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.