses linked to the set of explanations based on the assumptions and the observations". In our case, the two above figures have to be put together to represent our purpose, *i.e.* building a model and validating our assumptions.

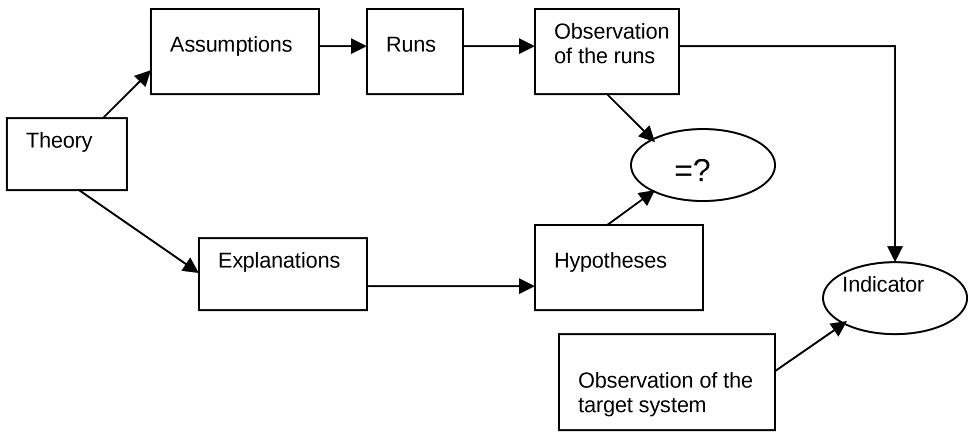

Figure 8: Model building and validation[13]

The indicator refers to the validation itself. This is actually going to be achieved via the comparison of statistical signatures of the distributions. As a preliminary assessment of the closeness of the simulated data and the observed data, some standard parametric statistics can be used to capture

[12] Courtesy of Dr D. Hales, original in ibid
[13] Courtesy of Dr D. Hales, original in ibid

main characteristics, but the nature itself of the distribution will be tested using non-parametric statistics.

These diagrams are trying to visually express the aims of this study. They show that there are two different steps. First, the reverse engineering part is the creation of a model that can generate specific scenarios. Second, the theory testing stage involves running the simulations in order to put these alternatives to the test.

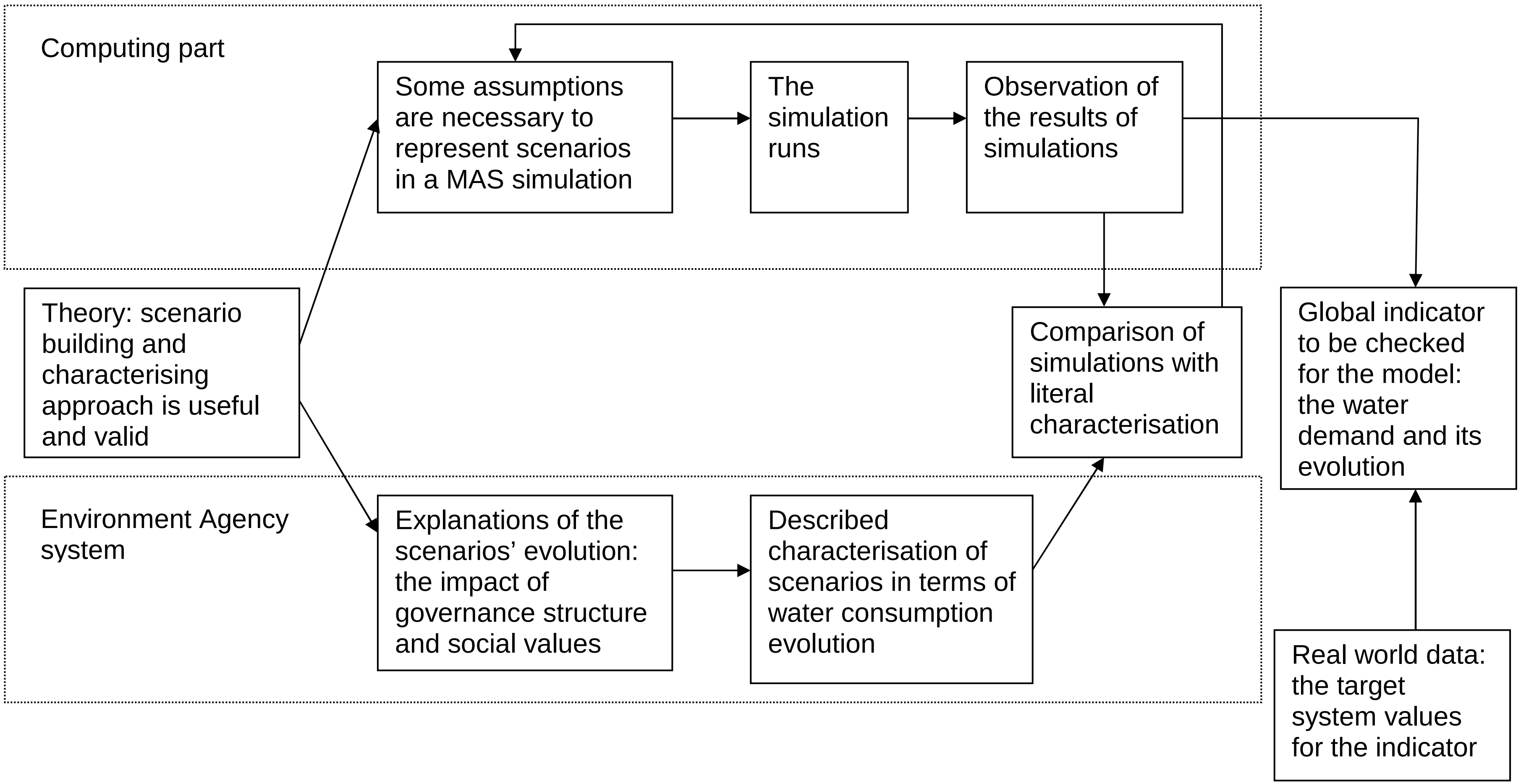

Figure 9: Overall links amongst model parts

It is important to keep consistency when building and using the model. In this research, consistency has two aspects. First, the verification of the model, expressing how appropriate the rules written are to the theoretical model described. Second, consistency is associated with validation, as it aims towards matching results obtained from the simulation with both foresight and objective observation.

Consistency is aimed at within the framework of this research and is twofold: via verification for the internal consistency of the model, and via observation and comparison of data for the consistency of the results with actual observation.

The internal consistency of the model (including for example identified and / or unique choices in decision processes, assumed knowledge every time step, and agent-specific knowledge) is partly ensured by using the right tools. In the present case, SDML and its underlying Strongly Grounded Autoepistemic Logic avoids logical issues with the formal representation. This is a step further than many languages, which mostly ensure the code is consistent.

The following section presents and discusses the participatory method and the tools allowing consistency to be maintained.

3.6.2 The limits of integrated assessment

3.6.2.1 Necessity of participation

The FIRMA (Freshwater Integrated Resource Management with Agents) and CCDEW (Climate Change: Demand for Water) projects tried to improve the understanding of consumption behaviour of potable water for household in the UK. They both used external expert knowledge to represent the best they could the various influences upon consumption behaviour (Moss, Pahl Wostl et al. (2001)). They were driven by two slightly different goals. CCDEW was investigating the impact of climate change upon households. In order to build appropriate plans, the water companies and regulators were concerned with the effects of climate change, including (or not) global warming, different rain patterns, and extreme climatic events, such as droughts and floods. FIRMA was more oriented towards the way to address the various problems faced by different European countries. Modelling came as a part of the integrated assessment, a plan to involve all stakeholders, making of the participatory component a major and necessary step to help understanding, while devising a typical scheme to implement this methodology in other similarly complex issues.

These projects have already provided useful conclusions for this research. First of all, the CCDEW project tends to demonstrate that the influence of climate change remains the same whatever the social values and governance structures. This backs up the relevance of the study of the scenarios. If the impact of climate change on the consumption is the same for every scenario possible, then the most important issue is certainly to investigate more about these various possibilities. The scenarios devised by the EA correspond to some “most likely” outputs, based on typical behaviours. Hence, checking the validity of such output scenarios with respect to the typical assumptions is worthwhile, and has not been addressed in the CCDEW research.

The FIRMA project has shown that a wide range of issues could be addressed using participation. Countries and research centres involved have addressed issues as different as for example drought management, negotiation regarding water use, flood control and river course remediation. It showed that the combination of multi agent modelling and of participation could result in useful debates, education of parties, and improved understanding.

3.6.2.2 Difficulties in having the stakeholders understand

Stakeholders involved in the FIRMA project have different goals, different schedules, and different points of view. One of the successes of the project is to have provoked meetings, and to have generated a tool that could make these various parties (or agents) make explicit their goals and constraints, confront each other, and ask some questions that were not asked before, or realise that they could be asked in a different way. Many of them were used to statistical models, and could not see at first the use of multi agent models. They expected researchers to come up with a model that they could make theirs or forget. As managers facing the uncertainty of the future, their prime concern was to find a model that would provide figures and if possible accurate ones. Most imagined models as predictors, in the narrowest sense, as a certain future. While some stakeholders involved reacted positively by realising the kind of meaning a multi agent model brought, some remained tied by more down to earth, pragmatic, economical, commercial expectations, and (understandably) statistical figures. This comes because of a trade off between generality and accuracy. While with hard sciences these two properties can sometimes cohabit, the presence of complexity prevents this happening. And in social science complexity, meta-stable behaviours and self-organised criticality are system properties that seem to be more common than the presence of a general equilibrium as described by Debreu (1959). In the case of statistics, the basic assumptions are very strong, and so is the output: as accurate as the assumptions it is based upon. The point of MAS in this case being to map the relevant system as closely as possible, there are few unlikely assumptions, and little certainty. Consequently, the results of such models are unlikely to give results as accurate as statistical models.

3.6.2.3 Integrated assessment requires interest

Therefore, due to the lack of “usability” of such a Multi Agent System for them, many were not interested in continuing the experience, unless forced to. That is one limit of the integrated assessment exercise. Participation requires some necessity for the results, or some curiosity. Also many stakeholders use an approach that has been clearly criticised, or that holds only thanks to unrealistic assumptions, which tends to hold them back. This is why integrated assessment, although successful in other cases, is not used in the present work.

As scenarios will be analysed here and their assumptions tested, the main interest of some stakeholders still lies in the attribution of a probability to each of the scenarios. They could hence build their plans / forecasts upon it. As each stakeholder (specially the water companies) has a unique region with some specificity, there is an obvious interest in developing techniques to reduce that uncertainty, such as Monte Carlo experiments, to avoid the need of specified probability density functions for model variables.

Based upon a model devised via an integrated assessment, the particular study of scenarios and their evaluation will be undertaken.

Hence the following modelling is based upon a model devised through integrated assessment. Unfortunately integrated assessment could not be used further due notably to the difficulty to have experts assess something they created or devised themselves. A lack of available resources meant the stakeholders involved initially were unable to provide further input. Therefore, all algorithms later presented will be accompanied by the reasons for their selection, but they will not have benefited from this iterative participatory process. It is worth noting that in the end, they have been presented and sometimes commented by stakeholders that did not comment negatively on them.

There is one exception to the fact that stakeholders need to show an interest in the study. In this particular research, the Environment Agency was interested, and discussions with the staff in general and Rob Westcott in particular have been extremely useful[14]. But because of its nature as a (non departmental) public body, when a member of the public submits a question, it becomes the organisation's duty to provide a reply.

In such cases, when a response is ensured, the critical issue remains to identify which section, department, group, or individual would be the most suitable to establish communication. The Water Demand Management team is not only a part of the Environment Agency it is also the successor to the National Water Demand Management Centre which created the scenarios in the first place.

As a stakeholder, the Environment Agency showed openness by having a critical discussion of the scenarios, and provided help in order to develop this model to assess them. Their interest did not lie in answers outside the scope of the tool. This is the reason why they are the most relevant stakeholder, whose views regarding the purpose of this study are presented in section 6.5

3.7 MAS as a framework needs appropriate tools

Benefits of MAS are important but require an appropriate tool. The language used in this work plays an important part in the modelling process. First as a declarative language it allows the representation of agents, and of rules of behaviour, and second, its internal consistency ensures an easier verification.

The MAS framework considers objects and the way they interact with each other and with their environment. In such a case, being able to analyse the specific focus, *i.e.* the process of interactions, in an easy-to-follow and accurate representation is not unimportant.

This presentation of SDML demonstrates how this tool is formally suitable, methodologically convenient, and logically sound for such an analysis

3.7.1 SDML: presentation of an appropriate tool

Programming a simulation model sets some requirements on the language that ought to be used. It should keep the model valid, usable, and extendable (Axelrod (1997)). Validity refers to the internal structure and consistency of the model, also called verification in our case. Usability refers to ease of following the various runs and interpreting the output. Extendibility refers to the possibilities for a future user to adapt the model by implementing or changing some of its features.

Modelling in this study is done with a specific declarative language that presents all of the necessary features. SDML stands for Strictly Declarative Modelling Language. It is an object-oriented language written in Smalltalk, and using a visualWorks engine, it is specifically developed in the Centre for Policy Modelling (Moss, Gaylard et al. (1996)). I will now present some basics, helping to understand the structure, and hence the programming references made in this research.

3.7.1.1 Under SDML: Smalltalk and VisualWorks

Smalltalk is a pure object-oriented language. While C++ makes some practical compromises to ensure fast execution and small code size, Smalltalk makes none. It uses *run-time binding,* which means that nothing about the type of an object need be known before a Smalltalk program is run.

Compared to the widely used C++, Smalltalk programming has several advantages. The use of libraries and inheritances allow a fast development. This object-oriented dimension makes the development process more fluid, so that "what if" scenarios can be easily tried out, and classes' definitions easily refined.

Unlike C++, which has become standardised, The Smalltalk language differs somewhat from one implementation to another. The most popular commercial

[14] It is from a discussion with Rob Westcott that the principles for an algorithm allowing for a longer memory have been sketched, and later implemented. See section 5.3.4 for the relevant analysis.

"dialects" of Smalltalk are VisualWorks from *ParcPlace-Digitalk, Inc.*, Smalltalk/V and Visual Smalltalk from *ParcPlace-Digitalk Inc.*, VisualAge from *IBM* and VisualWorks.

Only the latter is of interest for us for now.

VisualWorks was developed by ParcPlace, which grew out of the original Xerox PARC project that invented the Smalltalk language. VisualWorks is *platform-independent,* so that an application written under one operating system, say, Microsoft Windows, can work without any modification on any of a wide range of platform supported by ParcPlace, from Sun Solaris to Macintosh. VisualWorks also features a *GUI* (Graphic User Interface) builder that is integrated into the product and used in SDML.

3.7.1.2 SDML components

A brief overview of the components of SDML is given, although with simplicity in mind it might not be technically sufficient, or rather ambiguous to the aware reader.

A SDML program is made of modules, objects, definitions, rules, and rule bases.

A module can be saved as a separate file from the program itself. A single file can contain a module hierarchy if necessary. A module contains all the definitions, objects and rules. Several modules can be loaded into SDML, and as for standard objects, one module will inherit the contents of its parent, and allow access to its own to its eventual “child”.

The object part of the language means that we can define properties for some type of agent (they can be thought of as a “mould”), and later generate many objects (or more precisely instances) of this type. Some types already exist, and it is straightforward to create new ones with the properties that are relevant to the actual modelling.

Types (or classes, their equivalent in other object oriented languages) can be defined by the modeller. They can represent some characteristics or properties of an entity. The LoopingAgent will allow them to go through multiple time levels, while an equally important one is the ParallelAgent, from which many agents will inherit. It provides the capacity for multiple agents to act simultaneously, but due to the everpresent logic core of the language, it also prevents them from accessing information that would not be available before they start acting. This ensures the strict containment of information and a very rigorous behaviour with respect to the timeframe of the simulation.

There is necessarily a unique “root” agent, called the UniversalAgent, that every subagent will inherit from.

An agent’s actions can be of various natures. They are presented as rules, and use clauses.

One can define new appropriate clauses and their associated syntax. Some basic ones are already present, but this flexibility comes in very helpful. The syntax can be multiple. In this eventuality, the engine will fetch the corresponding components. The whole point in creating definitions that have a particular syntax is to be able to keep track of them. They are kept in a database.

This database is what allows us to keep track of the different values of particular arguments. This enables the possibility of backtracking decisions and assertions. When observing a simulation result, the user is able to analyse every value of every object, and devise queries that would return the exact set of values or parameters that were at the origin of that decision or event.

An object can be active, or inactive in a simulation. In our case, an inactive object will only have properties, while an active object will also have rules. Rules are composed of an antecedent and a consequent. They can be thought of as a “if (antecedent) then (consequent)” sequence. Antecedents define the conditions for firing a rule, while the consequent generates the set of arguments for the definition. Every entry in the database refers to initial conditions or has been asserted by a rule firing.

The antecedent to a rule is composed of assertions. The SDML engine will then retrieve the values of these assertions, and evaluate the eventual modifications. If the logical result of that computation is true, then the consequent will be asserted in the rulebase of the agent / type for which the clause was created.

As a declarative language, SDML facilitates exploration and analysis of the dynamics of the simulation. Internal consistency of a model is provided by the fact that SDML is based on the Strongly Grounded Autoepistemic Logic devised by Konolige.

In rule-based programming languages there are occasions when the ordering of rule-firing is underdetermined but may alter the results. In declarative programming, where rules represent relations this might result in inconsistent results (e.g. rule A fires, then rule B but the results of rule B invalidate the firing of rule A). SDML, like many other declarative languages uses a careful inference engine that ensures that rule-firing is consistent relative to a well defined sound and consistent logic. In SDML's case it is a fragment of Konolige's "Strongly Grounded Autoepistemic Logic".

A practical decision rather than one based on high principles, this logic was chosen because it allows the sort of inferences that support the production of social simulations. The inference engine of SDML is not complete in that it is possible to write rules which SDML will not be able to solve. However, the engine of SDML is optimised for the sort of rules that social simulators use, so this almost never happens in practice. The overwhelmingly important property that the logic confers on SDML is this: IF the simulations runs and finishes without SDML reporting inconsistencies THEN we know that the rule-firing was logically consistent.

A distinctive feature that is used in the model developed is the presence of a meta-agent. It is not an agent *per se*, but can be pictured more as the thinking part, or brain of an agent. It can devise rules that its agent will use during the course of a simulation, authorising for example a changing structure of preferences throughout the simulation period.

Because it is declarative, at every stage the program will look for values that conform to the rules, if possible. It can be forced to make assumptions. These assumptions are explicit and consequently easily traceable, therefore not hidden in any way and eventually subject to debate and discussion.

3.7.2 SDML nature and use

The representation of stochastic processes is of course possible. For that reason, there are random number generators. But in order to backtrack the various choices made, these random numbers can be uniquified by SDML, and can hence be retrieved by providing appropriate arguments for any posterior query.

Simulations generated by SDML show a trajectory within the space of possibilities. With a finite set of possibilities, mapping of these trajectories can still be immense. This is why the use of SDML is restricted. In the current case, it can be used to find trajectories, or to represent a sample of trajectories that can be obtained with a set of initial conditions. It is difficult to conceive that the results provided by SDML could be used in order to assert with certainty a set of properties to the result of a process with specified initial conditions.

Instead, what SDML can provide is a way to put assumptions to the test, and a logic-based example of what some process, associated with its representation via conditions and rules is likely to generate.

Many formal tools such as statistics or game theory attempt to provide strong assertions, representing imperfectly a phenomenon and using limited and constrained techniques. These techniques sometimes rely on assumptions that can be unlikely or unrealistic (Moss (2001)).

As this is not the case for Multi Agent Based Social Simulations, the nature of the tool invites a change of use. Modelling, as a representation of a system, can be considered as part of the answers that are sought for. The model itself as well as the modelling is then not used as input to a decision process, but as part of a decision process.

That is the purpose for which integrated assessment has been created, as an iterative and reflective process to link knowledge (science) and action (policy). Such a modelling method allows its use within a framework such as the integrated assessment.

The very nature of computer simulation can be seen as more than just an input. As expressed by Varenne (2003), the status of simulation can be an experience, a theory, or something intermediate. It is that latter stance that this research is attempting to emphasise. The particular status of the tool depends on the field and the spirit it is used in. For example, in artificial societies, a simulation is by definition an experiment, while in biology, the observed growth of a virtual plant will be strictly theory.

Varenne therefore defines computer simulation as treatment step by step by a computer of either a mathematical model without analytical solution, or an inference engine based upon rules. The latter is obviously relevant to this study.

3.8 Conclusion

This chapter intended to demonstrate that there is an improved alternative to modelling techniques commonly used. The improvements is twofold. Not only is it possible to find a technique (and the associated tools) that will capture both quantitative and qualitative aspects of the phenomenon observed, this technique will not depend on any underlying assumption, and will therefore be usable where statistics are not.

When observed with a particular tool or method, a society is most likely to be averaged via statistics, or detailed via surveys, that will themselves be treated as a representative sample. Most representations with the former require assumptions, as described earlier. In the later, the data gathering process itself must be very rigorous, using well-designed methods and experienced enquirers.

As seen in the previous chapter, the analysis of water demand has mainly been done within a single view, either qualitative or quantitative. Despite some reservations in some of these studies, they represent two options in the knowledge of household behaviour for water demand. The SDML implementation allows ignoring these dichotomies and including both qualitative and quantitative components in the model.

Section 3.2 argues that in order to communicate the various questions we want to investigate, a representation of the phenomenon involved, or model, is needed. A model is then defined as "*the representation of a structure*", while modelling is "*the devising or use of abstract or mathematical models*".

Section 3.3 presents facts regarding the data in the chosen case of water demand. It argues that social phenomena can present the characteristics of complexity, and demonstrates that sets of observed data do not comply with an often assumed normality. The statistical analysis of the observed data showed a property called leptokurtosis. Presenting the power law distribution as an alternative to take into account leptokurtosis lead to defining the property of self organised criticality. One of the potential causes for SOC is social embeddedness, which is a major characteristic of the target system in the present case. A critical consequence is that, as acknowledged by the SOC literature, there is not yet an analytical method to create models that generate processes with this property.

Section 3.4 introduces the concept of agent, and then of Multi Agent Systems. This section argues that Multi Agent Systems allow representing a system in a way that is compatible with the complexity conditions, observing emerging patterns of behaviour, and generating a model using a participative approach.

Section 3.6 presented the six modelling stages, their sequence and how they are linked and can be compared. It also discussed the necessity of integrated assessment, a method that was used to generate the initial versions of this model. Mostly, it emphasizes the importance of stakeholder participation, which can only be secured if there is sufficient interest from the stakeholders.

Finally section 3.7 presents the Strictly Declarative Modelling Language (SDML), arguing that its characteristics make it an ideal choice to implement the scenarios. The added value provided by using Multi Agent Systems as a framework and SDML as a tool is that this approach can be considered in two separate aspects. The first one is the possibility to investigate and assess both quantitatively and qualitatively, while the second one is the multiplicity of scales that can be used.

Now the problem is presented, and its properties analysed in order to select the most appropriate methods and tools to tackle the issues they raise, it is necessary to provide a more detailed view of the assumptions, and how these tools are used. This is the object of the following chapter.

4 Presentation of Scenarios

4.1 Introduction

The previous chapters introduced first the context and then the tools that have been selected to address the challenges of modelling water demand. It is now time to delve into the details of the way scenarios themselves are represented. This chapter first provides remarks on the assumptions made in the modelling process and their origins. It then presents the data used for the climate and for the appliances, and then describes the components of the model as well as the different steps of the simulation, in order to provide a global view of the inputs and processes. Finally, a discussion on the representation of innovators is followed by exhaustive detailing of the scenario parameters.

4.2 Model details

The Agency's scenarios developed are based upon 4 assumptions.

1. The future is shaped by human choice and actions
2. The future cannot be foreseen, but exploring it can inform present decisions
3. There are many possible futures
4. Scenario development involves rational analysis and subjective judgement

Principles for the model are categorised according to the governance and social values used in the scenario. The role of the regulator as well as the important assumption on household water supply is also addressed, as they are reasons for tackling the representation this way.

4.2.1 Representation of the social values through endorsements

The representation of the social values of households does not imply anything in terms of the modelling of the structures and the environment. There are implications regarding the way they see and judge that environment. The argument here is that someone caring about community will put a greater emphasis on the community as a driver of his own behaviour. Selecting the appropriate weights of influence in the already existing model can then represent this indicator. The endorsements can be ranked, from an individualistic (self-centred) point of view, to a more citizen (globally influenced) one. They can therefore be used to represent the concern and influence of a particular agent. There is a link here between the fact that an agent is community oriented, and its major influences are in the "community" around him, his neighbourhood. Nevertheless, while it is easier to argue that individualism can be linked with the references in the model to the self-centred beliefs and rules, community can be a bit more difficult in the framework of this model. What is called community in the Environment Agency approach is actually referred to as "neighbourhood" within the model as the immediate social environment of the agent. As it is expressed in their description, community also seems to have the meaning of "citizenship", or behaviour in line with the idea of not wasting limited resources.

4.2.2 Representation of the governance structure through the distinctive characteristics of the scenarios

While social values can be represented in such a way that various ones can be generated easily, through a simple choice of different ranking and / or values of the endorsements themselves, this is not possible for the governance structure. As expressed earlier, there are issues with the meaning of such an indicator that prevent us from implementing it in a single and specific way. Consequently, unlike the first part of the influences, this classification of the scenarios will be done using a detailed approach. For a given state of social values, the governance structure will be identified (and the scenario defined) by the range of available appliances, their associated values (ownership, frequency, volume, replacement rate), and the presence or not of technological regulations.

4.2.3 Representation of the regulator through availability of resource saving appliances

The representation of the technological regulator is simple. Since the regulations are enforced in the scenarios, there is no need for a dynamic adaptive regulation, *i.e.* the presence in the model of an agent that would evaluate the situation and eventually decide on the need for intervention. Like the emergence of new appliances, which was already implemented, it is present as a constraint upon the appliances. Since the scenarios describe accurately when regulation happens, the influence on the model is that from a given date onwards, some devices are made available or unavailable for the households.

4.2.4 Metering is not represented because of the uncertainty of the effects.

Metering is not implemented in this model for two main reasons. First, the current issues for forecasts are rather in the evolution of unmeasured customers. Meter penetration level is currently 23% of households in England and Wales, so the main concern in water consumption remains unmeasured customers. Second, there are many ongoing studies regarding metering. While there is evidence it influences water consumption, it is not actually known in which proportion this happens, or what factors trigger the decision of opting for a water meter. Also, there are multiple reasons for a household to switch to a metered supply. Among them, the most common is the change of occupancy (*i.e.* moving out/in), while opting in is currently negligible. As a consequence, the effects of metering are yet unclear (OFWAT (1992)). Some preliminary results are available, but they do not show the kind of consistency necessary to believe they can be used to match the target system in a model.

Also, as already detailed, the agents in the current model are not mobile, geographically or socially. The limits, in the necessary knowledge to implement metering and in the usefulness of this implementation, explain the decision to ignore this component.

4.3 Model data

4.3.1 Climate data

The dataset used for climatic conditions is partly simulated. It is originally based on the recording from the meteorological station in Lancing, West Sussex. The actual data goes from 1980 to 1997. The data for the following period were generated during the course of the Climate Change: Demand for Water (CCDeW) project (Downing, Butterfield et al. (2003)). They are based upon the UK Climate Impacts Programme (UKCIP) Medium High assumption of climate change. This was developed in 2002, and corresponds to the outputs of the UKCIP02 project (Hulme, Jenkins et al. (2002)).

The climate data files include projected temperature as well as rainfall. For the parameters in the ground module, monthly average temperature and total precipitation time series for Central England for 1970-1997 were used, as well as a 51° latitude for calculation of the hours of daylight .

To match the UKCIP02 Medium-High emissions 2050 scenario the above time series were modified to reflect this UKCIP02 forecast for the upper Thames region. This involved modifying the temperature and precipitation data as follows:

Month	Compensation factor (%)
January	12.5
February	10
March	0
April	-5
May	-10
June	-20
July	-30
August	-20
September	-15
October	-7.5
November	0
December	10

Table 5: Monthly modification to precipitation time series

Month	Compensation factor (%)
January	1
February	1
March	1
April	1.5
May	1.5
June	1.5
July	2
August	2
September	2
October	1.5
November	1.5
December	1.5

Table 6: Monthly modification to temperature time series

Regarding the values for Ownership, Frequency and Volume, the data used in this model originate from the data used by the Environment Agency during their 2001 forecast. They only represent a part of the largest sample used by the Environment Agency since they are valid for one resource zone of one single company.

The data were collected by Three Valleys Water PLC, a company that supplies mains water to the North and East of London, an area which includes Stansted, Luton and Heathrow airports, and is only relevant to the unmeasured population of their resource zone 2. Despite being estimates, they represent the actual data reported by the company to the relevant stakeholders.

Consequently, these values for Ownership, Frequency and Volume are only an example of such data. Nevertheless, they represent a valid choice, since they are consistent with other data sources.

4.3.2 Water consumption estimates

In order to check how representative the data are, some specific uses are given by a Survey of Domestic Consumption (SODCON) and the Water Facts that seem quite consistent.

	SODCON	Water Facts	Average of the previous ones	Thames Water Demand Model (2001 estimate)	Min/Max	Three Valleys
Drinking, cooking and food preparation	21	29	25	22.8 (sundry[15])	21/29	30
WC flushing	49	53	51	42	42/53	36
Car washing and garden use	8.4	5	6.7	10.5 (0.4+10.1)	5/10.5	14.9
pool				0.3	#	
Washing up	5.6	14	9.8	8.7	5.6/14	15
Laundry	16.8	19	17.9	19.9	16.8/19.9	25
Personal washing and bathing	39.2	40	39.6	56.6	39.2/56.6	54
Total	140	160	150	160.7	140/160.7	175

All amounts are l/h/d

Table 7: Comparison of measured Pcc depending on various sources

The total PCC seems “standard”, the current value for metered households according to OFWAT being 150 litres/head/day, while the Pcc for the actual data used is slightly higher, at 175 litres.

This is not only explained by behaviour, it is also a consequence of different ownership patterns.

[15] The sundry indoor uses are based on population and household uses, *e.g.* for drinking, cleaning and hand washing.

Appliance Ownership	Measured	Unmeasured
(corrected survey figures)	%	%
Baths	98.6	98.2
power showers	32.8	30.3
other showers	61.0	54.6
washing machines	95.1	95.3
dish washers	46.2	38.6
sink/wash basins	100.0	100.0
outside taps	65.6	70.8
cold water storage tanks	N/A	N/A
ordinary toilets	91.1	94.7
dual flush toilets	13.2	9.7
possess sprinkler	26.0	14.8
possess hosepipe	66.6	74.9
other mains fed watering system	2.1	1.3
possess swimming pool	4.1	0.8
possess paddling pool	10.7	10.2
possess greenhouse	15.8	21.5
possess garden pond	13.9	17.2
possess car	89.2	87.8
Total responses (excluding nulls)	3,324	2,280

Table 8: Comparison between measured and unmeasured ownership

It is clear from this presentation of ownership that unmeasured households are less likely to have water efficient appliances (*e.g.* dual flush toilets), while more possibilities of external uses are present, with higher proportions of greenhouses, hosepipes and garden ponds.

The exception of swimming pools is explained by the regulations that force owners of such water hungry items to be charged by volume by their water company.

In the end, the consistency of the Three Valleys data with the different sources mentioned could be considered as good, in spite of differences that could be interpreted as changes due to regional variations. This is the case for ownership of dishwashers, or to a lesser extent, of swimming pools.

4.4 Inputs and Outputs

The model devised for this research is supposed to represent an artificial society. It is not a totally abstract system, and it is meant to be used by stakeholders, and not only analysed. It is supposed to provide some insight into patterns of behaviour for water demand within a group of agents. It is also an opportunity to try a different approach, using multi agents systems, in order to reach the structural flexibility that is necessary for testing climate change scenarios.

The model is shaped by the relevant characteristics of the target system. The previous chapter showed that there were three main areas for which the modelling had to hold particular attention:

- the environment, made of the agent's location and the climate
- the imitation, composed of social influences and structures of preferences
- the innovation, including the rating, decision making and adoption of new technologies

A presentation follows of the underlying assumptions and the corresponding reasons for them.

4.4.1 Model components

4.4.1.1 The Agents

4.4.1.1.1 Agents are on a grid

The situation of agents within the model must resemble the situation in the real world. Using a grid to locate them could be seen as a twofold mechanism. The grid could represent either a social system, or a geographical situation. A grid also introduces the concept of population density, and distance. Agents can be placed at random, or in a given location if necessary.

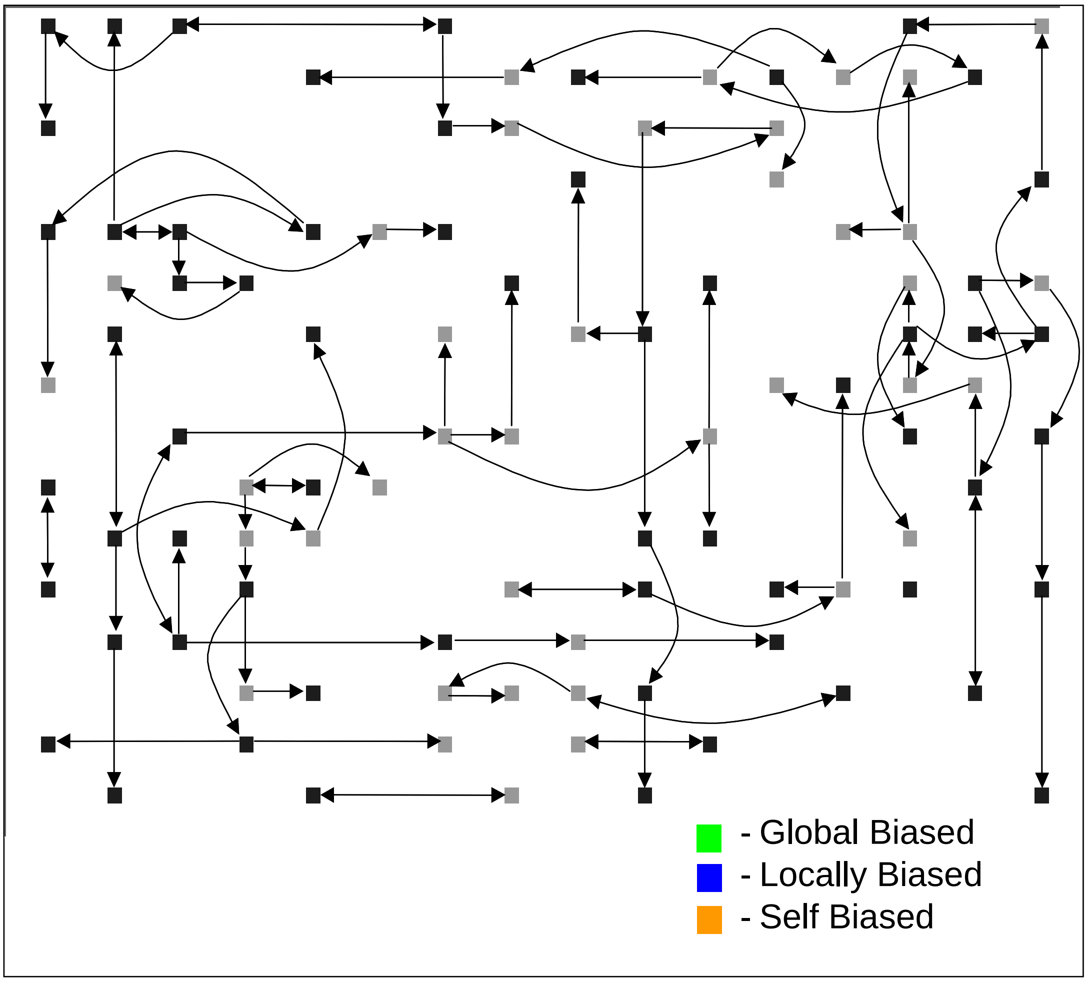

Figure 10: An example distribution of households (arrows show those households that are most influential to another)

The figure above is from Edmonds (2003) where the author discusses the relations between physical and social space. Edmonds describes the network between agents most influential to one another in a specific run of an earlier version of this model used in the CCDEW and FIRMA projects. In this article, the author expresses the view that "the particular network of social relations is important to the behaviour of the individual", and demonstrates that removing the neighbour to neighbour influence increases the volatility of the results. Nevertheless, Gotts, Polhill et al. (2003) point out that, *"imitation of neighbours […] will not invariably prove superior to random choice among all possible alternatives".* This is not contradictory to the results obtained by Edmonds but rather indicates that, as the authors conclude, it is necessary to analyse the processes involved in the imitation, the individual cognition, as well as the way decisions are made.

4.4.1.1.2 There is a policy agent

The Policy Agent is by design a public broadcaster. Every agent can access the information it contains. The reason for implementing such an agent is that there needs to be a representation for the public voice, the advice given on national media. It is something households are sensitive to, although with some nuances. It seems from experience that the households are reacting not to the media, or the government, but to the legitimacy of the message. During the drought in 1995, households reduced their water consumption when exhorted. But when it became known that the appropriate procedures were not followed, some quickly shifted back to their normal behaviour, till the same exhortation was repeated, this time with the insurance that it was a legitimate call.

There are various kinds of policy agents, as described in the first chapter. The OFWAT and the Environment Agency are regulating the water companies, but the latter is the body representing the wise and knowledgeable voice of the government, if not the sensible voice of humanity. Of course that particular representation in the model is too simple to pretend to being any specific body or media, but it allows the implementation of an example of media that would broadcast with the same spirit.

For example, between 1976 and 2000 in the Thames region, the Environment Agency has declared only 8 droughts in 1977, 2 in 1990 and 3 in 1992, while in our model the Policy agent is more active (reacting, in the simulations, to 23 droughts of various duration during the period 1977-1997, and 30 in the period 1970-1997).

The Policy Agent is an important source of information and guidance. Only one is currently implemented, because this is not one of the main issues for the model. Moreover, there is a significant difficulty in faithfully representing various kinds of policy agents, and a lack of information about their behaviours. Nevertheless, several policy agents could be implemented if needed, provided appropriate help from the stakeholders.

4.4.1.1.3 The policy agent reacts to droughts

The only concern for the policy agent is the current status of the water stocks in the system. It does not forecast, it only reacts to scientific evidence. This evidence is the soil moisture deficit, which is the quantity of water contained in the ground.

The weakest definition of a drought ultimately comes to the lack of moisture in the soil. Throughout this work we will refer to drought as hydrological droughts, which happen when surface and subsurface water supplies are below normal, (by opposition to meteorological[16], agricultural[17], or socio-economic[18] droughts). The reason for this choice is that the hydrological drought precedes the socio-economic one, and that it is the one upon which the water companies have some influence. Indeed, not only climate factors have an impact upon it, but also landscape and land use. Hence the presence of new dams can have a significant impact upon it.

Consequently, the soil moisture deficit can be considered as an appropriate indicator of the surface and subsurface water supplies. This indicator has been analysed, and is commonly used.

More formally, in the presence of a drought for the second (or more) consecutive month, the Policy agent will broadcast a message based on the average frequency of use and volume per use for a given appliance. In that case, the Policy Agent generates a factor equivalent to the square root of the current proportion of soil moisture that it applies to the frequency of use and the volume per use, in order to broadcast a recommendation with these new values.

One can see that with this implementation, when the drought increases, the recommendations of the Policy Agent increase as well.

4.4.1.1.4 Every household is defined by its set of Ownership, Frequency and Volume, which defines an output to the model

Some economic indicators are not used, such as the income of the household. Nevertheless, a household is defined by its location and by its endowments and its use of water. Taken globally, rate of ownership can be translated into effective ownership for a given household via probabilities, or it could be imposed to fit a situation, for example to the extent of imposing clusters of households that would

[16] A meteorological drought is a measure of departure of precipitation from normal. Due to climatic differences what is considered a drought in one location may not be a drought in another location.
[17] An agricultural drought refers to a situation when the amount of moisture in the soil no longer meets the needs of a particular crop.
[18] A socio-economic drought refers to the situation that occurs when physical water shortage begins to affect people.

possess (or not) some specific appliance. The associated frequency of use, and volume per use are also informed by real data provided by stakeholders.

Volume could be expressed per time, and not per use. This is not the case due to the nature of the data provided, and is nothing else than an average value of the former with respect to the frequency of use.

Due to the nature of this data, the volume is expressed per use, instead of as a time dependent debit. It can be noted that the ownership of appliances can be seen as an indirect way of representing wealth for a household. Although not a very accurate one, it can be tuned by the model user, eventually to the extent of imposing clusters of households that would possess (or not) some specific appliance.

Ultimately, the output of the model will be a demand for water, computed by multiplying for every household the ownership (then a binary value) by the effective frequency of use, by the volume per use, and summing up for all the agents.

4.4.1.1.5 Every agent has endorsements

The method to generate this subjective value is taken from Cohen (1985). The different endorsements are ranked in classes of importance, the higher the class, the higher its contribution to the total value of the endorsement.

The approached used here, is to define a number base b and evaluate each endorsed object according to the formula

$$V = \sum_{e_i \geq 0} b^{e^i} - \sum_{e_i < 0} b^{|e^i|}$$

where e_i is a (usually integer) value associated with the i^{th} endorsement token. Negative values of endorsement tokens indicate naturally enough that they are undesirable. The higher the value associated with an endorsement token, the higher the class of tokens containing that particular token. The value of *b* is the importance of an endorsement token relative to the value of a token in the class below. If the base is 2, then an endorsement of class three contributes 8 to the endorsement value of an object while an endorsement of class two contributes only 4. For values of b larger than the number of tokens in any class used to endorse any object, the results from this evaluation scheme are the same as from Cohen's evaluation scheme. For smaller values of *b* it is possible for a large number of lesser endorsements to outweigh a small number of endorsements of greater value

4.4.1.1.6 Every agent has a memory

The memory of an agent is limited. It restricts the choices for actions. Every month, the household eventually forgets some of the actions it has been doing. Its only choice remains between the actions that are remembered and the actions that are presently observed. Anderson (1993) is the reference from the cognition field used to implement this theory. The memory is associated in the model with a probability to remember past actions. This probability is decreasing as time goes, and is positively linked with the importance of the corresponding action. In other words, a household will always forget past actions, but it will forget less quickly (or remember more) those that were important at the time. When one makes a decision, it is likely to have a trace corresponding to its importance. The decision of buying a house, or proposing marriage remains in memory much longer than the decision to have rice or pasta for the next meal.

Hence the probability is as followed:

$$P(M) = \frac{\frac{|E|}{t^d}}{|\max E|}$$

where *P(M)* is the probability of remembering, *E* is the value of the endorsement, *t* is the time elapsed since the endorsement was created, *d* is the rate of memory decay, and *max E* is the maximum value of an action endorsement.

This function is consequently positive, between 0 and 1, and has the appropriate characteristics for our purposes (increasing with E, decreasing for *t* and *d*).

4.4.1.1.7 Every household is amenable to suggestion by the water authority to different extents

Every household can be different. Real life observation demonstrates that some people show more citizenship, while some others are more exclusively self-centred (*i.e.* selfish). They actually value (or endorse) a signal differently depending on its source. This particularity is implemented here with the help of the endorsements. An agent would rate in a specific order the actions suggested by the policy agent, the neighbour's observation, or its own actions. This represents the general influence of the household. The model allows the user to select the proportion of agents (on average) that would have a specific main influence.

I.e. the population can be purposely divided into 35% of households mainly influenced by their immediate neighbours, 55% influenced mainly by their own actions, and the rest influenced by global messages from the policy agent in our case.

4.4.1.1.8 Every household has public and private activities

Real life observation easily demonstrates that there are public and private behaviours. With respect to water consumption, some appliances are generally used in such a way that they will or will not be visible by the neighbours. Sprinkling a lawn is most likely to be observable, and not only during the act, but also as long as the traces induced remain (wet pavement, wet grass). The same applies for washing and drying clothes, for example, amongst other uses. Hence, the user can choose the activities that will be visible by the others (or public activities), and those which will not (or private activities).

4.4.1.1.9 Every household can evaluate its asymmetrical relationship with its neighbours

Neighbours are endorsed, *i.e.* households will have a subjective point of view upon every one of them. As it is subjective it is not symmetrical since for example a household can be envied by another one, while the opposite is not necessarily true.

4.4.1.1.10 Every household's demand is influenced only by its endorsements

Due to the purpose of the model, the focus is not the representation of instant demand. This study tries to analyse the social and cognitive influences upon consumption behaviour. In the event of seeking some more accurate and more detailed data, it would be necessary to implement a direct influence of climatic conditions upon the use of specific appliances. Nevertheless, this requires a much finer grain of analysis than can be devised. For example, climatic conditions of a bank holiday Monday in May would become the most important parameters for the demand for water. Also, this level of detail would certainly have huge costs in terms of data treatment, household surveying, and computation times. There are many difficulties for this research to use data gathered by the water companies. Firstly currently available data are difficult to obtain, and secondly, necessary data might not be yet collected, and could need the development of different surveying methods or questionnaires. Hence the requirement for finer grained data surely necessitates more time and influence upon the water companies than available to researchers at the moment.

4.4.1.1.11 Every household decides to use the pattern known by itself that it values the most

Using a simple principle of rationality means that when an agent has to make a decision, and in the absence of constraint, it will select the decision that has the highest value in its mind. The value can be the returns expected from that decision, or in the case of behaviour, the behaviour it rates the highest. In order to express subjective values for an agent, it is useful to turn towards the fields that have already tried to analyse and present a solution to his problem. The so-called consistency principle is presented in “Social Psychology” (Brown (1965)). It refers to the fact that social studies show that we tend to feel closer to what is like us, and we tend to like what seems closer to us. In Brown’s words, “*it seems to be a general law of human thought that we expect people we like and respect to associate themselves or agree with ideas we like and respect and to dissociate themselves or disagree with ideas from which we dissociate ourselves.*” This idea is also present in Heider’s closely related balance theory (Heider (1958)) (and its representation as the A-B-C model, in which the links between individuals A and B and another object C must balance each other), and in what the psychologist Eysenck (1954) refers to as the radical – conservative (or liberal – conservative) factor. This logic in attitudes and beliefs is labelled cognitive consistency.

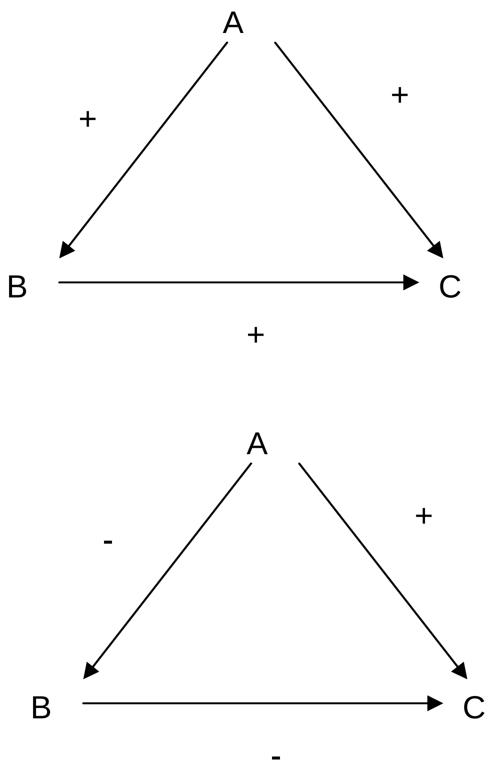

Figure 11: Representation of Heider's ABC model

4.4.1.1.12 Agents rate new products

As for every appliance, the emerging ones are subjectively rated. But unlike common ones that are already owned, these are rated on the basis of what information is communicated about them. They are eventually made available from a given point in time, from which they enter the knowledge of the household. Although some studies on the diffusion of innovation may suggest that some agents know before others that a product is becoming available, it can be argued that the small group we are dealing with here has a global perception of the available appliances.

4.4.1.1.13 Agents can adopt new products

There are two possibilities for a household to take the decision of changing a given appliance. The first case is if the already owned older substitute fails, and the second is the probabilistic representation that on average, a household will renew its appliances every 5 years. The adoption process is then triggered according to these 2 possibilities.

4.4.1.2 The environment

4.4.1.2.1 Soil moisture deficit is computed through the modified thornthwaite algorithm

Soil moisture deficit is a good indicator for water stocks, since it takes into account the evaporation, through the mean temperature, sunshine time and precipitation. It is commonly and internationally used for that purpose (Thornthwaite and Mather (1955)).

It is computing the Potential Evapotranspiration, or PET. PET is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply

The value of the unadjusted Potential Evapotranspiration at temperatures above freezing is calculated as:

PET	Temperature (T) range
- 415,8547 + 32.2441T – 0.4325T2	26.5 ≤ T
$16.5\ (9\ T / H)^{a}$	0 ≤ T < 26.5
0	T < 0

where H is heat defined as

$$H \equiv \left(\frac{T}{0.7}\right)^{1.514}$$

and the exponent *a* is

$$a \equiv 6.75e\text{-}7\ H^3 - 7.71e\text{-}5\ H^2 + 0.01792\ H + 0.49239$$

Day lengths are calculated from the day relative to the winter solstice and the latitude. Monthly PET values are adjusted to reflect the difference in water use between a grass surface and a mixed landscape of grass, trees and shrubs. Monthly correction factors are:

Nov – Dec - Jan – Feb - March	April	May	June – July – Aug	Sept	Oct
0.8	0.9	1	1.1	1.05	0.85

Table 9: Monthly PET correction factors

4.4.1.2.2 Appliances break according to some probability distribution

The breaking of an appliance or risk of failure is used in manufacturing processes studies to define Mean Time Between Failures (MTBF), a useful indicator for repairable items. Mean Time To Failure (MTTF) is its equivalent for non repairable ones, and the basis for a suitable warranty for the manufacturer. It should be noted that MTBF is commonly used for both repairable and non-repairable items. MTBF and MTTF are expressions of time, and represent the inverse of the failure rate (for constant failure rate systems). In that case, if a product fails 10 times in 250 hours, its MTBF is 25 hours.

In the industrial sector, reliability data have been gathered and are available, like the values of the observed failure rates. This failure rate is generally forecast using a weibull probability density function (Bloch and Geitner (1994)). This is composed of 2 arguments, the shape and the scale, and can model a wide range of data and life characteristics.

4.4.1.3 The interactions

4.4.1.3.1 Every household can observe its neighbours

On the grid, every agent can see its neighbours, according to two basic rules. First, they must share a coordinate, and second, they must be within a range of vision on that axis that is determined by the user. The fact that they must be on the same row or column has no real-world justification. Nevertheless, there is a lack of knowledge of social distances and neighbouring that prevents us from using an already validated technique in this case. The range of vision is then representing the fact that the neighbours from a given agent have to be within “sight” of that agent, and therefore provides that horizon.

The Moore neighbourhood consists in using every adjacent cell to the agent's. Alternatively, the Von Neumann approach consists in only the horizontal and vertical adjacent cells. The possibility to enhance the neighbourhood is taken into account in the modified versions of these definitions. Therefore, strictly speaking, this model uses the modified Von Neumann neighbourhood, although because it can be set as a parameter, it can sometimes simply use the Von Neumann one.

4.4.1.3.2 Every household is influenced by the neighbours, by itself, and by the global broadcast

Every household knows that it exists, that its neighbours exist, and that a greater entity exists (the Policy Agent, representing for example the Government, or manager of the system). It has beliefs that make it more or less sensitive to each of these entities.

4.4.1.4 Organisation

4.4.1.4.1 The size of the grid is limited

The grid is limited for several reasons. It is easier to analyse a system that is itself limited, whether it is to a postcode area, a region, or a country. Second, because of the simulation methodology and tools used in this case, there is a computational cost associated with the sample size of the system. The way the model is devised, this cost does not scale up linearly with the system's size and density, but much faster. While increasing size involves relatively linear costs (until a threshold is reached depending on the computer hardware), increasing density does multiply the amount of calculations necessary for a given agent.

Moreover, the size of the simulation will have a direct positive influence on the difficulty of analysing the results of that simulation. This includes computing limitations (for example the time to answer a query), as well as the ease of representation and analysis. It is for example a lot more tedious to check on the network structure during a simulation with a large grid than a smaller one.

This raises the issue of the extent to which a system can be scaled. The lower limit is the use of an average system, or average agent. Every individual is then summed up into a single one. This approach is widely used in microeconomics, but it is argued (Kirman (1992)) that heterogeneity of agents is needed, not aggregation, in order to generate rational collective behaviour.

4.4.1.4.2 The grid is toroidal

Initially, the grid is two-dimensional. There is a possibility to make it into a torus, *i.e.* it becoming doughnut shaped. This is to avoid corner effects in the grid that would tend to limit the possibilities of neighbours for some agents. It does create another phenomenon to look at since it is changing the topology of the underlying network.

The torus simulates a space that is bigger than it is computation-wise, and a society that is composed of multiple comparable elements. But with this method, it also enhances the amount of possible links, having important consequences upon the network structure.

4.4.1.4.3 The grid is regular

While there are possibilities of generating non-regular grids, this is not the case here. The situation of the agents on the grid allows us to represent their location, the abstract idea of installing them on a grid that represents some social space permits us already to consider various characteristics such as social distance, cliques, and the existence of neighbourhood. It is therefore not necessary (at least at this stage) to introduce some additional feature into the model that is not proved to be more suitable than the current implementation.

4.4.1.4.4 The time levels are naturally defined

The interest of simulations relies on the possibility to study the dynamics of a system, its processes. In order to keep realism, and due to the constraints from imported data (temperature and precipitation), the time levels must match those for which the model is intended. The level of detail to take into account will constrain the definition of the different stages. In this case, time levels are months and years, while another is added for technical reasons (namely the iteration level, for the synchronisation of information for agents that cannot access the component of a database that is created during the current time period).

This concludes the presentation of the model components. Now is the time for describing the model as a whole, and the sequence of events as they would occur during the simulation.

4.4.2 Model structure and sequence

Hence, the structure of the model is as follows:

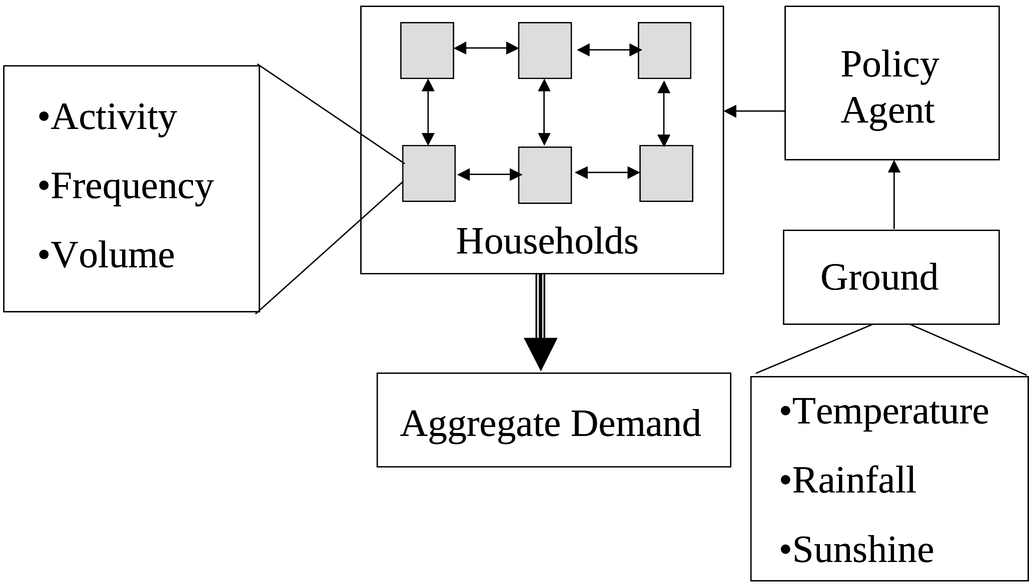

Figure 12: Model structure

The picture above represents the structure of the model, separated by main agent and influences. Temperature, rainfall and sunshine hours per day are inputs for the agent representing the ground. The policy agent observes the result. Simultaneously, the households are defined through their activity, frequency and volume, and can observe each other. The policy agent also has an influence on the households, while the latter process all the information and influences they have in order to generate individual and global aggregate demand for water.

The model is devised using SDML, which was described in the previous chapter. The formal stages used in order to represent more technically the process described in the previous chapter will now be presented.

When a simulation is run, the steps are as follows:

1. The simulation starts with initialising the Universe. This agent is unique, and like a matrix, will generate various kinds of agents according to the specifications provided.

2. Having read the rules in its rulebase, the Universal agent creates a first subagent called ThamesWorld. It also activates it so the software will read the instructions in this agent’s rulebase.

3. In turn, the agent ThamesWorld generates and activates two subagents: FirmaModel, and ThamesGround. These agents will represent respectively the society, and the soil represented in the model.

4. At this moment, ThamesWorld will describe different time levels, called “run”, “year” and “month”. Since they are inherited, from this point onwards the subagents will recognise these time levels as well.

5. In the FirmaModel and the ThamesGround rulebases are most of the parameters of the model, such as the maximum runoff or the extent of the vision for the household. They will be read and kept in the database, and will be available to all subagents

6. The FirmaModel will generate subagents called Citoyens, and give them random locations on a grid. It will also generate the unique PolicyAgent.

7. Every agent of type Citoyen then generates and activates its own subagent, a metaCitoyen, which can be compared to a brain, in that it will change the preferences and will make the decisions for the Citoyen.

8. At the level of this metaCitoyen, and in the first rules to fire are those which specify individual parameters for the households, such as the values for the endorsements, or the initial values for the ownership, frequency and volume.

9. In the “content” period the important processes are defined. Since they depend on past choices and parameters, the description of its sequence needs to be considered from the first step in the simulation.

a. Once every agent is created, and the metaCitoyen is endowed with individual values as well as more global parameters, the behavioural processes take over the simulation.

b. In the first time step, every household is provided with some arbitrary behaviour, copied from the initial values it has received. Therefore, the parameters randomly chosen are in effect the first actions a household will undertake.

c. The initial values for frequency and volume are the results of a function. This function can have multiple shapes or arguments. In this research, it will be assumed that this function is either of a power law form, or a normal form. The distinction and its results are addressed in the following chapters.

d. Every action a household has been using is observed by itself, and therefore it is associated with one or several endorsements, such as "selfSourced", or "recentAction".

e. Once every household has acted, they observe each other. As they are all on a grid, a simple rule can find any neighbours of a specific household, according to the particular support or type of "vision" available.

f. From the observation of the surrounding households and the way they behave, every household collects information on others' actions, as well as on their identity, and how similar or dissimilar they are in their ownership or use of appliances.

g. The information collected is treated using the filters provided by the endorsement schemes. A household will be endorsed as "most similar", or with the closest overall volume of use for example.

h. If some new appliances become available at some stage, the households then integrate the overall list of appliances and actions that will be endorsed. When this happens, every household is aware of the availability of the new appliance at the same time. The differences in the way each agent values that information will make them more or less likely to select it in the end.

i. At this stage enters the Policy Agent. Since for any month there are data for temperature, rainfall and sunshine hours, the status of the soil moisture is updated. The Policy Agent collects this information and according to its value may react or not. If the soil moisture is less than a specific threshold for a given number of consecutive months (here 85% for 2 months), it then broadcasts a message.

j. The message in itself consists of actions, *i.e.* of a set of appliance, frequency and volume. It is at first calculated to be below the societal average for each variable, and will decrease further if policy is still need in the next month.

k. So the household has several sources of information: its own observations, the eventual availability of new appliances, and the eventual presence of a message from the Policy Agent.

l. All these sources of information are compared with the household's subjective mind frame, represented by the endorsements. Any information on an action, an appliance or an agent will be analysed, and as some will match the definition of an endorsement, their value for the household will change. As an example, the history of a particular action in one of the simulations is described as follow:

Month 1: used, endorsed as *self sourced*

Month 2: endorsed as *recent* (from personal use) and *neighbour sourced* (used by agent 27) and *self sourced* (remembered)

Month 3: endorsed as *recent* (from personal use) and *neighbour sourced* (agent 27 in month 2).

Month 4: endorsed as *neighbour sourced* twice, used by agents 26 and 27 in month 3, also *recent*

Month 5: endorsed as *neighbour sourced* (agent 26 in month 4), also *recent*

Month 6: endorsed as *neighbour sourced* (agent 26 in month 5)

Month 7: replaced by action 8472 (appeared in month 5 as *neighbour sourced*, now endorsed 4 times, including by the most alike neighbour – agent 50)

m. Once the endorsement values of all possible items of information are known, the metaCitoyen is in a position to make choices. The output of this process is the selection of new appliances. According to the agent's previous ownership, to the potential new appliances, and to the probability that they are broken, a new set of endowments is selected.

n. The frequency and volume corresponding to this appliance are chosen using the same method, comparing the individual evaluations for the actions observed to keep the highest one.

10. As the meta-agents have made their choices, every agent simply executes this "order".

11. Finally, at the FirmaModel level, the individual consumption for a household is computed, and aggregated into monthly data, in order to be collected in a file.

12. Once all the rules have fired in the month, SDML jumps onto the next, and the process carries on.

In order to keep consistency in the simulation the smallest time level is not the month, but the iteration. For every month, there are two iterations. During the first one the information is gathered and stored, and during the second one, the selection process and the storage of the results take place.

4.5 Representation of innovators

The starting point is the observation of the introduction of power showers as a substitute for traditional showers. It leads to the conclusion that some new devices can appear and have important consequences upon household consumption. It is hence necessary to implement innovation, which raises the problem of representing innovators in order to study the diffusion of a technology.

4.5.1 An issue with several dimensions

Several different points of view on innovation are worth investigating. The way it appears and the way it diffuses are the main ones. I am not going to discuss and implement a way of modelling the emergence of innovation.

Although it is an interesting field of research, it is not one that matters in the present work. This research is focused on water demand. As such, it is only interested in how the new technologies will be adopted not which ones will emerge. One could argue that these two questions are linked, and that depending upon the nature of the technology, it will be adopted more or less easily. Several studies show this fact (Rogers (1995)). This additional problem would nevertheless make this present research harder to validate and remote from its original aim.

The complexity of modelling the emergence of innovation is certain. Existing models mainly deal with firms more than households (Gilbert, Pyka et al. (2001)). Since we expect to reach some understanding of the target system from our representation, the implementation of a whole theory of innovation emergence would eventually increase the difficulty of devising the model, as well as the difficulty of eventually concluding from it. Also, it would make it more likely to be criticised from a theoretical point of view.

The need to consider innovation actually comes from the observation of a real phenomenon. In the early ’90s, a new kind of appliance appeared: power showers. They were aimed at replacing showers, and were relatively easy to install. They included an internal boiler and pump, and would then replace the older shower jet and only required a water pipe and an electricity source. They were reasonably cheap and improved the water pressure from the shower jet. But that came at a cost. The additional pressure meant using about double the amount of water for the same use, reaching nearly the amount used in a bath. The frequency of use itself did not change much though (and even increased according to some of our data). The result was a major change in water demand levels and patterns. This is the reason why it is necessary to build our representation in such a way that events like this can be included.

Hence this research must give the user the freedom to include the emergence of new devices and their appropriate characteristics. It is then a matter of following the diffusion of that innovation through the society and its effects on local or global demand.

The focus is not on the generation of innovations, but because the consequences of innovations must be taken into account, diffusion has to be as well. That is why some representation of innovation diffusion amongst households must be implemented, while the innovation theory itself can be left aside.

4.5.2 Innovation and innovators

It is necessary to define the concepts, and some characteristics of the current literature on innovation.

Quite an exhaustive view of innovation diffusion can be found in Rogers (1995). He defines diffusion as “the process by which an innovation is communicated through certain channels over time among the members of a social system”.

Rogers presents all (or nearly) the aspects of innovation, from its generation to its consequences, through the study of its diffusion through the characteristics of the technology, of the user, and of the underlying network. It is noticeable that the diffusion of innovation depends a lot on the nature of the innovation. Innovations have specific characteristics that could explain the rate of adoption, *i.e.* the success or the failure of a given technology: relative advantage, compatibility, complexity, trialability, and observability. Some even display self-reinforced dynamics, when the technology can benefit from network externalities. What is taken into account then is the global influence of the number of adopters in the system, not only locally (Blume (1993), Ellison (1993)).

These characteristics are obviously tightly dependent on the technology itself and hence will not be included extensively in the present study for the aforementioned reasons. The common literature, mainly composed of surveys, presents these characteristics of the technology along with the characteristics of the individuals to explain the success or failure of some specific cases.

The survey-shaped studies on diffusion are numerous. Surveys have been done on villages in the Andes (Rogers (1995)), on computer software (windows 95), on farmers adopting a specific type of corn or seeds, on doctors prescribing new drugs, on plane hijackers, on contraception methods adopted by women in different countries, etc.

The vast majority (if not all) of these try to analyse the reasons for adoption, and specially the first adoptions. And most of them conclude that socio-economic status is related with innovativeness.

After many studies and debates, a scale and a classification appeared. Proposed by Rogers in 1962, it is based on the assumption that the frequency of adoption follows a bell-shaped curve, and the associated cumulative curve is S-shaped. The adopters are then categorised depending on their time of adoption.

- The innovators are the first 2.5%
- The early adopters are the next 13.5%
- The early majority is the next 34%
- The late majority is the next 34%
- The laggards are the last 16%

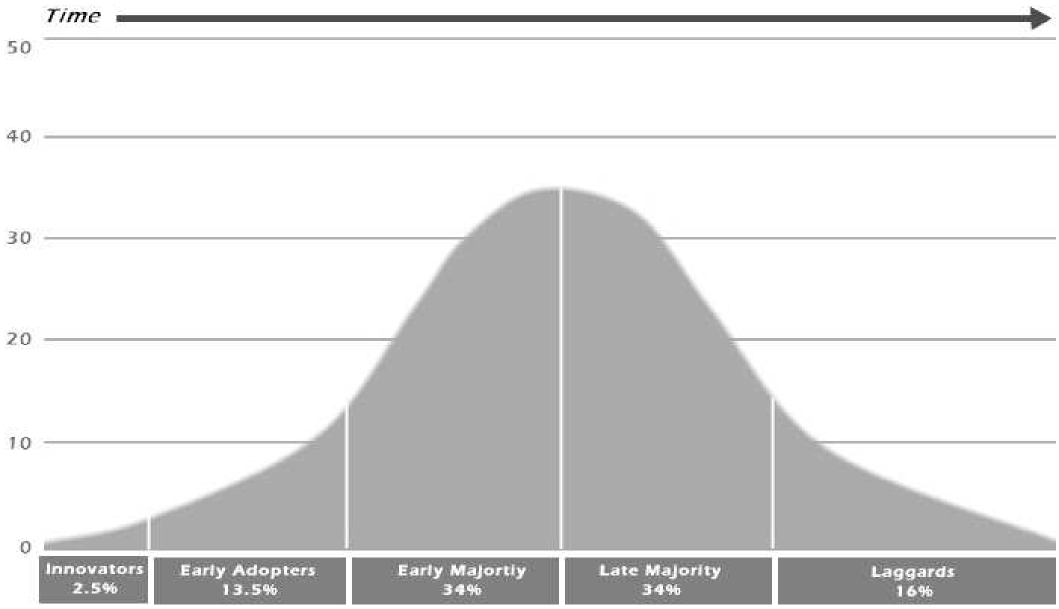

Figure 13: Identification of the class of adopters based on the timing of adoption by the various groups

These numbers are based on the intervals each side of the average time of adoption. The innovators are more than 2 standard deviations less than the average, while it is only one for early adopters, the early majority is situated within a standard deviation less than the average, the late majority is within a standard deviation more than the average, and the laggards are adopting a technology after a period of time that is more than the average plus one standard deviation.

This kind of categorisation is useful in order to characterise every type of individual. Hence, from the venturesome innovators to the traditional laggards, many generalisations can be drawn on the innovators and the diffusion of innovation. The bell-shaped curve for the adoption frequency in the case of a successful technology is stated in Rogers (1995).

Generalisation 7-1: Adopter distributions follow a bell-shaped curve over time and approach normality

While the general characteristics of a product, or condition for success, are generally similar through the literature, there are a variety of approaches towards the individual himself and the subjective influences upon him. A branch of the literature only describes ex-post the social, economical, psychological and cultural characteristics of the individual, as a synthesis of many surveys. Whereas the network component is seldom taken into account, using the network properties and the situation of individuals within that network is actually the other possible way to discuss the diffusion of innovation.

Intuitively, a model that would consider only internal or external influences does not seem close to representing real life phenomena. Those who actually tried to implement both reached better results with a mixed model, as in the ATM system case study by Dos Santos and Peffers (1998). While their external influence model assumes that adoption is only driven by information from a source external to the social system, the internal influence model assumes that adoption is driven by communication within a specific community or social system. The mixed model assumes both of these, and corresponds to the Bass model (a model based on differential equations, and hence for which it is a necessity to know the global proportion of adopters, or market potential).

The Bass model was devised in 1969, and attempts to predict the adoption of a new product or technology. Bass (1969) suggested that the likelihood that an individual would adopt a technology at a given time *t* was given by the equation

$$L(t) = p + \frac{q}{\overline{N}} N(t)$$

where

$N(t)$ is he number of customers who have already adopted the innovation by time t;

$\overline{N}$ is a parameter representing the total number of customers in the adopting target segment, all of whom will eventually adopt the product;

p is the coefficient of innovation (or coefficient of external influence);

q is the coefficient of imitation (or coefficient of internal influence).

The basic assumption of the model is that the probability of initial purchase by a consumer is related linearly to the number of previous adopters. Adopters are composed of both innovators and imitators. The number of previous adopters does not influence innovators in the timing of their initial purchase, while imitators are strongly affected by the number of adopters. Obviously, innovators have greater importance at the launch of a new technology than after it has become widely disseminated.

This model implies exponential growth of initial purchases to a peak and then exponential decay. The first component p refers to a constant propensity to adopt that is independent of how many other customers have adopted the innovation before time t. The second component is proportional to the number of customers who have already adopted the innovation by time t, and represents the extent of favourable interactions between the innovators and the other adopters of the product (imitators).

The main issue in this kind of modelling is that the market size must be known *ex ante*, as well as some additional conditions. Either the technology must have been recently introduced and its initial pattern of diffusion be known, or some similar technology adoption pattern can be found in history and used as a substitute. Extensions to the Bass model were devised, adding for example prices, advertising and other marketing variables into a generalised Bass model (Bass, Krishnan et al. (1994)).

One might feel that the structure of individuals' preferences needs to be distinguished from the underlying support for the interactions, namely the network. This is in a sense pointing towards Granovetter's idea that the communication (and hence the diffusion) in a system is largely dependent on the structure of the system (Granovetter (1985)). The possibility of a diffusion phenomenon that is not depending on social characteristics of the individuals was raised for example in Steyer (1995). He developed a model of diffusion based on avalanches, expressing social dynamics not anymore in terms of exponential law (as in the Bass model and its derivatives), but in terms of power law. This leads to the increased importance of the support of interactions.

Valente (1996) went even further in this direction, using models of diffusion with threshold effects, where no social component is present, and only the surroundings of an individual matter. It is using three examples (the diffusion of a medical innovation, the diffusion of hybrid corn, and the diffusion of family planning in

Korea), to demonstrate that the commonly used categorisation of individuals[19] can be obtained either via a model representing the social system, or via a model representing the individual personal network.

Importantly the focus has shifted from the diffusion of innovation in a “global system” point of view, or the whole network, to reach a “local system” point of view, or the local network. This research uses the latter. Diffusion as a whole is only the consequence of the decision making of an individual. Therefore the intent is not to propose a new standard representation of innovation, but a more sensible representation of innovators and their decision-making.

4.6 Assumptions and representation of a scenario

The assumptions for each scenario presented in this section reflect my understanding of Appendix 3 (“Micro-component forecast assumption tables”) of “A scenario approach to water demand forecasting”, representing the view of the Environment Agency.

Analysis of the assumptions underlying every scenario is difficult. Not really because of the assumptions themselves, but rather because of the lack of information about the way the scenarios have been generated. Nevertheless, the particulars of every scenario can be presented and debated (market penetration of devices, ownership and volume, absence or presence of future saving technologies, regulations and eventually metering) if some source of information can be found.

The various characteristics of scenarios for every micro component are as follows.

4.6.1 Toilets

The standard frequency of use for all WC type is assumed to increase from 4.12 in 1996 to 4.3 by 2021 due to the increase in density amongst the population.

4.6.1.1 Full flush toilets (9l)

Ownership

[19] Although composed of only 4 distinctive groups in this case: early adopters, early and late majority, and laggards.

scenario	A	B	C	D
Replacement rate	1/40	1/30	1/20	1/40

Volume is considered constant.

4.6.1.2 Dual Flush toilets (7.5l)

Ownership

scenario	A	B	C	D
Replacement rate	1/40	1/30	1/20	1/40

Volume is considered constant.

4.6.1.3 Low volume toilets (7l)

Ownership

scenario	A	B	C	D
Replacement rate	1/40	1/30	1/20	1/40

Volume is considered constant.

4.6.1.4 Dual flush toilets (4.5l)

Ownership

scenario	A	B	C	D
Replacement rate	1/40	1/30	1/20	1/40

Volume is considered constant. The different flushing uses are either 6 or 4 litres, used respectively with a ratio of 1/3 and 2/3.

4.6.1.5 Low volume toilets (6l)

Ownership

scenario	A	B	C	D
Replacement rate	Residual from 2001	Residual from 2001	1/20 Residual from 2015	1/40 Residual from 2015

Volume is considered constant.

4.6.1.6 Future technology

Ownership

scenario	A	B	C	D
Substitutable technology	N/A	N/A	4l low volume from 2015	4/2.5l from 2015

Volume is 4 litres in scenario C, and 3.25 litres in scenario D

4.6.2 Personal washing

4.6.2.1 Bath

Ownership declines from 97% in 1991 to 91% in 2021, keeping a minimum of 85%.

Frequency declines from 0.34 litres/head/day in 1991 to 0.31 litres/head/day in 2021.

Volume is considered constant.

4.6.2.2 Standard shower

Ownership

scenario	A	B	C	D

Penetration and replacement rate	Residual from PS (base 96%)	Residual from PS	From 50% in 1997 to 96% in 2025, replacement rate 1/20 after 2010	Same as C, rate 1/15

Frequency changes from 0.35 uses/head/day in 1991 to 0.5 uses/head/day in 2021, without going over a maximum of 0.6 uses/head/day.

Volume is considered constant.

4.6.2.3 Power shower

Ownership

scenario	A	B	C	D
	Max 50% in 2025	Max 59% in 2025	5% in 1991, 50% in 2021, then rate of decline 1/20	5% in 1991, 50% in 2021, then rate of decline 1/15

Frequency

scenario	A	B	C	D
	0.52 /h/d in 1991 to 0.6 in 2021, max 0.61	0.52 /h/d in 1991 to 0.6 in 2021, max 0.61	0.52 /h/d in 1991 to 0.6 in 2021, max 0.61	Similar to the others, but max 0.57 in 2010

Units are uses/head/day.

Resource zones with frequency higher than 0.61 remain constant for the period.

Volume

scenario	A	B	C	D

Volume per use	From 100 litres to 150 litres in 2025	From 100 litres to 150 litres in 2025	Constant (100 litres)	Constant (100 litres)

4.6.2.4 Hand basin

Everything remains constant

4.6.3 Clothes washing

4.6.3.1 Automatic washing machines

Ownership reaches saturation to 94% by 2015 then reduces by 0.5%/year in scenario D.

Frequency reduces from 4.5 uses/head/week in 1991 to 4.3 uses/head/week in 2021 for scenarios A, B and C, but remains constant from 2015 onwards in scenario D.

Volume:

scenario	A	B	C	D
Volume per use	Reduces to 80l by 2010, then constant	Reduces to 50l by 2025	Reduces to 40l in 2025	Reduces to 40l in 2025

4.6.3.2 Washing by hand

Ownership is obtained as residual from the users of washing machines.

Frequency and volume are constant. Therefore Per Capita Consumption (PCC) for this appliance depends on ownership only.

4.6.4 Dishwashing

4.6.4.1 Dishwasher

Ownership:

scenario	A	B	C	D

Evolution per annum	1.7% then 1.5% per year from 2010	2% per year	1.7% increase per year	1% per year

Frequency is considered as constant.

Volume:

scenario	A	B	C	D
tendency	Reduces to 30 litres in 2010	Reduces to 20 litres in 2025	Reduces to 15 litres by 2025	Reduces to 15 litres by 2025

4.6.4.2 Washing up by hand

Ownership is residual from dishwasher ownership.

Frequency is considered constant.

Volume is considered constant.

4.6.5 Garden watering

4.6.5.1 Garden sprinkler

Ownership

scenario	A	B	C	D
Tendency	Same as scenario B, with only +0.25%/year from 2010	+0.5%/year, maximum of 29% in 2025 (South East England only) and 20% others	Constant from 2010	Reduced to 7.5% in South East and 5% others

Ownership is currently 25% of garden owners.

Frequency

Scenario	A	B	C	D
Frequency of use	20 uses/year in 1991 to 25 in 2021	20 uses/year in 1991 to 25 in 2021	Increasing till 2010 then constant	Increasing till 2010 then halves

Volume is considered constant.

4.6.5.2 Other garden watering

Ownership is 54% in 1997/98 and in the South East of England increases by 0.5% per year with a maximum of 70% in 2025. It is constant for other regions.

Frequency

Scenario	A	B	C	D
Frequency of use	39 uses/year in 1991 to 58 in 2021	39 uses/year in 1991 to 58 in 2021	Increasing till 2010 then constant	Increasing till 2010 then halves

Volume increases for scenarios A, B and C from 132 litres in 1991 to 153 litres in 2021. In scenario D, volume decreases from 2010 to halve by 2025.

4.6.6 Car washing

Per Capita Consumption due to car washing with hose and bucket increases from 0.9 litres/head/day in 1991 to 1.5 litres/head/day in 2021 in scenarios A and B. In scenario C it is constant, and it declines in scenario D.

4.6.7 Direct heating system

Ownership of combination boilers is 13% for 2000, constant in scenarios C and D after 2015.

Frequency is 5 uses/household/day and remains constant.

Volume is 5 litres and remains constant.

4.7 Scenario drivers

Detailed and general characterisations of the scenarios are of course linked. Nevertheless, the way they are derived from one another is not clearly stated. This will have important influences upon the model design.

The different grains of description for the scenarios seem clear. On one hand there is a global situation with generic circumstances of governance structure and societal state, while on the other hand there are details about the various appliances, their appearance, replacement rates, and evolution of their characteristics of use. But going from one to the other requires a deep understanding of complex interactions, and the generation of assumptions. For example, the necessary assumption used that there will not be any major unpredictable event that would change the background of the study (such as the terrorist attack in 2001, it could be a nuclear incident, or some major earthquake/flooding, some financial crash, etc.)

It is not without difficulty that one can generate such accurate assumptions, starting only from a somewhat generic definition of environment.

The precise steps used by the Environment Agency to improve the grain of analysis are not publicly available. They are certainly based on detailed studies and extended knowledge of the common resources and the associated issues. The statistical methods they use are generally well devised according to the constraints they face.

Probably the most appropriate way to represent the various scenarios in a model would be to have indicators, variables that would correspond to the generic ways to classify the scenarios, and hence select or generate them. This straightforward method is difficult to apply in this case for several reasons.

The Environment Agency states that the scenarios differ according to governance structures and social values.

These indicators are not absolute. While one can argue about what are community or individual-oriented values, their definition can be given. Composed of perceptions, of values of what is good or bad, it might not be possible to represent them on a continuous axis (or thanks to a continuous indicator).

Implementing such differences within a Multi agent model is not possible though. There cannot be a single straightforward indicator that would signify something in a case, and something else in another.

For example globalisation in the case of a community-oriented society could have a different meaning (as translation into reality) from globalisation in the case of an individual oriented situation. There are different levels for which the word globalisation can be understood, and that cannot be implemented as such in the case studied here.

Another reason is that these scenarios have been selected as the most representative ones amongst certainly a fair number. Whether all of them could have been categorised this way is a question that will remain unanswered, but it seems unlikely.

The fact that the presentation of the scenarios lacks details has implications for the implementation, *i.e.* the model design.

Ideally, the different variables represented by the diagram axes would be implemented so they can be changed at will, preferably in a simple way. As presented above, this is not possible here. Therefore, the starting point of the scenario selection will be the social values, to which a specific indicator will be attributed, while the governance system will be imposed upon the variables in the model according to the details given in the fine description of the scenarios.

More precisely, the social values will be represented by the values of some specific endorsements, while the governance system will be represented by what are described as the consequences of such a state, *i.e.* the specific replacement rates and other details of the scenarios.

4.8 Conclusion

This chapter presented the way the scenarios are described by the Environment Agency, and will be implemented in SDML.

Section 4.2 pointed out four assumptions that the model relies upon:

- Social values are represented by endorsements;

- The governance structure is represented through the characteristics of a scenario;
- The presence of a regulator is represented through the availability of resource saving appliances;
- Uncertainty of its impact on water demand prevents us from including metering into the model.

Section 4.3 presented the source and details of climatic data. It is assumed that climate will change according to the UKCIP medium high assumptions. The data used for ownership, frequency and volume used for all appliances comes from Three Valleys PLC and are consistent with a sample for an unmeasured population.

Section 4.4 detailed the model components. It described the components and their characteristics, their main behaviour and the algorithms used to implement it.

Section 4.5 presented a point of view on the representation of innovators in the literature, pointing out the fact that the amount of information available while running the model is not compatible with the information required by a global equation (similar to the one in the Bass model). The analysis of threshold effects justifies the decision to use the agent rather than the society as the base to implement the diffusion of innovation.

Section 4.6 described all the assumptions from the Environment Agency's reference publication.

Section 4.7 discussed the scenario drivers, arguing that indicators would be the best way to represent social values and governance. Since governance values could have different meanings in the various situations of social values, there cannot be a single straightforward indicator, hence the remark at the beginning of this section that governance structures that characterise a scenario are represented via the values of the parameters of this scenario.

The next chapter describes the way these scenarios are implemented, results of the simulations for individual scenarios, and an analysis of the sensitivity of the results obtained.

5 Scenario implementation and analysis

5.1 Introduction

The previous chapters have introduced the context of this research, issues to consider and phenomena to capture that lead to the choice of the tools used, and the presentation of the thinking behind scenarios, as well as the explanations of the parameters that differentiate one scenario from another.

This chapter provides the parameters used in the simulations and reference runs for every scenario. An analysis of the extent to which the results are sensitive to certain parametric or structural changes, followed by two specific studies complete the chapter.

Many simulations have been undertaken during the course of this research. Their purpose varied: verifying the model, debugging the code, implementing the various scenarios, investigating the phenomenon observed, and studying the influence of specific aspects or values.

The simulation results presented in this document are a small portion of all those run. And while the structure of the document may suggest a sequence for the modelling and the simulations, it is not chronologically accurate. Important questions needed to be investigated before (or in the process of) implementing the scenarios themselves, and some aspects of the model.

That is why the actual first simulation runs are presented in section 5.5 (detailed study of a particular set of runs). It was followed by the assessment of the structural impact (presented in section 5.3.1), the analysis of visibility (in section 5.3.3), the study of innovation diffusion (in section 5.4), of the density of agents (in section 5.3.2), of the impact of the memory implementation (in section 5.3.4), and finally of the creation of all four scenarios (in section 5.2). Obviously constraints for the modeller are not relevant when it comes to presenting the results, hence the different sequence, which should make this an easier read.

5.2 Scenario Generation

This is the presentation of both common and specific modelling parameters. It sums up the information given above, and expresses the remaining parameters and variables in accordance with the scenarios involved.

Ownership is the probability that a household possesses the appliance. Frequency of use is the daily average frequency owners utilise the appliance. Volume per use is the average amount of water necessary for one event.

Unless explicitly stated otherwise, values used for this analysis are the following.

Appliance	Ownership	Frequency of use	Volume per use
bath	0.98	0.31	80
shower	0.542	0.4	31.25362
power shower	0.309	0.5	61.88837
sprinkler	0.14364	0.023976	2400.247
other_garden_watering	0.459403	0.048858	242.1583
washing_machine	0.954	0.264324	96.7
clothes_hand_washing	0.046	1	13.088
new_washing_machines	0.5	0.28	80
dishwasher	0.395	0.328393	41
hand_dishwashing	0.605	1	16.58634
toilets	1	4.15438	8.831

Table 10: Default values for scenario parameters

Baths have a fixed volume per use, *i.e.* at anytime in the simulation the volume per use is fixed and equal for every user.

Memory decay coefficient is set to 2.5.

Innovation is represented by the possible replacement of the full flush toilets by dual flush ones (effectively a saving water device), from October 1992, and the possible replacement of showers by power showers (effectively a device that tends to increase water use) from April 1990.

Some activities are considered as private, and hence cannot be observed by the neighbours. They are the use of baths, dishwashers and washing machines.

As in everyday life, households have some information about what appliances their neighbours own, not because they have been informed by the neighbour itself, but simply by observing or reflecting upon associated behaviour. These appliances are labelled “semi-public”. Appliances in full view of others, such as for example a sprinkler, are characterised for modelling purposes as “public”.

There are two different cases in which an appliance can be replaced. Either it has reached a “natural” replacement stage, when the household considers the appliance to be old enough for a replacement decision to be reasonable, or it broke. The assumed standard replacement rate is 5 years, *i.e.* on average appliances are changed or replaced every 60 months.

Whether an appliance breaks depends on a probability distribution. The Weibull probability distribution seemed the most appropriate, as it is one commonly used for white goods. The Weibull distribution has a sigmoid pattern, and parameters to adapt the slope and level of the graphical representation. The parameters generally used for white goods in order to approach the actual probability of breaking are 1.2 for the shape, and 35 for the scale.

5.2.1 Creation of scenarios

Generation of scenarios is done according to the method presented in chapter 2. The first step consists of interpreting the conditions described by the Environment Agency.

Parameters used to distinguish specific scenarios in the model are those linked to the appliances, and those linked to the population.

Scenarios have several drivers for household demand, which the Environment Agency classifies as follow:

Water policy drivers, which include metering and water regulations

Technology drivers, which include white goods, and miscellaneous

Behavioural drivers, which include the type and pattern of personal washing

Economic drivers, which include personal affluence

While some of these drivers are included in the current model, some of them have been ignored. There are several reasons for this choice.

Water policy drivers are included in the model as the water regulations are at the origin of the emergence of efficient appliances, and of the removal of high water use appliances from the market. As expressed in section 4.2.4, the limits both in the necessary knowledge to implement metering, and the usefulness of this implementation, due to the structure of the model, have led to the choice of ignoring this component.

Technological drivers are included in the model. They include the emergence of new appliances, or new technologies. Miscellaneous use is not included. The very name of this category expresses the fact that the appliances cannot be designated exactly. Although MAS models allow a very detailed representation of appliances, it is difficult to describe a “miscellaneous” equivalent, due to the lack of definition on what it actually is. Moreover, it would be brave to assume that this “component“ would evolve the same way as others, without mentioning what influences it is subject to.

Behavioural drivers are included, and the process involving behavioural changes is clearly one of the main parts of the model.

Economic drivers are included. They are not explicitly in the model, as there are no prices or wealth as such, for reasons explained in chapter 1. They are an indirect parameter, which is present via the behaviour of customers with respect to new products. Additional wealth is assumed when the rate of renewal of appliances is faster in one scenario than in another.

Therefore, keeping in mind these components, different scenarios can be interpreted and translated into assumptions and values of parameters for the associated simulation runs.

As guidelines for differentiating the scenarios, the following table will present endorsements for the influence weighting, as well as the most important point associated to the scenario.

Scenario	Global weight	Local weight	Self weight	Comments
A	10	30	60	Washing machine down to 50l/use Dishwasher down to 30l/use
B	30	10	60	Washing machine down to 80l/use Dishwasher down to 20l/use
C	55	25	20	New technology WC Dishwasher down to 15l/use
D	25	55	20	New technology WC Dishwasher down to 15l/use

Table 11: Main changes between scenarios

Below is a more detailed presentation of all scenarios and the possible evolutions they contain.

Scenario A, called “Provincial enterprise”, is based on individualism and regionalisation. Therefore, the level of self-influence will be the highest of the three. As regionalism is strengthened, the autonomy of local government increases, and the influence of global messages weakens, while the recent focus around smaller communities increases the values and respect of local environment and neighbours.

The weighting selected are:

globalInfluence 10

localInfluence 30

selfInfluence 60

In this scenario, the replacements and disappearance of appliances from the market is as follows:

1985: 9 litres full flush toilet cisterns can be replaced by dual flush (7.5 litres)

1990: showers can be replaced by power-showers

1992: dual flush (7.5 litres) cisterns can be replaced by low volume flush (7 litres)

1993: dual flush (7.5 litres) and full flush (9 litres) cisterns are not available anymore

2001: low volume (7 litres) cisterns can be replaced by low volume (6 litres)

low volume (7 litres) can be replaced by dual flush (4.5 litres)

low volume (7 litres) is not available anymore

2010: dishwashers can be replaced by efficient dishwashers (30 litres)

dual flush (4.5 litres) can be replaced by low volume flush (6 litres)

dual flush (4.5 litres) is not available anymore

washing machines can be replaced by efficient washing machines (60 litres)

Scenario B, called “World Markets”, is associated with a situation of individualism and globalisation. The level of self-influence will remain high, as above. But the government remains very much centralised, and the feeling of belonging to a nation is higher than the feeling of belonging to a local community.

The weighting selected are:

globalInfluence 30

localInfluence 10

selfInfluence 60

In this scenario, the replacements and disappearance of appliance from the market is as follows:

1985: 9 litres full flush toilet cisterns can be replaced by dual flush (7.5 litres)

1990: showers can be replaced by power-showers

1992: dual flush (7.5 litres) cistern can be replaced by low volume flush (7 litres)

1993: dual flush (7.5 litres) and full flush (9 litres) cisterns are not available anymore

2001: low volume (7 litres) cisterns can be replaced by low volume (6 litres)

low volume (7 litres) can be replaced by dual flush (4.5 litres)

low volume (7 litres) is not available anymore

2010: dishwashers can be replaced by efficient dishwashers (30 litres) dual flush (4.5 litres) can be replaced by low volume flush (6 litres)

dual flush (4.5 litres) is not available anymore

washing machines can be replaced by efficient washing machines (60 litres)

Scenario C, or “Global sustainability”, represents the plausible future in which strong communities and globalisation cooccur. The individualistic behaviours tend to disappear, with an increase in community values, while globalisation strengthens the central government system.

The weighting selected are:

globalInfluence 55

localInfluence 25

selfInfluence 20

In this scenario, the replacements and disappearance of appliances from the market is as follows:

1985: 9 litres full flush toilet cisterns can be replaced by dual flush (7.5 litres)

1990: showers can be replaced by power-showers

1992: dual flush (7.5 litres) cistern can be replaced by low volume flush (7 litres)

1993: dual flush (7.5 litres) and full flush (9 litres) cisterns are not available anymore

2001: low volume (7 litres) cisterns can be replaced by low volume (6 litres)

low volume (7 litres) can be replaced by dual flush (4.5 litres)

low volume (7 litres) is not available anymore

2010: washing machines can be replaced by efficient washing machines (40 litres)

dishwashers can be replaced by efficient dishwashers (15 litres)

low volume cisterns (6 litres) can be replaced by dual flush (4.5 litres)

2015: dual flush (4.5 litres) can be replaced by low volume (3.25 litres)

dual flush (4.5 litres) is not available anymore

dual flush (7.5 litres) can be replaced by low volume (4 litres)

full flush (9 litres) can be replaced by low volume (4 litres) low volume (7 litres) can be replaced by low volume (4 litres)

low volume (6 litres) can be replaced by low volume (4 litres)

low volume (6 litres) cisterns are not available anymore

Scenario D, or "Local stewardship", is a situation where strong communities and regionalisation co-occur. Also presenting a relatively low individualism, the society gives importance to local communities, and a decentralised government.

The weighting selected are:

globalInfluence 25

localInfluence 55

selfInfluence 20

In this scenario, the replacements and disappearance of appliances from the market is as follows:

1985: 9 litres full flush toilet cisterns can be replaced by dual flush (7.5 litres)

1990: showers can be replaced by power-showers

1992: dual flush (7.5 litres) cistern can be replaced by low volume flush (7 litres)

1993: dual flush (7.5 litres) and full flush (9 litres) cisterns are not available anymore

2001: low volume (7 litres) cisterns can be replaced by low volume (6 litres)

low volume (7 litres) can be replaced by dual flush (4.5 litres)

low volume (7 litres) is not available anymore

2010: washing machines can be replaced by efficient washing machines (40 litres)

dishwashers can be replaced by efficient dishwashers (15 litres)

low volume cisterns (6 litres) can be replaced by dual flush (4.5 litres)

2015: dual flush (4.5 litres) can be replaced by low volume (3.25 litres)

dual flush (7.5 litres) can be replaced by low volume (3.25 litres)

full flush (9 litres) can be replaced by low volume (3.25 litres)

low volume (7 litres) can be replaced by low volume (3.25 litres) low volume (6 litres) can be replaced by low volume (3.25 litres)

low volume (6 litres) cisterns are not available anymore

dual flush (4.5 litres) is not available anymore

All the following results have been obtained with a wide vision parameter, *i.e.* the households can potentially communicate with other households up to 6 cells away from their own location. As the grid is only a 7-cell square, this comes to considering the vision as complete.

The number of households is set to 20. The household density over the simulations is therefore close to 0.6.

As shown in Moss, Edmonds et al. (2000), the density obviously plays an important role in the result of the simulations. With a density that is not sufficient, the influences amongst agents will come to whether there is any interaction, rather than which agent would be influential in a group of neighbours.

According to the authors, for 100 agents, a grid size of 25x25 has the ability to support a specific phenomenon (in this case word-of-mouth communication), while grid sizes of 30x30 and 50x50 do not. Hence, a density of 16% seems to be sufficient (in his case) to ensure there are enough contacts in the population to allow the existence and / or emergence of the studied phenomenon. Some earlier simulations seemed to suggest some instabilities of water use, with important variation on short timescales. In order to avoid this effect, which will be discussed later, a high density was selected for typical runs.

Other simulations have been run in order to analyse the possible impacts of this parameter, and it will be addressed later.

The next section will present the simulations for the 4 typical sets of inputs associated to the scenarios described above.

5.2.2 Scenario simulations

The comments in this section describe specific simulations, and are therefore only valid with this support. To assist in the analysis, graphs of total water use are included, displaying not only the simulation runs themselves, but also the average of the runs (as the bold line), in order to better visualise the deviation of some of these runs.

The results shown here only refer to the initial simulations, and more detailed comments will accompany the studies of particular properties or phenomena later on, including reruns of the scenarios with slightly different parameters.

5.2.2.1 Scenario A: Provincial Enterprise

A few graphs are provided to help with the representation of the simulation results. When representing scenario outputs, each line represents a different run of the water demand simulation. The time, in months elapsed or in month / year format, is on the X axis and the water demand levels are on the Y axis is. When useful, the monthly average over all runs is also present and is indicated by a thicker line.

The graph shows a generally decreasing trend.

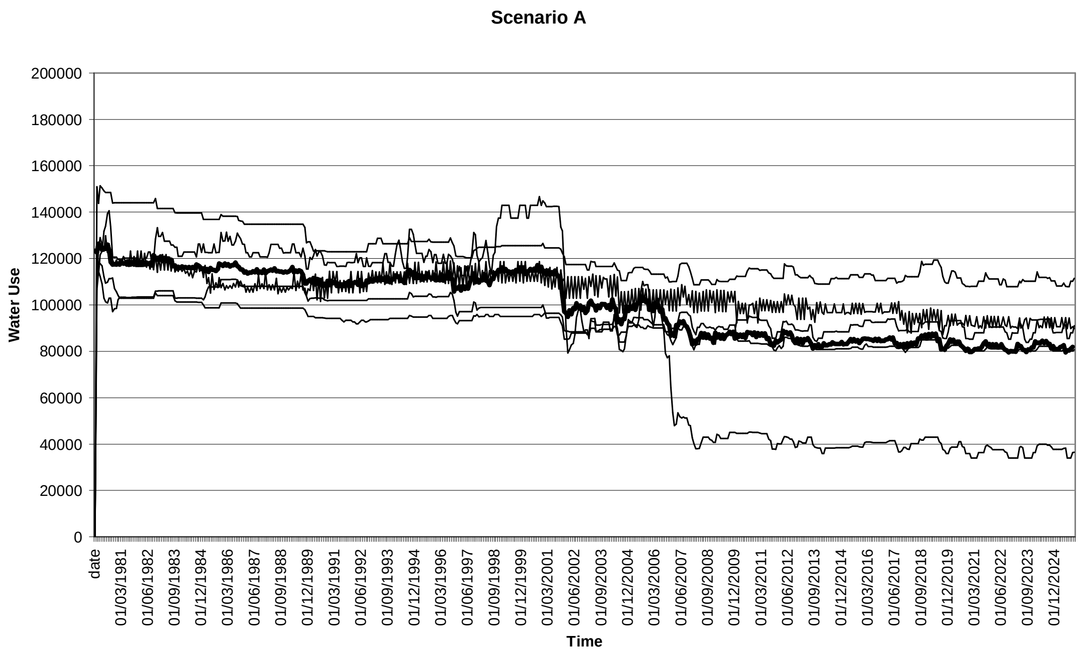

Figure 14: Scenario A

There are two notable series displayed. The first one is the one with extreme behaviours (series1 in the table below). In the same simulation, the variations are such that although it does not start as the highest or lowest water use, increases in 1998 and decreases in 2001 and 2006 have an important effect on the demand levels. Although the first large peak seems to be the obvious consequence of the drought starting in August 2001, the increase starting in 1998 does not seem to have an environmental cause.

The second drop, in 2006, is not justified by the climate either. One can observe that other simulation runs are not affected this way.

The other eye-catching pattern is the frequent micro fluctuations of the data from the second topmost series from 2004. Although the general shape of the water demand is not extreme, it is clear that there is an element of instability that is not present in other runs.

On a statistical aspect, the study of every run provides the following results:

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std.	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
serie0	551	80748,11	114462,00	96121,55	7560,382	5,7E+07	-1,170	,208
serie1	551	33953,98	146715,87	86194,47	40398,38	1,6E+09	-1,762	,208
serie2	551	79552,74	123162,00	90951,40	8004,305	6,4E+07	-,157	,208
serie3	551	87085,42	129830,00	105142,6	9087,055	8,3E+07	-,895	,208
serie4	551	107821,50	151307,00	121604,8	11207,89	1,3E+08	-,615	,208
Valid N (listwise)	551							

Table 12: Descriptive statistics for scenario A

The use of statistical software (SPSS in this case) allows a different analysis, investigating the underlying distribution of these data. As developed earlier in this study, the presence of defined second moments is a critical factor for using statistical techniques upon datasets. It was shown then that this assumption was unsafe. It is now interesting to check whether the generated data also has this property.

In the previous table, a kurtosis value is provided for every data set. The kurtosis value is a measure of the extent to which observations cluster around a central point, a measure of the peakedness of a probability distribution. For a random variable x with mean μ and standard deviation σ, kurtosis is the fourth central moment divided by the squared variance, $E\,(x-\mu)^4 / \sigma^4$. For a normal random variable, kurtosis is 3, but in many cases (including in this research), for clarity, 3 is subtracted away, hence the value becomes 0 for a normal distribution. Positive kurtosis indicates that the observations cluster more and have longer tails than those in the normal distribution (this property is leptokurtosis) and negative kurtosis indicates the observations cluster less and have shorter tails.

To strengthen this conclusion, the table below shows the KS analysis upon the relative changes for every run.

The Kolmogorov-Smirnov Test procedure is non parametric and compares the observed cumulative distribution function for a variable with a specified theoretical distribution, in this case, the normal distribution. The Kolmogorov-Smirnov Z is computed from the largest difference (in absolute value) between the observed and theoretical cumulative distribution functions. This goodness-of-fit test tests whether the observations could reasonably have come from the specified distribution.

The table below hence demonstrates that the probability that any of these differences (labelled as “lag0” to “lag4”, each corresponding to a simulation run) are normally distributed is effectively nil.

One-Sample Kolmogorov-Smirnov Test

		lag0	lag1	lag2	lag3	lag4
N		550	550	550	550	550
Normal Parameters [a,b]	Mean	-28,7096	-156,6409	-77,2439	-42,5606	-72,0661
	Std. Deviation	1445,808	3095,569	840,45950	6124,500	1150,932
Most Extreme Differences	Absolute	,323	,235	,319	,122	,351
	Positive	,323	,235	,319	,122	,351
	Negative	-,283	-,214	-,293	-,115	-,325
Kolmogorov-Smirnov Z		7,577	5,509	7,485	2,855	8,236
Asymp. Sig. (2-tailed)		,000	,000	,000	,000	,000

a. Test distribution is Normal.

b. Calculated from data.

Table 13: Kolmogorov-Smirnov statistics for scenario A

5.2.2.2 Scenario B: World Markets

In the representation of scenario B, there does not seem to be any extreme run. All have slightly decreasing trends, and seem to follow roughly the same pattern.

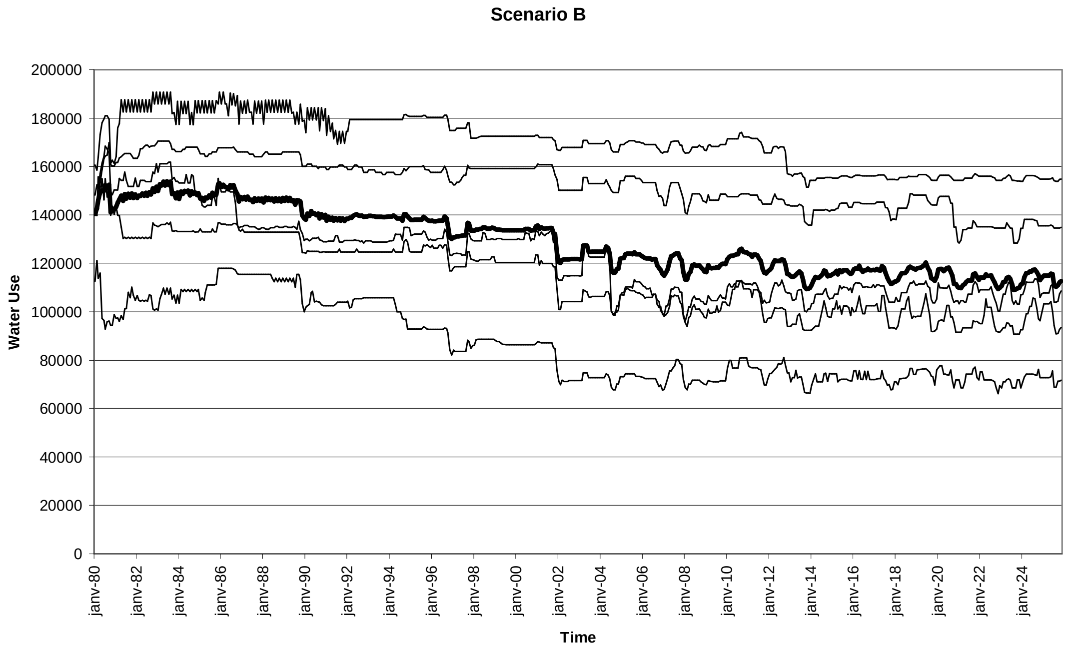

Figure 15: Scenario B

The highest run shows an interesting instability up to 1991. The cycle of households copying each other is broken by the appearance of power showers. The introduction of power showers and their adoption provide new recommendations to households, who discard their showers, and the system is then harmonised. This demonstrates that the high frequency variability observed could be due to a flaw in the processes.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std.	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
serie0	551	140767,00	190807,14	169831,8	11234,02	1,3E+08	-1,107	,208
serie1	551	90751,98	168418,00	119259,4	20231,82	4,1E+08	-1,005	,208
serie2	551	66148,00	121195,00	86511,40	16015,30	2,6E+08	-1,202	,208
serie3	551	128322,92	180953,00	153053,2	10603,98	1,1E+08	-,699	,208
serie4	551	96242,41	155748,00	117397,7	11897,34	1,4E+08	-,708	,208
Valid N (listwise)	551							

Table 14: Descriptive statistics for scenario B

The table above shows a lack of stability amongst various runs of a specific set of simulations. The variance as well as the standard deviation is fairly high, denoting the large differences in values from one series to another. The negative kurtosis expresses a distribution with tails shorter than they would be if it were normally distributed.

As before, the Kolmogorov-Smirnov 2-tailed asymptotic significance confirms the probability of effectively 0 for the assumption of normality to hold for relative changes (still labelled "lags") in the runs.

One-Sample Kolmogorov-Smirnov Test

		lag0	lag1	lag2	lag3	lag4
N		550	550	550	550	550
Normal Parameters[a,b]	Mean	25,6718	-99,2786	-74,1683	-46,7881	-57,0237
	Std. Deviation	3057,229	2518,925	2078,941	1577,696	2064,745
Most Extreme Differences	Absolute	,244	,205	,209	,318	,229
	Positive	,244	,185	,199	,318	,229
	Negative	-,236	-,205	-,209	-,285	-,220
Kolmogorov-Smirnov Z		5,719	4,818	4,897	7,456	5,375
Asymp. Sig. (2-tailed)		,000	,000	,000	,000	,000

a. Test distribution is Normal.

b. Calculated from data.

Table 15: Kolmogorov-Smirnov statistics for scenario B

5.2.2.3 Scenario C: Global Sustainability

In the runs representing this scenario, there are no micro instabilities as displayed in the previous runs. While one could wonder whether this could be due to the values of endorsements, a look at the results from scenario D (above) would suggest that this is not the case. Further studies of the instability phenomenon are undertaken later, and a possible link with the vision parameter is investigated.

While the patterns of the different runs look similar, there are interesting differences. The water demand does not always seem to change in a (roughly) similar manner. Some reactions to drought are unmistakable, but the 2010 changes in the highest run cannot be explained by climatic conditions. The simultaneous introduction of three new technologies seems to be the reason for such changes.

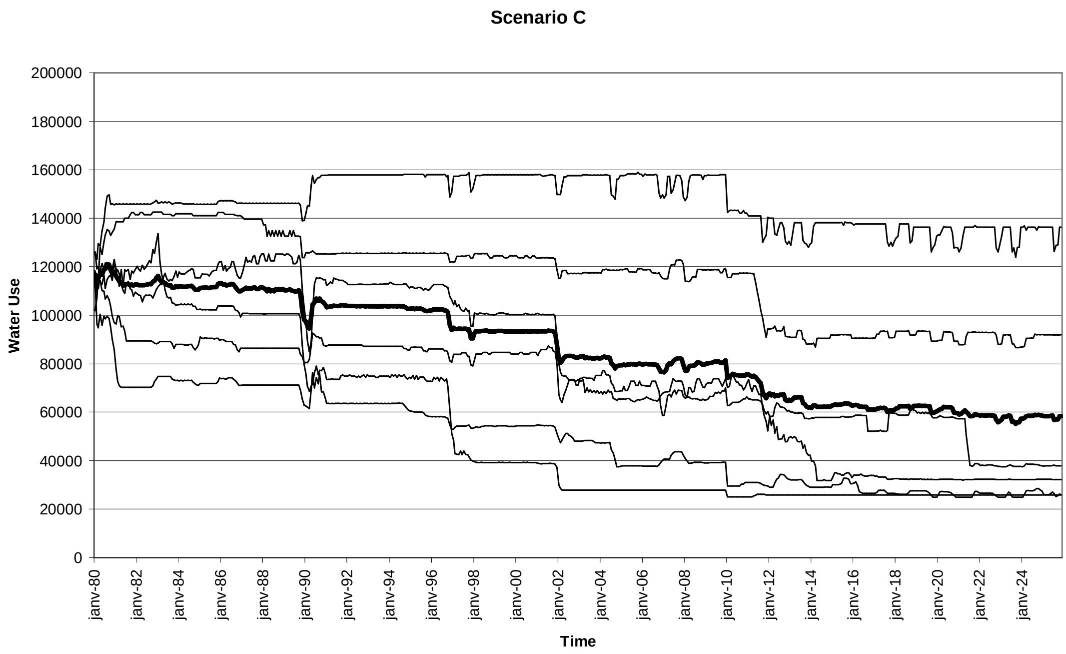

Figure 16: Scenario C

One can notice that from 2014 onwards, there is a grouping of some runs, even more visible after 2022. The 2010 drought does not seem to have a significant impact upon the second topmost series, while the 2011 drop in consumption of this series is the biggest and fastest of all.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std.	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
serie0	551	31783,43	118401,70	68079,39	23410,65	5,5E+08	-1,179	,208
serie1	551	123103,90	158948,99	147009,7	10003,60	1,0E+08	-1,191	,208
serie2	551	37508,86	126069,60	83933,97	28515,66	8,1E+08	-1,509	,208
serie3	551	86609,26	142442,99	115852,9	18021,78	3,2E+08	-1,247	,208
serie4	551	24988,80	114684,80	48777,34	18838,64	3,5E+08	-,818	,208
serie5	551	25129,30	133619,18	52787,83	33347,58	1,1E+09	-,956	,208
Valid N (listwise)	551							

Table 16: Descriptive statistics for scenario C

The descriptive statistics show the same negative kurtosis as for the previous scenarios, with shorter tails, also allowing the rejection of the normality assumption. Moreover, the differences in mean and standard deviation also hint at the differences of consumption levels amongst the runs.

One-Sample Kolmogorov-Smirnov Test

		lag0	lag1	lag2	lag3	lag4
N		550	550	550	550	550
Normal Parameters [a,b]	Mean	-156,7278	18,6116	-160,1026	-40,3668	-161,6186
	Std. Deviation	1430,572	2202,015	1814,540	1346,988	1391,846
Most Extreme Differences	Absolute	,270	,316	,247	,310	,281
	Positive	,245	,282	,197	,305	,273
	Negative	-,270	-,316	-,247	-,310	-,281
Kolmogorov-Smirnov Z		6,341	7,422	5,790	7,270	6,592
Asymp. Sig. (2-tailed)		,000	,000	,000	,000	,000

a. Test distribution is Normal.

b. Calculated from data.

Table 17: Kolmogorov-Smirnov statistics for scenario C

The use of the Kolmogorov-Smirnov test on relative changes confirms the fact that the relative changes are not normal either, with all probabilities of the sample of origin being normally distributed effectively equal to zero.

5.2.2.4 Scenario D: Local Stewardship

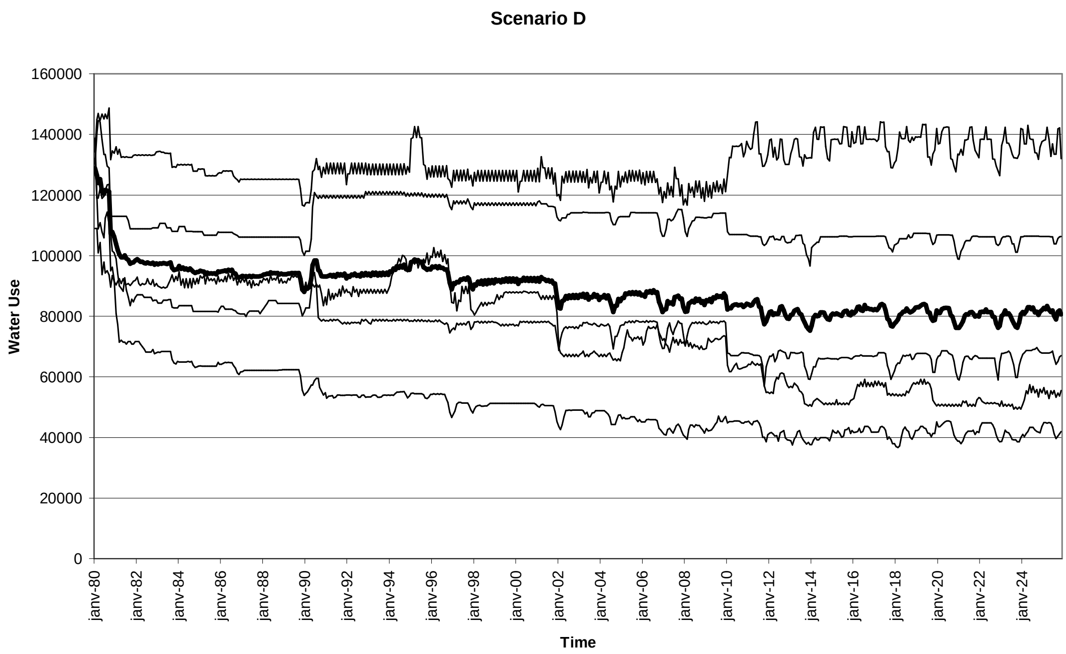

Figure 17: Scenario D

The noticeable increase in water use in the end of 1990, following a decrease a few months earlier can be explained by the events taking place then in the model. Towards the end of 1989, there are three consecutive months of relative drought, and the policy agent broadcasts its recommendations, which results in a decrease in water use. In 1990, the availability of power showers on the market is becoming clear, as their high volume per use translates into an upwards demand trend for all runs.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std.	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
serie0	551	36668,43	132069,60	51272,07	12545,27	1,6E+08	9,429	,208
serie1	551	116338,74	148685,10	130507,0	6435,298	4,1E+07	-,507	,208
serie2	551	49346,03	108936,60	74753,38	16780,64	2,8E+08	-1,517	,208
serie3	551	56920,26	138684,10	75792,09	9686,710	9,4E+07	8,381	,208
serie4	551	96523,20	146861,80	111127,7	6562,600	4,3E+07	3,536	,208
Valid N (listwise)	551							

Table 18: Descriptive statistics for scenario D

For the first time in assessing the scenarios, three of the runs have a positive kurtosis. This indicates that the observations cluster more and have longer tails than those in the normal distribution. The runs affected are the lowest one (series0), the second lowest one till 2002, which then becomes third lowest (series3), and the second to the highest (series4).

One-Sample Kolmogorov-Smirnov Test

		lag0	lag1	lag2	lag3	lag4
N		550	550	550	550	550
Normal Parameters[a,b]	Mean	-163,7762	2,9003	-97,0778	-130,3852	-50,4957
	Std. Deviation	1488,797	3456,891	1879,920	1826,011	1427,272
Most Extreme Differences	Absolute	,197	,126	,075	,266	,234
	Positive	,153	,117	,056	,193	,226
	Negative	-,197	-,126	-,075	-,266	-,234
Kolmogorov-Smirnov Z		4,619	2,951	1,766	6,232	5,493
Asymp. Sig. (2-tailed)		,000	,000	,004	,000	,000

a. Test distribution is Normal.

b. Calculated from data.

Table 19: Kolmogorov-Smirnov statistics for scenario D

Paradoxically, the first and only positive probability that a data set could come from a normally distributed sample, is one with a negative kurtosis, just as the scenarios A, B and C displayed. Nevertheless, the probability remains very low, and seems therefore reasonable to consider that it is not significant.

5.2.3 Comparison of simulation results and reference scenarios

When comparing the results obtained from simulations and those expressed by the Environment Agency, several differences are present. While the figures do not match well, the ranking of scenarios according to the evolution of demand they display is more accurate. The table below shows this evolution using the average of 24 values from the years 84-85 as a reference. Values for 2010 and 2025 are averages for the year indicated.

Scenario / Year	A	B	C	D
2010	-20 (+14)	-6 (+13)	-20 (+3)	-9 (+6)
2025	-26 (+33)	-14 (+19)	-38 (-28)	-11 (-20)

Table 20: Comparison of scenarios with reference

Amongst the reasons for the discrepancies are the fact that miscellaneous use is not taken into account, the fact that water use is mostly driven down by the new appliances never using more water than the previous ones, the lack of increase in population, and probably the characterisation of the scenarios via endorsements.

Scenarios A and B show an increase in water use in the Environment Agency, and the bias introduced by a steady population and the lack of miscellaneous uses can explain the failure to corroborate these scenarios. Scenarios C and D seem much closer to the Agency's estimates. Despite the absence of increase by 2010, the results for 2025 can be considered as reasonably close to the Agency's. This is encouraging, as these two scenarios include the diffusion of new technologies, and would tend to show that the method used to represent innovators in the model seem to be effective.

To better understand the causes of the changes in the different scenarios, one must look into the origin of specific behaviour, as well as investigate the sensitivity of the model to its parameters or structure.

5.3 Initial analysis

A qualitative analysis is now undertaken to study a particular phenomenon, such as a run with extreme values. Qualitative analysis is necessary when the numbers are less important than what they represent, or when differences are better expressed by words than by meaningful numbers (if they exist).

Sensitivity Analysis is necessary to understand the role of the multiple parameters in the model.

There are models that are simple enough so that the few parameters are meaningful ones with respect to the object of the modelling. It is for example the case when dealing with size and weight for a person in a sample. There are more complex models, which require many aspects of a problem to be taken into account. It is then possible that some parameters integrated into the model could influence the results significantly, while not being central to the modeller. Edmonds and Hales (2003) have given an example of modelling details that, although not really central to their issue, turned out to be decisive for the behaviour of the model, and the observed phenomenon. That was in an allegedly simple model. In the current case, there are many parameters and algorithms. The methods and values used are carefully selected as having appropriate characteristics and (in general a lack of) underlying assumptions. Nevertheless, their influence upon the results of the model needs to be understood, in order to improve comprehension of the model.

One needs to understand how the parameters that do not necessarily have direct links with the abstract model (*i.e.* that can be directly related to an artificial society) can be modified to change the behaviour of the whole system. This is the purpose of sensitivity analysis.

Sensitivity analysis is generally undertaken to assess the variability or stability of the outputs of a model or simulation with respect to the possible space of inputs. This is recommended when the computational burden is not too heavy. In this case, there are limiting factors that prevent standard sensitivity analysis. The first of these is the number of inputs and their possible values. The abstract model is based upon an existing description of scenarios. While some values can be debated and changed, most of the parameters would be set by the system that is being represented, and the values it explicitly provides. Also, there are many parameters in the model that are not thought to influence the end result, although demonstrating this would prove quite a challenge. So when sensitivity analysis is limited, it should focus on either (potentially) key variables, or explicit assumptions that cannot be backed up with evidence or reason.

Another difference from the standard approach is that generally, such tests aim to assess the sensitivity of the results to some input values. This research is more focused on the representation itself than its results. It is then only natural to assess the sensitivity of the model itself, to its assumptions and input values. Various indicators will be selected depending on the changes whose impact will be assessed.

Adopting this particular point of view regarding sensitivity also leads to the investigation of another aspect of the model. As already mentioned, it is common for scientific purposes to assess the impact of input values to a model. What can be left out is the study of the shape of the model itself, and of the parameters or processes representing assumptions its structure relies upon.

The parameters to analyse can be of different types. They can refer to single dimension (typically numerical) continuous values or sets of values, but also to discrete values or sets of values, as well as to the presence or not of some properties.

While models generally allow the input values to be changed, sometimes the outputs of the model also depend on how the model itself was though and implemented. This part will now investigate the impact of the input values and of the model structure upon its outcome.

First of all, the sample the investigation must rely on might not be composed of all the runs. It could be necessary to select some runs in particular, and have the analysis apply to a specific run, or to the representation of a set of runs. As presented earlier in this work, regrouping sets of runs could lead to statistical issues.

The literature provides some examples where the processes and internal structure of particular models are investigated.

Cohen, Riolo et al. (1999) present some interesting comparisons of methods. They represent a repeated prisoner's dilemma using a Multi Agent System, for which they analyse various parameters.

The model has three key dimensions: the strategy space, the interaction process, and the adaptive process. Changes in these parameters have impacts upon the results (payoffs) of the agents represented, and hence the emergence of patterns of activity. Although some conclusions could be drawn upon well-known and understood phenomena, some observations were unexpected (such as the high levels of co-operation when mixing agents with random strategies between games).

The prisoner's dilemma, because of its simplicity and its diffusion, is an appropriate subject for which to investigate sensitivity to various parameters. Also, these parameters are not numerical changes, but qualitative changes. They investigate the influence of the model structure upon the model results.

Generating a model, there are implicit modelling methods, and explicit ones. The explicit ones are for example strategy spaces, or neighbourhood definitions, while implicit ones could be the representation of cognition, or environment perception. Sensitivity analysis in often undertaken assessing the impact of the most explicit or representative assumptions. The example of Cohen, Riolo et al. (1999) does just that, because of the restrictive settings of the prisoner's dilemma: the case that is represented is composed of one game, one partner, no geographical or social space.

To complement that qualitative approach, sensitivity analysis is often undertaken on a numerical aspect, *e.g.* the sensitivity of the result, or indicator, to a specific value.

In other cases, the importance of sensitivity analysis comes to understanding and explaining the consequences of parameter variations (Barreteau and Bousquet (2000)). There can be several reasons for not testing alternative structures.

The structure of the model is already understood, and its effects are known

The model's structural part is not important to the results

The model does not include an agent's location: *e.g.* Hales representation of agents only uses tags, and does not use situated agents

The analysis of the structure is not generally undertaken. In most cases, the parameters that are included in the sensitivity analysis are numerical. The few times when this analysis is done, one can see that the underlying structure could have important impacts. In Duboz, Ramat et al. (2001) for example, the Multi Agent System used is tested for boundary conditions, *i.e.* a change in the algorithms that are involved in the spatial behaviour of agents (namely the way the agent bounces off a wall). Also tested are the distribution algorithms and the size of the space, and the conclusion suggests that the choice of the bouncing algorithm is a more important parameter than the distribution or size of the population of agents.

Studied impacts of structure or algorithms are common when the point of the research is to address specifically that influence, as in Cohen, Riolo et al. (1999), where the interaction mechanism is under scrutiny, along with the strategies' dimensions, and the adaptation process of strategies with time.

As in many other studies, the literature shows the effects that a simple change in the way the interactions take place sometimes has, giving extreme and opposite results (Edmonds and Hales (2003)).

An additional problem in MAS is choosing a reference run to compare to the others, since it is a stochastic process.

In the various runs generated by a set of specific parameters for the model, one can certainly distinguish several categories. There are generally 2 or 3 different sets of runs with the current model: some that are very high, that could correspond to the fact that the highest users of water are taken as examples, some that could be qualified as average runs, and some that are lower than all others, sometimes corresponding to a diffusion of patterns copied from households using low levels of water. Because of the nature of agent based modelling, it is not appropriate to use only statistical tools to select a representative run. The qualitative aspects of the simulation cannot be captured easily by means of software. The selection of the run that is used in order to compare will be done by presenting the set of runs, with both graphical and statistical properties, and then extracting what seems to be an appropriate run to consider.

The extreme behaviours that can be observed in the various runs remind the users that the results of the simulations are not to be understood as forecasts, but as indicators, examples of what the interactions could generate.

The size of the network and the characteristics of the agents (and especially their cognition) are important parameters that might influence strongly the dynamics of the system.

A number of hypothesis are going to be investigated in the following sections. They are part of a sensitivity analysis process, and will shed some light upon the possible influence of some aspects of the model, either built-in characteristics, or critical values and processes.

They are:

- the grid structure
- The density of agents
- The visibility parameter
- The agent’s memory

5.3.1 The toroidal structure

One could assume that grids with different structures produce different results. This section will compare the outputs obtained running the model using an extended grid with those obtained from the often used 2D grid.

It is necessary to mention that the simulation runs performed in order to observe the consequences of a toroidal structure have been run with the frequency and volume generated according to a power law distribution. This explains why some runs seem very high, since this implementation can sometimes generate unlikely large values. The power law distribution is assumed to be underlying in the frequency and volume used per appliance. In most other simulation runs, the frequency and volume are initially normally distributed around the mean that has been provided from observed data. At a given point in time, this might well be the case, and it does not mean in any way that this distribution is assumed to hold with time. More specifically, further analysis will demonstrate that both alternatives (power law and not power law distributed initial values) have a negative kurtosis.

Differences in the number of links between agents when the grid is toroidal or not can be represented via a matrix. The two figures below display these matrices for a specific simulation.

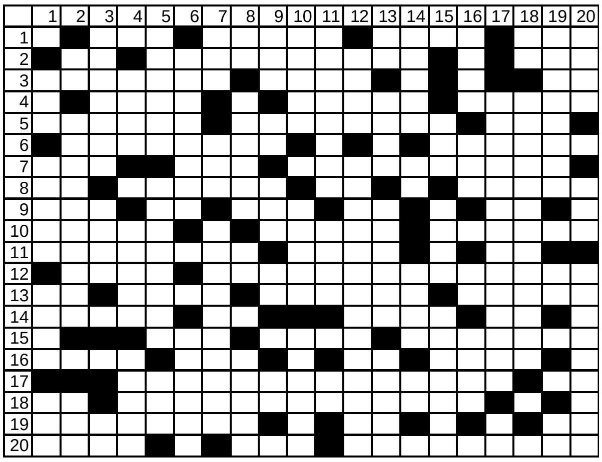

Figure 18: Matrix of links for a grid with a toroidal structure: in this case, the 20 agents are situated on a grid of size 8*8

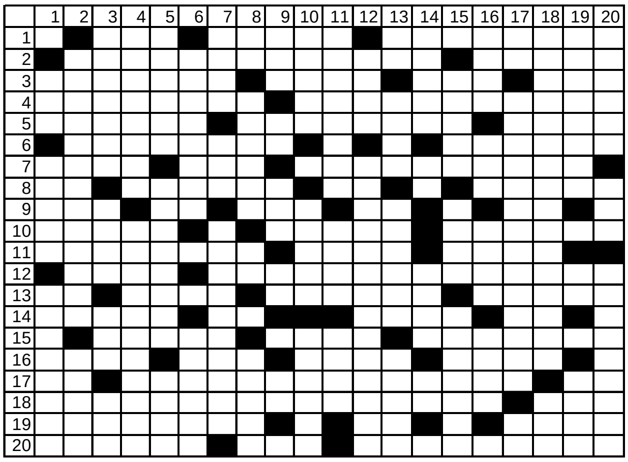

Figure 19: The equivalent matrix of links for the non-toroidal version

The black cells show the existence of an interaction between the agents listed horizontally and vertically, and it is easy to notice that the toroidal structure provides more contacts to each agent.

The diagrams below show the results of 46 reference runs.

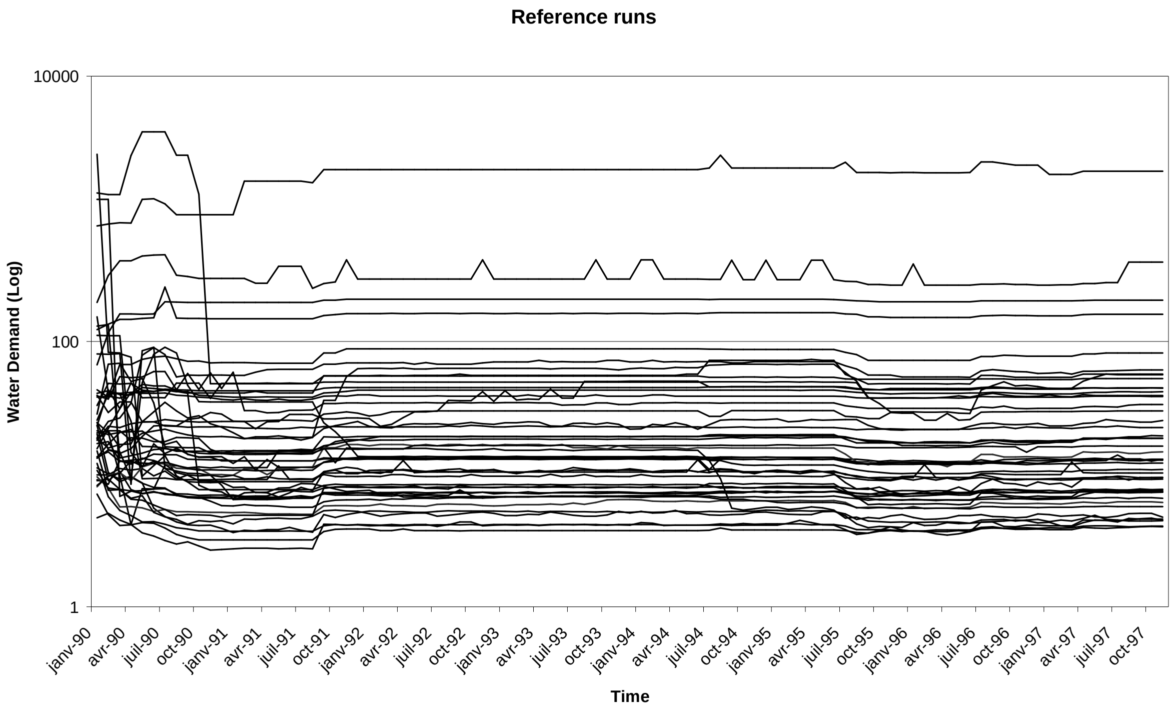

Figure 20: Multiple reference runs

This graph represents the total water demand for the system. It is here on a log scale, since this allows us to show all the runs, while there are some that are significantly different, with volumes being several orders of magnitude larger than the bulk of the others.

If the focus is upon that bulk of runs, the result is as follow.

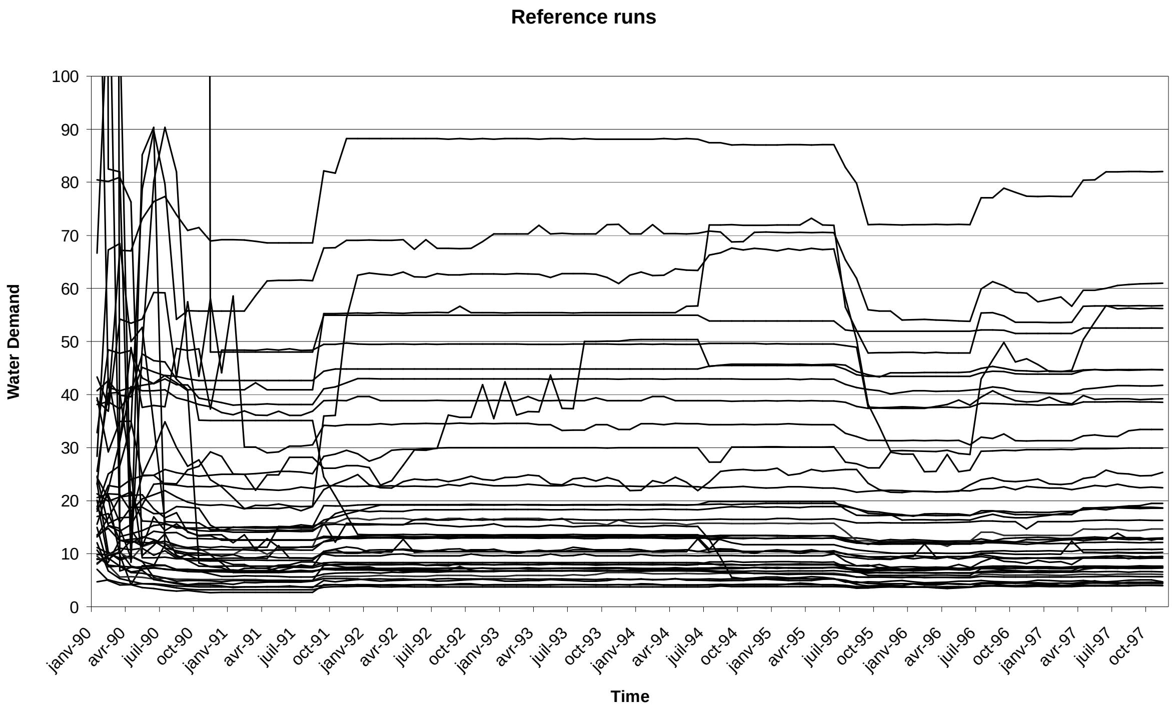

Figure 21: Focused reference runs

As it can be seen, the majority of the runs (29 of them) are below 20. That seems to indicate that a reasonable value would tend to be below this threshold.

By contrast, another set of runs, with the same parameters, just changing the structural property of having a finite (non-toroidal) space gives the following 34 runs.

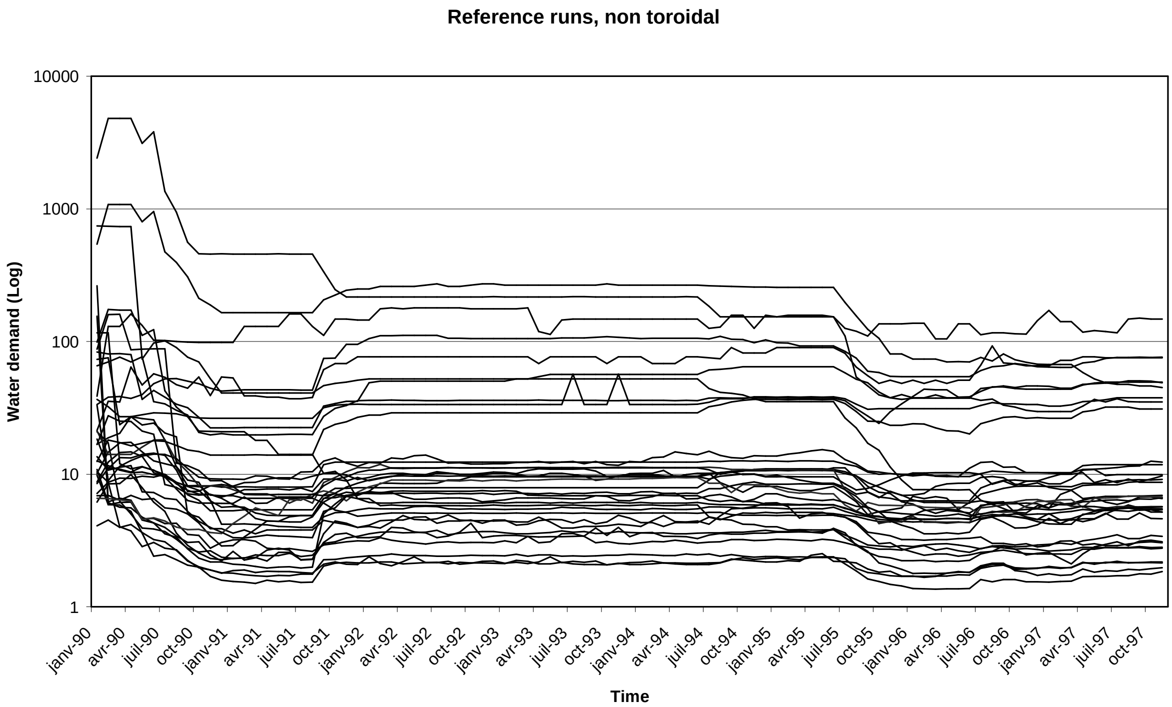

Figure 22: Reference runs, logarithmic scale

The same focus as before, gives the following:

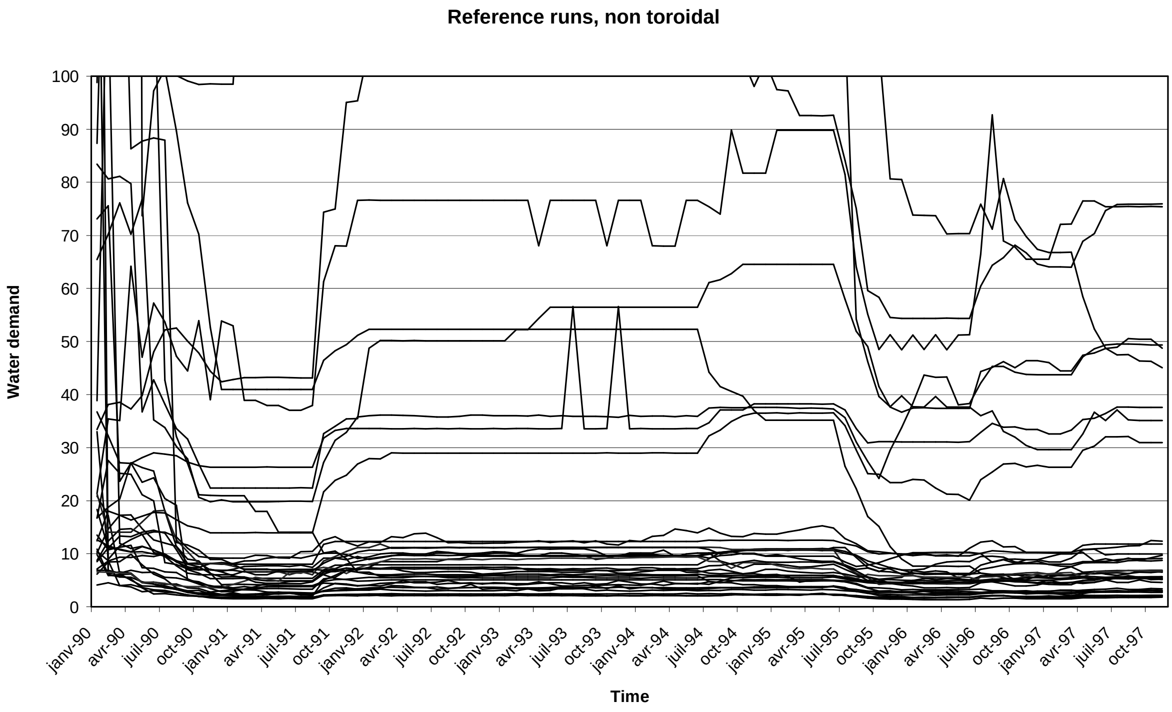

Figure 23: Focused reference runs

This time, it is 25 runs of the 34 that are concentrated within the [0 – 20] values. That is 75% of them. It seems that the space structure could have some effects upon the global dynamics of the model.

By extending the visibility (to 6 instead of 4 by default) on a finite grid, the proportion changes, as it reaches about 57% of runs only (51 upon 89) below that threshold.

If the month of December 1990 is taken as a reference, then the following dynamics can be observed.

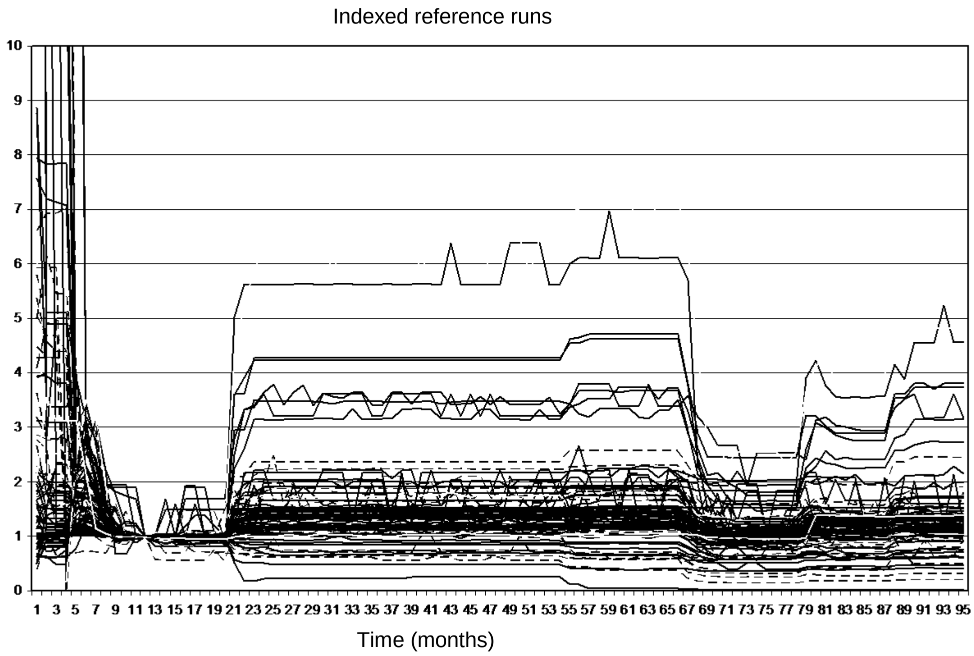

Figure 24: Reference runs, indexed December 1990

One can see that the variations of water demand have all a value of 1 for the 12th month. It is also visible that there seems to be a most likely dynamics, or a set of most likely dynamics, generating similar relative changes for the majority of the runs.

By using the particular case of a system with 10 agents on a 20*20 grid, that have no visibility, the following result is reached:

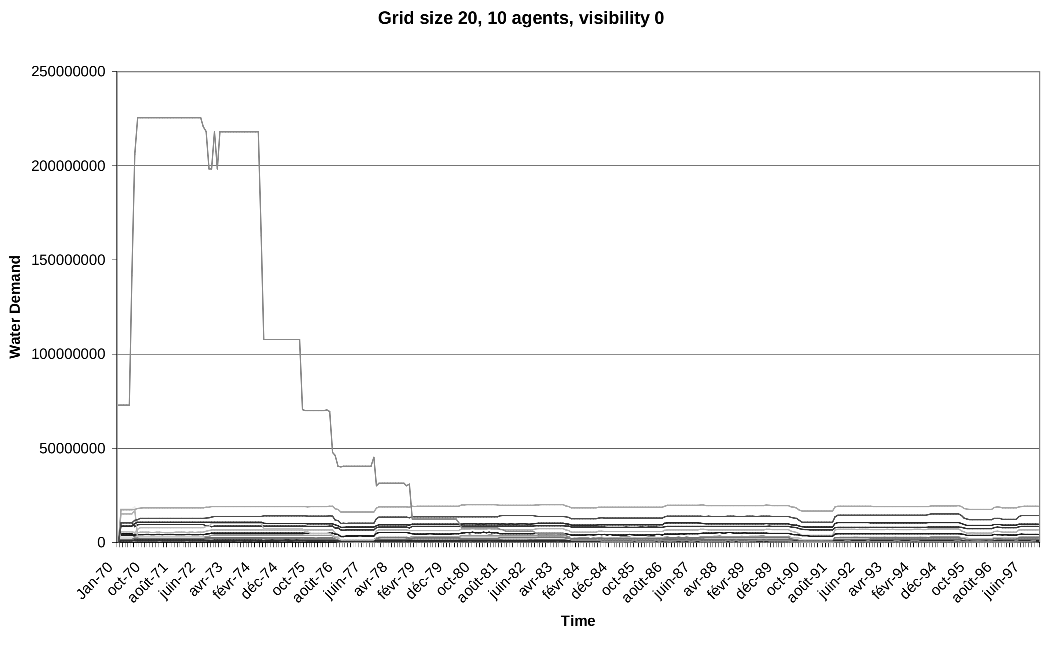

Figure 25: 4 agents, grid size 20, visibility 0

The topmost run displays an example of extreme behaviour. Removing it from this graph allows a more detailed view of the values for remaining runs. Focusing on the lower part of the diagram can further identify the similarities of some runs.

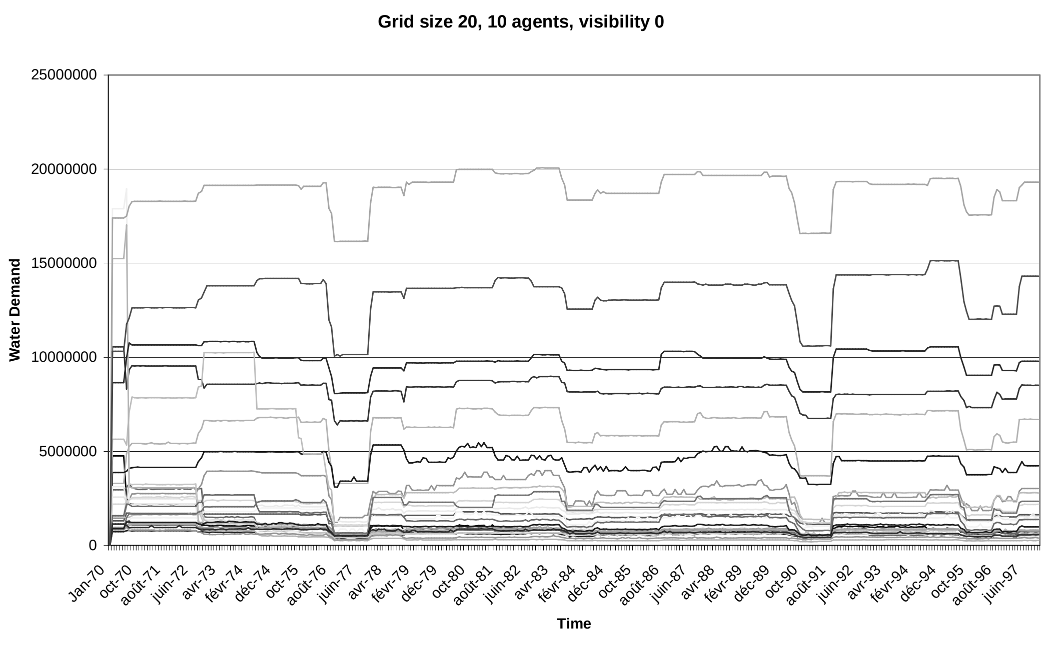

Figure 26: Detailed view, agents, grid size 20, visibility 0

The similarities of patterns one can observe on the figure below are applicable to all scenarios, regardless of the network structure. An example with a reduced number of agents on a toroidal grid tends to show that some runs seem to behave identically.

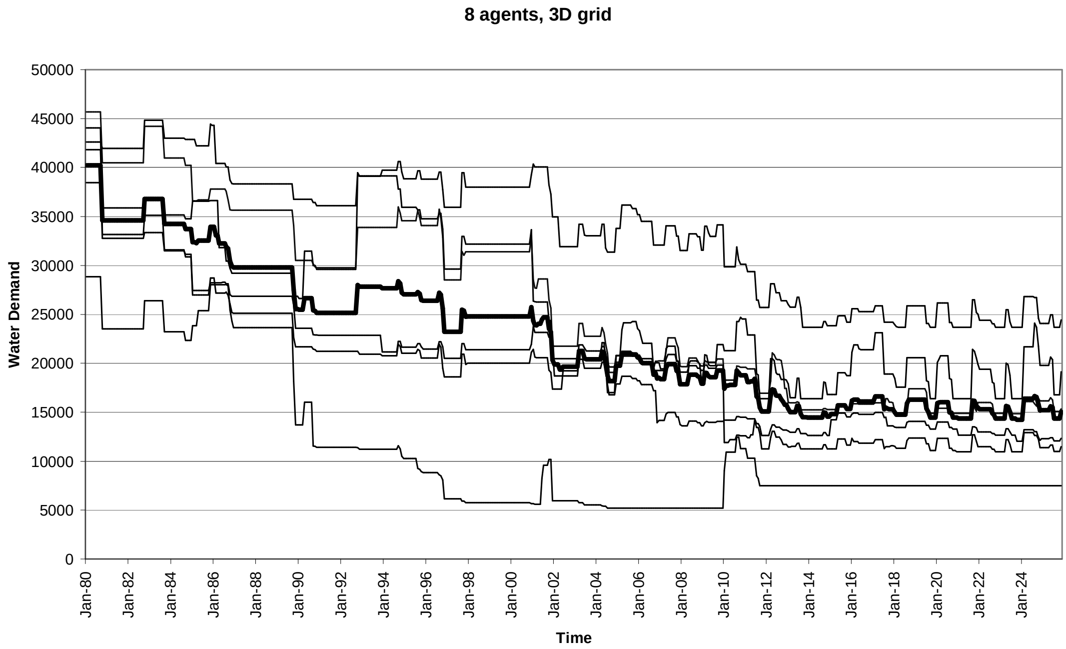

Figure 27: Similarities of runs on a toroidal grid

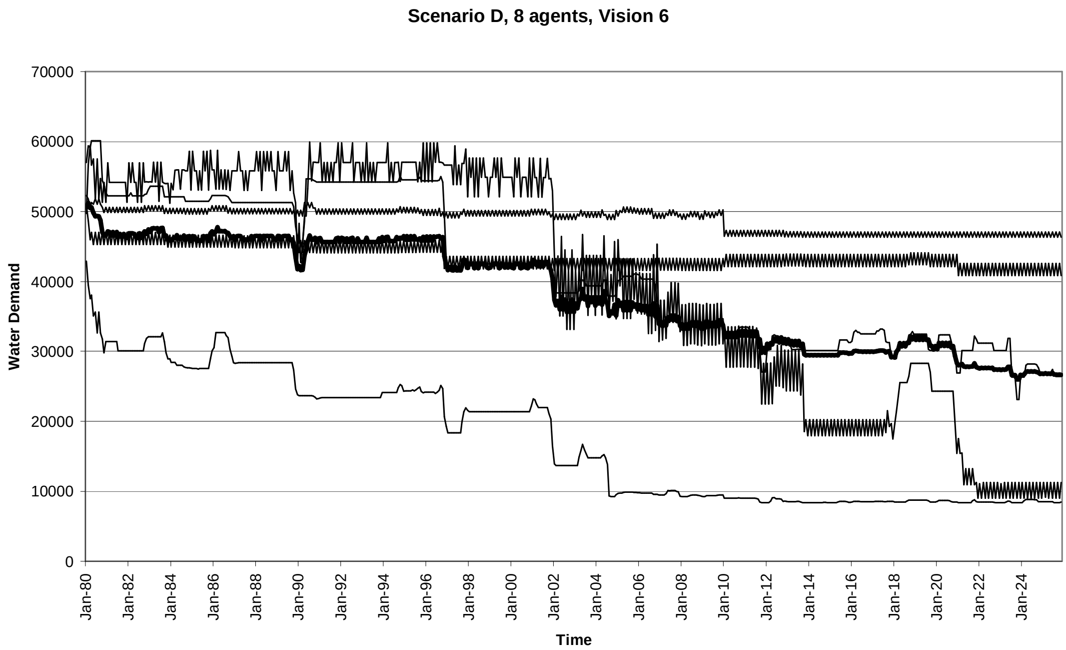

Figure 28: Runs on a non-toroidal grid

To investigate this idea, a formal analysis of the distributions involved is done in SPSS.

Testing the averages for both simulation results with SPSS, the results are not clear-cut, as shown in the table below.

Test Statistics[a]

	lag
Mann-Whitney U	146589,0
Wilcoxon W	298114,0
Z	-.901
Asymp. Sig. (2-tailed)	.367

a. Grouping Variable: VAR00008

Table 21: Testing sample independence (relative change)

The probability that the two distributions are extracted from an identical sample is not zero as was the case in earlier tests, but is now close 0.367. This means that the two distributions do have similarities. Nevertheless, it is not possible to assert with confidence that the averages are extracted from the same sample.

However, when using raw data instead of relative changes, the figures seem to improve. In several comparisons of specific series, the probability that the two sets of data are extracted from the same sample reaches values higher than 0.8. This value is high enough so the doubt is the opposite way, and it would be likely that the underlying distributions of both sample might be identical.

Test Statistics[a]

	lag
Mann-Whitney U	150384,0
Wilcoxon W	301909,0
Z	-.172
Asymp. Sig. (2-tailed)	.864

a. Grouping Variable: VAR00008

Table 22: Testing sample independence (raw data)

This could imply that there is a technical issue with the averages, and that the dimensions of the grid supporting the agents seem of no great influence upon the results.

Considering that the support itself has little influence, the number of agents present and the number of interactions taking place in the model must be looked into.

Altogether, as a rule, it is not clear that the dimensions of the underlying space make a difference in the way the processes take place and the results at a macro level. Nevertheless, some cases have been observed, when the positioning of agents upon the grid has generated a situation in which the links were so few that changing the toroidal space into a non-toroidal one did change in quite a radical way the shape of the network involved. Despite this, the overall patterns observed did not seem significantly sensitive to this parameter.

In such extreme cases, it appeared that a more critical index of how sensitive a specific set-up would be to changes was the density of agents.

The conclusion of such analysis is not clear-cut. On one hand, when both simulation results were compared using the standard output (*i.e.* in this case the water demand figure), the structure seemed to make a difference. On the other hand, when the relative changes of these two simulations were analysed, the statistics seemed to indicate that there was not a significant difference between them.

One could think that this could be explained by the fact that the absolute figures obtained can be very variable, due to the inclusion of randomness at the start of the simulation run. But the non-parametric statistics should not be assessing the values themselves, but rather the structure their hypothetical sample of origin would have.

Yet, the results are opposite when analysing the changes within these water demand figures.

It is debatable whether they both are the consequence of the same component of the model. The structure of the grid will have an impact upon the households that communicate with each other, and this might be a main driver for levels of water demand in this model. Similarly, the process that is embedded within every agent to describe its decisions and choices does not change when the grid structure changes. Consequently, one could associate the relative changes, which do not seem to differ, with the decision making process, while the absolute values would be more influenced by the amount of information that is available to an agent.

Also playing a part in the innovation diffusion, the network structure can intuitively be considered as a major parameter during the set-up of a simulation run. The fact that a network with a higher number of links seems to be associated with rapid uptake of innovation would tie in with the explanation suggested above regarding the different impacts of communication and decision making processes.

5.3.2 The density of agents

One could suppose that the density of agents on the grid can influence the outcomes of the simulation. This section will investigate whether there is a critical density below which some phenomenon do not emerge, or some conclusions do not hold.

The nature of the model makes it very sensitive to the amount of interactions that can take place. If the social environment of an agent is limited, what is the impact on that agent's behaviour and why?

The method used to answer this question is the following. For an equivalent grid size, different numbers of households are simulated. The runs generated can then be compared, and help to provide insight into this possible influence.

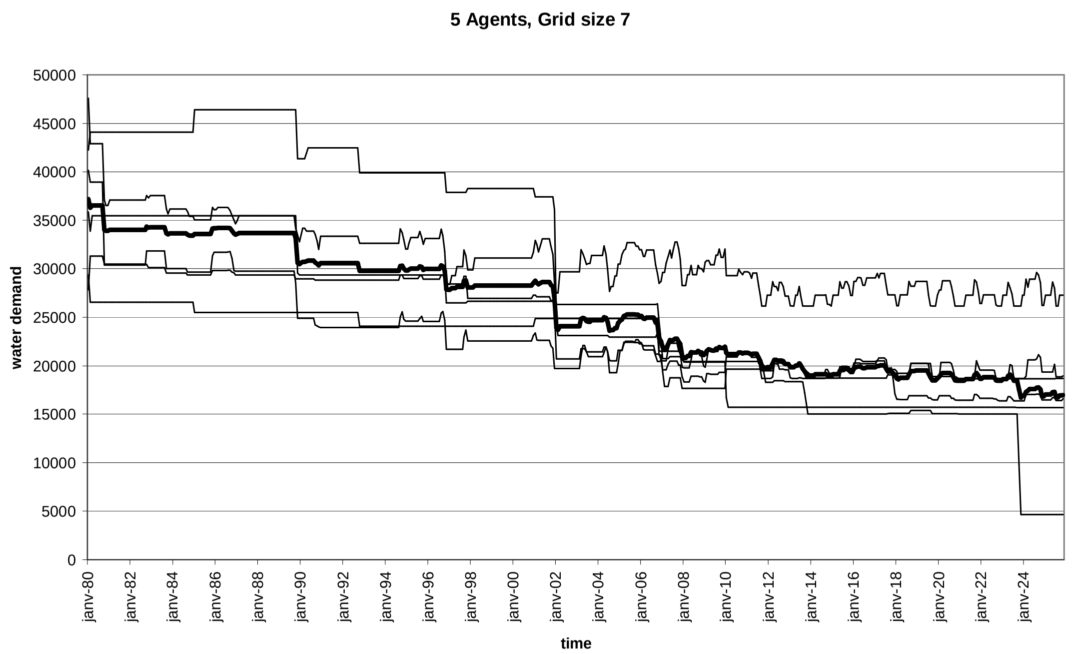

Figure 29: Water demand, agent density 0.1

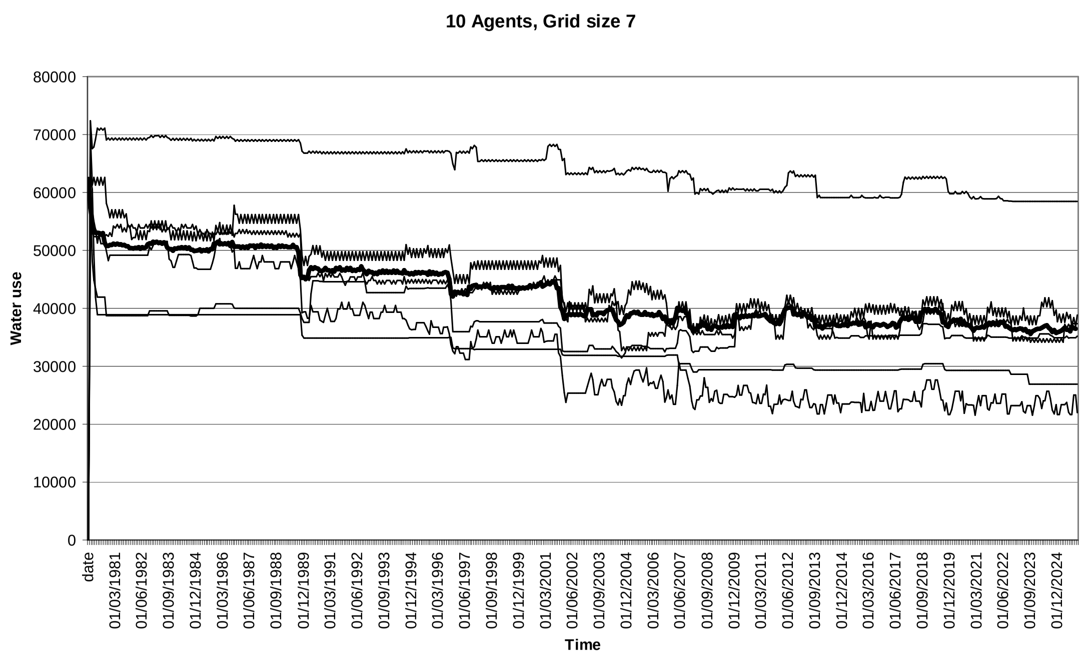

Figure 30: Water demand, agent density 0.2

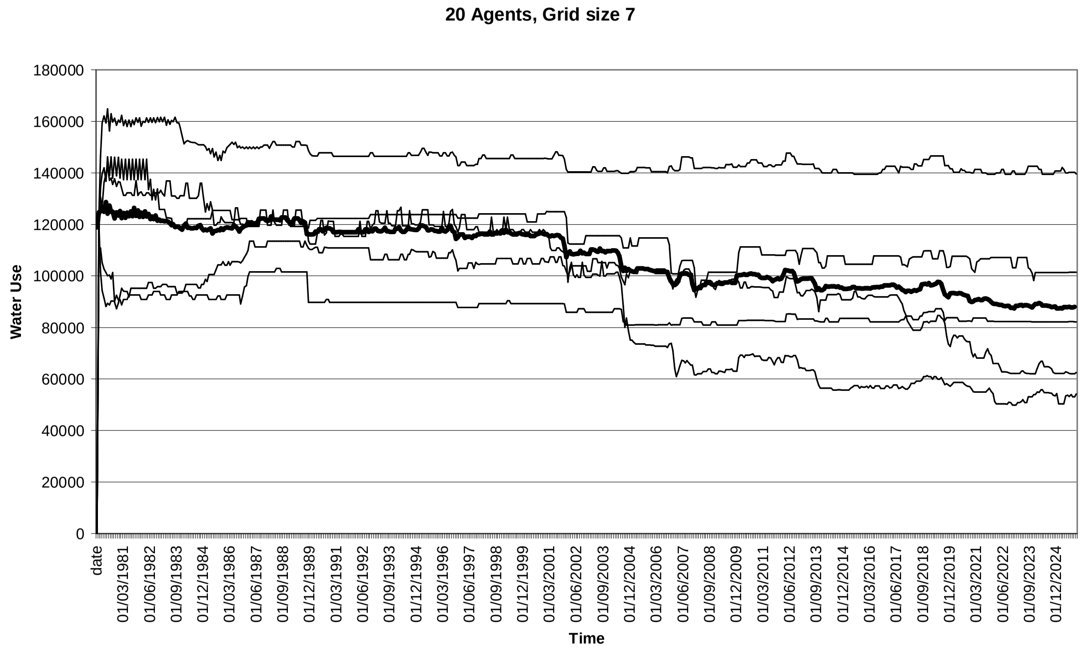

Figure 31: Water demand, agent density 0.4

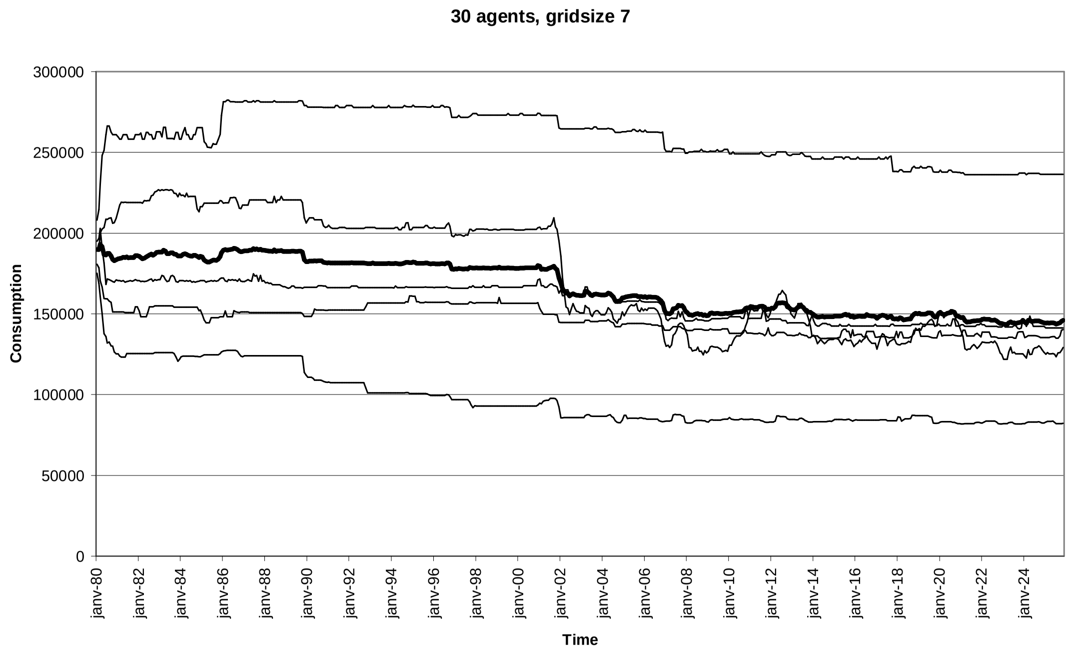

Figure 32: Water demand, agent density 0.6

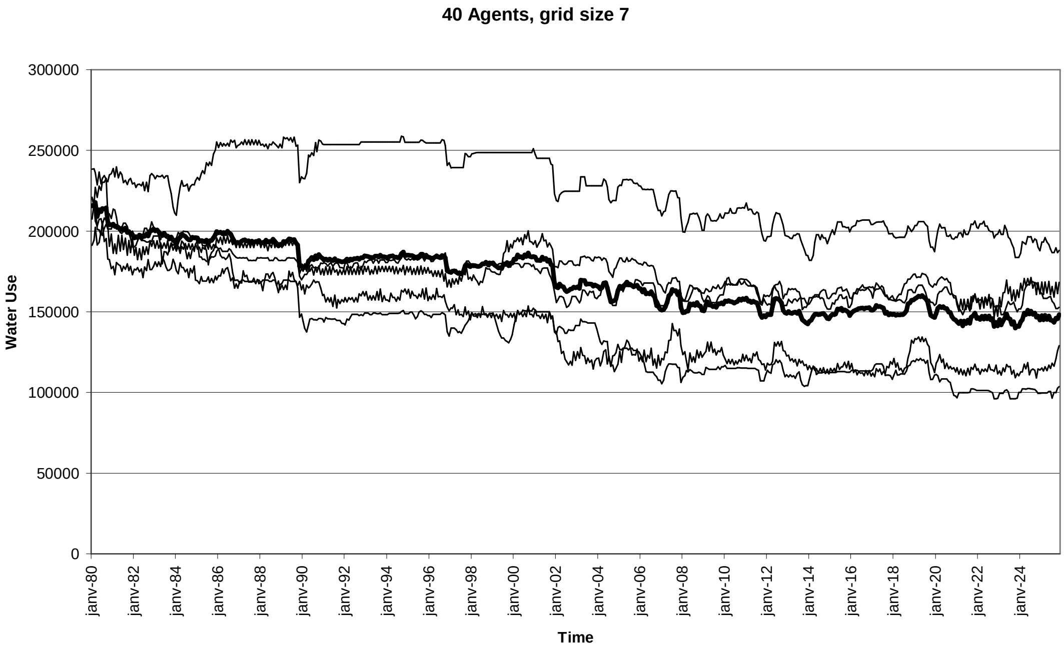

Figure 33: Water demand, agent density 0.8

The size of the grid can either be finite, or infinite. In this particular case, if the grid is actually a mapped 3D space, the size can be thought of as infinite (every agent has the same number of cells in its neighbourhood). Several important points must be made in order to explain the following assumptions and tests.

1) The size could be not important in itself

2) The number of agents could be not important in itself

3) The ratio agents / size, *i.e.* the density could be important

4) The social environment will define the extent to which an agent can see other agents.

Assertion number 1 is expressing the fact that the influence of the size of the grid cannot be evaluated as a single parameter. Changing it also impacts on the agents' density, as well as the communication paths. The same meaning is in assertion number 2. Number 3 and 4 represent the assumptions that will be tested below.

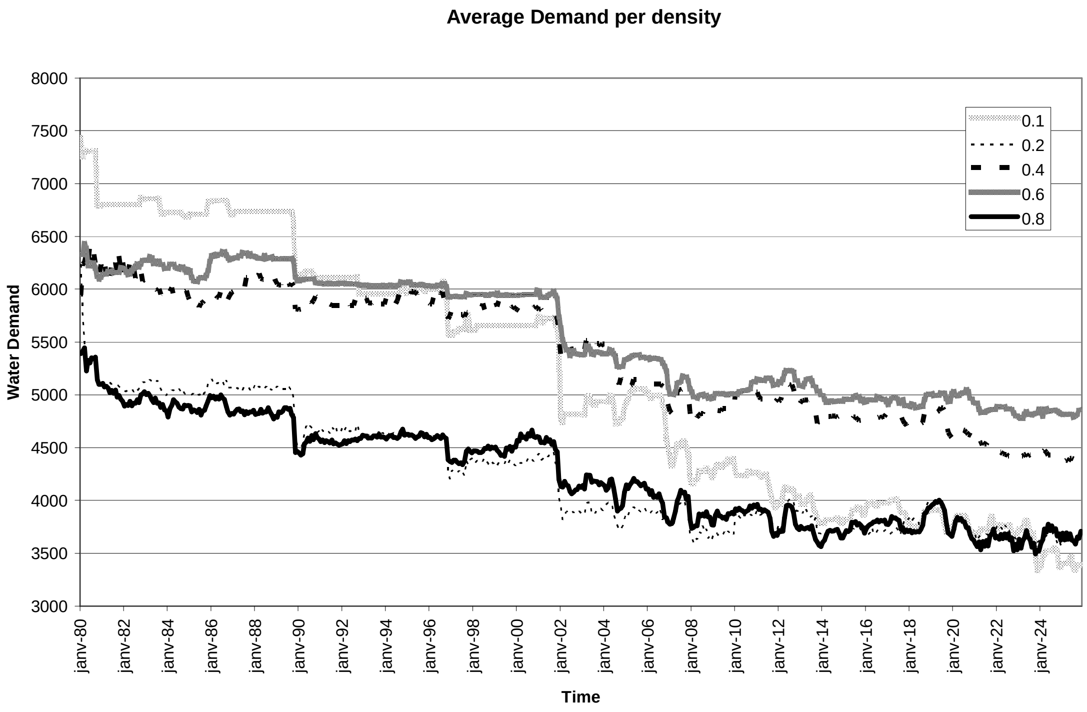

Figure 34: Average water demand with respect to agent density on the grid

One can observe in the above graph that, while the general trend is a decrease in water demand, there are differences according to the density of agents on the grid. A low density displays the most important variations, for example in 1990 and 2002. Due to this sensitivity, it is also the demand that falls the most quickly. There seem to be two different groups for the remaining densities, with the evolution of the simulations for densities of 0.4 and 0.6 close to each other, as are 0.2 and 0.8.

The tools used in this case are simple and descriptive. It would be interesting to assess more rigorously similarities amongst different sets of simulations, but currently, there does not seem to be any available software that can be used for treating the amount of data generated by the model.

Focusing on the different number of agents in a simulation, SPSS can be used in order to assess whether all sets of results might have similar statistical properties, and the conclusion is not equivocal. As shown in the tables below, when studying the relative differences in every series, the results are considered to be from the same sample with a probability superior to 0.96.

Test Statistics[a,b]

	lag
Chi-Square	.573
df	4
Asymp. Sig.	.966

a. Kruskal Wallis Test

b. Grouping Variable: VAR00008

Table 23: Kruskal-Wallis statistics for runs with various densities

An initial conclusion of this test could be that the density of agents does not matter. Intuitively, though, one can understand that the density is linked with the amount of interactions, and therefore this result would be surprising. But the non parametric method used is based on the ranking of data, and not their absolute value (see table below, displaying the mean rank of every run in the series). This could mean that the studied object would more likely be the process itself, leading to the interpretation that the process generates data with similar properties regardless of the size of the population. By increasing this size, the results themselves are changed, due to the increase in possible interactions, but their underlying distribution is not.

Ranks

Run	N	Mean Rank
0	55	1360.5
1	55	1375.1
2	55	1365.5
3	55	1390.5
4	55	1385.6
Total	275	

Table 24: Mean rank for runs with various densities

In fine, it seems that changes in density within a set of assumptions do not significantly impact on the output's distribution. Provided that the density is high enough to enable a minimum amount of communication amongst households, further increase would only lead to potential changes in absolute value of the output, but not leading to a change in the underlying distribution.

Since density as such does not appear to be a crucial parameter in this model, one then wonders whether this role could be played by the extent to which agents can see each other on the grid, and that is now the object of study.

5.3.3 The visibility parameter

One can consider visibility as a crucial parameter, with values at which the model's output differ. This section will study the potential consequences various ranges of visibility.

Different simulations were undertaken to assess the importance of the visibility parameter. This first set uses the standard simulation parameters, and is composed of 10 agents. The representation of the runs is as follows:

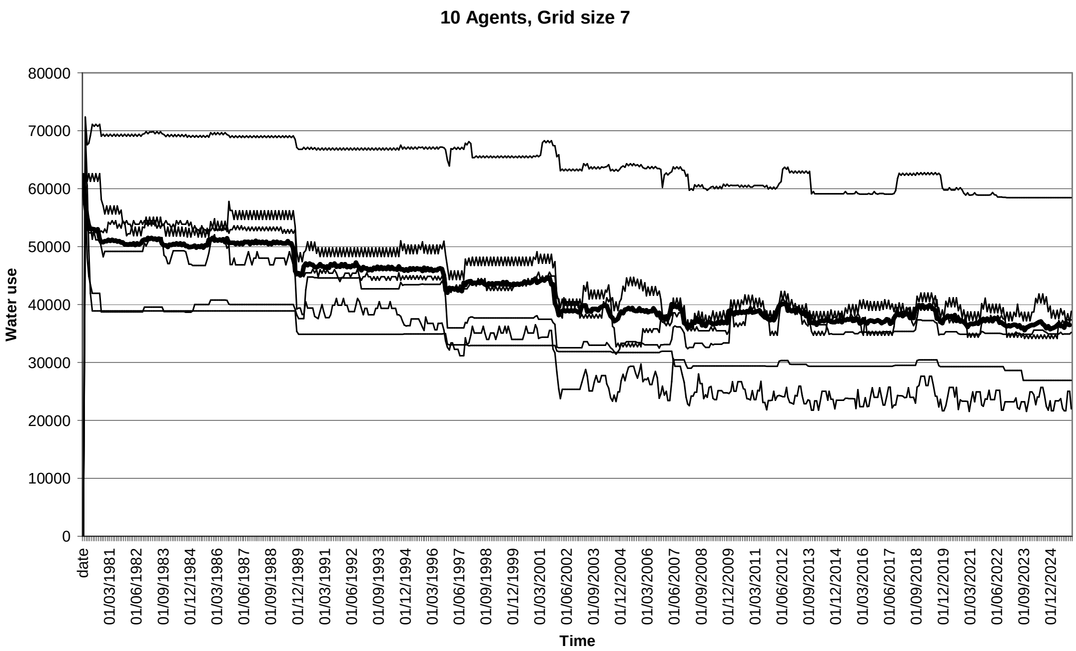

Figure 35: Reference run, visibility = 6

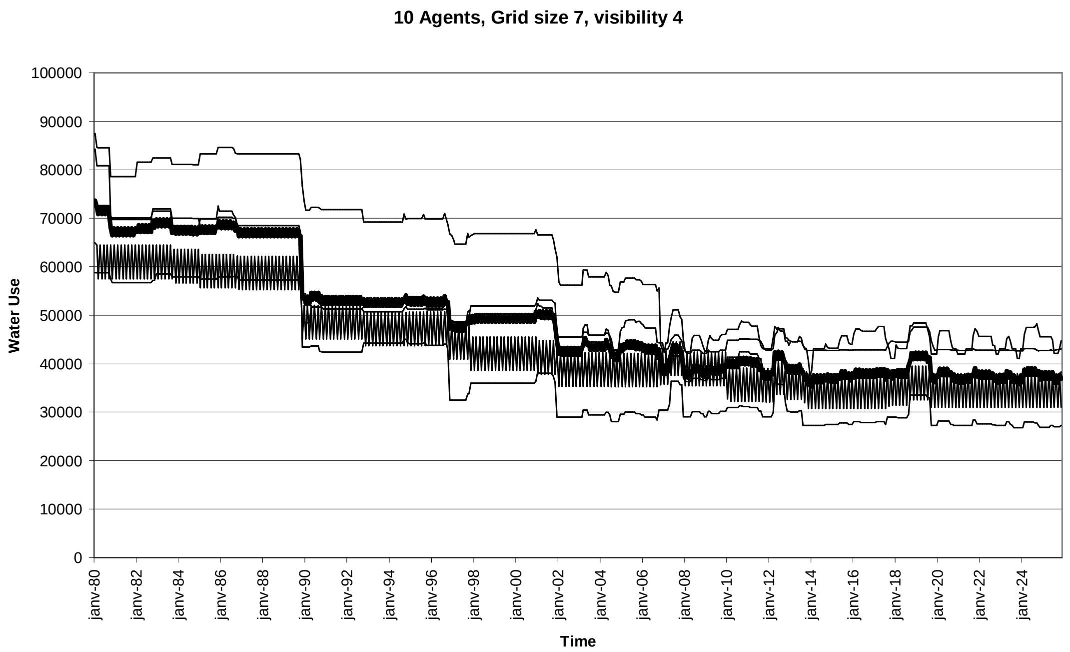

Figure 36: Reference run, visibility = 4

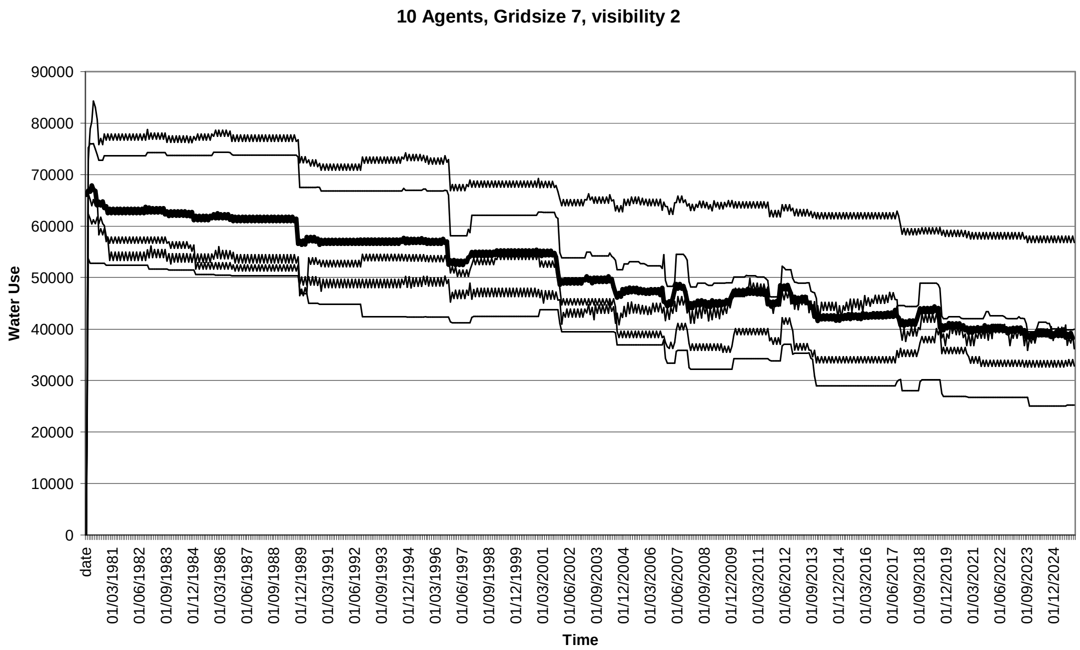

Figure 37: Reference run, visibility = 2

While there is only a single run showing micro instabilities with simulations whose vision is 6 or 4, there are 3 when it is equal to 2. This could lead us to assume that stability relies on a relatively high level of communication.

But some other simulations could cast a doubt upon this theory.

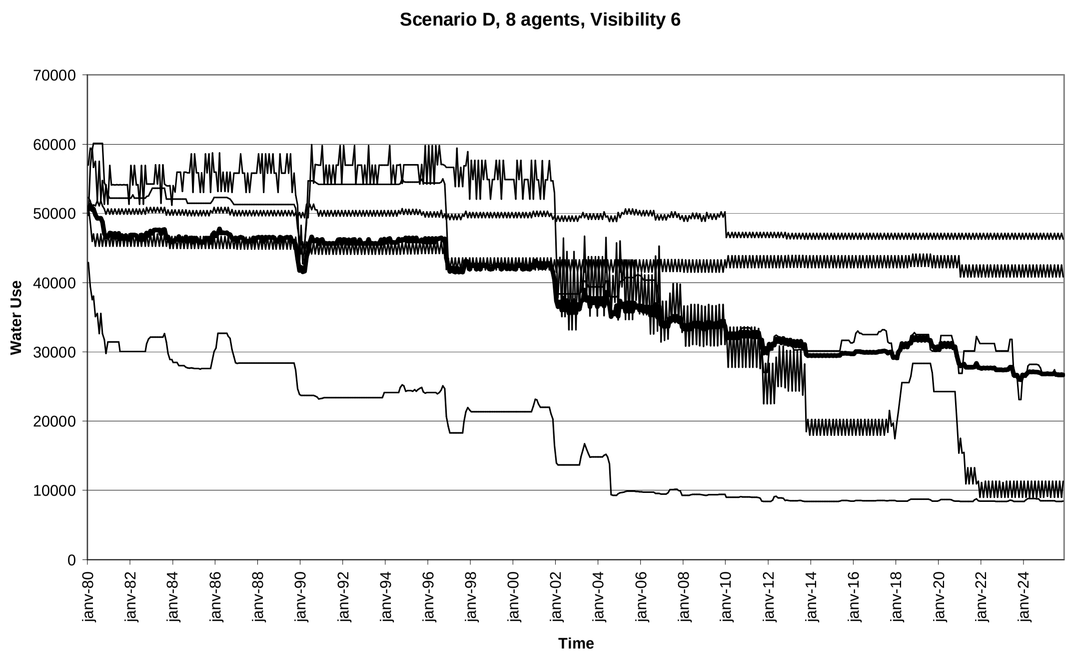

Figure 38: Scenario D, visibility = 6

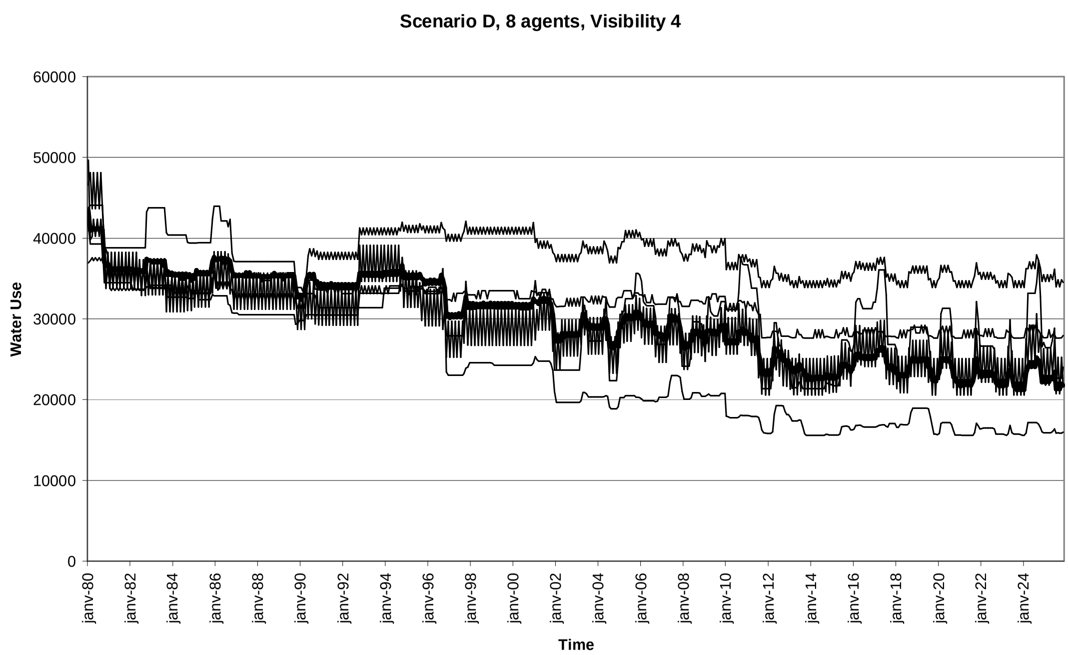

Figure 39: Scenario D, visibility = 4

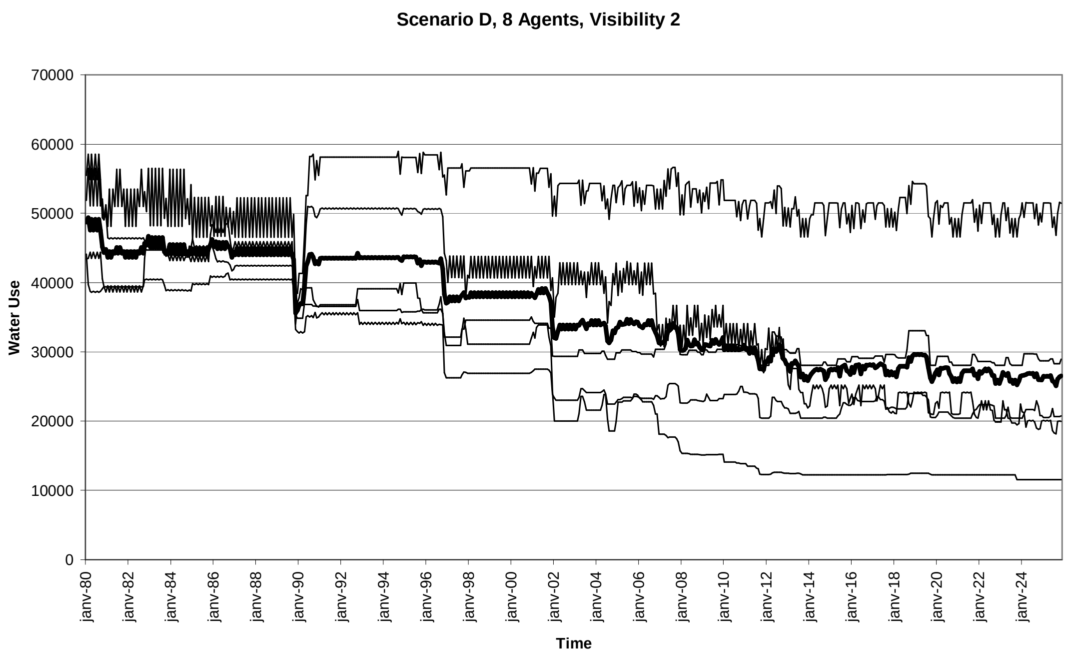

Figure 40: Scenario D, visibility = 2

In this case, the parameters used are those of scenario D. As one can see, the simulations with a larger vision parameter seem to show more micro instabilities than those with lower values.

In order to test this, a complete set of simulations was run that kept all previous scenario parameters, apart from a reduced visibility of 2. The aim is to analyse the behaviour of the changes. The most significant indicator is then the behaviour of the relative changes happening in the series, as well as their frequency and statistical properties.

Also, the results presented include a representation of the normal distribution with equivalent parameters to the sample used. It is obvious then that these are not normal and that they show the unmistakable fat tailed and high peaked distribution that is associated with positive kurtosis.

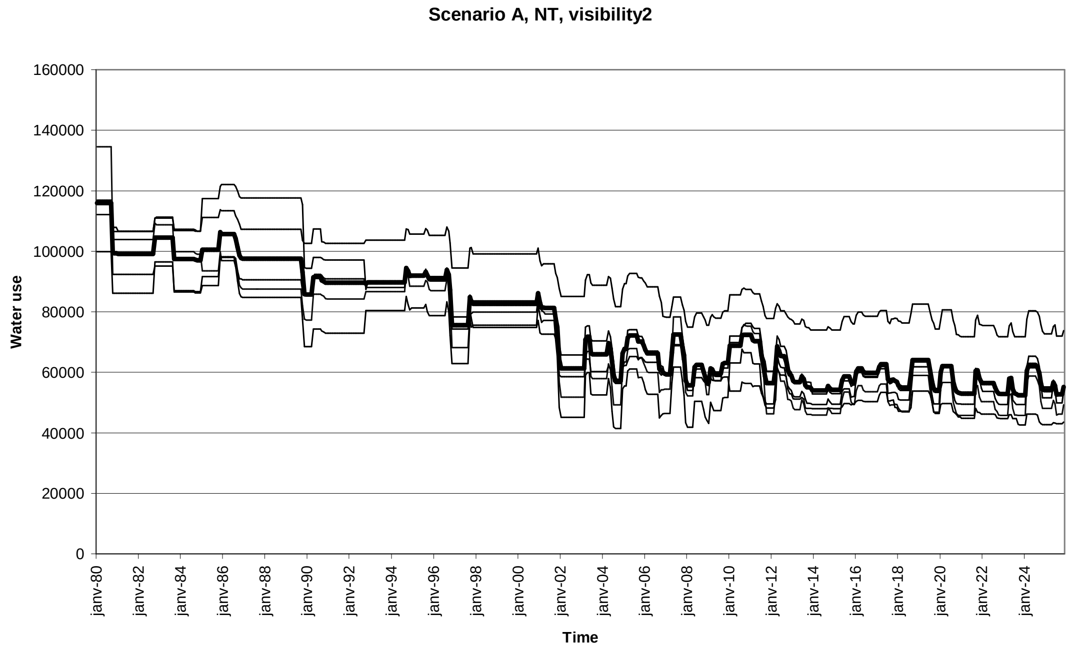

Figure 41: Scenario A, non-toroidal grid, visibility = 2

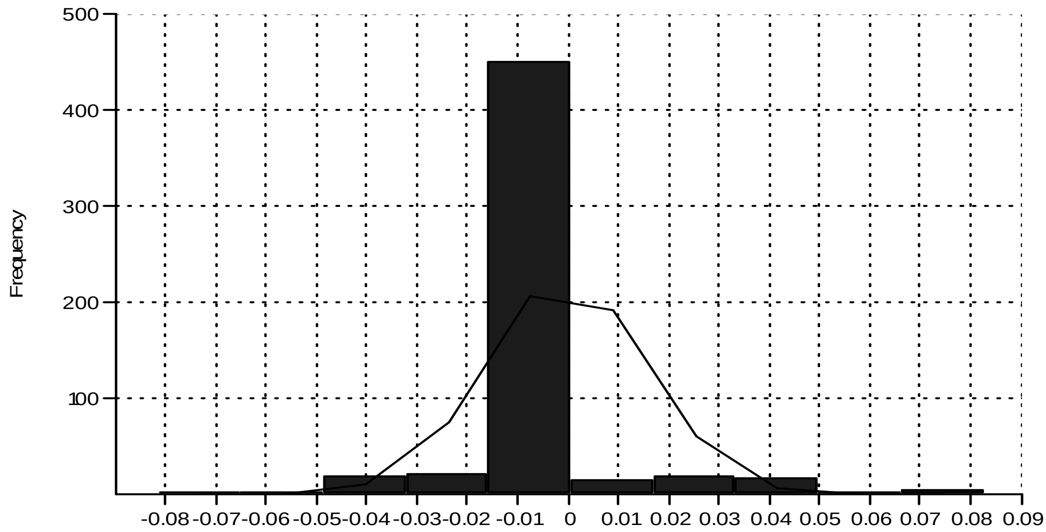

Figure 42: Comparison with normal distribution, Scenario A, non-toroidal grid, visibility = 2

The graph above displays relative changes for scenario A, with reduced visibility. The curve represents the normal distribution with equivalent parameters (mean and variance) to the relative changes.

Now looking at scenario B, the changes are as follows:

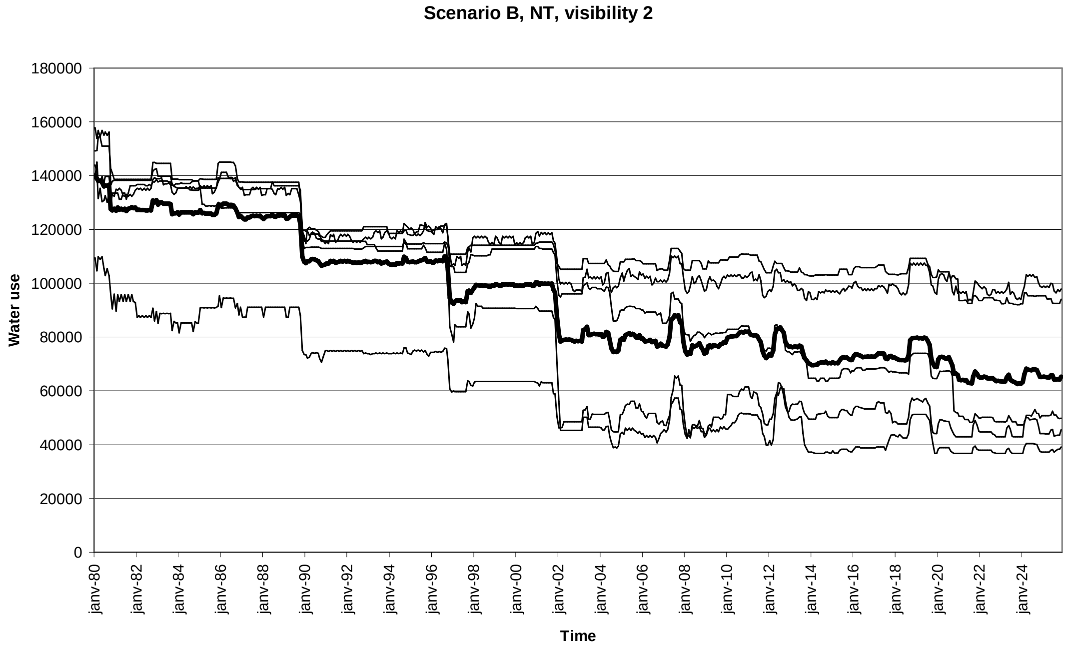

Figure 43: Scenario B, non-toroidal grid, visibility = 2

With respect to the standard simulation undertaken with parameters corresponding to scenario B, one can notice a more common reduction of water use in the simulations. The importance of self-endorsements in this scenario, coupled with a lower visibility tended to weaken the community-based endorsements, and resulted in several agents adopting new technologies.

The histogram of relative changes for scenario B with reduced visibility still demonstrates the presence of non-normally distributed changes, as shown below.

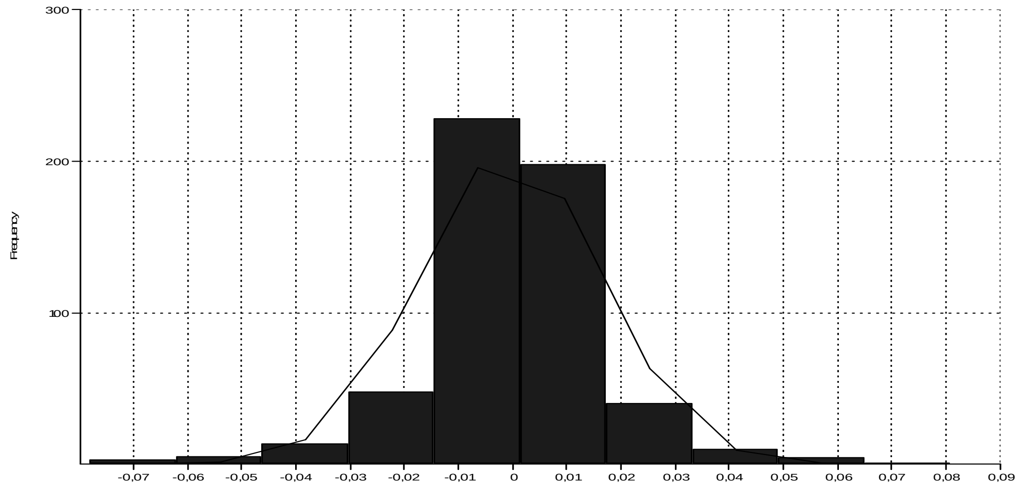

Figure 44: Comparison with normal distribution, Scenario B, non-toroidal grid, visibility = 2

The same type of analysis is now undertaken for scenario C.

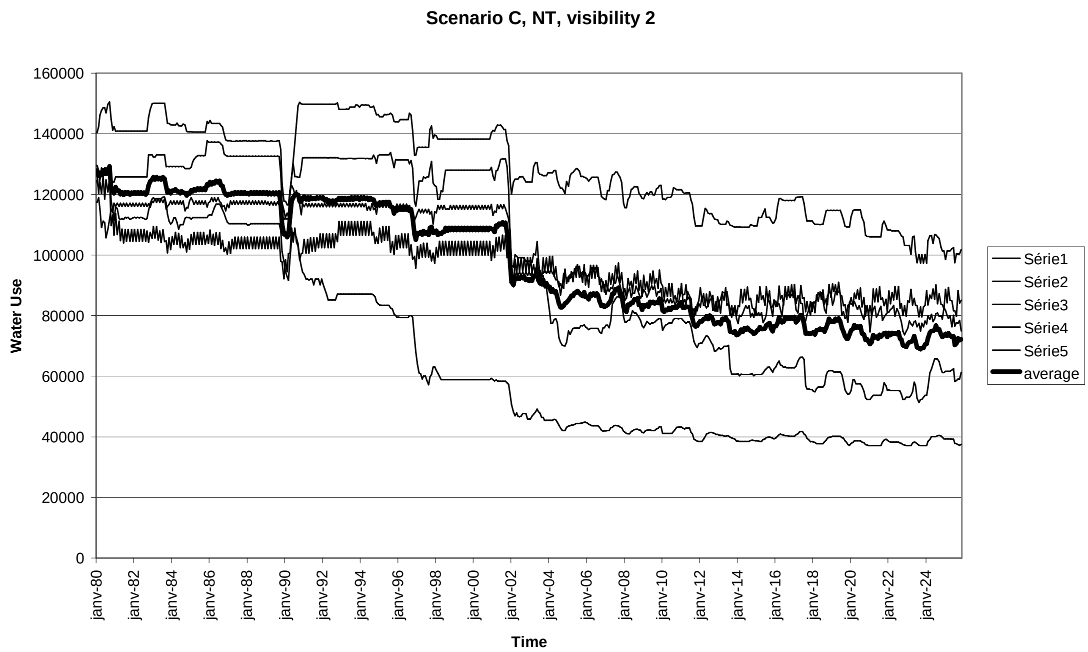

Figure 45: Scenario C, non-toroidal grid, visibility = 2

One can notice that the decreasing effect seen in scenario B does not seem to hold here, as the levels of water consumption are higher in this case than in the case of scenario C with standard parameters. Two series stand out in this set of runs, both presenting small repeated variations, both with fairly similar patterns to each other, but one with a smaller range of variations than the other. It is mostly visible in the period from 1990 to 2002.

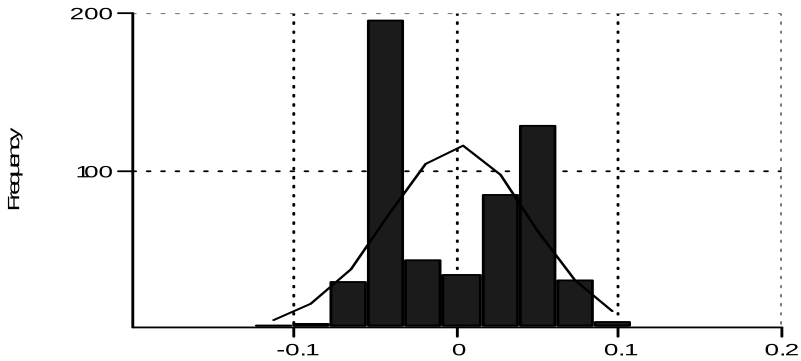

Figure 46: Comparison with normal distribution, Scenario C, non-toroidal grid, visibility = 2, series with small micro variations

The graph above represents the plotting of the higher of the two series, the one showing what could be denoted as small "micro variations"

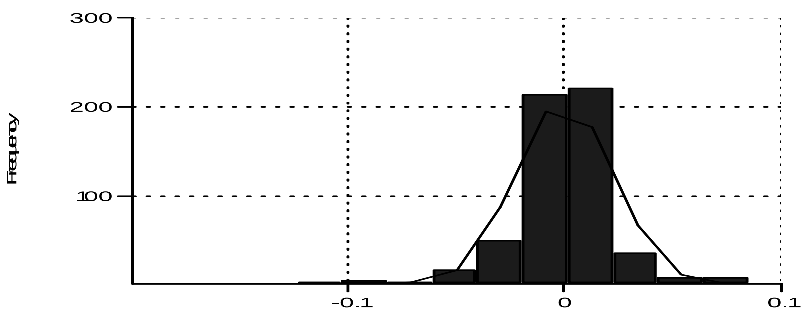

Figure 47: Comparison with normal distribution, Scenario C, non-toroidal grid, visibility = 2, series with large micro variations

This graph represents the result for the series displaying the lower of the series, the one showing larger "micro variations".

As one can see, in both cases the normal curve does not match the histogram shape, a phenomenon confirmed by the visible higher peaks and fatter tails.

For scenario D, as showed in the graph below, the main change is the fact that a decreasing trend is also present. As seen with scenario B, the cause lies in the endorsement value. The high value of local endorsements results in a relatively stronger influence of one neighbour on the other. One could understand this phenomenon as a compensation of visibility reduction by the increased importance of neighbours' activities in an agent's decision process.

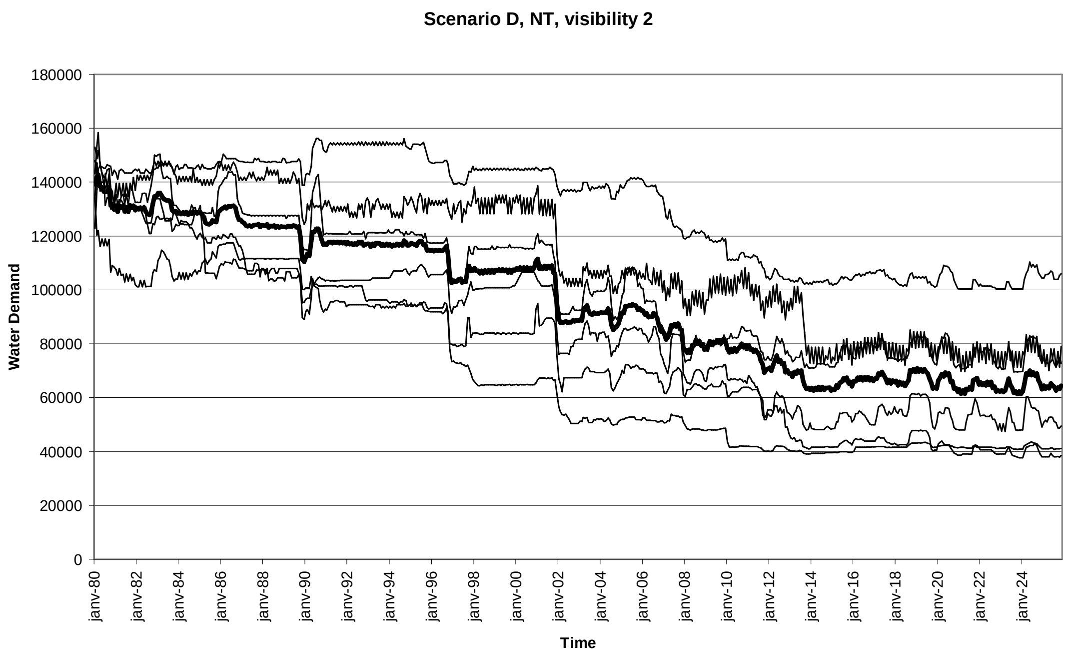

Figure 48: Scenario D, non-toroidal grid, visibility = 2

Still, as with previous scenarios, the relative changes are not normally distributed, and show the common characteristics, the distribution being fat tailed and high peaked, as the graph below demonstrates.

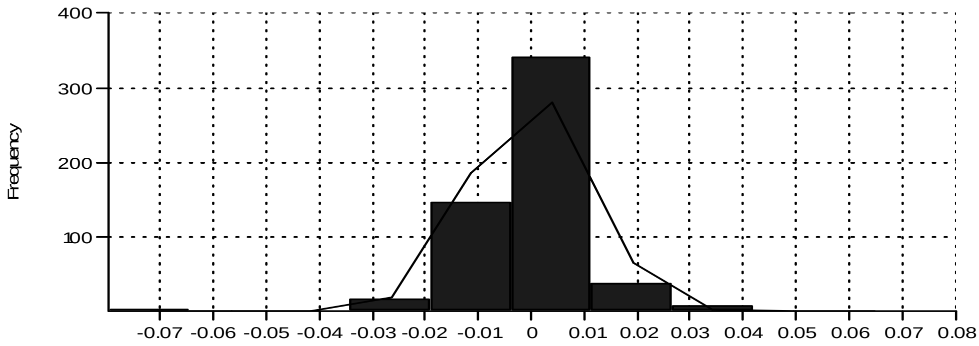

Figure 49: Comparison with normal distribution, Scenario D, non-toroidal grid, visibility = 2

In this case, the average relative variations have a mean of -0.000507754, and a standard deviation of 0.0285293. Also, the median is 0, and the skewness and kurtosis are respectively 0.123833 and 2.69326.

In the end, by enhancing the vision range of an agent, one increases the amount of information available to this agent. One of the conclusions from such an increase is equivalent to the comment made regarding the network structure, with potentially statistically significant changes between simulation runs. Also, the different values for the vision of an agent seem to have another effect. When associated with a low density, ensuring a minimal amount of connections, there seems to be another phenomenon, with what has been labelled in the previous chapter micro-variations. This could be justified by the fact that the subjective evaluation of this minimum amount of information would be very sensitive to changes in one endorsement value, such as the memorised ones.

Another parameter that one might argue plays an important role in the determination of a simulation's output is the extent to which an agent can remember what happened in the past.

5.3.4 The memory

Memory can be judged as a critical factor. By referring to events further into the past, can agents show distinct behaviours? This section will analyse this, comparing outputs from simulations with short and long memory.

One would expect that a “better” memory would yield different results, maybe inferring a more stable consumption, due to the greater amount of choice in an agent’s action, and the eventual probability it would reproduce its own pattern through the repetition of self endorsed actions.

There are other possibilities obviously, and the following simulations intend to assess the effect of an increased memory.

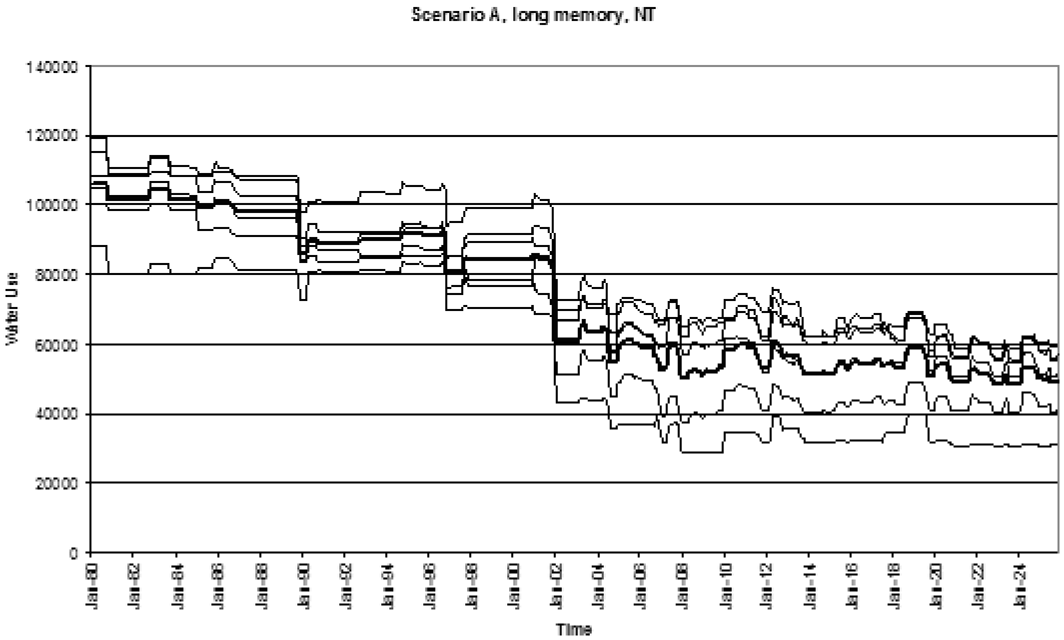

Figure 50: Scenario A, long memory, non-toroidal grid

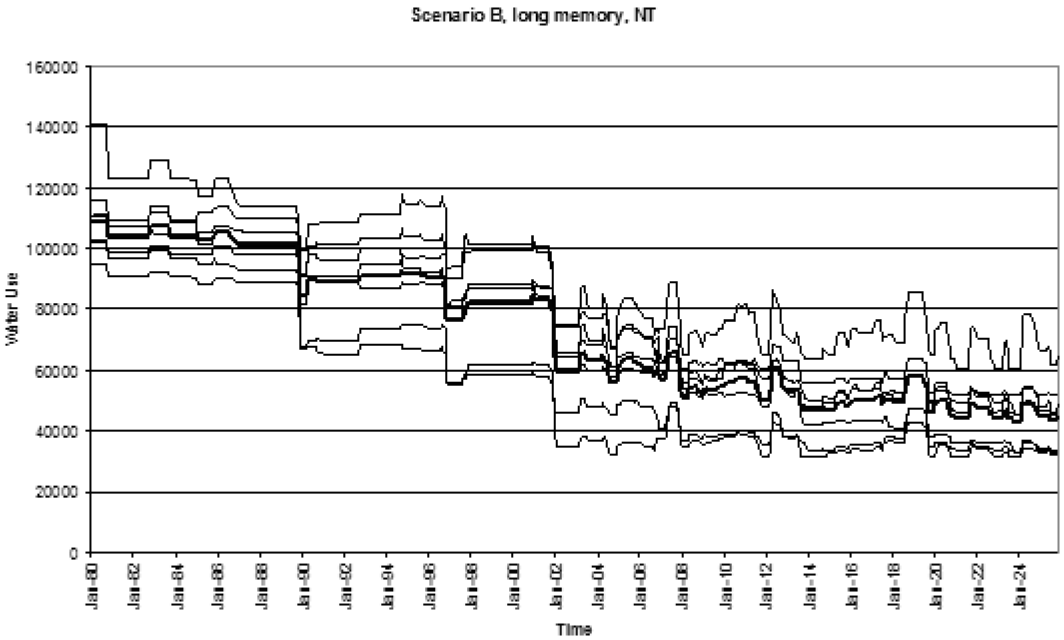

Figure 51: Scenario B, long memory, non-toroidal grid

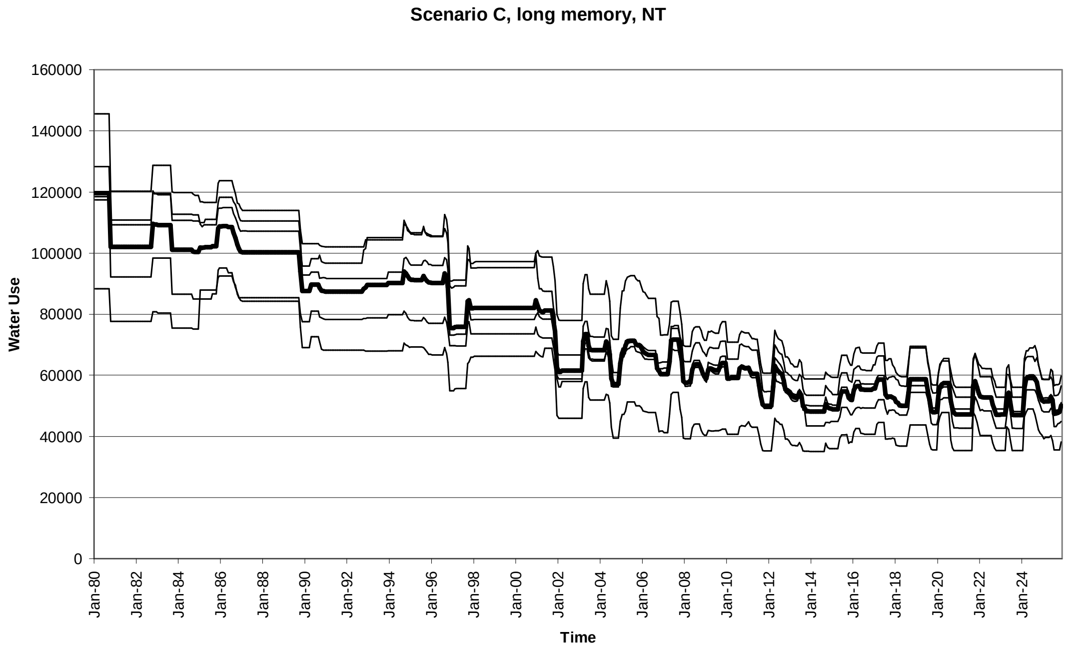

Figure 52: Scenario C, long memory, non-toroidal grid

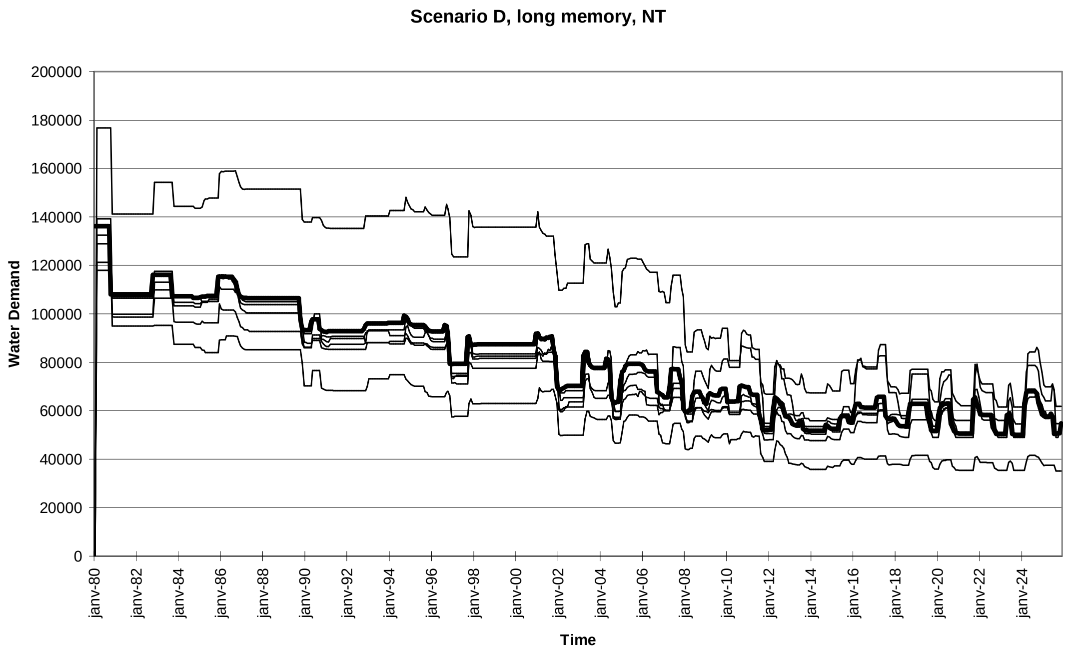

Figure 53: Scenario D, long memory, non-toroidal grid

One can compare the graphs above with the original ones from the four scenarios in section 5.2.2. The trends seem quite different as the better the memory (or the more the agents can remember) the more marked the decrease in water use over the period. The reason for this phenomenon is that they not only remember previous water use, but also previous drought periods when the policy agent was communicating on water use reductions.

Therefore memory allowing the agents to increase the amount of information available to them seems, in this particular case, to increase the decreasing trend of water consumption.

The explanation for this is that when remembering past uses, agents also remember past droughts, and their consequences. This seems consistent with a more sensible approach in the real world regarding the use of natural resources, as well as the building of a household's patterns of use from one year, or one season to another.

One could hence draw several conclusions from this change of behaviour as a consequence of a better memory.

The additional memory actually results in more information available to the agent. It could be argued that it is that additional information itself that drives the water consumption down, as this seems a behaviour that could be qualified of "reasonable" in the real world. Nevertheless, this relies on the assumption that increased information leads to the wisdom of reducing one's use, and also implies knowledge of (in this case) natural resources, as well as an awareness of at least financial and environmental issues.

This is obviously not the explanation for such a phenomenon. The actual reason for this trend is implied in the model itself. The memorable events are by definition of the memory algorithm those with the highest endorsement. At a time step corresponding to a normal (as opposed to drought) situation, the endorsements are regarding oneself, and the social environment. But at a time of drought, the endorsements also include those regarding the message broadcast by the policy agent. As there is a chance that this preached behaviour will be adopted, the actions / activities with lower water use will also be given endorsements from oneself, and the environment.

As the endorsements are superior in numbers, the chances that the values of the specific actions selected are higher increase. The consequence is that the memory of agents is likely to contain more patterns of low use at anytime and therefore is driving the overall consumption down.

It is worth considering that in a theoretical grid where no agent can see any other, this trend should happen anyway. The agents which are sensitive to the policy agent's message will decrease their water consumption while all others will only change as the replacement of old devices becomes a necessity.

Concluding this analysis, it is clear that the set up of a better memory has an impact upon the behaviour of the system. On a methodological side, this test showed that the implementation of an agent's memory is consistent with intuition and observation: more extreme events are likely to be remembered for longer than common ones, provided that the endorsement mechanism is set up appropriately. On a qualitative side, this demonstrates that the model tends to be built in such a way that the natural general tendency it demonstrates is a decreasing trend. The explanation for this lies in the fact that the only changes described in the Environment Agency's scenarios that do not depend upon the agent's own behaviour are embedded in the innovation and diffusion of new appliances.

A further analysis of this diffusion is the subject of the following section.

5.4 Detailed analysis of innovation diffusion

As detailed in chapter 3, for every household, appliances are available from the start of the simulation period. During the time interval, some become available to replace already present ones, or could emerge as new water use activities. At the same time, and to represent the assumptions about the changes of regulations, some appliances will not be available anymore for the households to replace or add to their endowments, as described in the first section of this chapter.

The process of adoption can then be, for increased convenience, presented as composed of several stages: observation, evaluation of current state, availability, endorsement, and decision.

In the observation stage, the agent gathers all the information regarding its environment, both geographical and social. The information collected refers to its own ownership and use of water, as well as its neighbours. It also refers to the situation of the neighbour with respect to his own characteristics, as to how similar they are in structure or pattern of use.

During the evaluation stage, the agent assesses whether any of its own appliances need replacing. First, a probability is used, taken from a Weibull distribution, which will determine if any appliance is broken. If it is not, then another probability is used to infer whether the agent has decided to replace the appliance anyway, as often people do not wait for appliances to break before they replace them, but do so at their will, for example for comfort or to update their installation.

If an appliance needs to (or is considered to) be replaced, the agent then checks which appliances are available on the market. The list of available appliances is updated every month, with new technologies or regulations having an immediate effect upon it. Once this list is known, the agent classifies the appliances into equivalent ones, *e.g.* considering all toilet-flushing technologies as responding to one particular activity. The list from which the agent will select its future appliances is therefore tailored to its current situation.

Every appliance is then endorsed. The agent gathers from its own observations some indication of who uses which technology, what is said about it, and how it is used. These qualitative assessments are transformed into a quantitative measure, which allows a direct comparison of appliances with each other (provided they are equivalent in the agent's activity list). The appliance with the higher endorsement is selected. Endorsements are described in a previous chapter, and are related to the product itself, to its users, and to the way they use it, as well as the way the observing agent can relate to the observed ones.

The way innovation is implemented in this model is not a typical use of the literature available (*e.g.* the implementation of a common diffusion process). It is drawn from observation, with properties of the process tailored for the representation of the model, and not implemented from a theory present in the general innovation diffusion literature.

Technologies in general have within the model, as in real life, three important stages in their lifecycle: their emergence, their diffusion, and their disappearance.

Emergence and disappearance, at least with respect to the availability to the households, are set exogenously, using specific variables. The diffusion itself is an endogenous process, based on endorsements of some components of the model by an agent, namely the other visible agents, their activities, and the policy agent.

In most innovation theories, the level of penetration follows an S-shaped curve with time, with the corresponding marginal adoption being a bell-shaped curve, as shown in chapter 3. The implementation of innovation in this case provides an opportunity to assess whether the process described would generate such shapes.

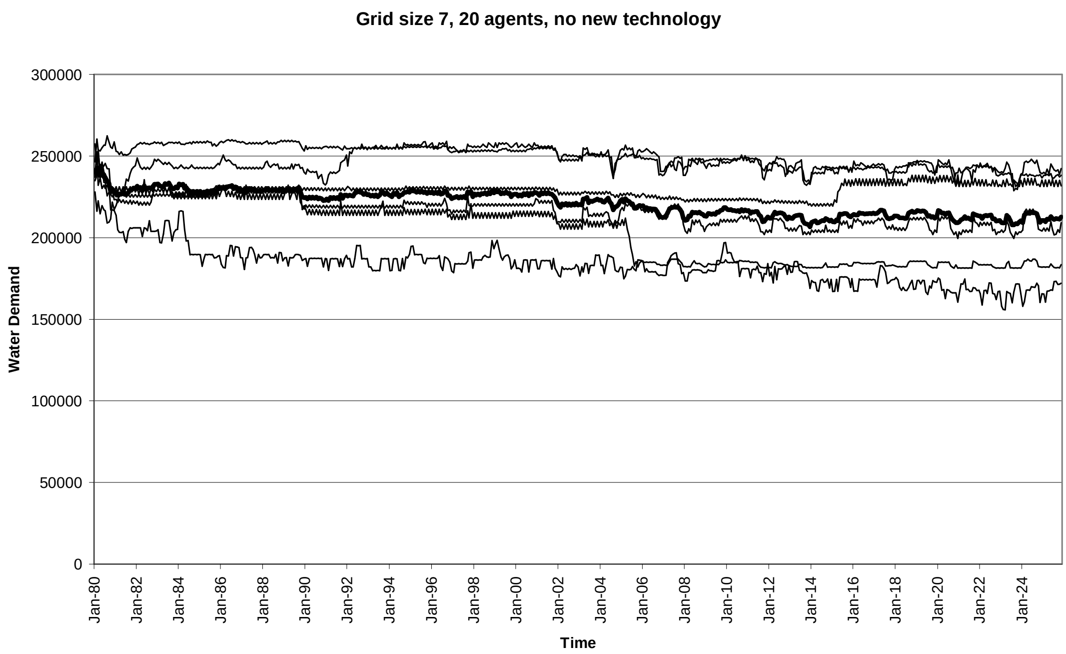

Figure 54: Scenario D, in the absence of new technologies

The graph below represents the diffusion of power showers in two runs with the parameters from the scenario delta.

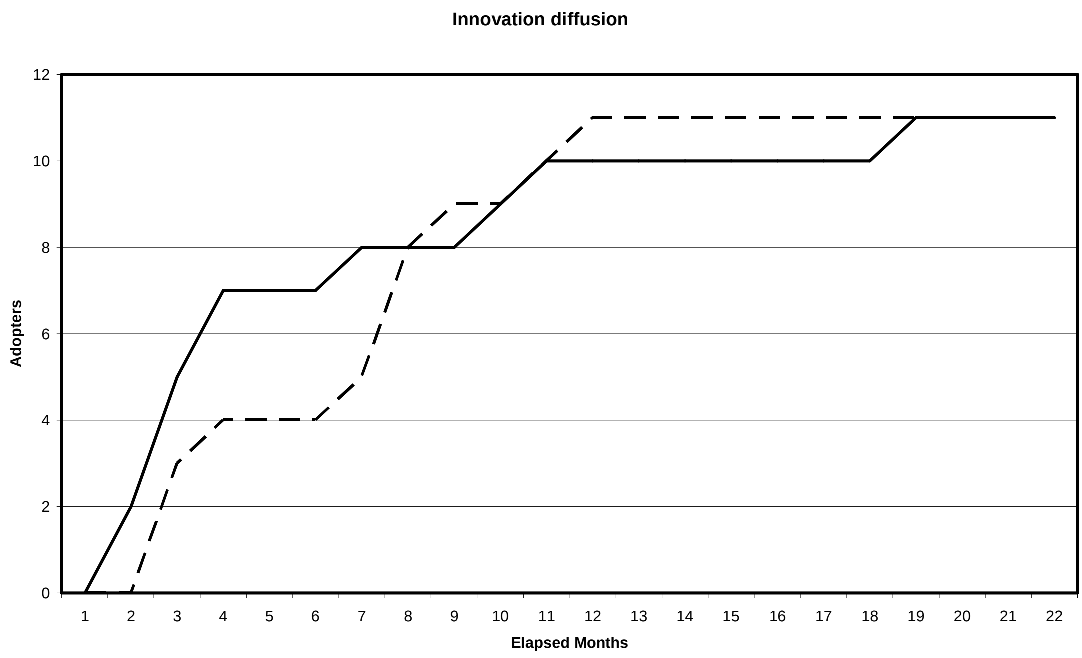

Figure 55: Diffusion of innovation

There are several patterns of diffusion that can be observed in a simulation, as shown in the graph above. While some can be considered as matching the sigmoid shape mentioned above, others show a rapid uptake that is difficult to consider equivalent.

As nearly all parameters are equivalent between simulations, the only justifications for this difference seem to be part of the network composed of the agents, and how linked they are.

The analysis of the network does not show any significant difference. The density of links is on average 5.5 per agent.

In the fifth run of scenario C, the adoption pattern for power showers is the most contradictory to a sigmoid. In this case, the network is composed of 9 cliques, which contain on average 4.11 agents.

For the first run of scenario C, which presents a pattern of adoption for power-showers which is sigmoid-shaped, there are also 9 cliques, but this time with an average size of 3.8 agents.

These kind of values seem to be consistently present when the density of agents and the size of the grid do not vary. Similar properties can be observed for the other runs: when the average size of the clique is low (around 3.8), the pattern observed is more similar to a sigmoid than when the value is high (4 and over).

Intuitively, one could assume that a lower average clique size, would limit the influence from the neighbours, and therefore allow for more innovative behaviour, due to the lower formal constraints upon the endorsements (as there are more households within an agent's neighbourhood, the absolute value the endorsement of a new appliance must reach gets higher).

Referring to scenario A, with agents that are relatively self centred, one could expect to observe agents less likely to be influenced by their immediate neighbourhood, and therefore a link between patterns of adoption and average clique size of the network that would not be as consistent. Unfortunately, the analysis of scenario A, in which the take up of new technologies is quite limited, does not confirm this hypothesis, as the main changes appear when appliances break and need to be replaced with their current equivalent, which is more water efficient and therefore reduces the water demand.

5.5 Detailed study of a particular set of runs

Some simulation results, although following standard rules, appear to generate extreme behaviours. The simple interactions in the model can lead to the adoption of very high or very low patterns, with no distinction. This certainly depends upon the randomisation system, as well as upon the initial values and attributes given to the households.

A representative example of such an extreme run is shown in the following diagram. The level reached for consumption is such that the other runs are not visible on a standard scale.

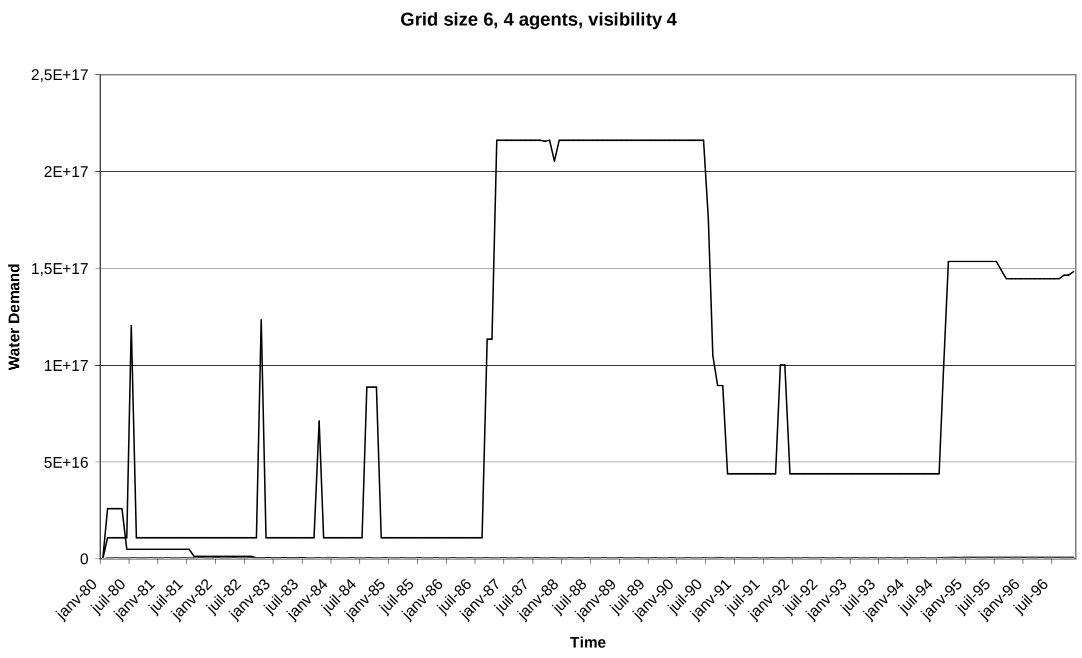

Figure 56: Standard scale representation of multiple simulation runs

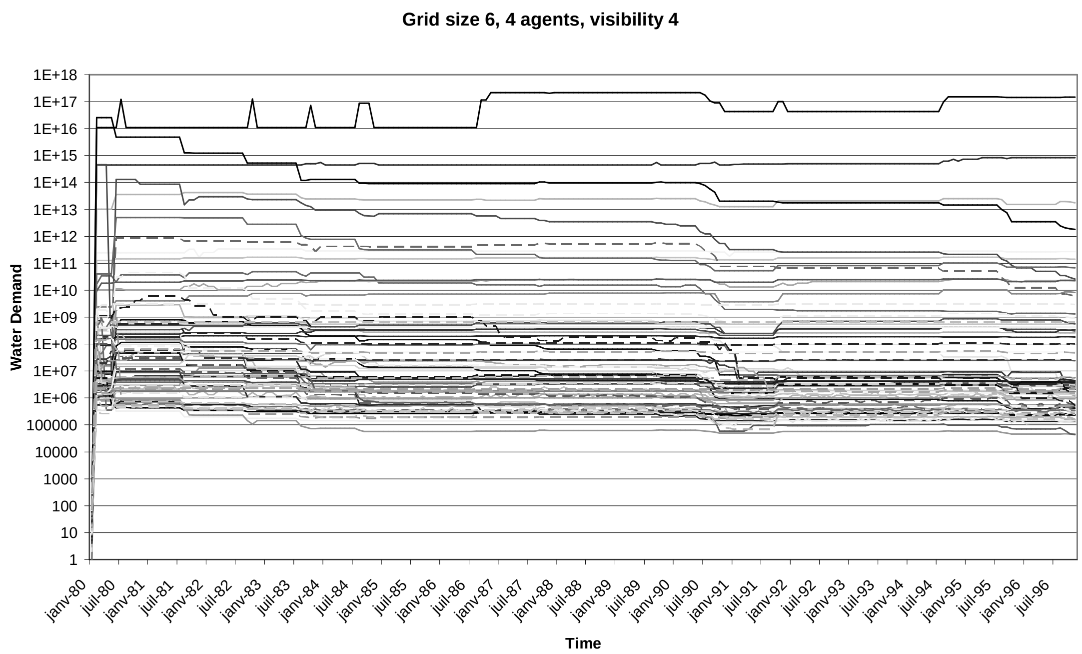

Figure 57: Logarithmic representation of multiple simulation runs

Only the transformation to a logarithmic scale allows the display of all the runs.

Obviously, the variations observed are well aligned within that set of runs, and referring to the external data that are input to the model shows the correlation for some of them. It is therefore worth remembering the global drought duration associated with this set of climatic data, and more precisely, stripping the data to the relevant timescale gives us the following.

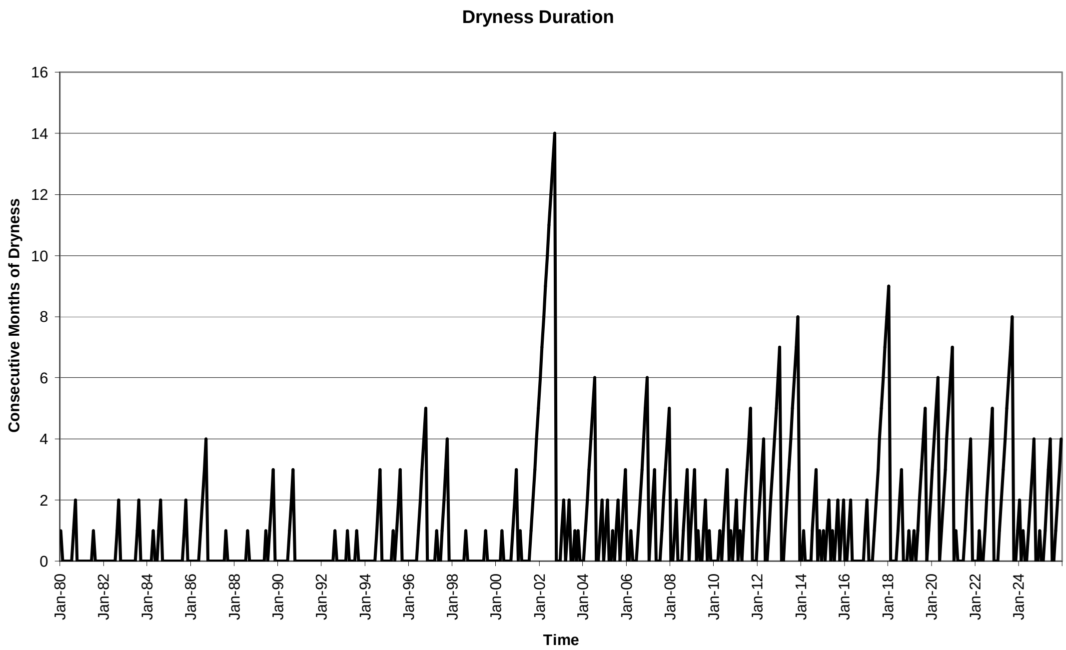

Figure 58: Dryness duration

Integrating the charts together one obtains:

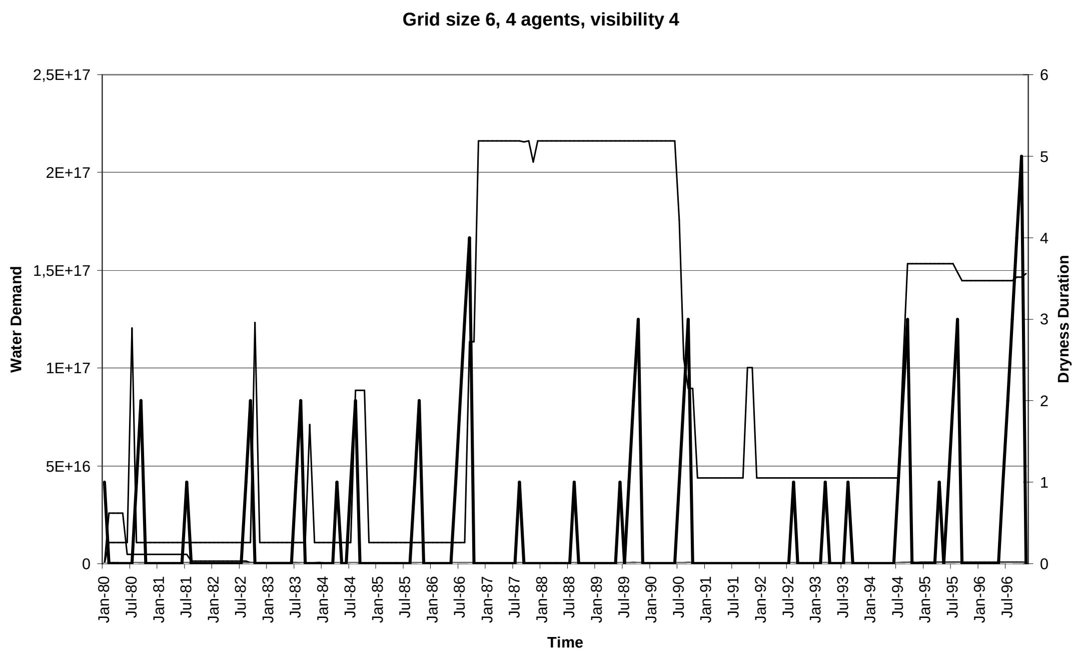

Figure 59: Multiple simulation runs and drought duration

One could expect that the effect of drought would drive consumption down. The matching of these visual indications reveals that the reaction to an exhortation from the policy agent is not always producing the expected effect. Only the major drought period lasting for 9 months in 1991 had an important and significant effect upon the water consumption. The other drought events do not seem to have any effect.

This demonstrates that either the behaviour of the agents is not implemented properly, or that there are other method related issues.

Although this behaviour does not seem to affect the vast majority of the runs, it requires investigation to understand what the cause of such variance within the simulations is.

The detailed study of this run shows exactly what is happening. As expressed in the description of the model, the policy agent uses a kind of average of the observed frequency and volume data from the households. Due to the initial conditions, the policy agent could then be biased by some extreme randomised value for the households.

It would therefore broadcast a message that would lead households to adapt by using patterns whose recommended values are higher than those in use by the households themselves.

5.6 Conclusion

This chapter is intended to provide simulation results for every scenario and a comparison amongst them. It is also intended to investigate the effects of parameters or structural changes upon the stability of the result.

Section 5.2 contained the detailed transcription and set-up of the different scenarios used by the Environment Agency. It also describes and justifies the values selected for the structure of the population for a set of simulations. It includes a detailed study of runs for each of the scenarios and is accompanied by a brief presentation of the results, both qualitatively and quantitatively. The quantitative analysis particularly demonstrates that the simulated data does not comply with the frequently encountered normality assumption.

Section 5.3 focuses upon the sensitivity of the model to some of its components. As Multi Agent Systems have been used after acknowledging the presence of complexity, and concluding that standard techniques presented limitations that made them impossible to use, this section presents a particular analysis of the sensitivity of the model. There were no thresholds to analyse, or derivatives to calculate. So in order to assess which changes they might induce, this section also includes an investigation of the effect of variations of parameters (or algorithms) associated to components deemed of importance.

Section 5.4 provides a detailed analysis of how innovation spread amongst the agents. The innovation diffusion relies upon a representation based on observation and evidence, and for which different tools such as endorsements have been used. The conjunction of endorsements as a means to evaluate subjectively another agent’s activities and a social location via grid coordinates is not present in the current literature. The first tests have demonstrated that it can represent correctly a process of innovation diffusion, as the discrete graph presented can be compared with a standard sigmoid generally observed.

In section 5.5 is an example of particular runs, providing the reason behind the emergence of extreme patterns, which contradict initial beliefs.

The next chapter will detail how these findings can be used, and their validity, as well as the opinions of the Environment Agency on the impact of this type of modelling, in the perspective of forecasting.

6 Discussion

6.1 Introduction

This final chapter presents some conclusions and remarks related to this work, as well as expectations both from the model and from the Environment Agency.

The first part addresses issues of validation and targets of the model. It is followed by remarks on assumptions or limitations of that model. Then the Environment Agency's own aims with the generation of the scenarios, and views upon this work are presented. Finally, the question of validation and consistency of scenarios is answered.

6.2 Aspects of scenarios

6.2.1 The conclusions of scenarios: figures of water demand

The scenarios and their associated assumptions were expected to result in multiple but typical water demand patterns. A representation of these patterns can be used in order to assess the differences specific assumptions and components bring to the values and changes in water demand from the agents.

As developed in section 5.2.2, individual runs for every scenario show significant differences. The complete set of runs for one scenario therefore creates an actual envelope for possible paths and / or values for the corresponding water demand. Due to the limitations of the method employed, mostly practical regarding processing power and timescale, the envelope is practical, and not theoretical. In theory it is possible that all scenarios actually have equal and very large envelopes. This would greatly reduce the information contained in the description of such an envelope.

In order to describe the evolution of water demand in different simulations, the indicator used and displayed in graphs is the average of water demand across the various runs with one particular set of parameters. Another relevant indicator could have been the median value. The graph below shows the average and median values for four different sets of parameters.

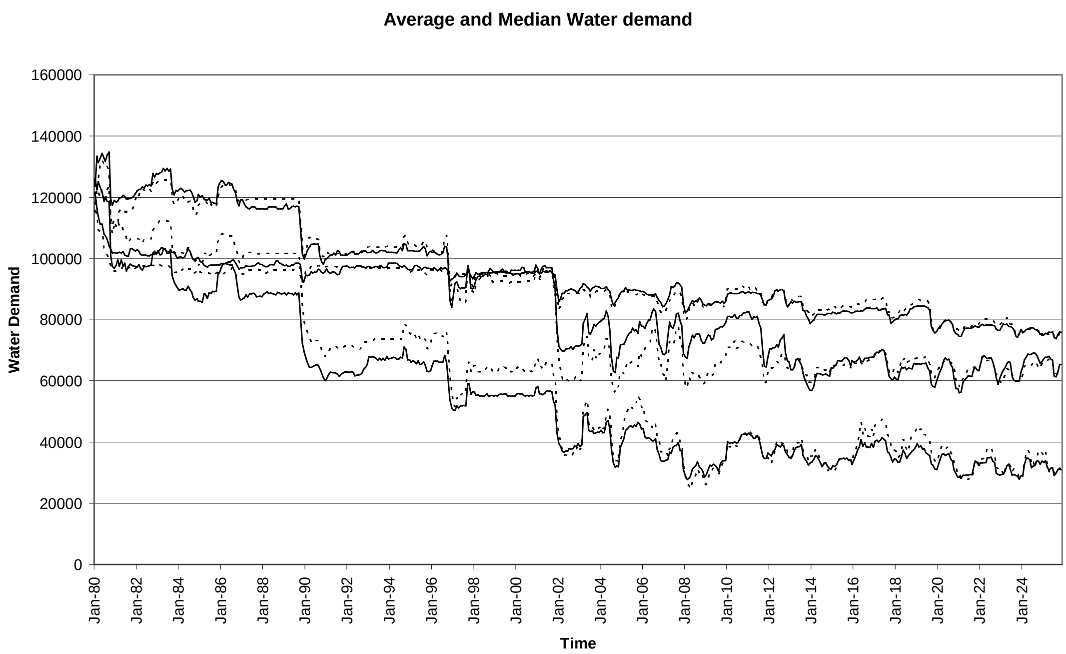

Figure 60: Average and Median Water Demand

Although there are differences, they are minimal when the simulation does not feature extreme values. Therefore in the absence of salient negative aspects of any of these two measures, the average is used, due to ease of computation.

The graph below represents averages of 10 runs for every scenario.

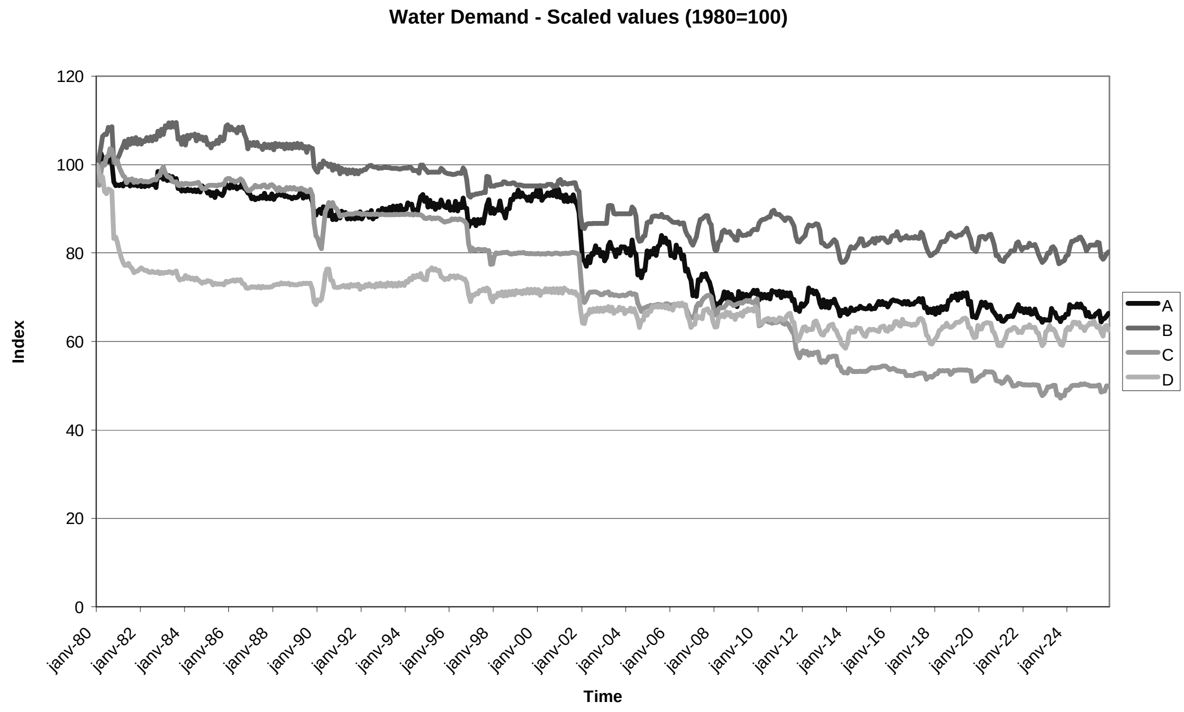

Figure 61: Results for each scenario – Scaled values

While one might argue that this is not representative enough to draw any conclusions on statistical grounds, the characteristics of scenarios seem clear enough.

Scenario A, provincial enterprise, shows a reduction of 33% in global demand. This decrease is partly explained by the sharp drops in 2001 and 2007, while during the other periods, the decrease seems much slower, although present.

Scenario B, world markets, remains the highest at all times. The decrease is also marked and reaches about 20% in total over the period. While the 2001 sharp drop is visible, the effects of other climatic changes are not long term ones, apart maybe from the one in October 1989. This scenario remains the one displaying the highest volatility in the evolution of global water demand.

Scenario C, global sustainability, shows a reduction of about 50% in water demand. This is consistent with the assumptions made regarding the commitment of institutions to research and development of innovative clean technologies. The decrease is steady, with sharper drops in 1997, 2001, and 2010-2012. It is worth noticing that the 1990 decrease has only been observed in the short term. This could indicate that while such a policy could work, the current technological progress alone might not suffice to achieve the expected decrease in water consumption.

Scenario D, local stewardship, also presents a decrease of about 38% in global demand. Nevertheless, most of this decrease (equivalent to a 25% drop) is between 1980 and 1982, with only a further 13% from 1982 to 2025. The 2001 drop equates to roughly a quarter of this reduction, and scenarios A and D reach the same level. Towards the end of the simulation, it seems that even scenario A results in lower demand than scenario D. These results seem to confirm that the major component of the reduction in this model remains the technological change. Scenario D is comparable to scenario C in its initial assumptions, but the regionalisation it considers removes the emphasis scenario C made on innovation.

6.2.2 The different ranges of figures inter scenarios

If one intends to draw conclusions at the aggregate level for specific scenarios, it is necessary to make sure of their validity. One of the conditions for validation of statistical results is that the sensitivity of these results is such that they cannot be mistaken for a standard error or somehow unrelated variations.

One might have assumed that the changes within scenarios could have provided some useful insight on the different influences and their combination. The situation is not so. By comparing the standard deviation intra-scenarios with the standard deviation inter-scenarios, it is unclear whether this model can be used as a tool for answering this question.

Based on averages of runs, the dispersion for every scenario is calculated via the inter quartile range. Results are as follows:

Scenario	Inter quartile range
A	29025
B	22426
C	40618
D	11908

Table 25: Dispersion per set of scenario simulations

It is visible from Figure 61 displayed above that scenarios A and B present similar patterns, despite differences in the levels of demand obtained. The statistics confirm this parallel. The confidence interval and standard deviation, while providing results in line with the inter quartile range, are not provided because as expressed earlier, the underlying distribution could have undefined moments.

Scenarios C and D are opposite, with C being the most variable, while D is the most stable. This high variability of scenario C partly describes the fact that it is the scenario achieving better savings, while the steadiness of scenario D is confirmed once again here.

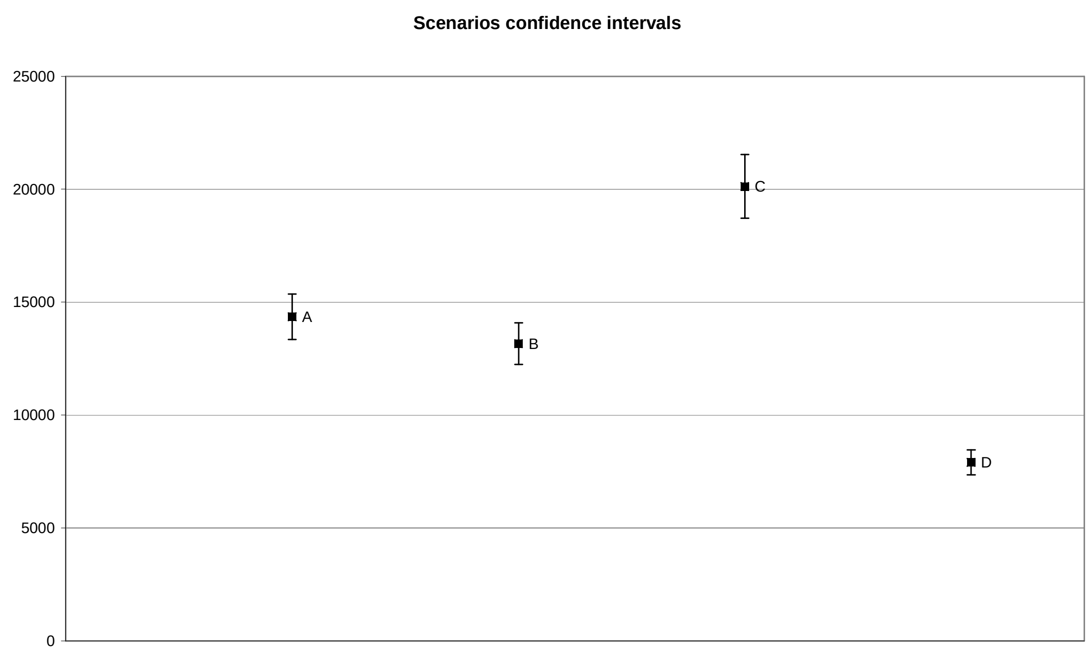

Figure 62: Scenario confidence intervals

6.3 *Remarks*

6.3.1 The miscellaneous component and its elements

Section 5.2 describes the reason why the nature of the object and the nature of the tool sometimes do not match and cause a flaw in the representation. It is not common when a tool points out the exact nature of the modelling problem and a clear expression of the tool's own limitations. It is a rare occasion where the tools actually help pointing out the difference in knowledge regarding the various components that can be identified as generating water use.

All common uses of water are accounted for by a microcomponent analysis. A household penetration of a few per cent is generally sufficient for the appliance to be included in the list to be considered. Water softeners and the appearance of "total showers" provide a recent example of such flexibility. As it is based on observation, mainly through surveys undertaken by regulators or undertakers, it picks up unlisted appliances as soon as they take a significant part of water use.

Miscellaneous uses include unidentified appliances, as well as already identified appliances that are linked with uncommon uses. For example, home based medical equipment resulting in a significant use of water is qualified as "miscellaneous". Similarly, as "miscellaneous" is the categorisation of unknown use from the supplier's point of view, it includes uses that are not authorised for the customer. An undeclared hairdressing activity in the house would significantly increase tap water use. The supplier, assuming a standard pattern of use, would estimate a reasonable use according to the social and physical characteristics of the household. The fact that they would be incorrect generates a discrepancy between the estimate and reality. This in turn causes the miscellaneous use component to increase.

A typical example of a common appliance filling an unusual function is provided in Jenking (1973) following the 1967-72 metering programme. The 400 properties were checked for leaks and other water supply issues before the demand became monitored. A specific house showed a large increase in water use overnight, resulting in technical teams looking for leaks. When they could not find any, the investigation started focusing on legitimate uses of water. They then discovered "the bath full of water, the cold tap and the overflow running merrily and a number of trout swimming around the bath with apparent contentment.” (Herrington 1996, p.237)

Hence, the nature of miscellaneous use makes it not only difficult to specify, but also difficult to represent as a generic component whose characteristics evolve with time.

A solution has been to distinguish amongst the miscellaneous uses and categorise them further according to the way this evolution takes place, resulting in three equal elements.

The first remains constant per capita.

The second remains constant per household.

The third varies at the same proportional rate as the total of the identified components.

The combination of these elements results in an implementation of the following type:

$$\text{Miscellaneous} = N \times [f1\ (Pcc) + f2\ (H) + f3\ (d(IMC)/d(t))]$$

where

H = number of households considered,

Pcc = average Per Capita Consumption in the sample considered

IMC = Identified Micro Components

t = time

Despite what might seem a convenient way to represent miscellaneous use, it is not included in the model described in this research. It is obvious that the formula above only provides clues concerning what miscellaneous use actually is, and what an estimate of it could be, based on related indexes. This is a statistical approach, whose field of application is too restricted to be used in this work, as expressed in chapter 2.

6.3.2 The static population

The agents in the model are situated, and their behaviour is defined according to rules set by the modeller / user. An important difference between the assumptions made by the Environment Agency and its implementation in this Multi Agent System is the static population.

Not only does it not evolve with time, it also does not move around on the grid. While the grid is not a geographic representation, one could observe that there is evolution even within the individuals' social "sphere".

There are practical reasons for this situation. The most immediate is one of coding difficulties. This covers several aspects. First, as every agent has a memory, via endorsements, of its environment, the calculations and computer memory space would have been much greater[20]. Second, the algorithm itself of how this evolution takes place would have to be devised, and to be as representative as possible, would require the inclusion of many more variables or assumptions, such as financial, familial or employment status. The scope of the research needed to be constrained by the goals set. Implementation difficulties are not an issue that should force a choice of model, assumptions or techniques. In the present case, one objective has clearly been set as interpreting and validating the model results.

As the model grows, and as the number of parameters and variables increase, the possibility to isolate, or identify phenomena and components of their causes reduces.

By implementing what some could consider to be more detailed behaviours for a society, Multi Agent Systems lose one of the very assets that resulted in their selection for the current model: the possibility to relate every rule to an observable and justifiable behaviour (if possible objective) for actual human societies.

The validation of behaviours and representation of models has been targeted for all components of the Multi Agent System. Including more (but uncertain) details and / or components would go against this aim.

[20] For information, in the final version of the model, simulations took several days, and results were stored in hundreds-of-megabytes-files.

In addition, the population projections themselves are fluctuating every year, as the changes in every census demonstrate. This further reduces the possibility to validate any result obtained from a simulation.

The Environment Agency used a very simple growth assumption in the scenarios, a linear increase of the population. This was the aggregation of data available from the companies' water resources plans, mostly using linear trends for simplicity.

6.4 Use and limitations of scenarios

Used with scenarios, MAS can be a powerful tool. This research demonstrates that pre-existing scenarios can be assessed with ABSS. Due to the nature of MAS, the main interest is in applications that are related to social phenomena. The variety of entities that one needs to consider, together with the potential complexity that might result are difficulties many modelling tools cannot overcome, unlike MAS.

The use of MAS with scenarios presents advantages:

- MAS will help fin possible conflicts within the scenario.

By implementing scenarios using a Multi Agent System, one has a possibility, with tools such as SDML, to use these as a way to detect whether all assumptions are consistent with each other. This can be either in the process of writing the formal model itself, or thanks to automatic verification procedures that might be built in the tool used.

- MAS will help assess drivers, influence and sensitivity

As a Multi Agent System needs to make explicit the status and role of agents (or stakeholders), as well as the processes involved in the model, all observed results can be tracked back to which element(s) is (are) responsible for a particular behaviour.

There are other challenges with Multi Agent Systems.

- computational issues, possibly a trade off between quantity and quality of information

Depending on the software one uses to build a model, and the available processing power, there is a possibility that the resulting model could so slow to run that it would not be practical. In order to keep simulation speed reasonable, it might be necessary to use fewer agents, or a simplified representation, with less rules. Ongoing improvements in computing technology will certainly help in overcoming this hurdle.

- MAS helps directing questions

Where an agent or a behaviour to represent in not immediately obvious, MAS help in focusing on what information is required: what is the nature of the agent, or what are its relations with the others / its environment, how does it perceive its environment, and in which way does it react to it, considering its aims, etc. Rather than describing a system as a whole, a multi agent based model requires a clear understanding of the elements of the system, and how they interact together. It is frequently while trying to provide this information that the lack of knowledge results in critical assumptions, or further, more focused, research.

As a consequence, Multi Agent Systems are currently an interesting prospect, already used in many fields. Evidently there is potential for expansion, as likely successes will get researcher's attention.

With the development of Multi Agent Systems, their use in representing scenarios is likely to become more widespread. Because of (or thanks to) the capability of MAS to deal with multiple levels of detail, from micro to macro components of a model, more research might be undertaken regarding the basic principles models of artificial societies are built upon.

Cognition, evaluation, subjectivity are some of many abstract concepts that are going to be investigated. Many alternative ways of implementing these will emerge, some certainly being better than others. They will all provide a better understanding, and a more accurate representation of basic processes.

One can consider that scenarios use a top down approach because they cannot manage otherwise.

Scenario forecasts will benefit from these improvements. Scenarios are currently imagined, or considered as the consequences of specific phenomena for a given set of relatively high level assumptions. In the current example, the main drivers are described as social values and governance structure. The corresponding scenarios require that experts translate this global situation into what would be equivalent beliefs for agents at a micro level.

By improving the representation of agents and their basic processes, it will become possible to devise scenarios via a bottom up rather than the current top down approach. The consistency of assumptions both at micro and macro level will become easier to compare and put to the test.

6.5 The future of Environment Agency scenarios

The second part of the discussion with Rob Westcott addressed the links between this research and the Environment Agency's own vision of scenarios.

The scenarios were generated in order to "*test how likely a set of objectives may succeed in different political, social, technological, environmental climates but they cannot readily predict the level of success under a specific set of circumstances, e.g. current perceptions, prejudice, infrastructure, governance, attitudes, etc. This would need a new scenario each time."*

Well aware of limitations of their approach, they wanted to "*allow time to adapt, scenarios' effects were delayed to 2010 generally".*

When asked to comment on this research, and whether they had particular expectations from these simulations, they replied they would look for *"an indication of more likely/less likely responses to a set of assumptions."* They are adamant that they do not want these simulations to investigate the likeliness of any specific scenario since, as they put it, "*No probability could be attached to Agency's scenarios."*

They envisage that this type of research and simulations could become useful to the industry, the regulators, or more globally institutions, fulfilling different aims: first at a generalised strategy / overview level, assessing complete sets of assumptions, consistency of hypothesis, or estimation of consequences; but also at a more detailed level, to "*test very specific responses to a single initiative.*"

Enquiring as to whether the scenario assumptions could be validated or invalidated by such simulations, the answer became more pragmatic. Their opinion was that neither was possible, "*as no one scenario will apply.*"

Nevertheless, discussing further, they agreed with the potential of simulations as a means to evaluate individual, specific relationships and assumptions regarding the consequences of policies or regulations, provided they are represented properly. The simplicity and accuracy of modelling that should be reached before this is possible is however an issue, and they are aware of this challenge, as it is according to them *"Impossible to validate whether an outcome is a consequence of competing traits, a coincidence or whether the "scale" issue is the cause."*

By "scale" they mean the size and complexity of the system, rather than only the size of a grid, or number of agents, and it is difficult to disagree with this, given the current state of knowledge.

Globally, the Environment Agency could appreciate the potential of social simulations and Multi Agent Systems. The emphasis on processes and the virtual indifference to geographical scale (but not its complexity) led them to consider this method when devising their next project addressing water demand forecasting issues. In particular its relevance was accepted for appraising the potential impacts of policies affecting behavioural changes.

6.6 Last words on scenarios

The subject of the modelling is the scenarios presented by the Environment Agency. The implementation of these scenarios has been undertaken as scrupulously as possible, and results have been analysed.

This research is not trying to assess which scenario is the best according to some targets, be they environmental or political or other. All scenarios have been modelled with equal care and method so the validation is not trying to assess which one has been implemented best.

The validity of a model depends on what the aim of the model itself is. This aim provides guidelines on whether the abstract model and its representation are consistent with the issue addressed. Therefore consistency has been leading the progress of this work. In chapter one and two, water demand and different modelling methods have been presented. The selection of tools such as Multi Agent Systems and object oriented social simulations was the result of their strength and the fact that they are appropriate for dealing with the issues raised.

It is not easy to find criteria that can be used for the assessment of a model that is representing social phenomenon. In hard sciences, where equations can be used to accurately represent the system observed, one way to judge a model, is to rely on its capacity to reproduce specific observed results, or to infer from its results, obtaining validation of the model via realisation of its prediction(s). A typical example for such a validation is the analysis of the trajectory of planets, and the discovery of Neptune at the location and time where the theory developed predicted there would be a planet.

The ease of proof and absence of ambiguity in this case are not valid for all sciences, especially not social sciences. Due to the doubtful representation of cognition and reflection, amongst other processes, the phenomena themselves that result from these are very difficult to take as an absolute benchmark for the model.

This is why the assessment is not going to be focusing on the results (although they can certainly be part of it), but mostly on the processes involved in the modelling. In the end, it all comes down to an evaluation of the representation as an example of best practice.

As expressed in chapter 3, Edmonds (2000) suggested that models should be judged according to process criteria for the modelling steps. The following list presents a selection of these:

1. Abstraction: is it specified?
2. Design: is it clear how the design relates to the abstraction?
3. Inference: is the inference of outcomes sound?
4. Analysis: is the analysis clear?

5. Interpretation: is the interpretation justified and relevant?
6. Application: are the conclusions in terms of the target systems justified?

The following paragraphs will argue that these criteria have been fulfilled.

The abstraction has been specified in chapters 4 and 5, demonstrating the structure and algorithms later implemented in the formal model. The limits of the phenomenon covered are also described, explaining earlier why some aspects such as the financial situation of a household are not taken into account.

The reasons for the design are provided in chapter 3, where the modelling principles used are presented, and as explained, the consistency testing of the scenarios devised by the Environment Agency, used with necessary stages of reverse engineering, help insure the link between the abstraction and its implementation.

In the previous chapter, the outputs of the model are presented according to the set of assumptions used. While these are benchmarks for the analysis, the stability results themselves are investigated when specific parameter values or phenomenon are put under scrutiny.

The analysis then undertaken assessing the differences between simulations of scenarios and how well they match the description of the scenarios from the Environment Agency is presented.

The interpretation of the results from this research is provided, from a quantitative point of view by statistical tests, as well as qualitatively via an interview with Rob Westcott.

In the end, the conclusion is that it is not unreasonable to consider the scenarios as distinct, plausible and consistent. Nevertheless, the quantitative aspects have not been, for reasons already provided, validated via the simulations in the current model.

6.7 Conclusion

Section 6.2 presented the different aspects of the results, first for each scenario individually, then comparing them. Figures of water demand were characteristic for each scenario, with the apparent confirmation that technological change is the most important parameter to explain decreasing water demand. The analysis of confidence intervals confirms the similarities between A and B, as well as the differences between C and D.

Section 6.3 emphasizes the fact that the model does not include all the characteristics presented in the original scenarios. A steady population and the absence of the miscellaneous component due to the inadequacy of such a catch-all concept in an agent based system could be the main reasons for not obtaining results closer to the Agency's.

Section 6.5 explained that discussion with the Environment Agency showed they appreciated the potential of social simulations and Multi Agent Systems. The emphasis on processes and the virtual indifference to geographical scale (but not its complexity) led them to consider this method when devising their next project addressing water demand forecasting issues. In particular its relevance was accepted for appraising the potential impacts of policies affecting behavioural changes

Section 6.6 provides an answer to the question whether the scenarios described by the Environment Agency are consistent and can be validated. The simulations undertaken during the course of this research seem to corroborate if not the absolute figures, at least the global trends considered by the Environment Agency.

7 Conclusion

This research intends to demonstrate the utility of modelling for assessing assumptions made regarding social phenomenon. The case selected involves using Multi Agent Systems in social simulations to represent and analyse the water demand forecasts developed by the Environment Agency using scenarios.

The conclusion of the study has been discussed with the Environment Agency, which concurs with the method and results developed in the previous chapters. In order to generate the arguments for this discussion, the research followed logical steps, each presenting challenges or technical findings.

Chapter 2 presents the point of view that demand management is useful to tackle the challenges of maintaining sufficient headroom. But demand management is not necessary. It can be overlooked, as it is only considered as part of a range of options to keep sufficient water supply.

This chapter provides several examples of how countries have been using and researching water demand management. These countries often are in a different position to the UK, or so people think. Rainfall and therefore water resources in the UK are not as high as one might think. Despite spells of floods, one can likely remember the drought warnings, and dry summers experienced in the UK (in recent years, 1995 and 1977 stand out). Some regions are hit more than others. With the issue of sustainable communities arising, the management of scarce resources such as water appears more and more in the media. As it has been advertised, the population density in South East England linked with low precipitation makes it a region relatively dryer than Spain, and than some African countries.

This justifies the interest in understanding water use and its components. It is currently too costly, or simply not possible to increase water supply. In order to help achieve a balance between supply and demand for water, government and institutions turn towards the study of water demand and water demand management (amongst other aspects). This equilibrium (or more likely inequality) is sought for the current situation, as well as the next 10 or 20 years.

Simultaneously with this growing interest, advances in electronics and computing have led to the development and diffusion of new processing tools and modelling techniques, one of them being computer simulations. An analysis of the system involved showed that it had characteristics that made it unsuitable for commonly used statistical tools.

There are phenomena in the sample, such as the presence of positive kurtosis and multiple interactions amongst households with subjective beliefs. The observations gained from the phenomena also display the property of what has been defined as Self Organised Criticality. This consequence of these phenomena and properties is the presence of complexity, which restricts the potential tools to tackle the representation of this system.

Chapter 3 proposes Multi Agent Systems as a solution to these difficulties. It provides details of the nature of Multi Agent Systems, and explains why they are an appropriate tool for modelling such phenomena as presented in the previous chapter. This chapter then describes modelling processes and the different ways they can be used.

Starting with the problems related to the representation of a range of social phenomena, the chapter also presents the different techniques that can be used. These can be mainly separated into qualitative and quantitative approaches. Presenting the bases of Multi Agent Systems introduces an approach that does not need to be restricted to this dichotomy. Also providing a few thoughts on integrated assessment and advantages and constraints of stakeholder participation, this chapter ends with the details of the necessary tools used in the modelling, with a focus on SDML.

Chapter 4 presents details of the scenarios devised by the Environment Agency as an example to demonstrate the suitability of Multi Agent Systems. The chapter begins with the introduction and analysis of the scenarios developed by the Environment Agency, and what particular assumptions they include. From these are devised principles, model assumptions and algorithms, which are then detailed. While the representation of innovation and innovation diffusion is treated separately, overall model details and important assumptions follow, addressing more general characteristics of the model. The various outputs and inputs to the model that result from these choices are then explicitly listed. First the components of the model are described, according to the characteristics and properties of the Agents, the Environment, the Interactions, and the Organisation. The model structure and sequence provides at the end of the chapter the global vision to tie the components together.

Chapter 5 contains the simulation results and the sensitivity analysis of these results. Following the presentation of the theoretical model, this chapter focuses on the model itself and the results of the simulation runs. Introducing the specific details and values that are integrated into every scenario, simulations corresponding to a scenario are presented. The analysis of results for every one of them demonstrates that the characteristics which invalidated the use of common techniques are still present. It also shows that every scenario yields a different output, and different evolution of water demand. This chapter also includes specific analysis of different variables of the model (the grid structure, the agent density, the vision range, the memory), and the study of the diffusion of innovation. The latter is found to be linked with some characteristics of the network's structure, and the overall impact of the previous properties or values can be considered as significant but moderate in this case, since only the combination of extreme cases would result in important differences in the outputs of simulations.

Chapter 6 concludes with a discussion on the findings regarding different aspects of scenarios and the Environment Agency's view of this research. The outputs of every scenario are analysed, comparing the evolution of water demand in the scenarios, but not the absolute levels. Scenario A, provincial enterprise, shows a reduction of 33% in global demand, with a slow decrease from 2007. Scenario B, world markets, remains the highest at all times with a marked decrease of about 20% in total over the period. This scenario remains the one displaying the highest volatility in the evolution of global water demand. Scenario C, global sustainability, shows a reduction of about 50% in water demand, consistent with the presence of innovative clean technologies. Scenario D, local stewardship, presents a decrease of about 38% in global demand but it seems that towards the end of the simulation, even scenario A shows a lower demand, which seem to confirm that the major component of the reduction in this model remains the technological change. This analysis points to the impacts of the assumptions upon the overall result of the simulation and demonstrates that the differences in these assumptions generate significantly different outputs.

Concluding remarks help understand the extent of the analysis, and its limits. There are characteristics of the model that do not cover all situations. An example is given with the miscellaneous component. The nature of the modelling and the nature of the miscellaneous uses are not compatible, but this is an issue only if one expects absolute results from this model. The fact that the population is static is another significant and immediate limit of the model. This is an aspect that the research could focus on in the near future.

An overview follows of the discussion that took place with the Environment Agency. They have shown a lot of interest in this research, when the results have been presented. They confirmed that their understanding and use of scenarios have been correctly interpreted, and that the scope of this type of modelling would be suitable, and could be considered, for their next set of strategic forecasts.

Ultimately, the results obtained allow concluding that the scenarios devised by the Environment Agency are consistent, and that the behaviour they exhibit seems reasonable at a global level.

In the eventuality of further development of this particular model for scientific purposes there are aspects of the model that could be addressed. It would be difficult to include the miscellaneous use, as this is a conceptual issue, at least with this type of modelling. But other parts of the model could be improved with additional research. Computational limitations can be tackled in at least two ways: first with a "natural" improvement of computer hardware and processing power; and second optimising the code or its compilation (including changing to a different language altogether). There are probably multiple ways to undertake the latter, and the processing power freed by such modifications could help either multiply the runs, or increase the level of detail taken into account.

The limits of the model's focus have been set at the beginning of this thesis, and it is unclear whether these can be removed. For example, including explicit financial aspects would require a much more complex model, and an enormous amount of information would need to be collected. But despite the difficulty, this might be one of the most immediate challenges to tackle. The current situation is that on average 75% of the households in England and Wales are charged a flat fee for their water use. This is changing with more and more companies amending their policies, and imposing a metered supply to households, according to specific criteria (new homes and change of occupancy being the most frequent).

On the other hand, there are some changes that could improve the details of the model without this type of burden. This is the case, for example, of family structure. One could decide to include the details of occupancy of households, as well as the characteristics of the occupants. This involves additional challenges regarding time in the model as the agents representing the people would age. It would therefore be necessary to include birth rates and death rates as part of the population management module or rules.

Increasing the number of appliances taken into account will be possible as they develop and become a part of the regular reports from water companies. This involves appliances and devices that were previously classified as miscellaneous uses, such as water softeners, or the use of rainwater harvesting systems (for example water butts) for external uses. Water softeners have a negligible impact on a household demand, and are more of an issue for the companies that are trying to assess what the minimum demand is. But rainwater harvesting systems are becoming more common, and with an increased metering penetration, some households start looking for substitutions for the public water supply. Such systems, when fitted, can replace up to 30% of all water used. This is significant and needs to be included in the reflection on the next development stages.

Another improvement would be to include not only characteristics of appliances for a household, but number of rooms. There is a statistically significant effect of the number of bathrooms upon the water demand for a household. A Multi Agent System, probably in cooperation with specific qualitative analyses, would be an ideal tool to try and address the reasons for this effect.

Finally, as an investigation of the structure of the model was undertaken, one could wonder whether a totally different form of communication between agents could be used. Based on a grid, the communication of agents depends on their location and their vision range, as well as on the algorithms used to represent the communication process. The impact of characteristics of the grid such as its size, shape, or dimensions needs to be examined in detail, to avoid building a model whose structure could have more influence on the result than the values of the variables and parameters used.

A solution to avoid the issue of location on a grid is to discard the concept, and use other means to link agents together. A possibility is to use tags. Tags are observable markers that can be attached to an agent, and can represent a wide variety of characteristics, such as cultural or personal traits. They are flexible, and according to the definition provided in Edmonds and Hales (2003), the tag approach could also be used to match endorsements. According to the authors, tags are "*identifiable markings or cues attached to agents that can be observed by other agents (…)* [that] *can also evolve or change in the same way that behaviours can evolve and change*". Moreover, the use of tags does not compromise with the benefits already presented of a multi agent approach, as they still allow the modelling process to be independent from potentially inadequate theories.

The comparison of the results obtained from models using the two approaches would be of interest. To start with there should be an investigation of whether the two models can validate each other. From that point, the influence of structural differences could be displayed. Both modelling techniques show equal promises, and comparing them with the current system is quite a challenge.

8 ANNEX 1: SDML module code

The code presented in this section is extracted from the main module used to run the simulations for a particular scenario. This is the most important part of the code, and is included for the sake of completeness of this research. While it is not expected or necessary to read it, it will provide some insight into the way the processes mentioned in earlier sections were formalised. The headings state explicitly which agent fires the rules, and in which rulebase.

1. Agent: CitoyenMeta Rulebase: Initial Iteration

Rule: closest family structure (endorsement)

Antecedents:

```
and
	cellOccupiedBy ?x ?y self@^\
	sortedList ?slist [?neighbours ?numb]
		(and
			neighboursOf ?x ?y self@^ ?neighbours\
			at ?neighbours (and
				metaAgent ?meta\
				at ?meta (householdComposition ?numb ?where)))\
	householdComposition ?myNumb ?here\
	minValue ?min ?absndiff
		(and
			includes ?slist [?neighbour ?numb]\
			is ?ndiff ?numb - ?myNumb\
			absoluteValue ?absndiff ?ndiff)\
	randomChoice ?best ?neighbour (wrt [run year month])
		(and
			includes ?slist [?neighbour ?numb]\
			is ?ndiff ?numb - ?myNumb\
			= ?ndiff ?min)\
```

Consequents:

all month (endorsementFor ?best closestStructure)

Comment:

Generates endorsement for (one of) the neighbours with the closest occupancy rate

----

Rule: max retention coefficient (memory)

Antecedents:

```
and
	memoryDecayCoefficient ?decay_coeff\
	time year ?thisYear\
	time month ?thisMonth\
	noOfMonths ?maxMonth\
	lastMonth (and
		maxValue ?max_retention_coeff ?retention_coeff
			(and
				endorsementFor ?object ?end ?uniq\
				(or
					= ?uniq [?endYear ?endMonth]\
					= ?uniq [?otherObject ?endYear ?endMonth])\
```

isKindOf ?endYear Integer\
greater ?endYear 1700\
isKindOf ?endMonth Integer\
notInferred
greater ?endMonth ?maxMonth\
endorsementScheme ?scheme ?type\
isKindOf ?object ?type\
endorsementValue ?endValue ?end ?scheme\
absoluteValue ?absEndValue ?endValue\
elapsedMonths ?elapsedTime [?thisYear ?thisMonth] [?endYear ?endMonth]\
is ?retention_coeff ?absEndValue / ?elapsedTime ^ ?decay_coeff))

Consequents:
all month (maxRetentionCoefficient ?max_retention_coeff)

Comment:
Calculates actual retention coefficient for the period. High endorsements increase the possibility of retention.

Rule: memory of actions (endorsement)

Antecedents:
and
time month ?month\
time year ?year\
lastMonth (actionOfOrigin ?activity ?action)

Consequents:
all month (and
endorsementFor ?action selfSourced [?month ?year]\
endorsementFor ?action recentAction [?month ?year])

Comment:
Endorses actions made by the agent during the current period

Rule: recent action (endorsement)

Antecedents:
and
time year ?y\
time month ?m\
endorsementScheme ?actionEndScheme Action\
lastMonth (and
activityFrequencyVolume ?activity ?freq ?vol\
(or

```
                        action ?action (activityFrequencyVolume ?activity ?freq ?vol2)\
                        lastMonth (action ?action (activityFrequencyVolume ?activity
?freq ?vol2))))
```

Consequents:
all month (endorsementFor ?action recentAction [?m ?y])

Comment:
Endorses previous own actions as recent

Rule: updating - not uniquified (endorsement)

Antecedents:
lastMonth (endorsementFor ?object ?end)

Consequents:
all month (endorsementFor ?object ?end)
Comment:
Updates last month endorsements – case where no uniquifier is present. When not time-bound (by uniquifier argument), endorsements are carried over from one month to the next

----

Rule: updating - uniquified endorsement (memory)

Antecedents:

```
and
        maxRetentionCoefficient ?max_coeff\
        memoryDecayCoefficient ?decay_coeff\
        time year ?thisYear\
        time month ?thisMonth\
        noOfMonths ?maxMonth\
        lastMonth (endorsementFor ?object ?end ?uniq)\
        (or
                = ?uniq [?endYear ?endMonth]\
                = ?uniq [?agent ?endYear ?endMonth])\
        isKindOf ?endYear Integer\
        greater ?endYear 1700\
        isKindOf ?endMonth Integer\
        notInferred
                greater ?endMonth ?maxMonth\
        endorsementScheme ?scheme ?type\
        isKindOf ?object ?type\
        endorsementValue ?endValue ?end ?scheme\
        absoluteValue ?absEndValue ?endValue\
        elapsedMonths ?elapsedTime [?thisYear ?thisMonth] [?endYear ?endMonth]\
```

is ?retention_prob ?absEndValue / ?elapsedTime ^ ?decay_coeff / ?max_coeff\
randomNumber ?crit_retention_prob (wrt [run year month] endorsementFor ?object ?end [?endYear ?endMonth])\
greater ?retention_prob ?crit_retention_prob

Consequents:
all month (endorsementFor ?object ?end ?uniq)

Comment:
Updates last month endorsements – case where uniquifier is present. Keeps in memory only sufficiently endorsed endorsements (comparison with random number)

2. Agent: CitoyenMeta Rulebase: Initial Year

Rule: action endorsement scheme (endorsement)

Antecedents:
true

Consequents:
all run (endorsementScheme actionEndorsementScheme Action)

Comment:
Creates the endorsement scheme for actions

Rule: action endorsement tokens (endorsement)

Antecedents:
and
endorsementScheme ?scheme Action\
= ?tokensList [globallySourced neighbourhoodSourced selfSourced considersApplianceOld newAppliance]

Consequents:
all run (endorsementTokensList ?scheme ?tokensList)

Comment:
Generates endorsements for the action scheme

Rule: adoption endorsement scheme (endorsement)

Antecedents:
true\

Consequents:
all run (endorsementScheme adoptionEndorsementScheme Innovator)

Comment:
Creates the endorsement scheme for innovators

Rule: adoption endorsement tokens (endorsement)

Antecedents:
and
        endorsementScheme ?scheme Innovator\
        = ?tokensList [considersApplianceOld newAppliance]\

Consequents:
all run (endorsementTokensList ?scheme ?tokensList)

Comment:
Generates endorsements for the innovator scheme

Rule: citizen endorsement scheme (endorsement)

Antecedents:
true

Consequents:
all run (endorsementScheme citoyenEndorsementScheme Citoyen)

Comment:
Creates the endorsement scheme for households / citizens

Rule: citizen endorsement tokens (endorsement)

Antecedents:
and
        endorsementScheme ?scheme Citoyen\
        = ?tokensList [closestActivityVolume closestActivityFrequency
closestActivityFrequencyAndVolume closestStructure mostAlikeNeighbour]

Consequents:
all run (endorsementTokensList ?scheme ?tokensList)

Comment:
Generates endorsements for the citizen scheme

Rule: decay coefficient (memory)

Antecedents:
and

```
	maxMemoryDecayCoefficient ?maxCoeff\
	randomNumber ?rand (wrt [run year] memoryDecayCoefficient)\
	is ?coeff 1 + ?rand * (?maxCoeff - 1)
```

Consequents:
all run (memoryDecayCoefficient ?coeff)

Comment:
Ensures the actual memory decay coefficient is in the [1,max Coeff) interval

----

Rule: define action endorsement scheme (endorsement)

Antecedents:
and

```
	endorsementScheme ?scheme Action\
	randomNumber ?baseRand (wrt [run year] (endorsementScheme ?scheme
RuleName))\
	is ?base ?baseRand * 3 + (1 - ?baseRand)\
	selfInfluenceWeighting ?ssEnd\
	socialInfluenceWeighting ?gsEnd\
	localInfluenceWeighting ?nsEnd\
	is ?tot ?ssEnd + ?gsEnd + ?nsEnd\
	is ?gP ?gsEnd / ?tot\
	is ?sP ?ssEnd / ?tot\
	is ?nP ?nsEnd / ?tot\
	is ?gnP ?gP + ?nP\
	randomNumber ?rn1 (wrt [run year] ?scheme)\
	(if
		notInferred
			greater ?rn1 ?gP\
		= ?order1 globallySourced\
		(if
			(and
				greater ?rn1 ?gP\
				notInferred
					greater ?rn1 ?gnP)\
			= ?order1 neighbourhoodSourced\
			= ?order1 selfSourced))\
	pairList ?end_wts [globallySourced neighbourhoodSourced selfSourced]
[?gsEnd ?nsEnd ?ssEnd]\
	sourceEndorsementWeightsList ?sources ?end_wts\
	length ?sources ?num_tokens\
```

sortedList ?randsR ?rand
(and
inInterval ?n 1 ?num_tokens\
randomNumber ?rand [?sources ?n])\
reversed ?randsR ?source_rands\
randomList ?order2 ?remains (wrt [run year])
(and
pairList ?end_wts [globallySourced neighbourhoodSourced selfSourced] [?gsEnd ?nsEnd ?ssEnd]\
sourceEndorsementWeightsList ?sources ?end_wts\
includes ?sources ?remains\
notInferred
= ?remains ?order1)\
appended ?orderedSources [?order1] ?order2\
endorsementTokensList ?scheme ?tokensList\
randomList ?randomisedNonSourceTokenList ?token (wrt [run year] endorsementTokensList ?scheme)
(and
includes ?tokensList ?token\
notInferred
includes ?sources ?token)\
length ?randomisedNonSourceTokenList ?numTokens\
randomList ?randNonSourceValueIndices ?rand (wrt [run year] ?tokensList)
(and
inInterval ?n 1 ?numTokens\
randomNumber ?rand (wrt [run year] ?tokensList ?n))\
appended ?randValueIndices ?source_rands ?randNonSourceValueIndices\
appended ?end_tokens ?orderedSources ?randomisedNonSourceTokenList\
mappedList ?linComs ?randValueIndices [0 5] linearCombination\
mappedList ?endValues ?linComs rounded\
pairList ?endTokensAndValues ?end_tokens ?endValues\
= ?endList [[recentAction 0] | ?endTokensAndValues]

Consequents:
all run (endorsementSchemeDefinition ?scheme ?endList ?base)

Comment:
Computes the endorsement values of all actions in the scheme

Rule: define citoyen endorsement scheme (endorsement)

Antecedents:
and
endorsementScheme ?scheme Citoyen\
randomNumber ?baseRand (wrt [run year] (endorsementScheme ?scheme Citoyen))\
is ?base ?baseRand * 3 + (1 - ?baseRand)\
endorsementTokensList ?scheme ?tokensList\

```
        length ?tokensList ?numTokens\
        randomList ?randValueIndices ?rand (wrt [run year] ?tokensList)
                (and
                        inInterval ?n 1 ?numTokens\
                        randomNumber ?rand (wrt [run year] ?tokensList ?n))\
        mappedList ?linComs ?randValueIndices [0 5] linearCombination\
        mappedList ?endValues ?linComs rounded\
        pairList ?allEndValues ?tokensList ?endValues
```

Consequents:
all run (endorsementSchemeDefinition ?scheme ?allEndValues ?base)

Comment:
Computes the endorsement values of all actions in the scheme

Rule: define innovator endorsement scheme (endorsement)

Antecedents:

```
and
        endorsementScheme ?scheme Innovator\
        randomNumber ?baseRand (wrt [run year] (endorsementScheme ?scheme
Innovator))\
        is ?base ?baseRand * 3 + (1 - ?baseRand)\
        positiveEndorsements ?scheme [?posend] ?posval\
        negativeEndorsements ?scheme [?negend] ?negval\
        appended ?tokensList [?negend] [?posend]\
        length ?tokensList ?numTokens\
        sortedList ?slist ?rand
                (and
                        inInterval ?n 1 ?numTokens\
                        randomNumber ?rand (wrt [run year] ?tokensList ?n))\
        mappedList ?linComs ?slist [0 5] linearCombination\
        mappedList ?endValues ?linComs rounded\
        (if
                includes ?tokensList ?negend\
                (and
                        index ?tokensList ?ind ?negend\
                        index ?endValues ?ind ?indValue\
                        is ?modValue ?indValue * ?negval\
                        modifiedList ?endValues2 ?endValues ?ind ?modValue)\
                = ?endValues2 ?endValues)\
        pairList ?allEndValues ?tokensList ?endValues2
```

Consequents:
all run (endorsementSchemeDefinition ?scheme ?allEndValues ?base)

Comment:
Computes the endorsement values of all actions in the scheme

Rule: define source tokens order (endorsement)

Antecedents:

```
and
	sortedList ?eList [?end ?tEnd]
		(and
			endorsementScheme ?scheme Action\
			endorsementTokensList ?scheme ?list\
			includes ?list ?end\
			printed ?endName ?end\
			(or
				(and
					appended ?endName "selfSourced"\
					selfInfluenceWeighting ?tEnd)\
				(and
					appended ?endName "neighbourhoodSourced"\
					socialInfluenceWeighting ?tEnd)\
				(and
					appended ?endName "globallySourced"\
					localInfluenceWeighting ?tEnd)))\
	pairList ?eList ?ends ?rest\
	maxValue ?max ?each
		includes ?rest ?each\
	randomChoice ?rList ?endors true
		(and
			includes ?eList ?couple\
			= ?couple [?endors ?value]\
			= ?value ?max)\
	differenceList ?diffList ?ends [?rList]\
	randomList ?randomRemains ?remain true
		includes ?diffList ?remain\
	appended ?result [?rList] ?randomRemains
```

Consequents:
all run (sourceTokens ?result)

Comment:
Computes the endorsement values of all actions in the scheme with preset values provided by user

----

Rule: endorsement signs (endorsement)

Antecedents:
true

Consequents:
and
positiveEndorsements citoyenEndorsementScheme [mostAlikeNeighbour] 1\
positiveEndorsements actionEndorsementScheme [newAppliance] 1\
negativeEndorsements actionEndorsementScheme [considersApplianceOld] -1

Comment:
Specifies which endorsements will bear negative values

Rule: equivalence list (adoption parameters)

Antecedents:
sortedList ?equivalenceList ?object
and
= ?file_name_string "equivalence"\
appended ?delimitorRequest "Delimiter for " ?file_name_string\
= [?delimiter] " "\
excelTable ?file_name_string ?delimiter [?fContents]\
includes ?fContents ?componentstring\
namedInstance ?object ConsumptionAppliance ?componentstring

Consequents:
permanent (equivalenceList ?equivalenceList)

Comment:
Provides a scenario-dependant list of appliances and their substitutes.

scenarios C and D :
= ?file_name_string "equivalencecd"\

scenarios A and B :

= ?file_name_string "equivalence"\

Rule: family structure (household parameters)

Antecedents:
and
cellOccupiedBy ?x ?y self@^\
normal01toAB ?res1 ?res2 2.4 1 self\
(if
greater ?res1 ?res2\
is ?result ?res1\
is ?result ?res2)\
rounded ?Tround ?result\

```
        max ?max 1 ?Tround
```

Consequents:
all run (householdComposition ?max [?x ?y])

Comment:
Provides the occupancy rate for households, based on a normal distribution of average 2.4 and standard deviation 1

Rule: replaceable ownership - action - value simulation start (consumption)

Antecedents:

```
and
        time month 1\
        time iteration 1\
        possibleReplacementNow ?list\
        length ?list ?length\
        = ?length 0\
        ownership ?appliance\
        endorsementScheme ?actionEndScheme Action\
        endorsementScheme ?citEndScheme Citoyen\
        endorsementScheme ?innoEndScheme Innovator\
        randomList ?actionValues [?action ?endAndCitValue] (wrt [run year month]
?appliance ReglePublique)
                (and
                        action ?action (activityFrequencyVolume ?appliance ?freq
?volume)\
                        endorsementValueOf ?endValue ?action ?actionEndScheme\
                        total ?totalCitValues ?citValue
                                (and
                                        visibleCell ?x ?y\
                                        cellOccupiedBy ?x ?y ?neighbour\
                                        thereExists
                                                endorsementFor ?action ?end [?neighbour
?any_year ?any_month]\
                                        endorsementValueOf ?citValue ?neighbour
?citEndScheme)\
                        total ?totalInnoValues ?innoValue
                                (and
                                        gridLocation ?x ?y\
                                        cellOccupiedBy ?x ?y ?me\
                                        neighboursOf ?x ?y ?me ?neighbour\
                                        (or
                                                thereExists
                                                        endorsementFor ?neighbour ?end
[?any_year ?any_month]\
                                                thereExists
```

```
                                        endorsementFor ?neighbour ?end
[?oldHard ?any_year ?any_month])\
                              endorsementValueOf ?innoValue ?neighbour
?innoEndScheme)\
                  is ?endAndCitValue (max 0 ?endValue + ?totalCitValues +
?totalInnoValues))\
        pairList ?actionValues ?actions ?values\
        sortedList ?actionList ?achoice
            (and
                  includes ?actions ?singleAction\
                  action ?singleAction (activityFrequencyVolume ?app ?f ?v)\
                  maxValue ?maxValue ?value
                        includes ?actionValues [?action ?value]\
                  includes ?actionValues [?achoice ?maxValue])\
        length ?actionList ?actionListLength\
        (if
            greater ?actionListLength 1\
            randomChoice ?actionChosen ?action2 (wrt [run year month])
                  includes ?actionList ?action2\
            includes ?actionList ?actionChosen)\
        action ?actionChosen (activityFrequencyVolume ?chosen_activity ?freqRes
?volTemp)
```

Consequents:
all month (replaceableActionValuePair ?actionValues ?appliance)

Comment:
Sociates to every action the sum of all its endorsements

Rule: replaceables ownership - first month of simulation (consumption)

Antecedents:

```
and
        time month 1\
        time iteration 0\
        possibleReplacementNow ?list\
        length ?list ?length\
        = ?length 0\
        ownership ?appliance\
        replaceableActionValuePair ?actionValues ?appliance\
        pairList ?actionValues ?actions ?values\
        sortedList ?actionList ?achoice
            (and
                  includes ?actions ?singleAction\
                  lastMonth (action ?singleAction (activityFrequencyVolume ?app
?f ?v))\
                  maxValue ?maxValue ?value
                        includes ?actionValues [?action ?value]\
```

includes ?actionValues [?achoice ?maxValue])\
length ?actionList ?actionListLength\
(if
greater ?actionListLength 1\
randomChoice ?actionChosen ?action2 (wrt [run year month])
includes ?actionList ?action2\
includes ?actionList ?actionChosen)\
lastMonth (action ?actionChosen (activityFrequencyVolume ?chosen_activity ?freqRes ?volTemp))

Consequents:
all month (ownership ?chosen_activity)

Comment:
Finds the appliances a household owns. Case when list of possible replacements is NOT empty, AND replacement CAN happen

3. Agent: CitoyenMeta Rulebase: Content

Rule: action known from observation (rules)

Antecedents:
and
time year ?year\
time month ?month\
visibleCellNT ?x ?y\
location ?x ?y ?agent\
semiPublicConsumptionActivity ?activity\
lastMonth (at ?agent (activityFrequencyVolume ?activity ?neighbourFreq ?neighbourCons))\
generatedInstance ?newAction Action [(publicConsumptionActivity ?activity) (activityFrequencyVolume ?activity ?neighbourFreq ?neighbourCons)]

Consequents:
all month (and
action ?newAction (activityFrequencyVolume ?activity ?neighbourFreq ?neighbourCons)\
endorsementFor ?newAction neighbourhoodSourced [?agent ?month ?year])

Comment:
Retrieves the public actions from last period and generates endorsements to put them in the agent's database
----

Rule: action known from usage (rules)

Antecedents:
and

```
        time year ?year\
        time month ?month\
        lastMonth (and
                ownership ?activity\
                (if
                        fixedVolumeAppliance ?activity ?value\
                        (and
                                at self@^ (activityFrequencyVolume ?activity ?myFreq
?value)\
                                (if
                                        thereExists
                                                action ?action (activityFrequencyVolume
?activity ?myFreq ?myVol)\
                                        action ?action (activityFrequencyVolume ?activity
?myFreq ?myVol)\
                                        lastMonth (action ?action (activityFrequencyVolume
?activity ?myFreq ?myVol))))\
                        (and
                                at self@^ (activityFrequencyVolume ?activity ?myFreq
?myVol)\
                                (if
                                        thereExists
                                                action ?action (activityFrequencyVolume
?activity ?myFreq ?myVol)\
                                        action ?action (activityFrequencyVolume ?activity
?myFreq ?myVol)\
                                        lastMonth (action ?action (activityFrequencyVolume
?activity ?myFreq ?myVol))))))
```

Consequents:
all month (endorsementFor ?action selfSourced [?month ?year])

Comment:
Generates endorsements for action used by agent the previous period

----

Rule: action remembered (rules)

Antecedents:

```
and
        lastMonth (action ?action ?clause)\
        thereExists
                (or
                        endorsementFor ?action ?end\
                        endorsementFor ?action ?end ?uniq)
```

Consequents:
all month (action ?action ?clause)

Comment:
Makes sure an action with an endorsement last period remains on the database

----

Rule: AFV 1st month public apps (init consumption)

```
Antecedents:
and
        time year 1980\
        time month 1\
        time iteration 1\
        ownership ?appliance\
        endorsementScheme ?actionEndScheme Action\
        endorsementScheme ?citEndScheme Citoyen\
        randomList ?actionValues [?action ?endAndCitValue] (wrt [run year month]
?appliance ReglePublique)
                (and
                        action ?action (activityFrequencyVolume ?appliance ?freq
?volume)\
                        endorsementValueOf ?endValue ?action ?actionEndScheme\
                        total ?totalCitValues ?citValue
                                (and
                                        visibleCellNT ?x ?y\
                                        cellOccupiedBy ?x ?y ?neighbour\
                                        thereExists
                                                endorsementFor ?action ?end [?neighbour
?any_year ?any_month]\
                                        endorsementValueOf ?citValue ?neighbour
?citEndScheme)\
                        is ?endAndCitValue (max 0 ?endValue + ?totalCitValues))\
        pairList ?actionValues ?actions ?values\
        sortedList ?actionList ?achoice
                (and
                        includes ?actions ?singleAction\
                        action ?singleAction (activityFrequencyVolume ?app ?f ?v)\
                        maxValue ?maxValue ?value
                                includes ?actionValues [?action ?value]\
                        includes ?actionValues [?achoice ?maxValue])\
        randomChoice ?actionChosen ?action2 (wrt [run year month] ?appliance)
                includes ?actionList ?action2\
        action ?actionChosen (activityFrequencyVolume ?chosen_activity ?freqRes
?volTemp)\
        sortedList ?fval ?fva
                fixedVolumeAppliance ?fva ?fv\
        (if
                includes ?fval ?chosen_activity\
                (and
                        fixedVolumeAppliance ?chosen_activity ?fv\
                        is ?volRes ?fv)\
```

```
                is ?volRes ?volTemp)\
        generatedInstance ?rule ReglePublique [true (activityFrequencyVolume
?chosen_activity ?freqRes ?volRes)]
```

Consequents:
all month (rule ?rule true (activityFrequencyVolume ?chosen_activity ?freqRes ?volRes))

Comment:
Generates rules when no previous endorsement is present (first timestep of simulation)

Rule: appliance failure (appliance)

Antecedents:

```
and
        gridLocation ?x ?y\
        time year ?ynow\
        time month ?mnow\
        newApplianceReplacedMonthYear ?new [?old] ?month ?year\
        lastMonth (activityFrequencyVolume ?appliance ?freq ?vol)\
        (or
                includes [?old] ?appliance\
                includes [?new] ?appliance)\
        (if
                last month (appliancePurchase ?appliance ?pmonth ?pyear)\
                is ?time 12 * (?ynow - ?pyear) - ?pmonth + ?mnow\
                (and
                        randomNumber ?rand (wrt [run year month] ?x ?y)\
                        is ?rand60 ?rand * 60\
                        floor ?frand ?rand60\
                        is ?time ?frand))\
        weibullParameters ?eta ?beta ?appliance\
        weibullDensity ?weib ?time ?eta ?beta ?appliance\
        randomNumber ?rn (wrt [run year month] ?appliance ?x ?y)\
        greater ?weib ?rn
```

Consequents:
applianceFailure ?appliance ?mnow ?ynow

Comment:
Calculates the probability of an appliance failure using weibull density

----

Rule: appliance replacement possibility now (consumption)

Antecedents:

```
randomList ?replacementsList ?replacements time
        and
                newApplianceReplacedMonthYear ?newActivity [?replacements]
?month ?yr\
                time month ?monthNow\
                time year ?yearNow\
                (or
                        greater ?yearNow ?yr\
                        (and
                                notInferred
                                        less ?monthNow ?month\
                                = ?yearNow ?yr))\
                notInferred
                        lastMonth (activityFrequencyVolume ?newActivity ?newFreq
?newVol)\
```

Consequents:
all month (possibleReplacementNow ?replacementsList)

Comment:
Provides the list of possible appliances to replace according to the date

----

Rule: AVpairing (ownership update)

Antecedents:

```
and
        endorsementScheme ?actionEndScheme Action\
        endorsementScheme ?citEndScheme Citoyen\
        sortedList ?listofApp ?app
                lastMonth (ownership ?app)\
        possibleReplacementNow ?prn\
        (if
                = ?prn []\
                = ?general ?listofApp\
                (and
                        sortedList ?newList ?newApp
                                (and
                                        includes ?prn ?someApp\
                                        newApplianceReplacedMonthYear ?newApp
[?someApp] ?m ?y)\
                        appended ?general ?listofApp ?newList))\
        includes ?general ?eachApp\
        randomList ?actionValues [?action ?endAndCitValue] ?eachApp
                (and
                        (or
                                lastMonth (action ?action (activityFrequencyVolume
?eachApp ?f ?v))\
```

```
                    action ?action (activityFrequencyVolume ?eachApp ?f
?v))\
               endorsementValueOf ?endValue ?action ?actionEndScheme\
               total ?totalCitValues ?citValue
                    (and
                         visibleCellNT ?x ?y\
                         cellOccupiedBy ?x ?y ?neighbour\
                         thereExists
                              endorsementFor ?action ?end [?neighbour
?any_year ?any_month]\
                         endorsementValueOf ?citValue ?neighbour
?citEndScheme)\
               is ?endAndCitValue (max 0 ?endValue + ?totalCitValues))
```

Consequents:
replaceableActionValuePair ?actionValues ?eachApp

Comment:
Fetches the endorsements associated to a specific action and adds their values
----

Rule: best neighbour (endorsement)

Antecedents:

```
and
     time month ?month\
     time year ?year\
     sortedList ?sList [?lengthList ?who]
          (and
               gridLocation ?x ?y\
               cellOccupiedBy ?x ?y ?me\
               neighboursOf ?x ?y ?me ?who\
               sortedList ?appList ?a
                    (and
                         last month (activityFrequencyVolume ?a ?f ?v)\
                         at ?who (last month (activityFrequencyVolume ?a
?fbis ?vbis)))\
               = ?bi [?who ?appList]\
               length ?appList ?lengthList)\
     maxValue ?max ?cval
          includes ?sList [?cval ?who]\
     randomList ?winList ?winners (wrt [run year month])
          includes ?sList [?max ?winners]\
     index ?winList 1 ?win
```

Consequents:
all month (endorsementFor ?win mostAlikeNeighbour [?year ?month])

Comment:

Attributes the mostAlikeNeighbour endorsement to the neighbour with the most similar list of appliances
----

Rule: endorse policy action (endorsement)

Antecedents:
and
        lastMonth (policyAction ?policyAgent ?action (activityFrequencyVolume ?activity ?policyF ?policyC))\
        time year ?year\
        time month ?month

Consequents:
all month (and
        action ?action (activityFrequencyVolume ?activity ?policyF ?policyC)\
        endorsementFor ?action globallySourced [?policyAgent ?year ?month])

Comment:
Provides an endorsement for last month's actions from the Policy Agent
----

Rule: init consumption action (init consumption)

Antecedents:
and
        time year ?y\
        time month ?m\
        ownershipFromData ?hardware ?prob\
        frequencyFromData ?hardware ?datafreq\
        volumeFromData ?hardware ?datavol\
        notInferred
                (and
                        newApplianceReplacedMonthYear ?hardware ?replaced ?month ?year\
                        (or
                                greater ?year ?y\
                                (and
                                        = ?year ?y\
                                        notInferred
                                                less ?month ?m)))\
        notInferred
                lastMonth (or
                        action ?anyAction (activityFrequencyVolume ?hardware ?f ?c)\
                        policyAction ?agent ?anyAction (activityFrequencyVolume ?hardware ?f ?c))\
        randomNumber ?rn1 (wrt [run year month] ?hardware ?datafreq)\
        randomNumber ?rn2 (wrt [run year month] ?hardware ?datavol)\
        is ?init_vol (ceiling ?datavol * 2 * ?rn2)\
        is ?init_freq (rounded ?datafreq * 2 * ?rn1 * 60)\

generatedInstance ?action Action (activityFrequencyVolume ?hardware ?init_freq ?init_vol)

Consequents:
all month (and
action ?action (activityFrequencyVolume ?hardware ?init_freq ?init_vol)\
endorsementFor ?action selfSourced [?m ?y])

Comment:
Initialises the frequency and volume values for an agent according to the averages.

Rule: init ownership (init consumption)

Antecedents:
and
time year 1980\
time month 1\
time iteration 0\
ownershipFromData ?hardware ?prob\
notInferred
newApplianceReplacedMonthYear ?hardware ?replaced ?month ?year\
randomNumber ?rn ?hardware\
notInferred
greater ?rn ?prob

Consequents:
all month (ownership ?hardware)

Comment:
Generates by means of a probability an appliance as part of an Agent's endowments

----

Rule: neighbour different appliance (endorsement)

Antecedents:
and
gridLocation ?x ?y\
cellOccupiedBy ?x ?y ?me\
neighboursOf ?x ?y ?me ?neig\
randomList ?rlist ?a ?neig
at ?neig (last month (activityFrequencyVolume ?a ?f ?v))\
randomList ?myrlist ?mya ?me
at ?me (last month (activityFrequencyVolume ?mya ?myf ?myv))\
differenceList ?res ?rlist ?myrlist

Consequents:
differentAppliance ?res ?neig

Comment:

Rule: neighbour with closest frequency of use (endorsement)

Antecedents:
and
```
	time year ?year\
	time month ?month\
	gridLocation ?x ?y\
	cellOccupiedBy ?x ?y ?me\
	publicConsumptionActivity ?myact\
	sortedList [[?score ?who] | ?rest] [?total ?neighbour]
		(and
			neighboursOf ?x ?y ?me ?neighbour\
			at ?me (lastMonth (activityFrequencyVolume ?myact ?myfreq
?myvol))\
			at ?neighbour (lastMonth (activityFrequencyVolume ?myact ?freq
?volume))\
			is ?total (absoluteValue ?freq - ?myfreq))
```

Consequents:
all month (endorsementFor ?who closestActivityFrequency [?myact ?year ?month])

Comment:
Selects the neighbour that has the closest frequency of use and endorses it.

For every activity an agent has, gives the neighbour with the closest frequency

----

Rule: neighbour with closest volume per use (endorsement)

Antecedents:
and
```
	time year ?year\
	time month ?month\
	gridLocation ?x ?y\
	cellOccupiedBy ?x ?y ?me\
	publicConsumptionActivity ?myact\
	sortedList [[?score ?who] | ?rest] [?total ?neighbour]
		(and
			neighboursOf ?x ?y ?me ?neighbour\
			at ?me (lastMonth (activityFrequencyVolume ?myact ?myfreq
?myvol))\
			at ?neighbour (lastMonth (activityFrequencyVolume ?myact ?freq
?volume))\
			is ?total (absoluteValue ?volume - ?myvol))
```

Consequents:
all month (endorsementFor ?who closestActivityVolume [?myact ?year ?month])

Comment:
Selects the neighbour that has the closest volume per use and endorses it.

For every activity an agent has, gives the neighbour with the closest volume

----

Rule: new appliance (endorsement)

Antecedents:

```
and
	time year ?y\
	time month ?m\
	frequencyFromData ?new_appliance ?datafreq\
	volumeFromData ?new_appliance ?datavol\
	newApplianceReplacedMonthYear ?new_appliance ?replaced_list ?month
?year\
	notInferred
		lastMonth (or
			action ?anyAction (activityFrequencyVolume ?new_appliance ?f
?c)\
			policyAction ?agent ?anyAction (activityFrequencyVolume
?new_appliance ?f ?c))\
	is ?limit_year ?year + 1\
	(or
		(and
			greater ?y ?year\
			less ?y ?limit_year)\
		(and
			= ?y ?limit_year\
			less ?month ?m)\
		(and
			= ?year ?y\
			notInferred
				less ?m ?month))\
	randomNumber ?rn1 (wrt [run year month] ?new_appliance ?datafreq)\
	randomNumber ?rn2 (wrt [run year month] ?new_appliance ?datavol)\
	is ?init_vol (ceiling ?datavol * 2 * ?rn2)\
	is ?init_freq (rounded ?datafreq * 2 * ?rn1 * 60)\
	(if
		fixedVolumeAppliance ?new_appliance ?fv\
		is ?volRes ?fv\
		is ?volRes ?init_vol)\
	generatedInstance ?action Action (activityFrequencyVolume ?new_appliance
?init_freq ?volRes)
```

```
Consequents:
all month (and
        action ?action (activityFrequencyVolume ?new_appliance ?init_freq ?volRes)\
        endorsementFor ?action selfSourced [?m ?y]\
        endorsementFor ?action newAppliance [?m ?y])

Comment:
Generates endorsements for actions related to new appliances

---------------------------------------------------------------------

Rule: new appliance endorsed for one year (endorsement)

Antecedents:
and
        newApplianceReplacedMonthYear ?newApp ?oldAppList ?m ?y\
        time year ?ynow\
        time month ?mnow\
        (or
                greater ?ynow ?y\
                (and
                        = ?ynow ?y\
                        notInferred
                                less ?mnow ?m))\
        notInferred
                (and
                        greater ?ynow ?y)\
        notInferred
                less ?mnow ?m\
        lastMonth (action ?action (activityFrequencyVolume ?newApp ?f ?v))

Consequents:
all month (endorsementFor ?action newAppliance [?m ?y])

Comment:
Endorses every appliance as new for the year after its introduction

---------------------------------------------------------------------

Rule: no purchase update (appliance)

Antecedents:
and
        purchase 0\
        last month (appliancePurchase ?appliance ?month ?year)

Consequents:
all month (appliancePurchase ?appliance ?month ?year)

Comment:
```

If no purchase has been done this month, use last month information for date of purchase of appliance

----

Rule: non replaceable rule generation (rules)

```
Antecedents:
and
        time iteration 1\
        ownership ?appliances\
        notInferred
                (and
                        newApplianceReplacedMonthYear ?newActivity ?replacements
?month ?yr\
                        (or
                                thereExists
                                        includes ?replacements ?appliances\
                                = ?newActivity ?appliances))\
        replaceableActionValuePair ?actionValues ?appliances\
        pairList ?actionValues ?actions ?values\
        sortedList ?actionList ?achoice
                (and
                        includes ?actions ?singleAction\
                        maxValue ?maxValue ?value
                                includes ?actionValues [?action ?value]\
                        includes ?actionValues [?achoice ?maxValue])\
        length ?actionList ?actionListLength\
        (if
                greater ?actionListLength 1\
                randomChoice ?actionChosen ?action2 (wrt [run year month])
                        includes ?actionList ?action2\
                includes ?actionList ?actionChosen)\
        (if
                thereExists
                        action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)\
                action ?actionChosen (activityFrequencyVolume ?chosen_activity
?freqRes ?volTemp)\
                lastMonth (action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)))\
        sortedList ?fval ?fva
                fixedVolumeAppliance ?fva ?fv\
        (if
                includes ?fval ?chosen_activity\
                (and
                        fixedVolumeAppliance ?chosen_activity ?fv\
                        is ?volRes ?fv)\
                is ?volRes ?volTemp)\
```

generatedInstance ?rule ReglePublique [true (activityFrequencyVolume ?chosen_activity ?freqRes ?volRes)]

Consequents:
all month (and
rule ?rule true (activityFrequencyVolume ?chosen_activity ?freqRes ?volRes)\
actionOfOrigin ?chosen_activity ?actionChosen)

Comment:
Generates the rule of behaviour for non replaceable items, selecting highest endorsed actions for every appliance.

Rule: non replaceables (ownership update)

Antecedents:
and
lastMonth (ownership ?ownership)\
notInferred
newApplianceReplacedMonthYear ?new [?ownership] ?m ?y

Consequents:
all month (ownership ?ownership)

Comment:
Updates ownership of non replaceable appliances

Rule: old appliance (endorsement)

Antecedents:
and
```
        gridLocation ?x ?y\
        cellOccupiedBy ?x ?y ?me\
        newApplianceReplacedMonthYear ?newActivity [?replacements] ?month ?year\
        time month ?monthNow\
        time year ?yearNow\
        (or
                greater ?yearNow ?year\
                (and
                        = ?yearNow ?year\
                        notInferred
                                less ?monthNow ?month))\
        randomNumber ?rn (wrt [run year month] considersApplianceOld)\
        randomNumber ?rn1 (wrt [run year month] considersApplianceOld false)\
        lastMonth (and
                ownership ?replacements\
```

action ?action (activityFrequencyVolume ?replacements ?f ?v))

Consequents:
all month (endorsementFor ?action considersApplianceOld [?me ?monthNow ?yearNow])

Comment:
Generates endorsement for an appliance randomly provided they are replaceable by a newer appliance
----

Rule: purchase after failure (appliance)

Antecedents:
and
gridLocation ?x ?y\
cellOccupiedBy ?x ?y ?me\
applianceFailure ?appliance ?mnow ?ynow\
newApplianceReplacedMonthYear ?newApp [?appliance] ?month ?year\
endorsementFor ?me considersApplianceOld [?newApp ?yearEndorsed ?monthEndorsed]

Consequents:
all month (purchase 1 ?newApp)

Comment:

Rule: purchase update (appliance)

Antecedents:
and
time month ?mnow\
time year ?ynow\
purchase 1 ?appliance

Consequents:
all month (appliancePurchase ?appliance ?mnow ?ynow)

Comment:

Rule: replaceables - generate rules from ownership (rules)

Antecedents:
and
time iteration 1\
time month ?month\

```
		time year ?year\
		ownership ?appliances\
		newApplianceReplacedMonthYear ?newApp ?oldApp ?m ?y\
		(or
			includes ?oldApp ?appliances\
			= ?newApp ?appliances)\
		replaceableActionValuePair ?actionValues ?appliances\
		pairList ?actionValues ?actions ?values\
		sortedList ?actionList ?achoice
			(and
				includes ?actions ?singleAction\
				(if
					thereExists
						lastMonth (action ?singleAction
(activityFrequencyVolume ?appliances ?f ?v))\
					lastMonth (action ?singleAction (activityFrequencyVolume
?appliances ?f ?v))\
					(or
						action ?singleAction (activityFrequencyVolume
?appliances ?f ?v)\
						lastMonth (lastMonth (action ?singleAction
(activityFrequencyVolume ?appliances ?f ?v)))))\
				maxValue ?maxValue ?value
					includes ?actionValues [?action ?value]\
				includes ?actionValues [?achoice ?maxValue])\
		length ?actionList ?actionListLength\
		(if
			greater ?actionListLength 1\
			randomChoice ?actionChosen ?action2 (wrt [run year month iteration])
				includes ?actionList ?action2\
			includes ?actionList ?actionChosen)\
		(if
			thereExists
				action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)\
			action ?actionChosen (activityFrequencyVolume ?chosen_activity
?freqRes ?volTemp)\
			lastMonth (action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)))\
		sortedList ?fval ?fva
			fixedVolumeAppliance ?fva ?fv\
		(if
			includes ?fval ?chosen_activity\
			(and
				fixedVolumeAppliance ?chosen_activity ?fv\
				is ?volRes ?fv)\
			is ?volRes ?volTemp)\
		generatedInstance ?rule ReglePublique [true (activityFrequencyVolume
?chosen_activity ?freqRes ?volRes)]
```

Consequents:
all month (and
rule ?rule true (activityFrequencyVolume ?chosen_activity ?freqRes ?volRes)\
actionOfOrigin ?chosen_activity ?actionChosen)

Comment:
Generates rules from current ownership, from highest endorsed actions
----

Rule: replaceables - nothing needs to be replaced (ownership update)

Antecedents:
and
time iteration 0\
comment "****all the appliances (?activity) I had last month that could be replaced (as they are ?oldApp)"\
newApplianceReplacedMonthYear ?newApp ?oldAppList ?m ?y\
includes ?oldAppList ?activity\
= ?activity ?oldApp\
lastMonth (activityFrequencyVolume ?activity ?lmF ?lmV)\
comment "****when something could have been replaced as the list is not empty"\
possibleReplacementNow ?list\
length ?list ?length\
greater ?length 0\
includes ?list ?oldApp\
comment "****but that do not fail nor are replaced by will"\
notInferred
(or
applianceFailure ?oldApp ?month ?yr\
(and
includes ?list ?oldApp\
randomNumber ?rn1 (wrt [run year month] ?oldApp)\
replacementRate ?oldApp ?rate\
is ?average 1 / ?rate\
greater ?rn1 ?average))

Consequents:
all month (ownership ?activity)

Comment:
Finds the appliances a household owns. Case when list of possible replacements is NOT empty, but replacement does not happen

----

Rule: replaceables - nothing to replace - list empty (ownership update)

Antecedents:
and

```
        time iteration 0\
        possibleReplacementNow ?list\
        newApplianceReplacedMonthYear ?new [?activity] ?m ?y\
        notInferred
                includes ?list ?activity\
        lastMonth (ownership ?activity)
```

Consequents:
all month (ownership ?activity)

Comment:
Finds the appliances a household owns. Takes the complementary set of the "possible replacement now" list hence ownership is as last month

----

Rule: replaceables - something needs to be replaced (ownership update)

Antecedents:

```
and
        equivalenceList ?equivalenceList\
        sortedList ?resultList [?actionChosen ?chosen_activity ?freqRes ?volTemp]
                (and
                        time iteration 0\
                        comment "****all the appliances (?activity) I had last month that
could be replaced (as they are ?oldApp)"\
                        newApplianceReplacedMonthYear ?newApp ?oldAppList ?m ?y\
                        includes ?oldAppList ?activity\
                        = ?activity ?oldApp\
                        lastMonth (activityFrequencyVolume ?activity ?lmF ?lmV)\
                        comment "****when something can be replaced as the list is not
empty"\
                        possibleReplacementNow ?list\
                        length ?list ?length\
                        greater ?length 0\
                        includes ?list ?oldApp\
                        comment "****and that fail or are replaced by will"\
                        (or
                                applianceFailure ?oldApp ?month ?yr\
                                (and
                                        includes ?list ?oldApp\
                                        randomNumber ?rn1 (wrt [run year month]
?activity)\
                                        replacementRate ?oldApp ?rate\
                                        is ?average 1 / ?rate\
                                        greater ?rn1 ?average))\
                        comment "**** computation of the endorsement value"\
                        replaceableActionValuePair ?actionValues1 ?activity\
                        newApplianceReplacedMonthYear ?newApp [?activity] ?m ?y\
                        replaceableActionValuePair ?actionValues2 ?newApp\
```

```
                    appended ?actionValues ?actionValues1 ?actionValues2\
                    pairList ?actionValues ?actions ?values\
                    sortedList ?actionList ?achoice
                        (and
                            includes ?actions ?singleAction\
                            action ?singleAction (activityFrequencyVolume
?app ?f ?v)\
                            maxValue ?maxValue ?value
                                includes ?actionValues [?action ?value]\
                            includes ?actionValues [?achoice ?maxValue])\
                    length ?actionList ?actionListLength\
                    (if
                        greater ?actionListLength 1\
                        randomChoice ?actionChosen ?action2 (wrt [run year
month iteration] ?actionList)
                            includes ?actionList ?action2\
                        includes ?actionList ?actionChosen)\
                    (if
                        thereExists
                            action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)\
                        action ?actionChosen (activityFrequencyVolume
?chosen_activity ?freqRes ?volTemp)\
                        lastMonth (action ?actionChosen
(activityFrequencyVolume ?chosen_activity ?freqRes ?volTemp))))\
        sortedList ?listOfAct ?chosen_activity
            includes ?resultList [?actionChosen ?chosen_activity ?freqRes
?volTemp]\
        sortedList ?others ?app2
            (and
                includes ?listOfAct ?app2\
                notInferred
                    includes ?equivalenceList ?app2)\
        differenceList ?diff ?listOfAct ?others\
        length ?diff ?l\
        (if
            greater ?l 1\
            randomChoice ?oneApp ?app1 (wrt [run year month iteration] ?diff)
                includes ?diff ?app1\
            true)\
        (if
            notInferred
                = ?others []\
            (and
                includes ?others ?others2\
                appended ?finalList [?oneApp] ?others)\
            = ?finalList [?oneApp])\
        includes ?finalList ?theApp\
        includes ?resultList [?action ?theApp ?freqRes ?volTemp]
```

Consequents:
all month (ownership ?theApp)

Comment:
Finds the appliances a household owns. Case when list of possible replacements is NOT empty, AND replacement CAN happen

----

Rule: update AFV to keep continuity (ownership update)

Antecedents:
and

```
	time iteration 0\
	lastMonth (activityFrequencyVolume ?a ?f ?v)
```

Consequents:
activityFrequencyVolume ?a ?f ?v

Comment:
Updates the ownership of appliances (technical issue)

4. Agent: CitoyenMeta Rulebase: Final Iteration

Rule: ownership check (report)

Antecedents:
and

```
	gridLocation ?x ?y\
	cellOccupiedBy ?x ?y ?me\
	sortedList ?slist1 ?a
		at ?me (lastMonth (activityFrequencyVolume ?a ?f ?v))\
	sortedList ?slist2 ?a1
		activityFrequencyVolume ?a1 ?f ?v\
	differenceList ?result ?slist1 ?slist2\
	sortedList ?app [?old ?new]
		newApplianceReplacedMonthYear ?new [?old] ?month ?year\
	pairList ?app ?myold ?mynew\
	(if
		= ?result []\
		false\
		(if
			(and
				includes ?result ?old\
				index ?myold ?pos ?old\
				index ?mynew ?pos ?new\
				includes ?slist2 ?new)\
			false\
```

true))

Consequents:
halt

Comment:
Rule checks that at any time agents own the same (or substitute to) appliances as they initially had

----

Rule: reporting (report)

Antecedents:
and
time run ?run\
time month ?month\
time year ?year\
gridLocation ?x ?y\
cellOccupiedBy ?x ?y ?me\
at ?me (activityFrequencyVolume ?a ?f ?v)\
printed ?yearString ?year\
printed ?monthString ?month\
appended ?dateString ?monthString "/" ?yearString\
= ?reportList [?run ?dateString ?a ?f ?v ?me]

Consequents:
reportNumeric ?reportList

Comment:
Reports for every month the appliance owned and the corresponding usage by the agent

5. **Agent: Ground Rulebase: Initial Eternity**

Rule: final year (timer management)

Antecedents:
and
initialTime year ?initYear\
printed ?initYearString ?initYear\
precipitationFile ?pFile\
excelTable ?pFile ?pTable\
length ?pTable ?numRows\
index ?pTable ?numRows ?lastDataRow\
index ?lastDataRow 1 ?lastYear\
printed ?lastYearString ?lastYear\
appended ?requestString "Final year? (" ?initYearString "-" ?lastYearString ")"\

userRequestedString ?finalYearString ?requestString\
parsed ?finalYearString ?finalYear\
notInferred
less ?finalYear ?initYear

Consequents:
finalYear ?finalYear

Comment:
Specifies the final year for every run, providing the last year of precipitation data as default value
----

Rule: initial month (timer management)

Antecedents:
true

Consequents:
initialTime month 1

Comment:
Time management, first month of the year is month 1

Rule: initial year (timer management)

Antecedents:
and
precipitationFile ?pFile\
excelTable ?pFile ?pTable\
index ?pTable 2 ?firstDataRow\
index ?firstDataRow 1 ?firstYear\
printed ?firstYearString ?firstYear\
length ?pTable ?numRows\
index ?pTable ?numRows ?lastDataRow\
index ?lastDataRow 1 ?lastYear\
printed ?lastYearString ?lastYear\
appended ?requestString "Initial year? (" ?firstYearString "-" ?lastYearString ")"\
userRequestedString ?initYearString ?requestString\
parsed ?initYearString ?initYear

Consequents:
initialTime year ?initYear

Comment:
Specifies the initial year for every run, providing the initial year of precipitation data as default value

----

Rule: max aet (parameters)

Antecedents:
and
        userRequestedNumber ?maxAET "Maximum actual evapotranspiration (AET)" "50"\

Consequents:
maxAET ?maxAET

Comment:
User input for maximum level of evapotranspiration (part of soil water calculations)

Rule: max runoff (parameters)

Antecedents:
and
        maxSoilWater ?maxSoilWater\
        userRequestedNumber ?maxRunOff "Maximum runoff" "150"\

Consequents:
maxRunOff ?maxRunOff

Comment:
User input for maximum runoff (part of soil water calculations)

Rule: max soil water (parameters)

Antecedents:
and
        maxAET ?maxAET\
        userRequestedNumber ?maxSoilWater "Maximum soil water" "100"\

Consequents:
maxSoilWater ?maxSoilWater

Comment:
User input for maximum soil water (part of soil water calculations)

Rule: no of months (timer management)

Antecedents:
true

Consequents:
noOfMonths 12

Comment:
Specifies that a cycle of 12 months results in an increment of the containing time level defined (year)

6. Agent: PilotFirmaModel Rulebase: Content

Rule: total citoyen consumption (reporting)

Antecedents:

```
lastMonth (and
        time year ?year\
        time month ?month\
        total ?totalConsumption ?consumption
                (and
                        activeSubAgent ?agent\
                        isKindOf ?agent Citoyen\
                        at ?agent (activityFrequencyVolume ?activity ?f ?c)\
                        is ?consumption ?f * ?c))
```

Consequents:
all run (totalCitoyenConsumption ?year ?month ?totalConsumption)

Comment:
Reports the consumption for the whole society indexed by date

7. Agent: PilotFirmaModel Rulebase: Initial Eternity

Rule: activate time levels (time)

Antecedents:
true

Consequents:
timeLevels [iteration]

Comment:
Activates iteration time level

Rule: activity ownership frequency volume (water consumption activities)

```
Antecedents:
and
        = ?file_name_string "alphahardrate"\
        appended ?delimitorRequest "Delimiter for " ?file_name_string\
        = [?delimiter] " "\
        excelTable ?file_name_string ?delimiter ?fContents\
        index ?fContents ?n [?hardware_string ?ownership ?frequency ?volume
?rate]\
        namedInstance ?hardware ConsumptionAppliance ?hardware_string

Consequents:
and
        consumptionActivity ?hardware\
        ownershipFromData ?hardware ?ownership\
        frequencyFromData ?hardware ?frequency\
        volumeFromData ?hardware ?volume\
        replacementRate ?hardware ?rate
```

Comment:
Generates average O-F-V data for each appliance from user defined file

----

Rule: banned appliances (innovation)

```
Antecedents:
and
        sortedList ?hardwareList ?hardware
                ownershipFromData ?hardware ?prob\
        sortedList ?orderedList ?item
                (and
                        includes [3 5 6] ?pos\
                        index ?hardwareList ?pos ?item)\
        notInferred
                = ?orderedList []\
        index ?orderedList ?pos ?appliance\
        printed ?appliance_string ?appliance\
        index ["01/2010" "01/1993" "01/1993"] ?pos ?month_year_string\
        index ?month_year_string ?n </>\
        is ?month_stop ?n - 1\
        is ?year_start ?n + 1\
        subList ?month_string ?month_year_string 1 ?month_stop\
        parsed ?month_string ?month\
        subList ?year_string ?month_year_string ?year_start\
        parsed ?year_string ?year

Consequents:
permanent (ruleSaysNoToAppliance ?appliance ?month ?year)
```

Comment:
Generates a list of appliance that disappear from the market, and the date at which this happens

----

Rule: fixed volume appliances (water consumption activities)

Antecedents:
and
    sortedList ?hardwareList ?hardware
        consumptionActivity ?hardware\
    includes [3 4 5 6 7 8 14] ?pos\
    index ?hardwareList ?pos ?hardware\
    volumeFromData ?hardware ?volume

Consequents:
fixedVolumeAppliance ?hardware ?volume

Comment:
Generates the list of appliance with fixed volume, so recommended volumes will remain fixed

----

Rule: influence weights for agents (parameters)

Antecedents:
and
    = ?gsEnd 10\
    = ?nsEnd 30\
    = ?ssEndn 60

Consequents:
and
    selfInfluenceWeighting ?ssEndn\
    socialInfluenceWeighting ?gsEnd\
    localInfluenceWeighting ?nsEnd

Comment:
Sets the weights for global / local / self influences in the society

----

Rule: maximum memory decay coefficient (parameters)

Antecedents:
= ?coeff 2.5

Consequents:
maxMemoryDecayCoefficient ?coeff

Comment:
Specifies the maximum rate of decay for remembered endorsements.

Rule: new appliance (innovation)

Antecedents:
and
sortedList ?hardwareList ?hardware
ownershipFromData ?hardware ?prob\
comment " first is replaced by second at date"\
= ?list [[2 3 "01/2010"] [6 5 "01/1985"] [5 8 "10/1992"] [8 4 "01/2001"] [8 7 "01/2001"] [7 4 "01/2010"] [11 10 "04/1990"] [13 14 "01/2010"]]\
includes ?list [?old ?new ?date]\
index ?hardwareList ?new ?innovation\
index ?hardwareList ?old ?olditem\
index ?date ?n </>\
is ?month_stop ?n - 1\
is ?year_start ?n + 1\
subList ?month_string ?date 1 ?month_stop\
parsed ?month_string ?month\
subList ?year_string ?date ?year_start\
parsed ?year_string ?year\
= [?olditem] ?replaced

Consequents:
newApplianceReplacedMonthYear ?innovation ?replaced ?month ?year

Comment:
Specifies which appliances can replace which, and at which date. Lists are scenario-specific

For example
Scenario alpha
= ?list [[2 3 "01/2010"] [6 5 "01/1985"] [5 8 "10/1992"] [8 4 "01/2001"] [8 7 "01/2001"] [7 4 "01/2010"] [11 10 "04/1990"] [13 14 "01/2010"]]\

Scenario gamma
= ?list [[2 3 "01/2010"] [6 5 "01/1985"] [5 9 "10/1992"] [9 4 "01/2001"] [9 8 "01/2001"] [8 4 "01/2010"] [12 11 "04/1990"] [14 15 "01/2010"] [4 7 "01/2015"] [5 7 "01/2015"] [6 7 "01/2015"] [8 7 "01/2015"] [9 7 "01/2015"]]\

Rule: private consumption activities (water consumption activities)

Antecedents:

```
and
	sortedList ?hardwareList ?hardware
		consumptionActivity ?hardware\
	sortedList ?private_hardware ?item
		(and
			includes [1 2 13] ?pos\
			index ?hardwareList ?pos ?item)\
	includes ?private_hardware ?hardware
```

Consequents:
privateConsumptionActivity ?hardware

Comment:
Specifies which activities are private so they cannot be observed by neighbours.

Rule: public consumption activities (water consumption activities)

Antecedents:

```
and
	sortedList ?hardwareList ?hardware
		consumptionActivity ?hardware\
	includes [4 5 6 7 8 9 10 11 12] ?pos\
	index ?hardwareList ?pos ?hardware
```

Consequents:
publicConsumptionActivity ?hardware

Comment:
Specifies which activities are public, and can be observed by neighours

----

Rule: semi public consumption activities (water consumption activities)

Antecedents:

```
and
	sortedList ?hardwareList ?hardware
		consumptionActivity ?hardware\
	includes [1 2 3 4 5 6 7 8 10 11] ?pos\
	index ?hardwareList ?pos ?hardware
```

Consequents:
semiPublicConsumptionActivity ?hardware

Comment:
Specifies which activities are semi-public, *i.e.* only part of the information can be known via observation

----

Rule: visibility parameter (parameters)

Antecedents:
= ?visParam 6

Consequents:
visibilityParameter ?visParam

Comment:
Specifies the number of cells agents can see in the cardinal directions

----

Rule: weibull parameters (innovation)

Antecedents:
and

```
        newApplianceReplacedMonthYear ?new [?old] ?month ?year\
        includes [?old] ?appliance\
        printed ?appstring ?appliance\
        appended ?etastring "what is the shape parameter for " ?appstring " ?"\
        = ?eta 1.2\
        appended ?betastring "what is the scale parameter for " ?appstring " ?"\
        = ?beta 35
```

Consequents:
weibullParameters ?eta ?beta ?appliance

Comment:
Specifies the parameters for the Weibull distribution used to test whether an appliance fails.

8. Agent: PilotFirmaModel Rulebase:Initial Iteration

Rule: dryness duration (environment)

Antecedents:
And

```
        at thamesGround (soilWater ?sw)\
        notInferred
                greater ?sw 85\
        (if
                time month 1\
                last year (drynessDuration ?lastDuration)\
                last month (drynessDuration ?lastDuration))\
```

    is ?duration ?lastDuration + 1

Consequents:
all month (drynessDuration ?duration)

Comment:
Increases dryness duration indicator if soil water still under 85%

Rule: dryness duration - none previous (environment)

Antecedents:
and
    at thamesGround (soilWater ?sw)\
    notInferred
        greater ?sw 85\
    notInferred
        (or
            last year (drynessDuration ?lastDuration)\
            last month (drynessDuration ?lastDuration))\
    = ?duration 1

Consequents:
all month (drynessDuration ?duration)

Comment:
Gives value of 1 to dryness duration indicator if dry soil this month, not preceded by dry soil.

Rule: dryness duration = 0 (environment)

Antecedents:
and
    at thamesGround (soilWater ?sw)\
    greater ?sw 85\

Consequents:
all month (drynessDuration 0)

Comment:
Resets dryness duration indicator when soil water is greater than 85%

Rule: garbage collect (housekeeping)

Antecedents:

true

Consequents:
garbageCollection

Comment:
Clearing unused / obsolete objects / variables in cache

9. Agent: PilotFirmaModel Rulebase: Initial Month

--

Rule: citoyen repartition (reporting)

Antecedents:
```
and
        sortedList ?SList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "S"] ?aaa)\
        length ?SList ?Slength\
        sortedList ?GList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "G"] ?aaa)\
        length ?GList ?Glength\
        sortedList ?NList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "N"] ?aaa)\
        length ?NList ?Nlength\
        sortedList ?NSList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "NS"] ?aaa)\
        length ?NSList ?NSlength\
        sortedList ?NGList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "NG"] ?aaa)\
        length ?NGList ?GNlength\
        sortedList ?GSList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "GS"] ?aaa)\
        length ?GSList ?GSlength\
        sortedList ?NGSList ?stg
                (and
                        endRanking ?alist\
                        occurrences ?alist [?stg "NGS"] ?aaa)\
```

```
        length ?NGSList ?NGSlength\
        = ?aaares ["G" ?Glength "GN" ?GNlength "N" ?Nlength "NS" ?NSlength "S"
?Slength "GS" ?GSlength "NGS" ?NGSlength]
```

Consequents:
all run (citRepart ?aaares)

Comment:
Stores the repartition of highest endorsements for all categories of agents
----

Rule: endorsement ranking report (reporting)

Antecedents:

```
sortedList ?alist [?cit ?res]
        and
                citGNS ?cit ?G ?N ?S\
                = ?list [?G ?N ?S]\
                includes ?list ?compo\
                max ?max ?G ?N ?S\
                = ?compo ?max\
                (or
                        (and
                                greater ?G ?N\
                                (or
                                        (and
                                                greater ?G ?S\
                                                = ?res "G")\
                                        (and
                                                = ?G ?S\
                                                = ?res "GS")\
                                        (and
                                                greater ?S ?G\
                                                = ?res "S")))\
                        (and
                                greater ?N ?G\
                                (or
                                        (and
                                                greater ?N ?S\
                                                = ?res "N")\
                                        (and
                                                greater ?S ?N\
                                                = ?res "S")\
                                        (and
                                                = ?S ?N\
                                                = ?res "NS")))\
                        (and
                                = ?G ?N\
                                (or
                                        (and
```

```
                                        greater ?N ?S\
                                        = ?res "NG")\
                                (and
                                        greater ?S ?N\
                                        = ?res "S")\
                                (and
                                        = ?S ?N\
                                        = ?res "NGS"))))
```

Consequents:
all run (endRanking ?alist)

Comment:
Provides the highest society endorsement for every agent

Rule: list of links NT (reporting)

Antecedents:

```
sortedList ?slist [?me ?result]
        and
                time year 1980\
                activeSubAgent ?act\
                isKindOf ?act Citoyen\
                at ?act (and
                        = ?me ?act\
                        visibilityParameter ?view\
                        location ?x ?y ?me\
                        gridExtent ?xtop ?ytop\
                        is ?xmax ?x + ?view\
                        is ?xmin ?x - ?view\
                        is ?ymax ?y + ?view\
                        is ?ymin ?y - ?view\
                        sortedList ?result ?who
                                (and
                                        inInterval ?xInt ?xmin ?xmax\
                                        inInterval ?yInt ?ymin ?ymax\
                                        notInferred
                                                less ?xInt 0\
                                        notInferred
                                                less ?yInt 0\
                                        (or
                                                (and
                                                        cellOccupiedBy ?xInt ?y ?who\
                                                        notInferred
                                                                = ?xInt ?x)\
                                                (and
                                                        cellOccupiedBy ?x ?yInt ?who\
                                                        notInferred
                                                                = ?yInt ?y))))
```

Consequents:
canSeeNT ?slist

Comment:
Returns the list of links for non-toroidal grid

Rule: list of links T (reporting)

Antecedents:

```
sortedList ?links [?me ?result]
        and
                time year 1980\
                activeSubAgent ?act\
                isKindOf ?act Citoyen\
                at ?act (and
                        = ?me ?act\
                        visibilityParameter ?view\
                        location ?x ?y ?me\
                        gridExtent ?xtop ?ytop\
                        is ?xmax ?x + ?view\
                        is ?xmin ?x - ?view\
                        is ?ymax ?y + ?view\
                        is ?ymin ?y - ?view\
                        is ?xtopminus ?xtop - 1\
                        is ?ytopminus ?ytop - 1\
                        sortedList ?result ?who
                                (and
                                        inInterval ?intxm ?xmin ?x\
                                        (or
                                                (and
                                                        less ?intxm 0\
                                                        is ?xIntm ?intxm + ?xtop)\
                                                (and
                                                        notInferred
                                                                less ?intxm 0\
                                                        is ?xIntm ?intxm))\
                                        inInterval ?intym ?ymin ?y\
                                        (or
                                                (and
                                                        less ?intym 0\
                                                        is ?yIntm ?intym + ?ytop)\
                                                (and
                                                        notInferred
                                                                less ?intym 0\
                                                        is ?yIntm ?intym))\
                                        inInterval ?intyt ?y ?ymax\
                                        (or
```

```
                    (and
                        notInferred
                            greater ?intyt ?ytopminus\
                        is ?yIntt ?intyt)\
                    (and
                        greater ?intyt ?ytopminus\
                        is ?yIntt ?intyt - ?ytop))\
                inInterval ?intxt ?x ?xmax\
                (or
                    (and
                        notInferred
                            greater ?intxt ?xtopminus\
                        is ?xIntt ?intxt)\
                    (and
                        greater ?intxt ?xtopminus\
                        is ?xIntt ?intxt - ?xtop))\
                (or
                    (and
                        (or
                            cellOccupiedBy ?xIntm ?y
?who\
                            cellOccupiedBy ?xIntt ?y
?who)\
                        notInferred
                            = ?who ?me)\
                    (and
                        (or
                            cellOccupiedBy ?x ?yIntt ?who\
                            cellOccupiedBy ?x ?yIntm
?who)\
                        notInferred
                            = ?who ?me))))
```

Consequents:
canSeeT ?links

Comment:
Returns the list of links for a toroidal grid

Rule: matrix of links NT (reporting)

Antecedents:

```
and
    time year 1980\
    canSeeNT ?list\
    sortedList ?all ?ag
        (and
            activeSubAgent ?ag\
```

```
                        isKindOf ?ag Citoyen)\
        maxValue ?nbAgents ?ind
                index ?all ?ind ?c1\
        sortedList ?pl2 ?p2
                (and
                        inInterval ?i 1 ?nbAgents\
                        index ?all ?i ?c1\
                        sortedList ?pl ?pair
                                (and
                                        inInterval ?j 1 ?nbAgents\
                                        index ?all ?j ?c2\
                                        (if
                                                (and
                                                        includes ?list [?c1 ?l]\
                                                        includes ?l ?c2)\
                                                = ?ent 1\
                                                = ?ent 0)\
                                        = ?pair [?j ?ent])\
                        mappedList ?row ?pl second\
                        = ?p2 [?i ?row])\
        mappedList ?mat ?pl2 second
```

Consequents:
all run (matrixOfLinksNT ?mat)

Comment:
Returns the matrix of links for a non-toroidal grid

Rule: matrix of links T (reporting)

Antecedents:

```
and
        time year 1980\
        canSeeT ?list\
        sortedList ?all ?ag
                (and
                        activeSubAgent ?ag\
                        isKindOf ?ag Citoyen)\
        maxValue ?nbAgents ?ind
                index ?all ?ind ?c1\
        sortedList ?pl2 ?p2
                (and
                        inInterval ?i 1 ?nbAgents\
                        index ?all ?i ?c1\
                        sortedList ?pl ?pair
                                (and
                                        inInterval ?j 1 ?nbAgents\
                                        index ?all ?j ?c2\
```

```
                    (if
                        (and
                            includes ?list [?c1 ?l]\
                            includes ?l ?c2)\
                        = ?ent 1\
                        = ?ent 0)\
                    = ?pair [?j ?ent])\
            mappedList ?row ?pl second\
            = ?p2 [?i ?row])\
    mappedList ?mat ?pl2 second
```

Consequents:
all run (matrixOfLinks ?mat)

Comment:
Returns the matrix of links for a toroidal grid

Rule: report citoyen endorsements (reporting)

Antecedents:

```
and
    finalYear ?year\
    endsOf ?cit ?scheme ?list ?base\
    printed ?schemeName ?scheme\
    appended ?schemeName "actionEndorsementScheme" ?rest\
    sortedList ?slist [?end ?val]
        (and
            includes ?list [?end ?val]\
            printed ?endName ?end\
            (or
                (and
                    appended ?endName "selfSourced" ?rest\
                    is ?res ?val)\
                (and
                    appended ?endName "neighbourhoodSourced"
?rest\
                    is ?res ?val)\
                (and
                    appended ?endName "globallySourced" ?rest\
                    is ?res ?val)))\
    = ?slist [[?G ?Gval] [?N ?Nval] [?S ?Sval]]
```

Consequents:
all run (citGNS ?cit ?Gval ?Nval ?Sval)

Comment:
Returns the endorsements of an agent regarding society

10. Agent: PilotFirmaModel Rulebase: Initial Year

Rule: citizens (agents)

```
Antecedents:
and
	gridExtent ?xDim ?yDim\
	is ?maxX ?xDim - 1\
	is ?maxY ?yDim - 1\
	randomList ?coordinatesList [?x ?y] (wrt [run year] cellOccupiedBy Citoyen)
		(and
			inInterval ?x 1 ?maxX\
			inInterval ?y 1 ?maxY)\
	is ?maxCit ?xDim * ?yDim\
	printed ?maxCitString ?maxCit\
	appended ?question "Enter the initial population of citizens (" ?maxCitString "
unoccupied cells):"\
	= ?numCitizens 20\
	notInferred
		greater ?numCitizens ?maxCit\
	inInterval ?agentID 1 ?numCitizens\
	index ?coordinatesList ?agentID [?x ?y]\
	generatedInstance ?citoyen Citoyen ?agentID

Consequents:
all run (and
	activeSubAgent ?citoyen\
	cellOccupiedBy ?x ?y ?citoyen\
	at ?citoyen (gridLocation ?x ?y))
```

Comment:
The initial population of instances of Citoyen are distributed randomly about the grid. The maximum number of citoyens is the number of cells in the grid.

Rule: frequency pareto coefficient (parameters)

```
Antecedents:
and
	numberOfPatterns ?pop
		(and
			activeSubAgent ?agent\
			isKindOf ?agent Citoyen)\
	volumeFromData ?hardware ?mean_vol\
	total ?denom ?x
		(and
			inInterval ?r 1 ?pop\
```

ln ?x ?r)\
is ?alpha ?pop * (ln ?mean_vol) / ?denom

Consequents:
all run (volumeParetoCoefficient ?hardware ?alpha)

Comment:
The value of alpha is calculated on the assumption that the frequencies and volumes for the different types of hardware is the geometric mean of the populations of values. consequently,

mn = (product of rank ^ alpha)^ (1/n)

where n is the number of citizens.

Taking the logs:

ln mn = (alpha/n) * sum(ln r)

and

alpha = (n*ln mn) / (sum ln r)

Rule: location (agents)

Antecedents:
and
activeSubAgent ?iamAgent\
isKindOf ?iamAgent IAMAgent\
notInferred
isKindOf ?iamAgent PolicyAgent\
cellOccupiedBy ?x ?y ?iamAgent

Consequents:
all run (location ?x ?y ?iamAgent)

Comment:
Helps determining agent and its location, to be used in later rules

----

Rule: network output file name (parameters)

Antecedents:
and
time run 0\
userRequestedString ?string "what is the name of the file for network configuration" "net.txt"

Consequents:
permanent (netOutputFileName ?string)

Comment:
User inputs the filename for saving network structure

Rule: output file name (parameters)

Antecedents:
and
    time run 0\
    userRequestedString ?string "what is the name of the file" "filename.txt"

Consequents:
permanent (outputFileName ?string)

Comment:
User inputs the filename for saving water use data

Rule: policy agent (agents)

Antecedents:
generatedInstance ?policyAgent PolicyAgent true

Consequents:
all run (activeSubAgent ?policyAgent)

Comment:
Generates one instance of policy agent

Rule: volume pareto coefficient (parameters)

Antecedents:
and
```
        numberOfPatterns ?pop
                (and
                        activeSubAgent ?agent\
                        isKindOf ?agent Citoyen)\
        volumeFromData ?hardware ?mean_vol\
        frequencyFromData ?hardware ?mean_freq\
        total ?denom ?x
                (and
                        inInterval ?r 1 ?pop\
                        ln ?x ?r)\
```

is ?vol_alpha ?pop * (ln ?mean_vol) / ?denom\
is ?freq_alpha ?pop * (ln ?mean_freq) / ?denom

Consequents:
all run (and
volumeParetoCoefficient ?hardware ?vol_alpha\
frequencyParetoCoefficient ?hardware ?freq_alpha)

Comment:
The value of alpha is calculated on the assumption that the frequencies and volumes for the different types of hardware is the geometric mean of the populations of values. consequently,

mn = (product of rank ^ alpha)^ (1/n)

where n is the number of citizens.

Taking the logs:

ln mn = (alpha/n) * sum(ln r)

and

alpha = (n*ln mn) / (sum ln r)

11. Agent: PilotFirmaModel Rulebase: Final Iteration

Rule: consumption report (reporting)

Antecedents:
and
time run ?run\
finalYear ?now\
time year ?now\
time month 12\
totalCitoyenConsumption ?year ?month ?cons\
comment "**********removed to keep 4 digit year
mod ?two_digit_year ?year 100\
printed ?yearString ?two_digit_year\
*******************"\
printed ?yearString ?year\
printed ?monthString ?month\
appended ?dateString ?monthString "/" ?yearString\
= ?result [?run "total" ?dateString ?cons]

Consequents:
reportNumeric totalTranscript ?result

Comment:
Generates a list containing date and water use

12. Agent: PilotFirmaModel Rulebase: Final Year

Rule: network report (reporting)

Antecedents:
and
time run ?now\
time month 1\
matrixOfLinks ?l\
matrixOfLinksNT ?ln\
= ?result [?now ["NT" ?ln] ["T" ?l]]

Consequents:
reportNumeric networkTranscript ?result

Comment:
Generates file with matrices of links for current network

Agent: PolicyAgent Rulebase: Content

Rulebase: Influence (Olivier runs 1.3p*)>PolicyAgent (content)

Rule: deepening drought rule (policy rules)

Antecedents:
and
```
time iteration 1\
drynessDuration ?duration\
greater ?duration 2\
comment "*************************************************
        make sure drought is deepening
*********************************************************"\
at thamesGround (and
        maxSoilWater ?maxSW\
        soilWater ?current_sw\
        last month (soilWater ?last_sw))\
less ?current_sw ?last_sw\
is ?policyRatio (sqrt ?current_sw / ?maxSW)\
environmentalState ?es\
comment "holding action"\
(or
        publicConsumptionActivity ?activity\
        privateConsumptionActivity ?activity)\
```

```
	mostRecent year ?y (mostRecent month ?m (and
		drynessDuration 0\
		randomList ?cData [?f ?c] (wrt [run year month iteration] average
activityFrequencyVolume)
			at self@^ (and
				activeSubAgent ?agent\
				isKindOf ?agent Citoyen\
				at ?agent (activityFrequencyVolume ?activity ?f ?c))))\
	average ?baseF ?f
		includes ?cData [?f ?c]\
	average ?baseC ?c
		includes ?cData [?f ?c]\
	comment "**************************************************
		make sure there is no increase in either frequency
		or consumption per event
	**********************************************************"\
	last month (policyAction self ?action (activityFrequencyVolume ?activity
?last_policyF ?last_policyC))\
	is ?policyF (rounded (min ?last_policyF ?policyRatio * ?baseF))\
	is ?policyC (min ?last_policyC ?policyRatio * ?baseC)\
	generatedInstance ?newAction Action (activityFrequencyVolume ?activity
?policyF ?policyC)
```

Consequents:
all month (policyAction self ?newAction (activityFrequencyVolume ?activity ?policyF ?policyC))

Comment:
When current soil water is less than last month's soil water, drought rules deepen

----

Rule: final iteration - no policy rule (time management)

Antecedents:

```
and
	time iteration 1\
	notInferred
		policyAction self ?action (activityFrequencyVolume ?activity ?policyF
?policyC)
```

Consequents:
final iteration

Comment:
Time check

Rule: final iteration - policy rule issued (time management)

Antecedents:
policyAction self ?action (activityFrequencyVolume ?activity ?policyF ?policyC)

Consequents:
final iteration

Comment:
Time check

Rule: first drought rule (policy rules)

Antecedents:
```
and
	time iteration 1\
	drynessDuration 2\
	at thamesGround (and
		maxSoilWater ?maxSW\
		soilWater ?sw)\
	is ?policyRatio (sqrt ?sw / ?maxSW)\
	comment "holding action"\
	(or
		publicConsumptionActivity ?activity\
		privateConsumptionActivity ?activity)\
	mostRecent year ?y (mostRecent month ?m (and
		drynessDuration 0\
		randomList ?cData [?f ?c] (wrt [run year month iteration] average
activityFrequencyVolume)
				at self@^ (and
					activeSubAgent ?agent\
					isKindOf ?agent Citoyen\
					at ?agent (activityFrequencyVolume ?activity ?f ?c))))\
	average ?baseF ?f
		includes ?cData [?f ?c]\
	average ?baseC ?c
		includes ?cData [?f ?c]\
	is ?policyF (rounded ?policyRatio * ?baseF)\
	is ?policyC ?policyRatio * ?baseC\
	generatedInstance ?action Action (activityFrequencyVolume ?activity ?policyF
?policyC)
```

Consequents:
all month (policyAction self ?action (activityFrequencyVolume ?activity ?policyF ?policyC))

Comment:
Establish a policy rule when the dryness duration is 2.

Rule: lessening drought rule (policy rules)

Antecedents:
and
```
        time iteration 1\
        drynessDuration ?duration\
        greater ?duration 2\
        at thamesGround (and
                maxSoilWater ?maxSW\
                soilWater ?current_sw\
                last month (soilWater ?last_sw))\
        notInferred
                less ?current_sw ?last_sw\
        last month (policyAction self ?action (activityFrequencyVolume ?activity
?policyF ?policyC))
```

Consequents:
all month (policyAction self ?action (activityFrequencyVolume ?activity ?policyF ?policyC))

Comment:
When current soil water is not less than last month's soil water, use last policy rule.

13. Agent: PolicyAgent Rulebase: Initial Month

Rule: deepening drought rule (policy rules)

Antecedents:
and
```
        drynessDuration ?duration\
        greater ?duration 2\
        comment "************************************************
                make sure drought is deepening
        ************************************************************"\
        at thamesGround (and
                maxSoilWater ?maxSW\
                soilWater ?current_sw\
                last month (soilWater ?last_sw))\
        less ?current_sw ?last_sw\
        is ?policyRatio (sqrt ?current_sw / ?maxSW)\
        environmentalState ?es\
        comment "holding action"\
        (or
                publicConsumptionActivity ?activity\
                privateConsumptionActivity ?activity)\
        mostRecent year ?y (mostRecent month ?m (and
```

```
			drynessDuration 0\
			randomList ?cData [?f ?c] (wrt [run year month iteration] average
activityFrequencyVolume)
					at self@^ (and
						activeSubAgent ?agent\
						isKindOf ?agent Citoyen\
						at ?agent (activityFrequencyVolume ?activity ?f ?c))))\
		average ?baseF ?f
			includes ?cData [?f ?c]\
		average ?baseC ?c
			includes ?cData [?f ?c]\
		comment "************************************************
			make sure there is no increase in either frequency
			or consumption per event
		**********************************************************"\
		last year (policyAction self ?action (activityFrequencyVolume ?activity
?last_policyF ?last_policyC))\
		is ?policyF (rounded (min ?last_policyF ?policyRatio * ?baseF))\
		is ?policyC (min ?last_policyC ?policyRatio * ?baseC)\
		generatedInstance ?newAction Action (activityFrequencyVolume ?activity
?policyF ?policyC)
```

Consequents:
all month (policyAction self ?newAction (activityFrequencyVolume ?activity ?policyF ?policyC))

Comment:
When current soil water is less than last month's soil water, drought rules deepen

----

Rule: lessening drought rule (policy rules)

Antecedents:

```
and
		drynessDuration ?duration\
		greater ?duration 2\
		at thamesGround (and
			maxSoilWater ?maxSW\
			soilWater ?current_sw\
			last year (soilWater ?last_sw))\
		notInferred
			less ?current_sw ?last_sw\
		last month (policyAction self ?action (activityFrequencyVolume ?activity
?policyF ?policyC))
```

Consequents:
all month (policyAction self ?action (activityFrequencyVolume ?activity ?policyF ?policyC))

Comment:
current soil water is not less than last month's soil water. Use current environmental state with last policy rule's consequents

14. Agent: ThamesWorld Rulebase: Content

Rule: final month (time management)

Antecedents:
and
    noOfMonths ?m\
    time month ?m

Consequents:
final month

Comment:
Time check

15. Agent: ThamesWorld Rulebase: Initial Eternity

Rule: subagents (setting up)

Antecedents:
true

Consequents:
activeSubAgents [thamesGround firmaModel]

Comment:
Activates two kinds of subagents

Rule: time levels (setting up)

Antecedents:
true

Consequents:
timeLevels [run year month]

Comment:
Activates time steps in the simulation.

16. Agent: ThamesWorld Rulebase: Initial Month

Rule: final year (time management)

Antecedents:
and
    time year ?year\
    finalYear ?year

Consequents:
all year (final year)

Comment:
Time check

17. Agent: UniversalAgent Rulebase: Initial Eternity

Rule: model (set up)

Antecedents:
true

Consequents:
activeSubAgent thamesWorld

Comment:

Activates subAgent to start building SDML model

18. Agent: Citoyen Rulebase: Initial Year

Rule: create meta (meta agent)

Antecedents:
true

Consequents:
all run (metaAgent citoyenMeta)

Comment:
Creates a meta agent valid for the whole run

Rule: net report (transcript setup)

Antecedents:
netOutputFileName ?string

Consequents:
reportToTextFile networkTranscript ?string

Comment:
Uses a predefined string as the name for output file containing representation of the network for the simulation

----

Rule: report (transcript setup)

Antecedents:
outputFileName ?string

Consequents:
reportToTextFile totalTranscript ?string

Comment:

Uses a predefined string as the name for output file containing water consumption and dates for the simulation

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