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# Group and Societal Decision Making: an exploration of modelling paradigms applied to nuclear facility siting

by

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[1] LaTeX $2_\varepsilon$ is an extension of LaTeX. LaTeX is a collection of macros for TeX. TeX is a trademark of the American Mathematical Society. The style package *warwickthesis* was used.

# Declarations

The work contained within this thesis is original work conducted by myself with support from my supervisors Prof. Simon French and Prof. Jim Q. Smith, unless specified otherwise in the text or the following list of publications arising from this thesis.

## Journal Submissions

Influence of Group Members in Multi-Attribute Utilities (accepted Autumn 2016)
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Siting a Geological Disposal Facility - a System Dynamics approach to modelling public response (submitted Spring 2016)
Journal of the Operational Research Society

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# Abstract

This thesis has explored the area of group and societal decision making applied to nuclear facility siting problems, and some of the common modelling paradigms used to assist decision makers (either to enhance understanding or serving as a vehicle to compare potential alternatives). We have explored common issues and the history surrounding the construction of decision support systems, and identified potential modelling paradigms that could be used to assist decision makers in our facility siting setting.

In the area of utilities, we investigate measuring the influence of some group members on others in decision making. Being better able to identify potentially influential behaviour would be useful in supporting and subsequently auditing a decision. A new measure of the influence of individuals is given, which is analogous to the well-known Cook's distance used to identify influential data in regression. The theoretical properties of this measure are explored. A simple method to identify sub-groups within the group of decision makers is given. We investigate the efficiency of our new measures using large scale randomised studies. We use these measures to identify sub-groups of individuals with similar beliefs in a data set collected in a previous experiment.

In the areas of system dynamics and discrete event simulation, we have constructed models of public response to the UK government's request for volunteer communities to host a Geological Disposal Facility (GDF) for nuclear waste in the 2009-2013 siting process. We create models in each paradigm to explore the influential factors behind Cumbria's withdrawal from the process in early 2013 based on opinion surveys during the 4 year public deliberation. We have considered the suitability of each paradigm as a modelling process for public response and deliberation, and explore whether the extension of the decision deadline requested by the councils could have biased the process. Our approach models the interactions between the 3 key stakeholder groups we included: the general public, the MRWS Partnership and Non-Governmental Organisations (NGOs). We show that a decision deadline extension may have biased the process. Additionally, we contrast the strengths and weaknesses of each model and paradigm both generally, and for our specific scenario through response analysis to a selection of alternative scenarios.

# Chapter 1

# Introduction

## 1.1 Decision Making

Decision making has always been an important part for an individual's life both inside and outside of the workplace (Raiffa et al 2002). In particular, it is common to make decisions more subconsciously than consciously. Subconscious decision making can leave individuals with little information about why they made their decision and potential alternatives. In simple cases, this often produces the 'correct' decisions for the individual. However, it relies on the assumption that the individual has all the required skills and insight to make an informed and rational decision. Often, this is not an issue in such simple cases. However, when this kind of decision making is expanded to more significant and complex problems, it becomes less likely to produce an informed analysis of the alternatives available. A potential explanation could be due to the individual being unaware that they do not understand some factors or alternatives of the decision at hand.

Uninformed decision making is one of the primary reasons for attempting to move decisions onto a more conscious level with a structured framework (such as utility functions, Dyer & Forman 1992). This allows the decision maker to assess their own level of knowledge and identify any factors which they may have initially missed, but which become clearer when the problem is described in a structured way. Making decisions in this way ensures that the decision makers are more informed, and can provide a strong basis for others to evaluate these decisions. The magnitude of this improvement is going to depend on many factors (e.g. the decision maker, the framework and tools used, familiarity with the topic), which a decision analyst tasked with supporting the decision maker has a varying level of control over.

A decision analyst must be able to evaluate these factors. However, the factor they have

most influence over is the framework and tools to be used to model the decision (DeSanctis & Gallupe 1987). This can be altered to suit the other factors. For instance, one decision maker may prefer to use simulation models, while another may prefer to use utility theory for the same decision. Because of this I must consider and develop a variety of potential tools and frameworks to assist in decision making, and understand where each is most applicable.

To fully understand the implications of each of these decision frameworks I needed a suitable scenario to explore. I focused on public participation within nuclear facility siting. This area has seen increasing interest, particularly within the UK, due to the movement away from traditional fossil fuel power and addressing the growing concern of the amount of nuclear waste being produced. Therefore I considered the area to be highly relevant to the current times, particularly in reference to siting a geological disposal facility for which a new public deliberations process is expected to start within the next few years. See Chapter 4 for more detail about this recent proposal, and the previous stalled siting process in Cumbria between 2009 and 2013.

This thesis focuses on ways to model public participation using the Cumbrian siting process as a specific context, while also considering the question of influence of deliberation structures and individuals. The modelling paradigms I have considered in detail are: utility theory (e.g. Keeney 1976), system dynamics (e.g. Sterman 2000) and discrete event simulation (e.g. Brailsford et al 2014). In each case, I explored some aspect of public participation in nuclear facility siting. My utility theory application had a larger focus on influential individuals and pressure group identification. While system dynamics and discrete event simulation were used to construct models of public response to the government siting proposal. These models could allow organisers to explore how different deliberation structures could have biased the process unfairly.

Utility theory and simulation modelling can be considered as quite different spheres of decision making. However, it is important to a decision analyst to understand a variety of methodologies, so that they can make a more informed decision on the 'correct' framework to use for the decision maker's scenario. This may bring into question of how a decision analyst would then apply an appropriate framework (consciously or subconsciously) for their choice of decision framework. However this moves into an area of meta-decision making I do not want to get distracted by given it could be worthy of a thesis of its own.

## 1.2 Objectives

With this general description of decision making and my overall aim of the thesis in mind, I present several more specific objectives. These objectives are revisted throughout the thesis in their relevant Chapters.

**Objective 1** *Explore past structures of decision support processes and several potential decision structure candidates for application to my area of interest in modelling public participation.*

My first objective was to understand the most important aspects of decision support processes, and how these might impact my models for public participation in nuclear facility siting. There were several distinct areas I needed to explore. The first was to explore how decision support processes (with a focus on software implementations) have evolved over time, with particular interest in the role group selection and interactions can play. Secondly, I needed to identify several potential models I could implement to assist decision making in public participation scenarios. The potential models I investigated were; utility theory, system dynamics and discrete event simulation (alongside considering other modelling paradigms seen in Chapter 4). Finally, I needed to explore how these two components tended to interact. Particularly in the past two decades where such modelling techniques were becoming more common in decision making. At this point I highlight my difference in meaning between decision processes and decision structures. I use the term process when referring to the overall aim of the paradigm. Structure, however, refers to the details of how this process is applied in practice. This objective allowed me to have a strong understanding of the options available to me, and how to best develop my own models for decision assistance.

**Objective 2** *Understand where the ideas of influential individuals, groups or scenarios would fit into each of these decision structures, and where appropriate develop new methodologies to provide a measure of this influence.*

With my decision structures established, I also wanted to consider how the idea of influence had been explored or could be developed. I have provided my definitions of influence in Chapter 3. In a more general sense, I sought to provide a measure that could answer the questions; could anyone in this decision making group be exerting considerable (and possibly unexpected) influence over the group's beliefs, and could there be members of the decision making group that are working together in secrecy? Both these questions are important to ask when making decisions in groups, particularly when there is a lack of trust between group members. However there are few tools available to help answer these

questions. I also considered the feasibility of extending some of these types of measure to the other methodologies I considered, although this appeared to be not very informative.

**Objective 3** *Apply each decision structure considered to data or a real-life scenario related to public participation in nuclear facility siting.*

My third objective was to demonstrate how each decision structure could be used to assist in decision making design related to public participation in nuclear facility siting. My aim was to assess how helpful it could be when applied to a real scenario. What I mean by 'helpful' here depends upon the decision structure I are considering. For instance in utility theory identifying influential individuals or groups could be particularly useful. However in system dynamics and discrete event simulation then identification of changing trends over time in response to differing deliberation structures could be useful. These applications placed me in a good position to provide a fair and informed evaluation of each decision structure.

**Objective 4** *Evaluate the differences of these decision structures with regards to these applications*

This objective focuses on the benefits my work can provide. In particular my aim was to provide a suggestion for how to best model upcoming public participation structures, using the experience I have gathered from my work in the area. I focussed on several characteristics of model building here, and evaluated each simulation methodology against these characteristics. Utility theory was excluded at this stage due to the difficulty of implementation for large scale planning in comparison to my other decision structures. This work provides a basis for those interested in using more informed decision making tools in this area to explore the strengths and weaknesses of the decision structures I considered.

**Objective 5** *Consider evolutions of these decision structures that use a strong probabilistic model such as a Bayesian Network.*

In terms of future work, I have specifically focussed on the links between the more traditional modelling methods I used (system dynamics and discrete event simulation) and a more recent probabilistic modelling technique known as Bayesian networks. Expanding these modelling methods to include or be associated with Bayesian networks could help improve validation techniques, as it provides a strong basis to explore the probabilistic side of any models that are produced. In particular it gives a specific set of conditional probabilities that can be checked by the model builders and experts in the field, to assist in building confidence in the model. Expanding methods of validation, while improving the predictive power of traditional modelling techniques is a suitable improvement to chase. I intended to lay some of the groundwork to start exploring this area.

## 1.3 Methods for Evaluating Group Decisions and Opinion Dynamics

Group decision support covers a wide area of research that has become more popular in practical applications over the past few decades. This support can come in many different forms. For example, systems developed specifically for decision support, or models used to aid decision making and understanding. I have focussed primarily on the latter of these forms. However, my literature review includes a consideration of support systems as well. Both businesses and governments have had an increasing interest in methods able to assist their standard decision making processes. Implementing these methods into real life scenarios has become more challenging. Groups of decision makers are more spread out, both temporally and spatially, due to globalisation. This makes it difficult for groups of decision makers to have face-to-face meetings, which is the preferred meeting format by both decision makers and analysts.

This gave increased reliance on software that can function as a decision analyst for a group which preferably does not require them to be all in the same room. Several such systems are in wide use, such as ThinkTank[1] and Logical Decisions[2]. However the fundamentals of these pieces of software (and perhaps the decision process as a whole) could be considered outdated. The decision process has often focused on a sole decision maker. This can lead to confusion about where a group fits into the framework. For example, I often seek exactly one utility function to evaluate each of the possible outcomes of a decision regardless of whether there is a single decision maker or a group of decision makers.

My initial focus was on the exploration of potential changes to the decision process that better incorporate some of the natural characteristics seen in groups that has been thus far ignored. In particular, I have explored the inclusion of both trust between individuals in the group and personality of group members. The main obstacle I faced was that much of the literature is qualitative, and few strong and suitable models have been produced. This led me to ask the question: what would be best to introduce to the decision process and how exactly would I measure it? For instance, there are many methods that have been developed by psychologists for measuring personalities (e.g. Revised NEO Personality Inventory as seen in McCrae & Costa (2010)). However, the process should be kept as simple as possible. Many of the personality measurements require additional tests at the start of the process and so would be unsuitable for general use.

I first examined what the end result of the decision process should be. For a single decision

[1] http://www.groupsystems.com/
[2] http://www.logicaldecisions.com

maker this is simple: utility values for each alternative. In group decision making, while it is common that all of the group members have the same objective, it is not always the case. One solution would be to explore both the utility of the suggested option, and also some other variable of interest such as the acceptability of the suggestion. This would hold several similarities with consensus decision making. Applications could include scenarios with decision maker conflicts. It is unlikely that using the current utility process would produce a useful suggestion agreed by all parties. For example, while a suggested solution may be acceptable to both parties, additional benefits on top of each parties acceptance criteria could be incredibly biased.

While ample work has been done in the area of conflict in game theory, it has been relatively unexplored in the area of group decision support. Issues that could arise from this could be: arguments between decision makers over their likelihood and benefits analysis of an outcome, or experts providing judgements that are conflicted by other experts or the decision makers. I could use a naive method of combining two judgements of probabilities into one, however this is unlikely to be representative of the actual situation. Additionally, group members may act covertly to secure a stronger position which can have a significant impact on the result of the decision. I have developed a possible adaptation to the current method that provides a measure of how influential each group member may have been over the decision process. This type of adaptation reduces the reliance on having an analyst present when using decision support software. Flexibility needs to be contained within the software and methods used as opposed to the analyst that is assisting in the software's use.

Given the focus on group decisions, and the dynamics involved, the other major area that needs to be considered is opinion dynamics. This is an area that is important in Chapter 4 and onwards. Understand how opinions can form (e.g. Gerard & Orive 1987) is key to being able to develop later models of opinion change. In particular, it allows identification of key influencers of public opinions (e.g. the media, Gamson & Modigliani 1989) to develop more representative models. A historical review can be seen in Xia et al (2013). See Chapter 2 for a general literature review on group decision making and opinion dynamics.

## 1.4 Construction of a Decision

There are many different ways that a decision problem can be structured, and often the best choice for how to structure the problem is scenario specific. I have focussed on two main types of decision structuring: utility theory and simulation models. Utility theory was my initial focus, and I hoped to explore the possibility of identifying influential or colluding group members in order to assist decision makers understand the dynamic within the group.

However, I decided to diversify the frameworks I considered, as the assumptions required for my technologies for group utilities were quite restrictive. Using system dynamics (SD) and discrete event simulation (DES) allowed me to explore some more specific scenarios for which I had access to additional data.

While the simulation-based paradigms are considerably different in structure to utilities, they are all potential decision frameworks and so worth investigating. This diversification between these three methods also gave me a strong understanding of the strengths and weaknesses of each paradigm. Throughout the rest of this section I give a brief overview of each paradigm considered, along with some initial conclusions. Keep in mind though that my developments in utility theory had been applied to a different aspect of nuclear facility siting than the simulation paradigms (this included a different dataset).

### 1.4.1 Utility Theory

My first hypothetical scenario was a situation where there were several competing sides attempting to agree to a decision that would be mutually beneficial (for instance division of an oilfield to two companies that discovered it independently). Both sides would wish to appear very truthful to the other party. However there is a strong incentive to misrepresent beliefs in order to get a more beneficial agreement without the other party knowing. I sought to provide a technology that could be applied to this situation to provide some measure of how influential each side was trying to be over the group decision. A high influence could indicate misrepresentation of beliefs and prompt further investigation into the allegations. To do this I decided to develop these technologies in the strong technical framework of utility theory.

Utility theory essentially aims to describe an individual's (or group's) preferences over a set of pre-defined attributes in order to improve understanding of the situation and rank potential alternatives. The strength of these preferences can then be elicited to provide a function that describes the individual's (or group's) utility (or perceived benefit/profit) over any given set of values for the attributes. This could then be used in assessing the strength of each potential alternative available to the individual (or group) by inputting the relevant values of attributes. This type of paradigm is usually used to de-construct a decision problem in a formal way to provide clarity for public reporting on decision making.

The technologies I constructed depended on a specific group structure, and their common agreement to use the same decision framework to construct the problem. In particular I assumed that each individual in the group could provide their own individual utility function (their preferences) over a common set of attributes. These individual utility functions

would then be combined into a single group utility function according to some group decision operation that has been agreed by the group. These type of restrictions were quite severe, specifically as eliciting individual utility functions could take quite a long time, for both the facilitator and the individuals. However, in important decisions it may be possible to convince smaller groups to do this, and also I could explore scenarios with automatic elicitation of preferences such as an online study.

I suggested two technologies to assist decision makers that fell under these conditions for group setup. The first was an individual influence measure that was initially inspired by Cook's Distance, which is commonly used in regression. I explored several ways of constructing this measure, such as using different measures of distance between probability distributions. My second technology was the adjusted $R^2$ value, which again drew inspiration from $R^2$ used in regression. My adjusted version of this provided me with a crude measure of whether a set of individuals within the group could have been colluding and attempting to change the group's preferences unfairly. Both of these technologies demonstrated strong results from both my randomised studies, and when applied to a data set exploring public preferences towards issues surrounding the construction of a new nuclear facility.

### 1.4.2 System Dynamics

Following the more general application of my utility theory technologies, I moved to a more specific scenario and explored the usage of different simulation modelling paradigms. In particular, I aimed to develop models based on the previous geological disposal facility (GDF) siting process performed by the UK government between 2009-2013, which ended with a rejection from the councils involved. My aim was to provide a model that could be used to explore public response to the different deliberation structures that could be enacted by the MRWS Partnership (that were championing for the UK government), and so the output of the model was the support levels within each community for the siting proposal. This type of model was expected to contain large amounts of feedback interactions. I explored how well SD (which is well-known for its feedback capabilities) could be used to capture this scenario.

System dynamics is a deterministic modelling paradigm traditionally applied to high-level decision making where information on individual units are not as important. This is important because in SD I lose all information about these individual units because I model general movements from one state of the system to another without considering which units are the ones moving around. While this was quite a good initial fit to my scenario from my

perspective (the overall movement of people between states of support), it posed some problems moving forward as potential users of the model may be more interested in individual movements.

This problem highlighted the importance of understanding the purpose and limitations of the model. Potential users would look for a more predictive model rather than a model to develop understanding and identify trends. I felt that due to the more deterministic nature of SD, my model would be useful in identification of trends when changing deliberation structures or exploring different initial scenarios. This is because the removal (or deterministic approximation) of any stochastic elements of the scenario makes it changes to results clearer when adjusting input parameters. Specifically, it allows for the identification of the overall trends, rather than specifying how much a result would change. However, care would need to be taken if using it for more predictive purposes due to its bias towards the data that it was constructed from. This distinction of models for trend identification (or development of understanding) and as a predictive tool is important to make and present to prospective users of the model.

My model was based on the data collected by the MRWS Partnership, my literature review and expert opinion. While the predictive results looks relatively accurate given the lack of data available (the only quantitative data available was from a set of 4 public opinion surveys spread over the 4 years, offering only a few 'snapshots' of public opinion), the main power of the model was in easy identification of trends. In particular, I explored a variety of scenarios including different deliberation structures and world conditions and was able to identify a clear trend in public response as a result for this change. This could therefore be used to help develop understanding of the process, allowing for a stronger deliberation process to be developed when attempting the siting process again. I also considered expanding my influence technologies from utility theory into SD. However, I found that the results from this were not particularly useful over more standard validation and sensitivity analysis done on SD models.

### 1.4.3 Discrete Event Simulation

My SD model showed promise in terms of trend identification in changes of public support, but there were two main problems with the SD paradigm that were identified (see Brailsford et al 2014 for a general discussion of the differences between SD and DES). First, it would be ideal to be able to track a single individual's change of opinion throughout the process. This would allow better exploration of the effects of selective targeting for the deliberation structure. Secondly, as the SD model was purely deterministic, there was no measure of uncertainty which is highly relevant for more predictive purposes. To deliver improvements in

these two categories, I decided to construct an analogous DES model of the same process, using as similar a structure as I could to the original SD model. In the case of DES I would be able to track individuals throughout the process, and as it is stochastic in nature, would be able to produce some measure of uncertainty in my predictions.

Discrete event simulation is more commonly used in industry than SD (Swain 2011). This could be due to its debatably lower level of abstraction than SD (it is easier to directly relate to the system), or the additional information it can provide about single units moving through the system. Common applications include constructing large-scale logistical systems or factory production lines. This additional familiarity with the paradigm would be helpful in explaining the model to potential users because of the more direct links that can be drawn to the real-life system.

My DES model produced quite encouraging results, especially in terms of how the public responded to certain events (for instance stakeholder engagement periods) and how the uncertainty in support levels changed after these events. For instance, each of the stakeholder engagement periods had a delayed effect on the amount of uncertainty. This is because of the delayed feedback effect from the engagement periods. Additionally I saw that the uncertainty almost always increased, again due to the feedback effect. This strong feedback effect means I need to be clear that consecutive values are highly correlated, and not random within the 95% confidence interval I have provided. However, my model appears to be able to identify trends similarly to in the SD model, whilst also providing a measure of uncertainty for predictive purposes.

The introduction of stochastic elements to the choice of opinion state and in the key influencers of public opinion (NGOs and Partnership) provided a slightly more robust model to changes than SD (see Chapter 7 for a detailed discussion). Some of these differences may have come down to design choices when transferring the model from a SD framework. However, having a measure of uncertainty has helped provide more confidence in the predictive power of the model. Although in some cases these uncertainty bounds are quite large, showing how volatile the process has the potential to be.

## 1.5 An Application Within Nuclear Facility Siting

Nuclear facility siting is a significant issue posed to government bodies that wish to enlarge their nuclear power infrastructure (Morton et al 2009). These expansions may include anything from new power plants to meet increasing energy demands, to larger or improved waste storage facilities for new or legacy nuclear waste. As mentioned earlier, my overall aim was to provide assistance to decision making in this area, especially when public

participation is involved. These decisions could be anything from a range of topics such as facility location, size and type, benefits packages for involved areas, or the public deliberations process itself. To help make these decisions, the UK government has committed to a heavy focus on public participation (2014 Government White Paper). They hope that appealing to the public would provide a clearer process and build the public's trust in the government's ability to carry out the suggested plans. While these are all difficult decisions to make, and I aim to explore how assistance can be provided specifically for deciding the public deliberation process. This is how the government interacts with the public about their facility siting plans. To see more information about the attempted Cumbrian siting process between 2009 and 2013, see Chapter 4.

I have explored the applications of three different decision structures to this area. My first application was using my developments on influence and sub-groups in group utility theory to identify particularly influential individuals, or individuals that may belong to the same belief group directly from their attribute weights. The data used for this application was taken from the first experiment in Atherton (1999), which explored the temporal issues in decision making and facility siting. To see more information about this data see Section 3.5. Using my methodologies, I was able to understand common trade-offs when assigning attribute weights, identify when individuals had not understood the elicitation process and show that groups of individuals that gave similar attribute weights tended to be in the same demographic group. These were some promising results that showed my new technologies could be useful should a similar study be undertaken again.

In a more extensive study I then constructed system dynamics and discrete event simulation models for the 2009-2013 Cumbrian geological disposal facility siting process that could be used to assist with structuring future similar public deliberations. One of the benefits of these models was that they could easily be applied to other applications and so were highly generalisable as long as there was a deliberation structure that needed to be put into place. Alongside evaluating each model individually and comparatively, I explored influence from the perspective of scenarios rather than the utilities of potential users of the model as this was far more pragmatic. My initial tests suggested that there was little need for new technologies to be able to do this. Using several modelling paradigms for this application has also allowed me to explore the more general suitability of each paradigm for group decision making. There has been a variety of literature that explores what is required of a decision support system which has been useful in analysing potential software packages for each paradigm, some of which I have explored in Chapter 2.

In summary, I have explored extensions to a utility based framework that could be useful

in nuclear facility siting, or more general settings. Particular focus has been given to the impacts of influence and deception in group decision making, alongside identification of hidden coalitions. These extensions have a variety of uses, such as helping to evaluate elicitation processes or minimise unintentional bias within groups. Following this, I explored the use of different paradigms for modelling the previous failed Cumbrian geological disposal siting process. These models were designed to explore the impacts of different deliberation structures. However I also explored influential events and groups where appropriate.

## 1.6 Thesis Structure

The rest of this thesis is structured as follows. Chapter 2 explores general topics in group decision making, with a particular focus on decision support processes. This serves as a foundation from the literature to explore the various modelling paradigms. Alongside serving as a strong base to build from, I aimed to address the first half of objective 1 here: exploring past structures of decision support processes. This exploration included topics such as the type of decision support system used, the impacts of different group characteristics and how these characteristics have been accounted for. I also provide a literature review on opinion dynamics, which is vital for Chapters 4 and onwards.

Chapter 3 was solely focused on the group utilities paradigm I had considered. Within this chapter I explored methodologies that could be adapted from other areas (such as regression). These adaptations formed the basis of both my measure of influence and sub-group identification method. I conducted numerical studies with both large-scale simulated data and real-world data to refine these adaptations. Throughout this chapter I primarily aimed to address objective 2. In particular, I presented my definitions of influence in the scenario considered and what my measures could be used for. From the data set from nuclear facility siting, I was able to draw several conclusions about the survey and participants, and have highlighted the usage of my adaptations to come to these conclusions. This additionally linked in to objective 3 as I could apply the utility framework to a real-life scenario to demonstrate how it may be used in practice.

Following my work in the applications of utility theory, a natural extension was to explore the applications of other modelling paradigms to aid group decision making. Chapter 4 aimed to introduce these and also provided a description of a specific case study (siting a geological disposal facility) and sources that I would apply these other modelling paradigms to. This chapter allowed me to explore objective 1 more fully through an exploration of potential modelling paradigms. Additionally the chapter provided the real-life scenario I used as my base scenario in later chapters for objective 3.

I develop simulation models for this scenario in both Chapters 5 and 6. Chapter 5 introduces the system dynamics paradigm in more detail, and shows some of my earlier work that led to the development of my current models. Additionally, I explored the idea of influential groups in the context of system dynamics. This allowed me to finish my contribution towards objective 2 (concerning influence). Chapter 6 on the other hand explored the discrete event simulation paradigm in more detail when applied to the same scenario. This chapter provided a contrasting modelling style to system dynamics seen in the preceding chapter, with a directly comparable setting. Both of these chapters were aimed at exploring objective 3 (applications of the paradigms considered).

Chapter 7 moves away from the basic application of modelling paradigms to a specific scenario, and instead contrasts the paradigms I had considered. This chapter's aim was to address objective 4: evaluating the differences of these modelling paradigms in this application area. I focussed on contrasting the models constructing in Chapters 5 and 6 (system dynamics and discrete event simulation) due to how directly comparable they were. I conducted analysis into each model to see how it responded to changing scenarios, and drew from this (and my more general understanding of each paradigm) a set of scores for 5 of the characteristics I considered important when choosing a modelling paradigm.

My final two chapters explored some of the extensions I had considered to my work, and drew some overarching conclusions and learning points from the work done for this thesis. In particular, Chapter 8 sought to explore objective 5 by linking system dynamics and Bayesian network models in an attempt to provide additional validation options for system dynamic models. I explored how a Bayesian network could be used for structural validation (through conditional independence statements). I identified ways that a Bayesian network could be used for more functional validation of a system dynamics model, and have highlighted some of the problems I encountered when attempting to implement this to my model. Finally, Chapter 9 draws broad conclusions from the thesis and evaluates how well I met each of the five objectives I initially set out with.

# Chapter 2

# Group Decision Making and Opinion Dynamics

## 2.1 Group Decisions and Opinion Dynamics

Throughout this section I review some of the work done in the area of group decision making. While there is a broad range of literature in this area, I focus on reviewing the work done on how group decision support systems (GDSSs) interact with groups and should be structured. Support systems here refers to software implementations that aid decision making. Other common areas of this literature include large scale groups such as the population of a country, for example in e-democracy, policy management and combination of expert judgements. My aim was to contribute towards objective 1 during this chapter, particularly towards developing understanding of decision support systems and some developments in utility theory.

Additionally, this chapter provides a review of literature in the area of Opinion Dynamics, which is particularly relevant for the work done in later Chapters. Opinion Dynamics has natural links to the group decision making literature as it can help understand both the dynamics of the situation being modelled, and the group that is required to make an informed decision. This is particularly relevant to keep in mind when exploring influence measures in groups using utility functions, as in Chapter 3. In later chapters I provide additional reviews of the literature relevant to the modelling paradigms considered and simulation modelling as a whole, particularly in Chapter 4.

The structure of this literature review is as follows. First, I explore some factors that impact how group characteristics. For example, size and spatial dispersion could affect the decision making process and the construction of a GDSS. Following this, I discuss the transition to,

and methods adapting the decision process for groups of decision makers as opposed to a single decision maker. Finally, I look at recent work into the elicitation of utility functions in groups of decision makers.

### 2.1.1 Group Decision Support Systems

One of the most cited papers in the area of GDSSs is by DeSanctis and Gallupe (1987) (see also Gallupe et al 1988, Gallupe & McKeen 1990, Ilze & Buckland 1998, Davey & Olson 1998). The authors performed a review of the role GDSSs could play in assisting with group decisions. They also outlined some of the most important factors to consider when designing a GDSS for a group of decision makers. For example, what the purpose of a GDSS should be, and factors that should influence its design. They also presented a taxonomy of GDSSs sorted into group size (large and small), and member proximity (face-to-face and dispersed). Behavioural studies have shown that groups function differently in each of these categories (Cartwright & Zander 1968, Hoffman 1979). These studies suggest that it becomes more difficult to reach consensus with larger groups due to the increasing difficulty of resolving differences in opinion. They also state that more dispersed groups tend to promote more equity between members, and are able to move slightly further from each individual's initial thoughts. This often increases 'decision accuracy'. However, it also tends to reduce the satisfaction of the decision making process, and may lead to additional conflicts between group members (Boje & Murninghan 1982, Siegel et al 1986). It has also been shown that group members present different behaviour and performance when they are physically dispersed to when using computer mediated communication (Valacich et al 1994). The differences between categories of DeSanctis and Gallupe's taxonomy has unfortunately not been visibly extended into the development of current decision software.

Group size has also been explored by Howard Raiffa (e.g. Raiffa et al 2002), who suggests to "invite the people you need, and no more". However, the definition of need can be unclear in current society. For instance, the difference between need for a small group could be different than for a democracy. He supported that having too many people in a group leads to conflict, as individuals compete for time to speak and can become less engaged with the process. Keeping group sizes smaller helps keep the process easier to manage (Walton et al 1986). He also suggested a set of selection criteria for group members. An individual should only be included if they either can contribute to the process, or their approval is needed for the decision. See Raiffa et al (2002) for a more in depth description of this set of criteria. He also stated that where more than one individual could be selected, they should be chosen based on their characteristics. For example, team-working skills (similar to a measurement of personality that is discussed later by Recio-Garcia et al 2013) or avail-

ability. He stressed that this is not a one-time selection because decision making should be a dynamic process. However, the viability of this paradigm is questionable when applied to more complex decisions. Integrating new team members half way through the process can be very difficult. Additionally, it is quite common that you do not have the power of invitation to the group. For instance, regulations may require an individual be involved in the process when they have very little to add to the discussion. So while there may be benefits to constructing the decision making group in this way, it may be impossible to achieve in practice.

Similarly, French et al (2009) outlined some of the factors that could influence group decision making following Baron and Kerr (2004). These factors are a summary of some of the native issues with group decision making. There are several common themes, such as exploring group size (DeSanctis & Gallupe 1987), effect of interactions between group members (Chen et al 2008) and group member characteristics (Recio-Garcia et al 2013). A factor that is of particular note is that groups tend to only discuss knowledge that all members possess. This was investigated by Hinsz et al (1997). Thus groups naturally tend to avoid one of the most significant benefits of being in a group: having a larger pool of knowledge. The writers assert that these inhibitions with group decision making are some of the primary problems that should be highlighted to groups. A significant problem comes from combining individual views into a single group view. A statement that was made regarding this was ”procedures designed to support group decision making may be effective only if they complement the strategy adopted by the group”. This was referring to the strategies presented by Hastie et al (1983), who explored how mock juries reached consensus on innocence or guilt. Janis (1972) also looked at problems in group decision making, who termed these problems as ’groupthink’. This is another outlook on the issues previously discussed, mostly similar to those discussed by French et al (2009).

There was quite a lot of work in the 80’s on the impacts that a GDSS could have on a group. In particular, Watson et al (1988) performed a relatively large scale experiment to analyse the impacts of using a GDSS. They compared groups that received no support to those that received ’pen and paper’ support. They sought to explore some of the benefits and problems of using a GDSS. Such benefits included; the hope that the GDSS would help provide higher quality decisions by bringing about a more democratic process to the group, and providing more equality between members throughout the meeting (Lewis 1982, Siegel et al 1986, Turoff & Hiltz 1982, DeSanctis & Gallupe 1987). They drew particular attention to the work done by Kiesler (1986), who pointed out that there could be some negative effects that result from using a computer interface. For example, less efficiency within the group from a greater volume of information flow, or a higher level of conflict in the group which

ties in to the point made by Miller (1989).

While their experiment provided relatively little in terms of quantitative results, they made several qualitative statements. For example, they found that groups using the GDSS tend to have less face-to-face communication as people focussed more on the support system. This also resulted in some 'quiet time' for the groups while everybody took time to read what was presented to them. They also found that the groups using the GDSS became very focussed on the procedures presented to them, and would rarely explore outside of the structure of the GDSS. Groups that were provided the same sort of support on paper were much less focussed on these procedures, and instead spent more time discussing the issues. One conclusion that could be drawn is that a GDSS should not be seen as a check-list which provides an answer once each section has been completed.

More recently, Schoop et al (2014) looked at the effects of decision support alongside communication support on groups (as usually just one of these is considered). Their findings further cemented the idea of communication support being integral to the decision process. They suggested that, with suitable communication support in place, the decision support is likely to be a much better experience for users. Their findings showed that groups with both communication and decision support had more communication than expected. This contrasted conclusions from Weber et al (2006), who argued that the communication support used in their experiment was more integrated with the decision support system, resulting in group members feeling more open to questions and arguing points that were raised.

DeSanctis & Gallupe (1987) also had a significant focus on the types of decision support systems (DSS) that could be used. They defined three levels of a GDSS in terms of how interactive the DSS was with the participants. For example, a level 1 DSS only attempts to facilitate information exchange between group members. However, a level 3 DSS almost entirely controls the discussion, from who is allowed to speak to what topic they will speak about. These different levels are a good way of thinking about the purpose a GDSS holds, as it explores how the group wants to interact with the GDSS. If a group wants to use a GDSS that helps them formulate and analyse their decision, but not entirely control the process, then that falls under a level 2 DSS. While if they only want the GDSS to help display the information they are working with, then they only need a level 1 DSS. The idea of changing how groups interact is also considered by Mitroff & Mason (1981), who explored assigning a 'devil's advocate' in a group, whose job it was to criticise any recommendation put forward by the group. This could be combined with a level 3 DSS described by DeSanctis & Gallupe, where a set amount of time would be given to the devil's advocate to state their current criticisms, followed by time specifically spent to discuss these criticisms.

It is also important to consider how using different levels of DSS, as defined by DeSanctis & Gallupe (1987), could impact the communication ability of the group that is using the DSS. For example, I should consider the social choice theory that was developed by Short et al (1976). This theory states that the more a communication medium restricts the transmission of standard social cues, then the less personable and socially sensitive the group becomes. This is supported by previously mentioned studies such as Kiesler (1986) and Miller (1989). The effect on the group dynamics has been shown to have an antisocial impact on the group. From the focus on communication so far (DeSanctis & Gallupe 1987, Siegel et al 1986, Turoff & Hiltz 1982), the GDSS could have a noticeable negative effect on group decision making. From this, I can conclude that it is important to allow group members to have as much ownership over the problem being discussed as possible.

While DeSanctis & Gallupe (1987) considered the levels of a DSS in terms of the communication within a group, they had very little focus on the actual decision analysis aspect of the software. This is fortunately explored in a similar way more recently by French & Insua (2010), where they define 4 levels of DSS, shown in Figure 2.1. Higher levels of systems provide more in depth support, whilst taking into account the amount of knowledge available for the decision (French et al 2009). For example, a level 3 DSS explores the evaluation of the alternatives, whereas a level 2 DSS only performs basic analysis of the decision.

A significant difference between these two definitions of DSS is their application. French & Insua (2010) are less concerned with group composition. Instead they consider the Cynefin framework shown in Figure 2.2 (French 2013) that was developed by Snowden (2002) and Snowden & Boone (2007). This framework characterises decisions into contexts, albeit with blurred boundaries. For example, the majority of situations where a GDSS would be most applicable is in the 'Complex' domain, where it is more difficult to predict system behaviour due to the lack of quantitative models in this domain (see French (2013) for a more detailed analysis). The 'Complex' domain is where my own models and methods lie. However, it could be useful to consider the 'Known' or 'Knowable' domains, where relationships between cause and effect are known or can be discovered, and so it is easier to get a quantitative answer and to provide a strong basis for the theory.

**Table 5.1** Levels of decision support

| | |
|---|---|
| Level 3 | Evaluation and ranking of alternative strategies in the face of uncertainty by balancing their respective benefits and disadvantages |
| Level 2 | Simulation and analysis of the consequences of potential strategies; determination of their feasibility and quantification of their benefits and disadvantages |
| Level 1 | Analysis and forecasting of the current and future environment |
| Level 0 | Acquisition, checking and presentation of data, directly or with minimal analysis, to dms |

Figure 2.1: Levels of decision support systems, as described by French in Chapter 5 of French & Insua (2010)

The Cynefin model, while initially developed for knowledge management, has received attention in a variety of areas. For example, in information systems (Hasan & Kazlauskas 2009) where it was shown to improve sense making in a previously very ordered discipline, or in decision making (French & Insua 2010) where it can be used to identify the type of support needed for the client. This idea is quite prevalent throughout applications of Cynefin. Both Hasan & Kazlauskas (2009) and French (2013) came to the conclusion that Cynefin could be used to better match a problem to the tools that would be best suited to finding a solution. French (2013) argued that when decision support is being given in the complex or chaotic spaces, it is important to provide exploratory support and focus on facilitating collaboration between group members. Because in these spaces most of the knowledge would be gained through socialisation. This enables the problem to be pushed from the complex space into the knowable space, as I learn more about the interactions between entities of interest.

In the knowable and known spaces, it may be better to initially undertake a confirmatory analysis as I already possess the understanding to do this. It is key to understand where the problem lies, so that I can apply the correct tools to the problem. French & Insua (2010) and Deloitte (2009) argued that using the Cynefin model can enhance the understanding of group members when proceeding through the decision process. It can help groups understand that some of the old processes that were used to solve their decision problems may not be applicable, as they may now fall in different spaces.

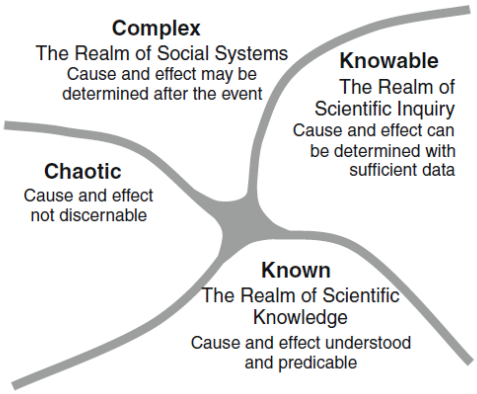



Figure 2.2: Description of the Cynefin model developed by Snowden (French & Insua 2010, Chapter 5)

The thought that decision support should be tailored to each group has become clear throughout the literature. Factors to tailor support around could be group size and proximity (DeSanctis & Gallupe 1987), space of the Cynefin framework that the decision falls in (French & Insua 2010), or changing group interactions (DeSanctis & Gallupe 1987, Mitroff & Mason 1981). Raiffa et al (2002) also suggested different processes according to the type of group. This idea was also explored by DeSanctis & Gallupe (1987), where they identified three main group types: an established group making joint decisions, unitary decision makers with advisers and negotiations among many unitary actors (Raiffa et al 2002). For example, when I support a group of unitary actors, it is likely they will have competing objectives. This would need a different approach to an established group who are making a joint decision that benefits all of them roughly equally. This is perhaps the most important idea to take away from this; it is very important to ensure that the right type of support is being given to the group.

### 2.1.2 Consensus and Adaptations to the Group Decision Process

I also explored potential adaptations that have been considered to translate a standard decision process to a group of decision makers. This is an area that has received less attention, particularly in the statistics domain. However, there has been some developments in social sciences. For example, Chen et al (2008) explored methods to offer better movie or item recommendations to a group of people. They estimated the rating of an item from the interaction effects between group members. This was calculated by using both the individual's rankings of items, and a set of 'group rankings' which consists of a subset of the whole group. Any missing data was then approximated by a genetic algorithm which was

detailed in the paper. The key point was that while other ways to get more detailed information about an individual's preferences exist (McCarthy & Anagnost 1998, Jameson 2004, Ardissono et al 2003), they are often too difficult to implement or can ask questions that the individuals themselves may not even be certain about. I must find a measure that is either easy to gather information for, or can be deduced from the standard information given for the decision process. Chen et al looked to estimate the impact of interaction between two people in terms of the correlation between their individual rankings.

Recio-Garcia et al (2013) is another relevant paper from social science. The writers looked at including a measurement of the personality value and a trust value between two individuals when calculating the 'goodness' of a suggested item or movie. The next two paragraphs give some of the formulae behind the model for Recio-Garcia et al's measurements, primarily to give an example of a current model in the area. However, this formulation is used as an example, and not revisited in later chapters.

Suppose that $p_u$ and $p_v$ are values that reflect the personalities of two users of the system which are computed from the Thomas-Kilmann Conflict Mode Instrument (Kilmann & Thomas 1977). A value of 0 is a very cooperative person, while a value of 1 is a very selfish person. Let $\Delta p_{u,v} = p_u - p_v$, be the personality difference between group members u and v, which can help model the impact that personality will have on the argumentation process when these two users are arguing. Next define the trust value between two users as $t_{u,v} = \Sigma_{i=1}^{10} \alpha_i f_i(u, v)$. Where $f_i(u, v)$ for $i \in \{1, ..., 10\}$ are the values for different factors that the writer selects that are believed to be relevant and feasible to obtain from social media sites to compute a trust value between two users, and $\alpha_i$ is the weighting given to each of these factors. See Recio-Garcia et al (2013) for more information about these factors and weights. These values are then used to compute a modified 'goodness' value, $g'_{u,i}$, of a suggestion $i$ from user $v$ to user $u$, where the original 'goodness' value, $g_{u,i}$, is computed by a fuzzy system described in Recio-Garcia et al (2013);

$$g'_{u,i} = t_{u,v}(g_{u,i} + \Delta p_{u,v}) \tag{2.1}$$

When $p_{u,v}$ is positive, member $u$ will be more selfish than member $v$, and so their 'goodness' is scaled to take account of this. This value is finally adjusted down by their trust value, so the best possible situation for $u$ would be to be very selfish with a very cooperative person whom you trust completely, giving $p_{u,v} = 1$ and $t_{u,v} = 1$.

Their approach is somewhat ad hoc but considers some potentially interesting factors that could be explored further in a more formal model such as personality traits and trust between individuals. In particular, I may be able to include some interactions that could be

observed and are known to have a significant impact on group behaviour. This is more relevant for groups that are less cooperative. Trust could be problematic to use in practice. It is more applicable to groups that consistently work together, or at least meet face-to-face. Handy (1995) argued that trust is actually impossible to develop between group members that cannot meet face-to-face and monitor each other's activities. Others have argued that while trust might be able to be established early on, it can very quickly deteriorate (Jarvenpaa & Leidner 1999, Piccoli & Ives 2003).

Following on from groups working cooperatively is the idea of consensus. In consensus, the proposed course of action should be acceptable to all individuals involved in the decision. There are two papers I discuss. The first by Fu & Yang (2010), who explored group consensus using an evidential reasoning approach. The second is by Wu & Xu (2012), who considered consensus using an analytical hierarchical approach. Group consensus is usually measured by a metric that calculates how close each of the individuals are to the proposed group solution, which is then compared to a pre-defined level to assess if consensus had been reached.

Fu and Yang produced a measure for the group consensus overall, on an alternative and on each attribute for an alternative based upon a set of T experts. Suppose first that I have a set of M alternatives $a_l$ ($l = 1, ..., M$), a set of L attributes $e_i$ and corresponding weights $w_i$ ($i = 1, ..., L$). Then starting with the overall compatibility for each expert $j \in \{1, ..., T\}$, $oc^j(e_i(a_l))$, for an attribute $e_i$ and alternative $a_l$, I define the group consensus on attribute $e_i$ and alternative $a_l$ as;

$$gc(e_i(a_l)) = \frac{\Sigma_{j=1}^{T} oc^j(e_i(a_l))}{T} \tag{2.2}$$

Given this, I then average over the attributes with given weights $w_i$ to give a consensus value for the alternative $a_l$, and then average over all alternatives to get an overall consensus value, when $i \in \{1, ..., L\}$ and $l \in \{1, ..., M\}$, as given below;

$$gc(a_l) = \Sigma_{i=1}^{L} w_i gc(e_i(a_l)) \text{ and } ggc = \frac{\Sigma_{l=1}^{M} gc(a_l)}{M} \tag{2.3}$$

These three levels can then be compared to the predefined thresholds $\delta_i$, $\delta_M$ and $\delta_G$ at each iteration of the process, when I check to see if the global consensus requirements have been met. This can be seen in Figure 2.3. The fact that all three of the consensus formulae have been normalised means that it is relatively easy to prescribe a method to select these thresholds before the process has started. There is also always the flexibility to change them at any time, for instance if it was clear that they were set too high. Splitting up consensus requirements is a good idea, as it allows for easier identification of problem origins when

consensus is not reached. However, it does add a lot of complexity to the process

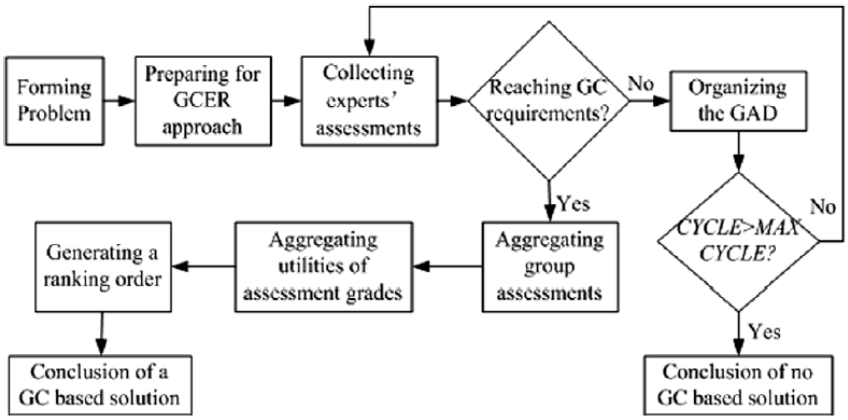



Figure 2.3: Procedure of the Group Consensus Evidential Reasoning (GCER) approach taken from Fu & Yang (2010), page 605. Key: Group Analysis and Discussion (GAD)

Iterative checks of consensus is key to assisting a decision for a group of individuals that consists of competing parties, where the gain of one party may be the loss of another party. If I use a standard decision procedure, the recommendation will be somewhere in the middle of everything and is not a good solution for any group member. Raiffa et al (2002) also explored this problem in detail from a game theoretic standpoint. He considered consensus on the fair division of capital or resources, which could possibly be applied in a slightly different way to the fair division of utility weights among group members. This idea of equity is something that should be considered, as it is often what groups strive to achieve when trying to reach a fair decision. Equity has also received some attention earlier on, with some prominent papers written by Kirkwood (1972) and Keeney & Kirkwood (1975).

Others have also explored reaching consensus in a group. For example, Hall (1971) considered a set of rules for reaching consensus in groups. This set of rules was then manipulated, along with a similar set by Nemiroff et al (1976), to produce an implementation for testing by Schweiger et al (1986). Schweiger et al (1986) compared groups using a consensus based approach following these rules, a devil's advocacy approach and a dialectical inquiry approach (where a debate is held between two recommendations based on contrary assumptions and the assumptions that either side agreed on could be used as a basis to create a new recommendation). The results from this experiment are interesting, as although it seemed that group consensus produces the least accurate decision recommendations, group

members felt more satisfied with the process and happier with the outcome. However, it is debatable how measurable 'decision accuracy' is as that implies knowing the correct decision. Also the study showed that the group consensus methods tended to make group members happier to work with the same group in the future. Alongside the experiment by Eils and John (1980), which showed that groups trained to use these consensus rules tended to make better decisions. Together, this shows that the tested consensus method could be best suited to consistent groups such as a board of directors.

Miller (1989) argued that the closer I come to requiring group consensus to make a decision (as opposed to something like majority rule), then the more group members find the process uncomfortable, difficult and confrontational. However, group members also feel more satisfied with the process, and feel it is more thorough and adequate for their needs. This also links to the findings of Schweiger et al (1986). I are presented with a natural dilemma. Ideally all group members should agree with the solution, however for many decisions the effort or time required to get to this stage is too substantial. This again shows the need to adjust the decision procedure to the type of group, and what type of decision it is to be made. French (1981) also mentioned that if an analyst tries to promote methods that will achieve consensus first, and then these results are combined, while it would be saving the analyst work it could also stray from rationality. This dilemma should be considered in future work in group decision making.

There is also the natural question of how to reach consensus. I first consider the Delphi method, developed by Dalkey & Helmer (1963). This method attempts to pull a group of experts towards consensus. In the initial study by Dalkey and Helmer, they asked experts about the number of atom bombs required to cut munitions production by a specified amount in the United States. After a group of experts are selected, which is considered to be the most important part (Judd 1972, Taylor & Judd 1989, Jacobs 1996), they are all asked for their thoughts on the matter and any requests for extra information, either by questionnaire or interview. Once all experts are accounted for in this way, they all receive some feedback in the form of all of the data that was requested by themselves and anybody else, and any questions that could be considered (which the facilitators should try to exclude opinions from). It is then repeated several times until some level of consensus is met. This produced relatively good results, reducing the spread of estimations from 50 to 5000, down to 167-360 after the final iteration. This method has since been quite commonly used (Hsu & Sandford 2007, Adler & Ziglio 1996, Schmidt 2007, Baker et al 2006).

However, the Delphi method has several problems. It is dependent on the facilitators being able to pass on feedback without including any opinions from the other experts (Altschuld

2003, Scheibe et al 1975). I also think the method could be considered too restrictive on communication between group members. While anonymity can be a good thing, here it prevents in depth discussion about the problem and instead you need to make assumptions about the other group members. This goes against my earlier discussion that communication is the most important part of the group decision making process.

Despite these flaws, it succeeds in circumventing some of the problems identified when

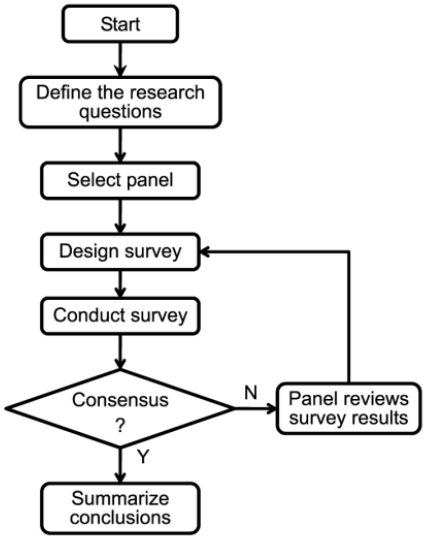



Figure 2.4: Summary of the Delphi Method.

working in a group (Hsu & Sandford 2007, Gustafson et al 1973), such a 'groupthink' by Janis (1972). This is due to the anonymity that is involved in the process (also a potential weakness). It helps reduce the effect of dominant individuals, and controlled feedback provides focus and helps reduce the effect of group discussions distorting the data (Dalkey 1972). It would be useful to incorporate some of these ideas into a GDSS, such as the focus on anonymity. For instance, when using an online platform to facilitate discussions, it could be beneficial to allow each user to remain anonymous but still participate fully in discussions. I must be careful however, as the Delphi technique is a level 3 system, as described by DeSanctis & Gallupe (1987). It entirely controls when people can contact each other (or in this case the facilitator), which could inhibit productivity of the group.

From this, I can say that consensus could potentially improve the standard decision procedure. However, it should not be the only improvement considered due to its rigid structure for only a few circumstances. For example, a co-operative group with common objectives.

Similarly to how different GDSSs would be needed for different group sizes, I need a different type of GDSS (and procedure) for non-cooperative groups, which is where consensus could be a strong first step. The problem with using consensus in this way was outlined in the first half of the paper by Wu & Xu (2012), who focused on the consistency of the preferences produced by individuals in the group. It is likely that to achieve consensus, the utility functions of some of the group members will have to change drastically. Careful changes are required so that they still represent what the group member values in the decision.

It is difficult to just think of consensus in this way without exploring how it might not be achieved, in other words exploring conflict within groups. Kling (1991) pointed out that research into group communication (and hence this can be extended to group decision making) that ignores coercive, competitive and conflictual relationships is not realistic. While the group might be quite clearly in open conflict, meaning hostility becomes more of an issue (Keyton 1999), it is more likely that most conflict is less visible - through deceit (George & Carlson 1999). It is clear that acting covertly and lying to achieve personal gain or objectives is a part of everyday life (Ekman 2009). However, it is important to understand the impact this can have on a group decision, or in other words - how influential can these 'deceivers' be? This has been recently explored in quite a lot of detail (e.g. Burgoon et al 2010, Marett & George 2013) and has not given the most positive results. In the study done by Marett & George (2013), where they explored if using computer mediated communication would change how people performed deception. The conclusion was that of 120 receivers (truthful group members), only 8.4% of the deceptive statements given to them were detected. This was replicated when the deceitful group member did not have any time to prepare, in light of what they were supposed to be lying about. However, this could be due to the natural truth biases described by Stiff et al (1992). Group members that had not met prior to discussions tend to be more trustful of each other than I might expect in the standard decision making scenario.

It has been suggested that using electronic media such as computer mediated communication or GDSSs can make group members more vulnerable to deceit, as it is easier for deceivers to find opportunities to spread false information (Zmud 1990, Markus 1994, Sussman & Sproull 1999, Philips & Eisenberg 1993, Kahai & Cooper 2003). However, this conclusion was not entirely supported by Marett & George (2013) who showed that while using computer mediated communication does increase the amount of deceptive statements made over traditional face-to-face meetings, there is not enough evidence to say it influenced the success rate of these deceptions. The writers also suggest that, due to the issues when using computer mediated communication described in George & Marett (2005), deceivers could perceive lying as relatively low risk in these circumstances. For example, they

could feel more protected from being challenged outright as group members tend to try to avoid disrupting the group harmony.

The main result from the study by Marett & George (2013) was that while the use of computer mediated communication did not seem to have a significant impact on deceit success rates, the group proximity had a significant effect. More precisely, they stated that ”Whether group communication was held using the GSS or in the traditional face-to-face manner, proximate deceivers were almost always successful in swaying the final decision in their favour”. This was strongly supported by their data which showed about a 90% success rate for deceivers in close proximity to the rest of their group. They suggested that the reasons for this was that deceivers in closer proximity to their groups may have more perceptions of mutuality and teamwork within their groups. These potential benefits allowed the deceivers to take more risks when submitted deceitful statements than those in dispersed groups. This suggestion also coincided with the findings of Burgoon et al (2002 a,b).

Another observation they made was that lies that were ’anti-other-project’ seem to be the most successful and were also more common in proximate groups. These were statements that sought to demean other project suggestions in the hope that other group members would see their preference more favourably. Finally, it was quite clear to the writers that real-time communication tends to favour the deceivers of the group, as it discourages significant analyses of the arguments put forward by the deceiver. This is also supported by Burgoon et al (2010), who explored the effect of synchronisation on deceivers. They found that when the groups were asked about how the discussion went, the deceivers were judged as more credible than the receivers themselves, potentially suggesting they became more influential over the decision. They continued to a statement in line with the findings of Marett & George (2013): ”When users have ulterior motives, interactivity can instead amplify vulnerabilities to manipulation; it can sabotage rather than facilitate decision-making.”. This statement highlights the need to consider the impacts of manipulation on the group, instead of assuming that all group members have the same objective.

A large study was done by Zhou et al (2013) who were primarily interested on the effects that a deceiver’s individual characteristics has on deception in an online environment. An interesting part of this was how they split up the results of an attempted deception; they looked at the deception success rate (measured as a win or not in the devised game), however they also explored the impact on their deceptive survivability (the ability of a deceiver to remain undetected during repeated interactions), and also deceptive productivity (the amount of interaction deceivers had with the receivers). This is a useful split as even though an attempt at deception may not be successful initially, it could be used as a stepping

stone for further interactions with the same group as remaining undetected could help them increase their credibility in the group. This could be seen as the most important factor to whether a deception is successful (Bond & DePaulo 2008).

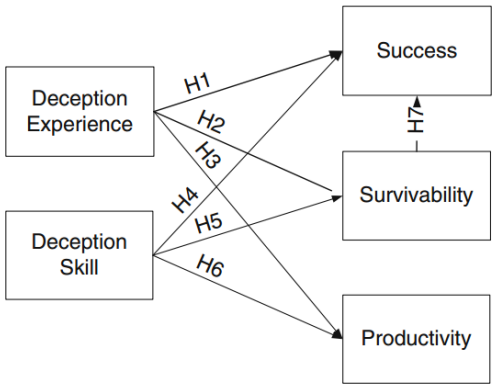



Figure 2.5: The research model taken from Zhou et al (2013), page 156, showing expected positive impacts between individual characteristics (left) and deception performance (right)

The experiment resulted in using the data from a large number of 'Mafia' games (see Zhou et al (2013) for details), to produce various regressions for the three deception performance measures: success, survivability and productivity. Their expectations can be seen in Figure 2.5, where each of the arrows represents an expected positive impact from one of the deceiver's characteristics to the performance measures. The results supported the majority of these hypotheses with the exception of H1, which was found to have a negative impact. The writers explain that this could have been caused by some of the reasons described by literature offering criticisms to the conjecture that deception experience contributes positively to deception success, for example in Kraut & Poe (1980). Indeed, counter-examples have shown that extensive experience in an area will not always display superior performance (Choudhry et al 2005, Ericsson 2004), possibly due to becoming overconfident in the area. This study showed that higher deceptive skill, which leads to more success, also tended to lead to less productivity as they interacted with the group less to avoid exposure. This could then potentially be exploited in a DSS by combining it with an analysis of influential individuals. If one group member has become highly influential with little interaction to the group, make them the focus of attention to see if it helps other group members discover any deceptions. This area then has suggests a gap in the literature that attempts to produce models of deception, as most of the work has been done through quantitative studies.

### 2.1.3 Opinion Dynamics

When studying group decisions, it is also important to consider group behaviour and interactions. A field which focuses on these topics is Opinion Dynamics, which has strong roots in both sociology and psychology (e.g. McDougall 1920, Freud 1922). However, this area has seen increasing interest in the past few decades with the growth of simulation methods such as agent based modelling and social networking (e.g. Hegselmann & U. Krause 2002, Acemoglu & Ozdaglar 2011, Holyst & Kacperski 2001). With a more connected world through the use of the internet and social networking (and thus higher availability of data), it is now far more feasible to conduct studies and plan targeted marketing campaigns (e.g. Leskovec et al 2007). Xia et al (2013) provide a historical review of opinion dynamics, alongside some of the current opinion dynamics models. Their comparative review of these opinion dynamics models is provided in Table 2.6.

| | | **Opinion Representation** | **Local Rules of Interaction** | **Environmental Structure** |
|---|---|---|---|---|
| Voter Model | Peer-to-Peer Interaction Model | Commonly binary value, in some cases discrete value | • Random mutual influences between direct neighbors;<br>• The influence of persistent minorities accounted in the zealot model (Mobilia 2003);<br>• Spontaneous flipping of opinions accounted in Granovsky and Madras (1995)'s noisy voter model<br>• Other variations… | • The regular lattice (e.g., Frachobourg & Krapivsky 1996);<br>• Networks (e.g., Sood and Redner 2005). |
| | Majority Rule Model | Commonly binary value | • The majority rule in local groups and the hierarchical voting process in the Galam Model (2000);<br>• The majority rule in odd-sized groups as in Chen & Redner's (2005) model. other variations… | • The hierarchical structure as adopted in the Galam model;<br>• Networks (e.g., in Lambiotte, 2008) |
| Sznajd Model | | Binary value and discrete value | • One agent's opinion influenced by an agreeing neighbor-pair (i.e., R1 of the original Sznajd Model)<br>• Other variations… | • Regular lattice, e.g., Weron-Sznajd & Sznajd (2000) for the one-dimensional lattice, and Stauffer (2002) for the two-dimensional;<br>• Networks (e.g., Rodrigues and da Costa 2005) |
| Culture Dissemination Model | | Array of discrete values | • A sort of "homophily" rule (one agent only interacts with a similar agent, and the interaction further increases the similarity between them);<br>• Other variations… | • Regular lattice in Axelrod (1997) and followers;<br>• Networks (e.g., in Vitzthum 2007) |
| Bounded Confidence Model | | continuous values, real vectors and discrete values adopted in a few researches | • Opinion exchange with bounded confidence<br>• Averaging of opinions in pairs (Deffuant model) or in groups (HK model)<br>• Other variations (e.g., heterogeneous bounds of confidence)… | • Regular lattice,<br>• Networks |

Figure 2.6: Brief comparison of the model presented in Xia et al (2013). Taken from Xia et al (2013), page 322

How opinions are formed is the primary driver in this area. For instance, Gamson & Modigliani (1989) explore the relationship between several types of media (television, mag-

azines, editorial cartoons, and opinion columns) and public opinion on nuclear power. The writers also discuss the impact that antinuclear and social movement organisations can have on public perception, through their representation of recent events. One of the primary drives of the discussion is to understand how complex issues, such as nuclear power, can be explained to ordinary citizens. The role of the various types of media is vital in this regard. The effect was evaluated through the use of a case study on the media coverage of Chernobyl in 1986, which saw a shift from more progress orientated opinions on nuclear power, to runaway and public accountability being the main opinions being represented in the media. They noted this shift toward blame had a noticeable impact on reducing public confidence in nuclear power.

Gerard & Orive (1987) propose a method of opinion formation that is discrete. An opinion changes in specific stages after following a selected action. The two strategies considered are: reducing the opinion-forming imperative, and generating supporting information. There are additional considerations to how supporting information can be generated (socially or non-socially). More recently, Watts & Dodds (2007) explored the impact of influentials on the formation of public information. These influentials are described as a minority of individuals who influence an exceptional number of peers. Figure 2.7 shows targeted marketing in opinion formation, where the advertisements target key influencers, which have the ability to change the opinions of multiple people around them.

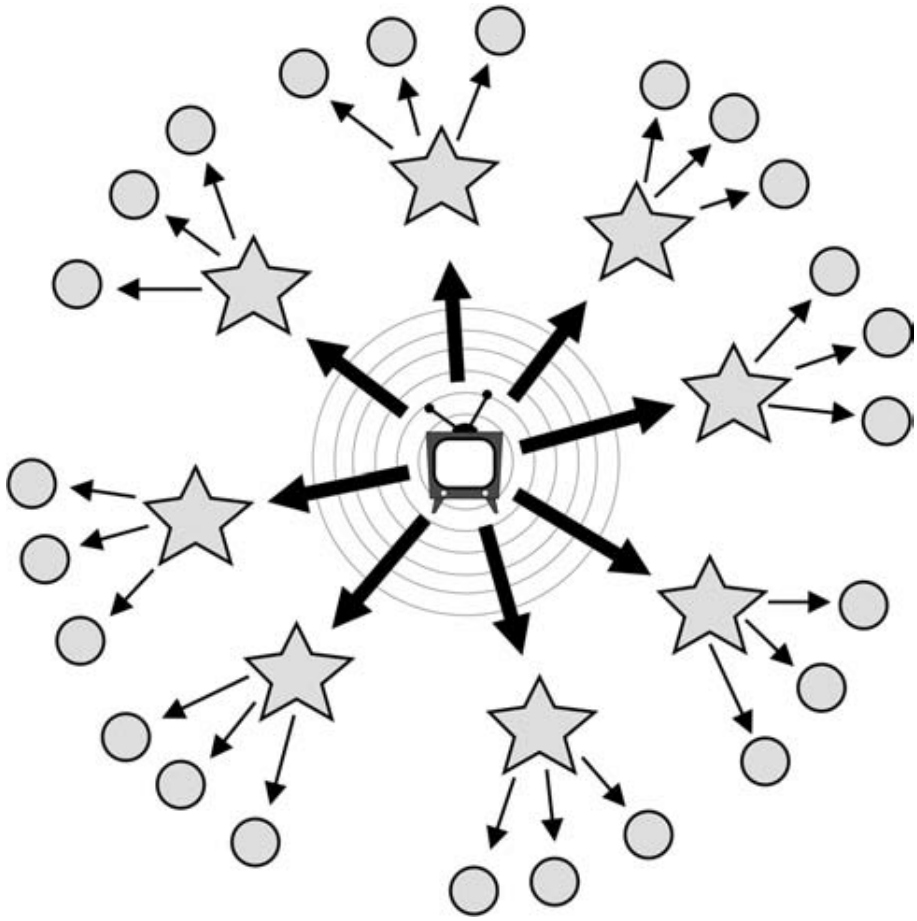


Figure 2.7: Schematic of the two-step flow model of influence. Taken from Watts & Dodds (2007), page 441.

There are a variety of ways that opinion dynamics can be modelled, often depending on the level of granularity required for the desired purpose. Some modelling methods have been presented in Table 2.6. Opinion models can use discrete opinion states (e.g. Hu & Wang 2009), or customised agent based modelling where each agent can behave independently and have a continuous opinion (e.g. Hegselmann & Krause 2002, Gandic et al 2010) where each agents opinion is along a continuous scale, or any other modelling technique which seeks to mimic opinion change.

# Chapter 3

# Influence in Utilities

## 3.1 Introduction

In Chapter 2 I discussed several issues facing decision making in a group setting, and what methods have been suggested to improve the decision making procedure for groups. I focus on two specific interactions unique to a group setting, and propose a novel method that can be applied ad hoc to a group decision process where utilities are used: influence and coalitions. Previous results show me voting systems cannot be entirely democratic: Arrow's Impossibility Theorem (Arrow 1950), and work following from this, has shown the only hope of democratic group decisions is to use relative weights for each alternative (Keeney 2002, Keeney 2009, Nguyen et al 2009). Also, I know that every voting system is susceptible to manipulation (Gibbard 1973, Satterthwaite 1975). Although I may be able to design a voting system such that it is too complex to feasibly manipulate (Procaccia 2010). Despite these negative results, group decisions are an important part of society where in most contexts a group decision rule might not exhibit unacceptable behaviour. However, the development of diagnostic technologies within the formal frameworks of decision making has received little attention.

In particular, I suggest methods that help identify individual influence over the group decision. These methods also help identify sub-groups or cultural groups that could be active within the group. An obvious family of diagnostics for this purpose exploits the long development within statistical regression to identify influential data. A natural choice is Cook's Distance (Cook & Sanford 1982) and the coefficient of determination (Magee 1990). On a more experimental level such problems have already been considered in social choice and game theory (Marett & George 2013).

The work in this Chapter had been carried out with two specific contributions in mind to-

wards my second objective. The first is to provide an adaptation of Cook's Distance from regression that can be applied to the group decision making setting. Specifically, to when a group utility function has been formed from several individual utility functions. This adaptation could then be used to identify potentially interesting or influential behaviour of individuals demonstrated within the group, to ensure that no group members are attempting to unfairly influence the group's utility function.

My aim in this Chapter was also to provide some valuable additions to the group decision making literature (when using utilities), and some potential contributions to opinion dynamics on a less detailed level. In particular, I sought to address the gap in the current literature for formal and measurable considerations of influential group members. While the initial assumptions made for the measures presented in this Chapter are quite restrictive, the technologies produced should serve as a foundation to build from towards more generic scenarios.

The second contribution is to provide an adaptation to the $R^2$ value from regression, which can be applied to the group decision making setting. This could be used to identify hidden coalitions that could have formed which could be attempting to control the group's utility function. In other scenarios (for instance e-participation surveys), it could be used to identify group members from similar background or cultural groups. These two methods have the overall aim of helping to provide more confidence in the other group members, and a more fair and stable platform for group discussions.

In Section 3.2 I motivate the need to identify interesting behaviour, and define contexts and notation. Section 3.3 explores the theoretical aspects and definitions associated with the influence measure given earlier, and draws the necessary links to regression to allow methods for sub-group selection to be developed, alongside giving a metric that can assess the success of the diagnostics. Section 3.4 applies these methods to large scale randomly generated groups, both with no influential group members and with a set of influential group members. Section 3.5 applies these diagnostics to a dataset from the selection of a nuclear waste disposal facility. Section 3.6 concludes by exploring some possible extensions and discusses some shortfalls and strengths of these methods, along with their practicality in real scenarios.

### 3.1.1 Literature Review

#### 3.1.1.1 Utility Function Aggregation

I now review a selection of methods of combining individual utility functions in a group decision setting. I specifically state utility functions here as despite the analytic hierarchy

process being quite commonly used and useful for group decision making due to its simplicity (Dyer & Forman 1992), manipulating preferences directly poses several problems primarily due to Arrow's Theorem (Arrow 1950) shown below for voting systems. Utility is therefore more suited to group scenarios as utilities include a measure of the strength of preference. This allows me to explore a group weighting of different attributes as opposed to a group preference order with no knowledge of how much one outcome is preferred to another.

However, as pointed out by Brock (1980), I need to be able to compare two utility functions which does not often follow the same scale. The writer then goes on to suggest a method designed for this combination problem which is focussed on combining utilities according to 'relative need'. This is a much less extreme approach than those such as maximising the sum of the utility functions, which can often heavily bias one individual (Keeney & Raiffa 1976). The method assigns utility based on the derivative of the cumulative utility curve, as shown in Figure 3.1 below. In these examples, $u_i$ and $u_j$ represent the utilities for individual $i$ and $j$ respectively. The slope in case A is exactly 45 deg which suggests each individual is equally needy and can assign utilities as such. However in case B, the slope of the cumulative utility function is $-\frac{6}{5}$ and so I can say that individual $i$ is 20% more needy than individual $j$, so he suggests giving 20% more utility to individual $i$. This is in comparison to maximising the utility which would give all of the utility to individual $i$. This is a simple example. However, it was quickly extended to smooth curves by the writer, and does provoke some thought into methods that promote equity when dealing with utilities of multiple people as I have in a group scenario.

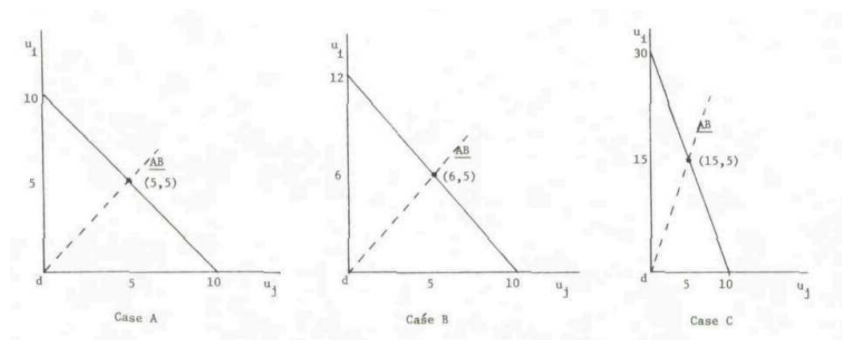



Figure 3.1: Three examples taken from Brock (1980), page 181, that demonstrates the use of assigning utility based on relative need.

Another approach criticised by Brock (1980) was Rawls' MAXIMIN rule (Rawls 1971), which tries to give the decision which is the best for the worst off party. Brock was joined

in this endeavour by several others, such as Harsanyi & Rawls (1975), who showed that it can produce some counter-intuitive results. Unfortunately, each method does not promote equity between the parties as I would hope to achieve. However, the suggestion by Brock was an initial step in the right direction.

**Conditions of a fair voting system**

(1)**Universality**: Transitivity should be the only restriction placed on a voting system
(2)**Positive Association of Individual Values**: Voting systems should be monotone
(3)**Independence of Irrelevant Alternatives**: The societal preference of two candidates should only depend on the individual voters' preferences for those two candidates
(4)**Citizen Sovereignty**: Voting systems should not be imposed in any way
(5)**Nondictatorship**: Voting systems should not be dictatorial

**Arrow's Theorem**

For an election with more than two candidates, it is impossible for a voting system to satisfy Arrow's conditions (1)-(5).

Arrow's Theorem shows me that is impossible to aggregate preferences into a group preference democratically. However, one way to circumvent this is given by Keeney (1976) who exploits the fact that these conditions did not consider the strength of preference at all. So by using individual utility functions which represent each individual's strengths of preferences, such as those developed by Neumann & Morgenstern (1953), proves that a group utility function, **u**, of the form $u(a_j)$ below is the only type of function that satisfies a set of conditions analogous to Arrow's conditions described above but for utility functions, as described by Keeney (1976).

$$u(a_j) = \Sigma_{i=1}^{N} k_i u_i(a_j) \tag{3.1}$$

Where I have $N > 2$ individuals in a group, where each individual $i \in \{1, ..., N\}$ has a utility function that gives their utility for each alternative $a_j \in \{a_1, ..., a_M\}$, $u_i(a_j)$ and where $k_i$ is the weighting given to individual $i$. This idea is also supported by the earlier work done by Harsanyi (1955), who showed that a weighted additive form follows if the von Neumann-Morgenstern axioms, developed by Neumann & Morgenstern (1953), are applied to both the individuals and the group.

Following this work was then the question of how to develop these weights. This question was touched on by Keeney (1976) after proving the form of the group utility function. He considered two ways that groups could decide on these weights: the first is a 'benevolent' dictator whom decided it for the group, and the other is a participatory group model.

However, in both cases he suggested that the same sort of thinking would be suitable; comparing one utility function to another to see which is preferred. For example, suppose that $u(1,0,...,0) = k_1$ and $u(0,1,0,...,0) = k_2$, then if the former is preferred this implies that $k_1 > k_2$. So by following similar arguments a ranking can be developed. However, the most significant problem is that it is difficult to know how much $u_1 = 0$ and $u_1 = 1$ actually means in comparison to $u_2 = 0$ and $u_2 = 1$ as they are likely to be on different scales. Once I consider the participatory group model I see alongside this consensus must also be reached, which could pose a lot of problems in itself. Whereas with the benevolent dictator, it is up to that one person to decide what different utilities mean to people to be able to compare them well.

Following on from this work has been some recommendations on how to select these weights for the individuals. Bodily (1979) suggested a method derived from convergence of a Markov Chain. He first identified two distinct results from the selection of weights; an 'agreed upon decision rule for a series of decisions' and 'the selection of an alternative for the choice at hand'. The procedure that he selected is based upon delegation and is iterative. Each individual $i \in \{1,...,N\}$ is asked to assign weights, $w_{ij}$, to each other individual $j \in \{1,...,N\}\ \{i\}$, where $w_{ii} = 0$ and $\Sigma_{j=1}^{N} w_{ij} = 1$ for all $i \in \{1,...,N\}$. Individual $i$'s utility function is then updated to be $u_i^1 = \Sigma_{j=1}^{N} w_{ij} u_j$, where $u_i$ is the utility function for individual $i \in \{1,...,N\}$. This then leads to multiple stages of substitution of the utility functions, where each substitution is called a 'step of delegation'. This means that after r steps of delegation I have;

$$u_i^r = \Sigma_{j=1}^{N} w_{ij} u_j^{r-1} \text{ for all i and } r = 2,3,... \tag{3.2}$$

The author stated that this sort of repetitive delegation is required as it is not always possible to achieve compromise on the first step. He also commented that groups may wish to use a different set of weights for the first step (where the other member's utility functions are being weighted) and later steps (where the other member's selected weights are being weighted). This then affects the number of delegation steps. For example, in the first case where a decision rule is produced I need the delegation process to continue indefinitely so the delegated utility functions will converge. This can be done by finding the weighting limit $\mathbf{a} = a_1,...,a_N$ that satisfies; $\mathbf{a} = \mathbf{aW}$ and $\Sigma_{i=1}^{N} a_i = 1$, where $\mathbf{W}$ is the NxN matrix of weights $w_{ij}$. However, for the second case where a specific alternative is chosen, he instead suggested exploring the alternative that satisfies Pareto optimality, which is when an alternative with the highest expected utility for one individual whilst also not having a lower expected utility for another individual. This style of thinking could be useful as it is perhaps easier for people to understand what their utility function in comparison to other group

members' utilities as opposed to dealing with a lot of comparisons to try to see how much one utility function is preferred over another.

There are also other suggestions on how to select the weights. Theil (1963) looked at symmetry of measurable utilities in terms of selecting an optimal group decision such that the harm done by individual $i$ to individual $j$ by selecting $i$'s optimal decision should be the same as the harm done vice versa. This follows the same vein as some of the more recent work by Yue (2012), who looked at distances between each individual's decision and the 'positive ideal decision', which was defined as the average of all individual decisions. Alongside this there has also been other suggestions by Bodily (1979) and Mirkin & Fishburn (1979), who proposed models based on eigenvectors to assess the relative importance of each group member. Similarly, Ramanathan & Ganesh (1994) explored another eigenvector method that used the group members' own subjective opinions. This has been an important topic due to the lack of restrictions on weights when considering Arrow's Theorem; the aggregation must be a weighted summation, but I are free in choosing how to assign these weights.

### 3.1.2 Issues in Trust and Deception

In this section, I explore some of the particular challenges of modelling group rather than individual decision making in more detail. First, I review recent work by Recio-Garcia et al (2013) in more detail, who rightly stated that none of the current approaches to group decision support take into account that different groups have different characteristics. A summary of their model has been given in Section 2.1.2. In particular, I aim to highlight some of the issues with the current models in the area to show that more developments need to be done.

The first problem that becomes apparent is using the basis of case-based reasoning to calculate how good each item is for an individual. Their system attempted to reproduce the real argumentative process through the use of agents to represent each individual involved in making the decision. To summarise their model: each agent assess how good a suggestion is (given by a proposing agent) by providing counter examples that are similar to the suggestion but rated badly. The proposing agent can then offer a defence to that counter example by giving another example that is also similar to the initial suggestion but rated highly, from this each item is given a value to indicate how good an alternative it is. The main problem with case based reasoning lies in the ability to find suitably similar examples to the suggestion. While it can be easy for film recommendation, it may be far more difficult in more complex situations where there are many outcomes and intricacies. While this limits the scope of the suggested system, it is still clear why they would use this basis. They

have looked at implementations of recommendation software into social networks where it becomes easy for agents to be defined and identify the counter examples that it needs in such a richly informative environment. However, this could have been of less concern if a more concrete model, or at least more information, was provided about the production of these goodness values considering this was the basis of the model. From this, I can conclude that a strong formal framework is very important for technologies I can develop.

The authors must however be commended on their use of trust and personality in this way to improve the accuracy of recommendations. However, their definitions of these characteristics could be improved to further increase accuracy of the system. For example, when considering personality, they assume that the only impact on the process is from how cooperative or selfish a person is. While this is is an important factor, it could be combined with other aspects of an individual's personality such as extroversion or impulsivity. Also, their definition of trust between two individuals seems rather dubious, as they define it by looking at factors such as the number of common friends and how often they talk to each other on social media. This seems more like a measure of friendship than trust, which is not necessarily a homogeneous concept. However, it is understandable why they used these factors. It is all readily available information for testing and naturally follows from their social media applications, but it does make the wider applicability more difficult when considering environments with less open information. It would be beneficial to assess the influence of group members by combining measures such as these for personality and trust between group members, as this has a far clearer impact on the result of the process.

The experiment was conducted to give more quantitative support for their model in several categories; multi-agent architecture connected by real social ties improves accuracy over the fully connected model, inclusion of social factors improve accuracy and increased satisfaction from their model. They used 15 groups to test their system, by filling out various questionnaires resulting in each group's top 3 film choices of the 15 options. These results are then compared with the top 3 selections their system provided, and it is checked how much of an overlap there is with the real lists provided by the groups. These comparisons are measured with s@3 being at least 1 film common to both the suggested and real lists, and 2s@3 being at least 2 films being common to the suggested and real lists. It is quite clear that the sample size here is too low with only 15 groups, and so any conclusions from the data should be made with care.

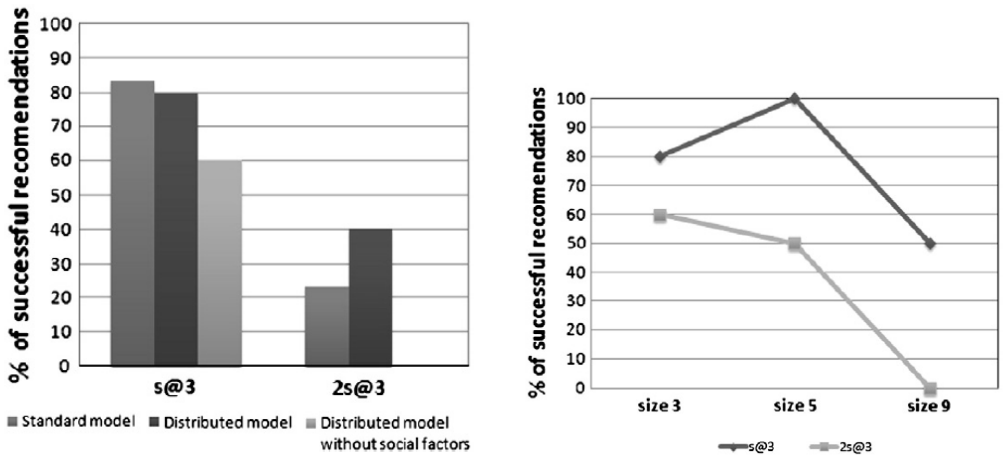



Figure 3.2: Comparison of the results for the different systems of interest for the whole study (left) and the results when using their system compared to group size for different success definitions (right) both taken from Recio-Garcia et al (2013), pages 53 and 54.

As can be seen in Figure 3.2, it is unclear that their model was noticeably better than the standard model (this is the fully connected network with no social issues included). The largest difference they saw was in the 2s@3 case which was where their system worked better for about an extra 3 groups. This could have easily just been due to the particular groups they used. Also an important area for improvement in their evaluation was that they did not compare how well their system performed against the standard system in terms of group size when it was clear that their system struggled with the larger group size of 9. However, this study provides some evidence that the social factors that were introduced seemed to improve their distributed model in terms of system accuracy. While this can be difficult to say from the relatively low sample size, it still seems to have a noticeable positive impact in both cases. It would have been very interesting to see how the fully connected model would have performed with the inclusion of the social factors given how poorly their model performed in comparison without these social factors.

Finally, I explore the idea of deception. Deception has been becoming an ever more important topic that has seen relatively little attention in the group decision support domain. The main problem therefore comes from a lack of established models. However, there have been several extensive studies into the effects deception has on the decisions made by groups (e.g. Marett & George 2004, 2013, Zhou et al 2013). These studies have been useful for understanding deception. They have shown that deception success seems to be largely related to how proximate a group is rather than the style of meeting used as shown by Marett & George (2004, 2013). Another study explored how deception skill or experience affect

various outcomes of deception as seen in Zhou et al (2013). However, these are all studies that analyse the data they found as opposed to actually creating a model and testing how well it fits to real world scenarios.

| STATE OF NATURE | | $S_1$ | $S_2$ | $S_3$ | EXPECTED VALUE | |
|---|---|---|---|---|---|---|
| TRUE PROBABILITY ($q_i$) | | 0.5 | 0.3 | 0.2 | | |
| PERCEIVED PROBABILITY ($q_i'$) | | 0.2 | 0.3 | 0.5 | $E_i$ | $E_i'$ |
| ALTERNATIVE | $A_1$ | 0 | 2 | -3 | 0 | -0.9 |
| | $A_2$ | 4 | 1 | 0 | 2.3 | 1.1 |
| | $A_3$ | 5 | -6 | 2 | 1.1 | 0.2 |
| | $A_4$ | 2 | -1 | 4 | 1.5 | 2.1 |

OPTIMUM STRATEGY - CHOOSE $A_2$; EXPECTED PAYOFF = 2.3

MISPERCEIVED OPTIMUM - CHOOSE $A_4$; EXPECTED PAYOFF = 2.1

DECISION MAKER CHOOSES $A_4$; ACTUAL EXPECTED PAYOFF = 1.5

LOSS DUE TO DECEPTION = 2.3 - 1.5 = 0.8

Figure 3.3: Simple example looking at the value of deception, taken from Greenburg (1982) page 144.

There has also been some work in the field of game theory where similar behaviour can be seen in more competitive games. Greenburg (1982) defined a simple value of deception which is the difference in utility from the true scenario with the deceptive scenario. This can be seen in Figure 3.3, where a decision maker has been deceived into thinking the true probabilities for the states of nature are given by $q_1'$, and so ends up choosing a sub-optimal strategy resulting in an expected utility loss of 0.8. From this I can see there is a clear gap in the literature: creating models of how deceptive an individual is likely to be and being able to counter the effects of any deceptions throughout the process. This could be done by using studies like these to understand how deceivers work in groups, and attempting to identify them using a model based on the results of the group discussion or by looking at how beneficial it would be for them to act covertly, in a similar way to that introduced by Greenburg (1982).

## 3.2 Context & Motivation

### 3.2.1 Measures in Different Contexts

The influence or sub-group measure can have different meanings depending on the context (DeSanctis & Gallupe 1987). For instance, group discussions may allow the possibility for an individual to influence preferences of other individuals, making detection of influence more difficult. In large-scale on-line elicitation group members may not be able to work together, but instead I may be able to detect similar cultural groups. I identify 3 specific types of context that could be of interest based upon the type of interactions between group members (although this list is not exhaustive).

**Scenario 1:** Face-to-face group meeting, where group members can see the other members whether it be in person or using video call software such as Skype, for example a board of directors.

**Scenario 2:** 'Chat Room' decision making, where group members could be anonymous and discuss the situation without identifying other members, for example an online deliberation forum of local council.

**Scenario 3:** Non-discussion decision making, where there is no formal discussion between group members with their only interaction being through elicitation of their individual beliefs, for example the CORWM elicitation (Phillips et al. 2006).

In Section 3.5 I explore a data set that falls under the Scenario 3 category which, as there is no formal discussion mechanism, causes the influence measure to pick up other interesting behaviour. For example, extremist views or the possibility that a group member did not understand the elicitation process. The common theme is that in these contexts it is worth investigating any individual that is flagged as 'potentially influential'. I say potential influence as I are only able to detect a chance of being influential. The influence value may also be high due to other reasons that should be explored on a case-by-case basis.

### 3.2.2 An Example

To further motivate the need for such influence measures (and sub-group identification methods), I have provided a small example. Consider 2 large companies that are discussing a mutually beneficial business agreement alongside a single external representative of the area that will be affected by the agreement. The group is relatively small (2 people from each company and the representative, totalling 5 people), and meets face-to-face (scenario 1 meeting) to discuss several options available for the agreement (and to produce a group utility functions through each individual's utilities). The external representative has openly stated their support of the agreement, citing the financial benefits the area would see from

it, and so the meeting is expected to proceed quite smoothly. However, there is some concern that there may be ulterior motives at play during the decision making process. Ideally the group members would like a diagnostic tool that could be used during the group meetings, which could identify potentially influential (and strange) behaviour. If this type of behaviour could be identified for one or more of the individuals involved, then they could have grounds to launch an investigation into why this behaviour had been exhibited.

On the other hand, consider a similar deal being made between 4 companies who also meet face-to-face. In this circumstance it would be a concern of some of the attendants of the meeting that other companies may have agreed to sway the decision a certain way to better benefit their own interests (so a secret coalition had formed). In this case it would be useful to have a tool that could attempt to identify the groups of people that hold suspiciously similar beliefs, in the hopes of identifying any such secret coalitions. Once identified, the other companies could then take appropriate actions to mitigate the decision against such 'unfair' activities. These are the types of tools I aim to lay the foundation for, by adapting methodologies developed in the area of regression into this utility setting.

### 3.2.3 Mathematical Formulation

Suppose I have a group that decides on the weights of a linear utility function describing the beliefs of the group based on the following set of properties.

- A group comprised of N members, indexed by $i = 1, ..., N$, which can be described by s subgroups, where $1 \leq |s| \leq N$.
- All utility functions describe the individual's preferences in terms of K attributes, $(A_j)_{j=1}^{K}$, where $a_j \leq A_j \leq b_j$ with $a_j, b_j \in \mathbb{R}$ for $j = 1, 2, ..., K$.
- An individual's preferences are described by a vectors of weights for the associated attributes, $\mathbf{u}_i = (u_i^{(1)}, u_i^{(2)}, ..., u_i^{(K)})$ for $i = 1, ..., N$.
- I assume that these weights are normalised such that $\sum_{j=1}^{K} u_i^{(j)} = 1$ and $u_i^{(j)} \geq 0$ for $j = 1, ..., K$ and $i = 1, ..., N$.
- There exists a group decision operation, $G$, that maps from the N individual weight vectors to a single weight vector that describes the group's preferences, $\mathbf{u}_G$.

**Definition 1** *Define $(K-1)$-simplex that each normalised linear utility function is contained in to be $S := \{(x_1, ..., x_K) : \sum_{j=1}^{K} x_j = 1, x_j \geq 0$ for $j = \{1, ..., K\}$. Then define an operation $G : S^N \to S$ to be a* ***group decision operation****.*

**Definition 2** *Take the normalised linear utility function over K attributes:* $\mathbf{u} = (u^{(1)}, u^{(2)}, ..., u^{(K)})$. *The value* $u^{(j)}$ *is defined as the* ***attribute weight*** *for attribute j, for* $j = \{1, ..., K\}$.

This group decision operation could be decided by the group, or an average function across each of the attribute weights could be used (I assume the latter for the sake of consistency).

**Notation** Given a group decision operation $G : S^N \rightarrow S$. I state the **group attribute weights**, $\mathbf{u}_G$, to be;

$$\mathbf{u}_G = G(\mathbf{u})$$

**Definition 3** *Define the* ***group attribute weights when individual i* is excluded****,* $\mathbf{u}_{G_{-i*}}$*, as;*

$$\mathbf{u}_{G_{-i*}} = G'(\mathbf{u}_{-i*})$$

*Where* $G' : S^{N-1} \rightarrow S$ *is the group decision operation G which has been adjusted for* $N - 1$ *individuals and* $\mathbf{u}_{-i*} = (\mathbf{u}_i)_{i=1, i \neq i*}^{N}$.

Throughout this chapter I have dropped the index, and used $G$ for all group decision operations because the dimension of the co-domain should be clear from the context.

## 3.3 Influence Measures

### 3.3.1 Influence in Regression Modelling

In a standard regression scenario (Sen & Srivastava 2011), I look for a model which describes how a set of explanatory variables can be used to predict a dependent variable. Suppose I have N data points and K explanatory variables, then I have a NxK matrix, $\mathbf{X} = (x_i)_{i=1}^{N}$, where each row is the set of observed explanatory variables for each data point. Each data point is also paired with their corresponding value for the dependent variable $\mathbf{Y}$, a Nx1 matrix.

In the case of linear regression, I assume that the model is of the form $\mathbf{Y} = \mathbf{X}\beta + \epsilon$. Where $\epsilon$ is a term describing the random variation of the scenario. The objective is to estimate the parameter matrix $\beta$, a Kx1 matrix, such that the model describes the data well. This set-up is where I draw the first clear link to group decisions using utility functions. In regression analysis, I usually know $\mathbf{X}$ and $\mathbf{Y}$. However, if I translate this across to the utility context I know $\mathbf{X}$ (N individuals on K attributes) and $\beta$ (the group decision operation) and wish to estimate $\mathbf{Y}$, which I can see as my group utility function. This link prompted me to consider translating ideas from regression to my context, such as variable selection or Cook's Distance.

| | Explanatory Variables | Dependent Variable | Parameters | Random Error |
|---|---|---|---|---|
| Linear Regression | $(\mathbf{x}_i)_{i=1}^N$ | Y | $\beta^*$ | $\epsilon$ |
| Group Decisions | $(\mathbf{u}_i)_{i=1}^N$ | $\mathbf{u}_G{}^*$ | $G$ | No random error |

Table 3.1: A brief comparison of the group decision and linear regression scenarios. The starred elements are those I wish to estimate from the given data.

### 3.3.2 Group Decision Operation

The success of the influence measure developed in this paper hinges on the group satisfying the properties outlined in Section 2.2. The most debatable property is that the group decides upon a group decision operation, so I consider this here.

**Property 1** *The group has agreed to use a group utility function to represent the beliefs of, and help make choices for the group.*

**Property 2** *The group defines a group decision operation, G, that maps from N attribute weight vectors to a single weight vector for the group's preferences,* $\boldsymbol{u}_G$.

In particular I assume that the group uses a single group weight, $\mathbf{u}_G$, to describe the beliefs of the whole group. There are problems with this as the group utility function loses information about each individual's personal preferences, and the differences between the group members.

This may not be a problem in certain circumstances that call for consistency in public reporting. One example is an issue in public safety from the introduction of nuclear power to an area. The group overseeing public and environmental safety would meet to discuss the importance of different factors concerned with the issue, however when submitting reports to the public it should be clear that there was agreement within the group or the public will have little trust in the organising group. Using a single group utility function to describe the beliefs of the group allow for this consistency through being a clear statement of beliefs.

I focus only on contexts where using a group utility function has an advantage over less restrictive methods. This leads on to the problem of understanding what form the group decision operation can take. First I introduce two properties below, adapted from those seen in Arrow's view of a 'fair group' that ensured the behaviour exhibited was consistent and rational (Arrow 1950). Note that with the introduction of highly correlated utility weights there is no analogous property to independence of irrelevant alternatives as no attributes can be irrelevant.

(1) *If all individuals in a group select their utility weight for attribute j such that* $u_i^{(j)} > k$ *for all* $i = 1, ..., N$ *and some constant* $k \in (0, 1)$*, then the group utility function must also have* $u_G^{(j)} > k$.

(2) *There is no individual* $i*$ *such that* $u_{G_{i*}} = u_G$ *for any choice of utility functions for individuals* $i \neq i*$ *and* $i = 1, ..., N$.

Results from Keeney (1976) and Neumann & Morgenstern (1953) show that the form of decision operation in Assumption 3 below is the only type of group decision operation that satisfies similar conditions to Arrow's Theorem. An important assumption to allow for this combination is that I have interpersonal comparisons of utilities, which is a key assumption in my context. This should be applicable when as the elicitation process is clear to all group members.

**Property 3** *For individual weight vectors* $(\mathbf{u}_i)_{i=1}^N$ *let* $u_G^{(j)} = \sum_{i=1}^N w_i u_i^{(j)}$*, where* $w_i$ *is the weight assigned to individual i and* $\sum_{i=1}^N w_i = 1$.

There are adaptations to this form that could be useful under certain contexts. For example, requiring one attribute to have a minimum weight would cause the group decision operation to be similar to, but not quite, a linear combination as suggested. However it would still satisfy the conditions I have given above under the assumption that the group recognises that this type of minor dictatorship is required and adjustments are applied after the combination (e.g. government requirements).

**Definition 4** *Individuals* $i_1$ *and* $i_2$ *are* ***permutable*** *if* $C_{i_1}(\mathbf{u}, G) = C_{i_2}(\mathbf{u}*, G)$*, where* $C_{i_1}(\mathbf{u}, G)$ *is a measure of influence for individual* $i_1$ *over the group attribute weights* $\mathbf{u}$ *using the group decision operation G and* $\mathbf{u}*$ *exchanges the attribute weights of* $i_1$ *and* $i_2$ *in* $\mathbf{u}$*. A group is permutable if all subsets of* $\{1, ..., N\}$ *are permutable.*

The group decision operation that I use is the arithmetic group mean where $w_i = N^{-1}$ for all $i = 1, ..., N$, which gives a simple average utility function. It must be highlighted that my choice of group decision operation is not a requirement on the suggested influence measure, but instead is being used for simplicity. This particular case allows for the permutability of the individuals seen below.

**Observation 1** *If* $u_{i_1}^{(j)} = u_{i_2}^{(j)}$ *for* $j = 1, ..., K$*, then* $C_{i_1}(u, G) = C_{i_2}(u, G)$.

While this is a nice property for the influence measure, it is often not be the case when the group decides to value the beliefs of one member more than another member (for instance the chairman of a committee) which could typically be the case in scenario 1.

**Theorem 1** *The only group decision operation of the form in Assumption 3 to exhibit permutability of individuals is when* $w_i = N^{-1}$ *for all* $i = 1, ..., N$.

This property may be useful in a more general context where I assume that all group participants are to be treated equally, as sub-groups are less dependent on having a high weight group member included. An example of this could be from scenario 3 where I may have a large scale web-studies where participants do not know each other, and provide their individual utility function. In the case of a weighted group decision operation, I can draw similar conclusions with the added condition that the individuals have the same weight assigned to them.

**Theorem 2** *For individuals $i_1$ and $i_2$, $u_{i_1}^{(j)} = u_{i_2}^{(j)}$ for $j = 1, ..., K$ and $w_{i_1} \in (0, 0.5)$. Then if $w_{i_2} > w_{i_1}$ I have that $C_{i_2}(u, G) > C_{i_1}(u, G)$.*

### 3.3.3 Influence

#### 3.3.3.1 Influence Measure

The base influence measure that was used is given as $C_i(\mathbf{u}, G) = K^{-1}D(\mathbf{u}_G, \mathbf{u}_{G_{-i}})$. The function $D(.,.)$ is chosen from those given in Section 3.3.2 below. First however, note that I initially are considering influence with respect to the attribute weights as opposed to the final utility values of each individual. This is to allow me to answer both whether the influential could be influential, and how that individual has attempted to exert influence. Focussing only on the final utilities scores would provide me with the answer to the first of these questions, but it would require more work to understand how the individual had been attempting to exert influence. However I plan to perform further work on this to assess whether this extra information is useful, and to consider a more general but simple influence measure which would be easier to explain to groups. I initially need to address what is meant by influence more precisely.

**Definition 5** *Given a distance measure $D : S \times S \to \mathbb{R}_{\geq 0}$ and an influence measure $C_i(\mathbf{u}, G)$, then individual $i$ is **influential at specified level** $\delta > \mathbf{0}$ if $C_i(\mathbf{u}, G) > \delta$.*

This gives a clearer understanding of an influential individual, and also gives groups freedom in how sensitive to manipulation they wish to be. Unfortunately I cannot appeal to asymptotics for a suitable $\delta$ level due to a limited number of both group members and attributes. The selection of a suitable $\delta$ value is explored in Sections 4 and 5.

**Definition 6** *If $C_i(u, G) = 0$, then individual $i$ is **influentially irrelevant** to the decision for this specific set of utility functions and group decision operation.*

The concept of an influentially irrelevant individual should be interpreted with care. I define this with respect to the decision and utilities given at the moment the influence measure is used. Any change in utilities from the group members could make a previously influentially

irrelevant member relevant. Justification of a group member being influentially irrelevant in scenarios 1 & 2 due to the impact they could have on other utility functions, however the concept does make sense in scenario 3 where I can define extremely non-influential group members.

To better understand this diagnostic I consider two methods of introducing influence based on increasing the individual's utility weight of a single attribute (I can assume attribute 1 for individual 1 without loss of generality) by a fixed amount L. This value of L has bounds to ensure the utility weights stay within $[0, 1]$ after adjustment. The two methods are in how I choose to balance this increase with the other attributes, as I still have the requirement for the utility weights to sum to 1. This means that the reductions to the other utility weights must sum to L. Define the utility function of individual 1 after influence is introduced to be $\mathbf{u}_{1,m}*$ where m is the case number from below, then I consider the two cases below;

**Case 1**

$\mathbf{u}_{1,1}* = (u_1^{(1)} + L, u_1^{(2)} - L, u_1^{(3)}, ..., u_1^{(K)})$

**Case 2**

$\mathbf{u}_{1,2}* = (u_1^{(1)} + L, u_1^{(2)} - \frac{L}{K-1}, u_1^{(3)} - \frac{L}{K-1}, ..., u_1^{(K)} - \frac{L}{K-1})$

Here I see that case 1 directly moves weight from one attribute to another, while case 2 increases the weight of attribute 1 at the expense of all other attributes equally. My main interest was how the value of depends on the case used. For this I compared $D(\mathbf{u}_G, \mathbf{u}_{G,1}*)$ and $D(\mathbf{u}_G, \mathbf{u}_{G,2}*)$, where $\mathbf{u}_{G,m}*$ is the group utility function when considering case m.

**Theorem 3** *Assume I introduce influence to individual 1 on attribute 1 as in Case 1 and Case 2 above, if I also assume that* $u_G^{(2)} < u_G^{(j)}$ *and* $u_1^{(j)} > 0$ *for* $j \neq 2$ *and* $j \in \{1, ..., K\}$ *and choose L such that all adjusted utilities are in* $(0, 1)$ *then I have;*

$D(\boldsymbol{u}_G, \boldsymbol{u}_{G,1}*) > D(\boldsymbol{u}_G, \boldsymbol{u}_{G,2}*)$

This theorem shows that transferring weight from one attribute to another is easier to detect when the attribute being reduced is small relative to the other utilities. Note that these calculations were done for the KL-Divergence, although all distance measures behave similarly. The non-negativity condition is for simplicity. This result extends trivially for zero utility weights.

The more interesting property is that the case which produces a higher value for the influence measure depends on the size of $u_G^{(2)}$ relative to the other utilities $u_G^{(j)}$ for $j = 3, .., K$. When $u_G^{(2)}$ is relatively large then case 2 gives a larger value, while when $u_G^{(2)}$ is relatively small the opposite is true. The behaviour of the influence measure between these extremes seems relatively smooth, although the details have yet to be specified (in particular for

equality between the cases). This behaviour comes from the fact that when $u_G^{(2)}$ is relatively large, the other utility weights change by a relatively larger proportion than $u_G^{(2)}$ due to all utilities being reduced by $\frac{L}{K-1}$. This shows that the influence measure responds more to relative changes in utilities rather than absolute changes, which is what I would hope. If I had changed case 2 to reduce each utility weight relative to the original weight for each attribute, it is likely that the influence measure would perform similarly in both cases.

#### 3.3.3.2 Distance Measures

The distance measures considered for use in $C_i$ are given below and all give similar behaviour. The first three are common measures of distance between probability distributions, while the Cosine Divergence was adapted from Chung et al (1989).

| Distance Measure | Definition |
|---|---|
| Jeffreys' Distance | $D(\mathbf{w},\mathbf{v}) = \Sigma_{j=1}^{K}(\sqrt{w^{(j)}} - \sqrt{v^{(j)}})^2$ |
| KL Divergence | $D(\mathbf{w},\mathbf{v}) = \Sigma_{j=1}^{K}(w^{(j)} \log \frac{w^{(j)}}{v^{(j)}})$ |
| J-Divergence | $D(\mathbf{w},\mathbf{v}) = \Sigma_{j=1}^{K}((w^{(j)} - v^{(j)}) \log \frac{w^{(j)}}{v^{(j)}})$ |
| Cosine Divergence | $D(\mathbf{w},\mathbf{v}) = \frac{1}{2}[1 - \Sigma_{j=1}^{K} f(w^{(j)}, v^{(j)})]$ where $f(w^{(j)}, v^{(j)}) = \begin{cases} (w^{(j)}v^{(j)})^{\frac{1}{2}} \cos(\alpha \log_2 \frac{w^{(j)}}{v^{(j)}}) & \text{for } \lvert\alpha \log_2 \frac{w^{(j)}}{v^{(j)}}\rvert < \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases}$ |

Table 3.2: Definitions of the four distance measures I have considered. Both $\mathbf{w}$ and $\mathbf{v}$ represent vectors of length K, where $\mathbf{w}^j$ and $\mathbf{v}^j$ are the $j^{th}$ element of each vector.

#### 3.3.3.3 Sub-Groups

The method used to assess the likelihood of a sub-group collaborating was based on the widely used $R^2$ value in regression, and thus was called the adjusted $R_s^2$ value which is given below for a specific sub-group s.

$$R_s^2 = 1 - \frac{\sum_{i \in s} \sum_{j=1}^{K} (u_i^{(j)} - u_{G_s}^{(j)})^2}{\sum_{i \in s} \sum_{j=1}^{K} (u_i^{(j)} - u_G^{(j)})^2} \tag{3.3}$$

The adjusted $R^2$ value attempts to measure how different a sub-groups beliefs are to the whole group by re-evaluating a group utility function using only the members of that sub-group. Similarly to $R^2$ in the regression sense, I expect groups with values close to 1 to be potentially working together. This preliminary definition of $R_s^2$ has provided promising results when applied to generated data and to my data set. However for particularly large groups (for instance I considered interactions between 46 people as a single group in my

data set) using this method to consider all possible subgroup possibilities is very inefficient. As such I would only recommend using this method for smaller group sizes, or evaluating specific sets of sub-groups in larger group settings.

#### 3.3.3.4 Assessment of Success

For my influence measure, I assessed success by generating the individual utility functions for large numbers of groups with and without influential individuals to compare the true and false positive rates. A true positive in this setting is when an individual that was constructed to be influential is flagged as being potentially influential. A false positive however is when an individual that was not constructed to be influential is flagged as potentially influential. The true positive and false positive rates are therefore the percentage of cases which falls under each definition respectively. Traditionally in statistics I fix one of these rates and maximise (or minimise depending on the rate) the other, however in this situation both of these rates are very important to success and the trade-off between them should be considered (Lashner 2006).

For the sub-group identification method I first checked that I can identify a sub-group designed to work together in a larger group. I then applied the method all non-trivial sub-groups (sub-group size between 2 and $N - 1$) of newly generated groups where there were no sub-groups specifically designed to be working together. I counted the number of flagged sub-groups of each size. This was repeated for newly generated groups where a sub-group designed to work together had been included and contrasted with results from when no sub-groups were specifically included. Finally, I applied these methods to my dataset and analysed whether the reported sub-groups and potentially influential individuals were sensible in the given context.

## 3.4 Numerical Studies

To explore the potential of the suggested measures, and to provide a recommendation on the $\delta$ level, they need to be applied to actual data. Therefore, I have conducted a study with a large number of randomised independent groups to explore specific behaviour of the influence measures. These groups are not based on any true data at this stage, but instead are based off a specific utility function structure in each case (number of attributes, number of individuals in the group). Studies are done for a baseline case with no intentionally influential individuals, groups where an influential individual is present (trying to change the group attribute weights), and additional studies for specific behaviour (such as cosine divergence performance at different $\alpha$ levels ).

### 3.4.1 Single Influential Individual

The first studies take a set of simulated utility functions, and manipulated the utilities of one individual on a single attribute, so that I would expect them to be flagged as potentially influential. I then compare this with simulated utility functions where no group members should be particularly influential. Unless otherwise specified I assume 10 group members providing utility functions on 8 attributes.

To create an individual's utility function, a randomised 'base' utility function, $\mathbf{u}_b$ is sampled to represent the average preferences of the group. This base utility function is taken and a random deviation is applied to each attribute weight to reflect the individual's personal preferences. The utility function is then renormalised such that the utility weights sum to 1. The algorithm used is given below;

**Step 1:** Sample the base utility function through $\mathbf{u}_b^{(j)} \sim U[0,1]$, for $j = 1, ..., K$.

**Step 2:** Renormalise the base utility function such that $\sum_{j=1}^{K} \mathbf{u}_b^{(j)} = 1$

**Step 3:** Sample each individual's utility function from the base utility function through $\mathbf{u}_i^{(j)} \sim N(\mathbf{u}_b^{(j)}, \frac{\mathbf{u}_b^{(j)}}{2K})$, for $i = 1, ..., N$ and $j = 1, ..., K$.

**Step 4:** Renormalise all individual utility functions such that $\sum_{j=1}^{K} \mathbf{u}_i^{(j)} = 1$ for $i = 1, ..., N$.

All individuals in the group derive their personal utility functions from the same base utility function $\mathbf{u}_b$ so that the utility weights remain relatively consistent. This was not a requirement for any of the methods, however it mirrors a real situation more closely than when there is no dependence. It also makes it simpler to introduce the concept of influence into the group.

The randomisation around the base utility function was sampled from a normal distribution with parameters $\mathbf{u}_b^{(j)}$ and $\mathbf{u}_b^{(j)}(2K)^{-1}$ to ensure that the groups beliefs stay centred around the base utility function, but with enough variance to demonstrate individuals having different beliefs. The variance is dependent on $\mathbf{u}_b^{(j)}$ to keep utility weights close to the base weight, relative to the value of the weight itself. For instance a weight of 0.05 should have less variance than a weight of 0.4. The variance is divided by $2K$ to account for the effect large changes would have on other utility weights at the normalisation step. Note that if the utility weight became negative, it is set to 0 to suggest the individual does not believe that attribute is important.

When an influential individual is introduced into the group, an independent selection of m attributes will become inflated relative to their initial value (assume $m = 1$ unless otherwise

stated). This adjustment will be independently repeated for every influential individual introduced to the group. When I introduce an influential individual, I follow the steps below to introduce influential individuals 1 to $n$ (assumed to be independent of each other).

**Step 5:** Sample each influential individual's utility functions independently from their original utility function using $\tilde{\mathbf{u}}_i^{(l)} \sim N(\mathbf{u}_i^{(l)} + \frac{2}{3}\mathbf{u}_i^{(l)}, \frac{\mathbf{u}_b^{(l)}}{K})$ where $l \sim U[\{1, ..., K\}]$, for $i = 1, ..., n$.

**Step 6:** Renormalise the influential individual utility functions such that $\sum_{j=1}^{K} \tilde{\mathbf{u}}_i^{(j)} = 1$ for $i = 1, ..., n$.

The parameters of the normal deviation were chosen as they usually place the attribute value far enough away from the rest of the group, but also not far enough such that it is obvious the individual is trying to be influential. While I have only presented results for when $n = 1$, my influence measure works for larger numbers of influential individuals. In this case I would consider success of result on the individual level, rather than on the whole group. For instance, if I introduce 2 influential individuals, and only one of the individuals is flagged, then only one true positive value would be recorded. The undetected influential individual would still be accounted for in the false negative rate (opposite of the true positive rate, these two rates must sum to 1) of the influence measure.

#### 3.4.1.1 Scaling

Using this algorithm for generating group utility functions and influential individuals, tests were done with 1000 generated groups, of differing sizes to investigate what $\delta$ levels are suitable for each of the distance measures. The distance measures were found to need some slight scaling to account for group size, attribute number (for all distance measures) and $\alpha$ value (for just the cosine divergence). An example plot is shown below showing robustness to group size after this scaling for Jeffrey's Distance.

My tests suggested that it would be simpler to include attribute number scaling directly on the $\delta$ value I compare the influence measure to, rather than the influence measure itself. To do this I need a base value $\delta_b$ which can be used to calculate the $\delta$ level for different numbers of attributes. Thus I define $\delta$ to be $\delta = \frac{\delta_b}{K+1}$. I have provided an initial suggestion of $\delta_b$ in Section 3.4.1.3 when using the Cosine Divergence. Note that the Cosine Divergence displayed slightly different patterns to the other distance measures, and needed to be scaled by $N^2$ and $(K+1)^2$ instead of $N$ and $(K+1)$ like the other distance measures. The scaled form of the influence measure for each set of distance measures is given below where scaling for attribute number is used for the $\delta$ value.

$$C_i(\mathbf{u}, G) = \frac{N^2 D(\mathbf{u}_G, \mathbf{u}_{G_{-i}})}{K\alpha^2} \text{ for Cosine Divergence.} \tag{3.4}$$

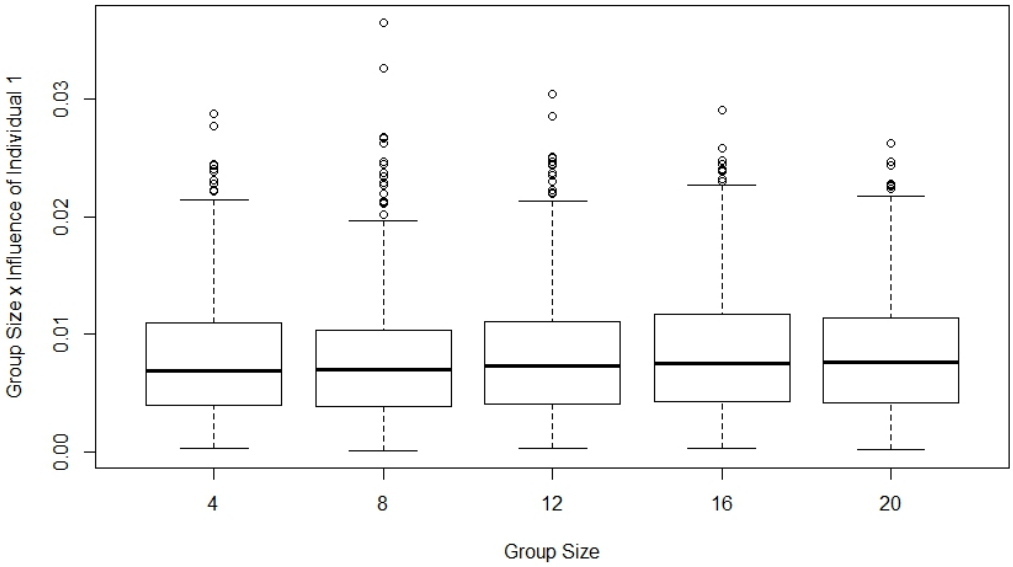



Figure 3.4: Set of box plots showing the distribution of scaled influence values for influential individuals in groups of sizes 4, 8, 12, 16 and 20 using Jeffrey's Distance.

$$C_i(\mathbf{u}, G) = \frac{ND(\mathbf{u}_G, \mathbf{u}_{G_{-i}})}{K} \text{ for other distance measures.} \tag{3.5}$$

#### 3.4.1.2 Selection of $\delta$

With my influence measures producing similar values no matter the group or attribute set-up, I can move my attention to the selection of a suitable $\delta$ level for each distance measure. Recall in section 3.3.3.4 I reviewed the definitions of true and false positive results, and the need to balance these rates in my scenario. I aim to maximise the true positive rate, while minimising the false positive rate. However the optimal trade-off between these two rates is dependent on the group's preferences. I provide a value of $\delta$ that I think is suitable for most cases in 3.4.1.3. This $\delta$ value corresponds to a 93.4% true positive rate, and between 2.7% and 4.4% false positive rate dependent on the distance measure chosen. This value can then be used, along with the scaling options suggested in Section 3.4.1.1 to calculate $\delta_b$, which allows generalisation to other attribute numbers for the same true and false positive rates.

#### 3.4.1.3 Results

The groups I use for analysis during this section were randomly generated according to the process seen in Section 3.4. Each group had 10 members, with 8 attributes and a single

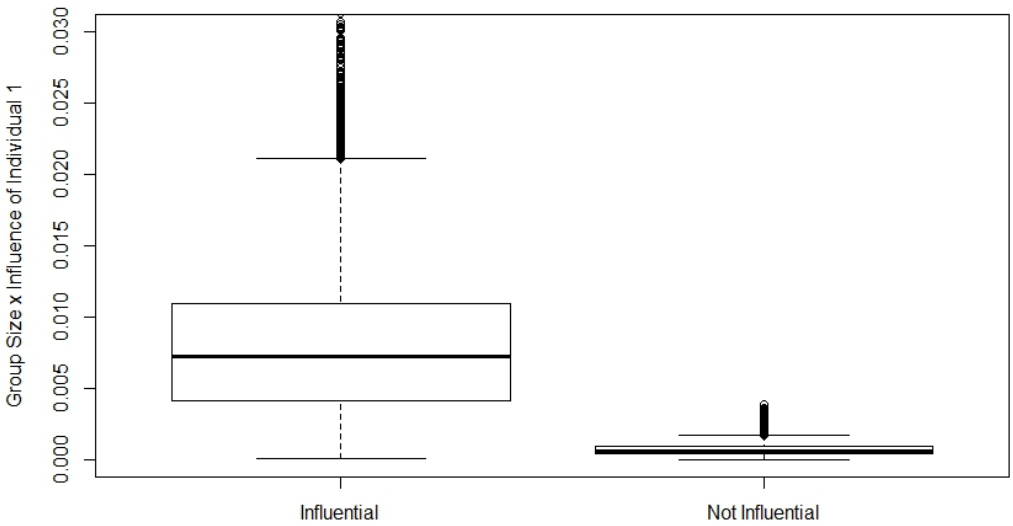



Figure 3.5: Box plots comparing distribution of 25000 scaled influence values for an influential and non-influential individual in groups of size 10 using Jeffrey's Distance.

influential individual being introduced where appropriate. In other words, $N = 10$, $K = 8$ and $n = 1$ or 0 for influential and non-influential groups respectively. Figure 3.5 shows a clear difference between the influenced and non-influenced groups, however larger values of the non-influenced group are close to the lower quartile of the influenced group. This means I cannot choose a perfect $\delta$ value. So I need to decide on a $\delta$ value with the right balance of true and false positives.

| **Jeffrey's Distance** | 0.0072 | 0.009 | 0.0108 | 0.0126 | 0.0144 |
|---|---|---|---|---|---|
| Influential positives (%) | 97.96 | 96.94 | 95.86 | 94.72 | 93.42 |
| Non-Influential positives (%) | 32.59 | 20.38 | 12.31 | 7.44 | 4.38 |
| **KL-Divergence** | 0.0216 | 0.0243 | 0.027 | 0.0297 | 0.0324 |
| Influential positives (%) | 95.88 | 95.00 | 94.10 | 93.14 | 92.23 |
| Non-Influential positives (%) | 12.31 | 8.48 | 5.77 | 3.79 | 2.44 |
| **J-Divergence** | 0.0432 | 0.0486 | 0.054 | 0.0594 | 0.0648 |
| Influential positives (%) | 95.86 | 94.97 | 94.06 | 93.09 | 92.19 |
| Non-Influential positives (%) | 12.31 | 8.49 | 5.76 | 3.79 | 2.46 |
| **Cosine Divergence** ($\alpha$ = 1) | 0.03888 | 0.04374 | 0.0486 | 0.05346 | 0.05832 |
| Influential positives (%) | 96.12 | 95.25 | 94.34 | 93.38 | 92.40 |
| Non-Influential positives (%) | 10.15 | 6.74 | 4.24 | 2.68 | 1.73 |

Table 3.3: Comparisons of true positives against false positives from two sets of 25000 simulated groups for each distance measure, and associated $\delta$ values as column headings.

| $\alpha$ value | 0.5 | 0.9 | 1 | 1.1 | 1.5 | 2 |
|---|---|---|---|---|---|---|
| Influential positives (%) | 97.3 | 91.5 | 92.9 | 92.2 | 91.4 | 93.9 |
| Non-Influential positives (%) | 5.8 | 2.6 | 2.1 | 3.4 | 1.8 | 1.4 |

Table 3.4: Comparisons of true positives against false positives from sets of 1000 simulated groups for the Cosine Divergence with different values of $\alpha$ at $\delta$ = 0.05346.

By comparing a true positive rate of roughly 93.4% with the associated false positive rate, Jeffrey's Distance performs the worst while KL-Divergence and J-Divergence performed similarly to each other. Cosine Divergence performed the best as it minimised the false positive rate the most, improving it by over 1% from the KL Divergence. I can calculate $\delta_b$ from these values. For example for Cosine Divergence, if I select $\delta$ = 0.05346 then I know $\delta_b$ = 4.33026.

Due to the best performance coming from the Cosine Divergence I may ask if I can improve the results by considering different values of $\alpha$. I must be careful as increasing $\alpha$ too much makes the influence measure too concentrated, and so I only consider values of $\alpha$ up to 2. Table 3.4 shows I can see a slight downward trend for the false positive rate as I increase $\alpha$. I reran the tests with the larger sample size of 25000 groups for just $\alpha$ = 2 to explore the consistency of results. The false positive rate was 1.76% and the true positive rate was 92.61% which was only a slight improvement over when $\delta$ = 0.05832, and so I proceed by keeping $\alpha$ = 1.

### 3.4.2 Sub-Groups

The method proposed to identify possible sub-groups is the adjusted $R^2$ value. I have considered two group types; a 'standard' group with individual utility functions derived from steps 1 to 4 seen in Section 3.4.1, and an 'altered' group where I have adjusted the attribute weights of a known sub-set of the members to reflect collaboration. This ensures I know which sub-group has been specifically designed to collaborate at this stage. When I introduce a collaborating sub-group, there are two variables to be defined. The number of attributes the subgroup is trying to influence is $m$, and the size of the sub-group is $n$. To introduce a sub-group to the group I followed the steps below.

**Step 1:** Create a set of individual utility functions for the group as before.

**Step 2:** Produce a mean utility weights vector; $\bar{\mathbf{u}}^{(j)} = \frac{\sum_{i=1}^{N} \mathbf{u}_i^{(j)}}{N}$ for $j = 1, ..., K$.

**Step 3:** Sample each individual's utility function (in the sub-group) from the mean utility weights vector through $\mathbf{u}_i^{(j)} \sim N(\frac{3}{2}\bar{\mathbf{u}}^{(j)}, \frac{\bar{\mathbf{u}}_b^{(j)}}{2K})$, for $i = 1, ..., n$ and $j = 1, ..., m$.

**Step 4:** Renormalise individual utility functions (from the sub-group) such that $\sum_{j=1}^{K} \mathbf{u}_i^{(j)} = 1$ for $i = 1, ..., n$.

This produces a sub-group of size n that have roughly similar beliefs which fall outside the average of the group, allowing for personal preferences within the sub-group (hence the relatively tight variance). I specifically move people away from the group as this is the situation I are more interested in, as having a sub-group that is just as average of the rest of the group is not very informative.

#### 3.4.2.1 Scaling

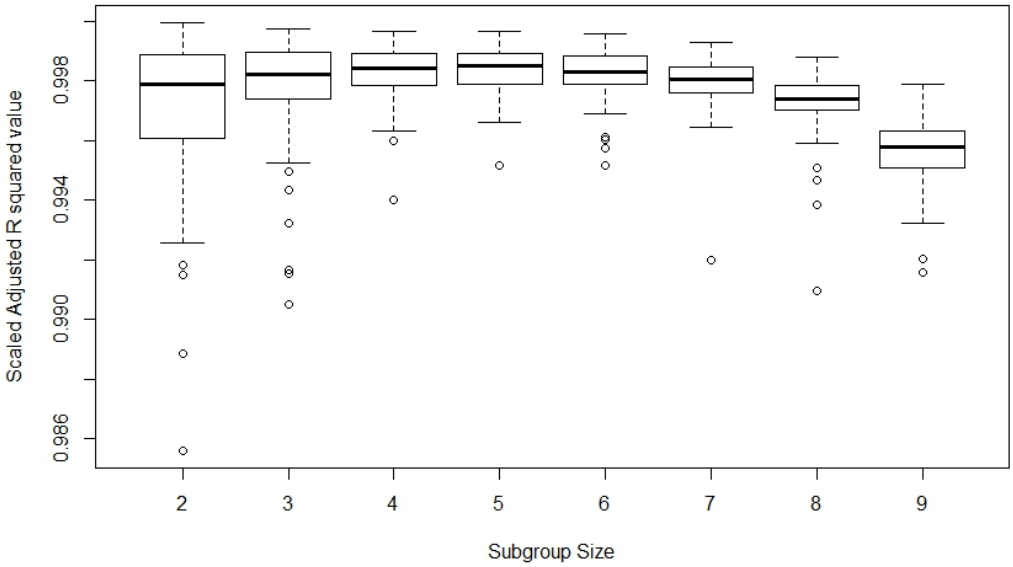



Figure 3.6: Box plots comparing the distributions of scaled adjusted $R^2$ values for 100 groups of size 10 considering 6 attributes when I introduce sub-groups of various sizes.

Raising the adjusted $R^2$ value to the power $\frac{1}{n}$, where n is the sub-group size, addresses the scaling issue of the adjusted $R^2$ value for sub-group size.

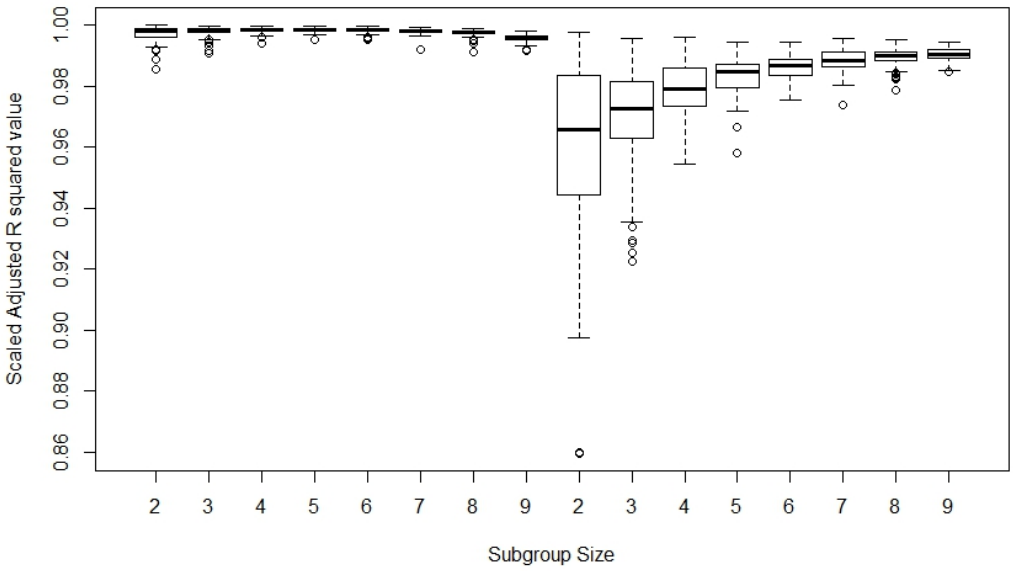



Figure 3.7: Box plots comparing the distributions of scaled adjusted $R^2$ values for groups of size 10 considering 6 attributes when I introduce sub-groups of various sizes (left 9 groups) or when I do not introduce sub-groups (right 9 groups).

This scaling is not perfect but it does group them mostly together near the same values, even if the extreme sub-group sizes tend to produce lower values. The adjusted $R^2$ value therefore had its definitions changes slightly to account for this, as given below.

$$R_s^2 = (1 - \frac{\sum_{i \in s} \sum_{j=1}^{K} (u_i^{(j)} - u_{G_s}^{(j)})^2}{\sum_{i \in s} \sum_{j=1}^{K} (u_i^{(j)} - u_G^{(j)})^2})^{\frac{1}{n}} \tag{3.6}$$

I can see that when I look at groups where I have forcibly introduced a sub-group (the left side of box-plots) it gives a far higher value than when looking at a group with no sub-groups. Unfortunately the scaling has had the opposite effect on the sample with no sub-groups, but despite this the difference between the two sets of groups is still clear.

#### 3.4.2.2 Results

I can see from my initial explorations that the adjusted $R^2$ value can identify sub-groups relatively consistently when I introduce them and I know which sub-group I are looking for. However this is unlikely to be the case in practice if members of the group are concerned about any coalitions that have been formed that they are unaware of. Because of this I

looked at all possible sub-groups of 100 generated groups, that have each had a sub-group included of a specific size, and record how many sub-groups are discovered for differing group sizes and sub-group sizes. The three main scenarios I consider are;

| Test Number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Number of Group Members (N) | 8 | 8 | 12 | 12 | 16 | 16 |
| Number of Attributes (K) | 6 | 6 | 10 | 10 | 10 | 10 |
| Sub-Group Size (n) | 3 | 0 | 4 | 0 | 6 | 0 |
| Number of Sub-Group Attributes (m) | 3 | 0 | 5 | 0 | 3 | 0 |

Table 3.5: Summary of the sub-group tests performed

All of these 6 tests were repeated 100 times, and all sub-groups were checked each time to see if the adjusted $R^2$ value was greater than 0.995 (which was a preliminary value chosen from initial tests). I then counted the number of sub-groups that passed this check for each possible sub-group size, and these results are given below. Keep in mind that these are the number of reported sub-groups for all 100 simulated groups, not just a single group, and so 300 reported sub-groups is an average of 3 sub-groups reported per group.

| Sub-Group Size | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Test 1 (Sub-group) | 170 | 50 | 4 | 1 | 0 | 0 |
| Test 2 (No Sub-group) | 22 | 2 | 0 | 0 | 0 | 0 |

| Sub-Group Size | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Test 3 (Sub-group) | 1213 | 1283 | 1420 | 1456 | 1029 | 418 | 71 | 0 | 0 | 0 |
| Test 4 (No Sub-group) | 35 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Sub-Group Size | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Test 5 (Sub-group) | 2814 | 5418 | 9482 | 13883 | 14208 | 9595 | 3967 |
| Test 6 (No Sub-group) | 61 | 9 | 3 | 1 | 0 | 0 | 0 |

| Sub-Group Size | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|
| Test 5 (Sub-group) | 910 | 93 | 0 | 0 | 0 | 0 | 0 |
| Test 6 (No Sub-group) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 3.6: Number of significant sub-groups of each size.

These results demonstrate a relatively low false positive rate. For all groups with no sub-group forcibly introduced, the average number of significant sub-groups was less than 1. I can also see that there may be some difficulty in detecting smaller sub-groups, as on average only half of the sub-groups of size 3 in test 1 were reported as significant. This behaviour could be expected when recalling Figure 3.6 and is something that should be kept in mind

when exploring a set of data for sub-groups.

It is from tests 3 and 5 I can start to see the benefits of sub-group identification because in both cases there is a noticeable peak around the size of the sub-group I specifically included for these tests. The reason that the average number of reported significant sub-groups is relatively larger (for example 14.2 for test 3 and 142 for test 5) is that I are counting small changes to the sub-group as well. For instance including 3 of the 4 group members contained in the sub-group I had included in the tests, and one other non-sub-group member that has similar attribute weights. This means the best way to use this method is to look for sets of common individuals in the reported sub-groups. This allows me to deal with the larger number of report significant sub-groups.

## 3.5 Case Study

### 3.5.1 Dataset

The data I use is taken from Atherton (1999) which explored the temporal issues in decision making, and I used the data gathered for her first experiment 'The Hypothetical Decision'. Participants in a web experiment were asked to give attribute weights (using an on-line tool) on the importance of several attributes over several eras of different lengths on the construction of types of facility for nuclear waste disposal. 5 attributes were considered (Construction, Health, Environment, Operating and Accidents) over 4 time periods (Immediate, 0-100 Years, 100-500 Years and 500-1000 Years). In other words, each participant provided 4 utility functions, one for each time period. The participants were then asked to weight the importance of each of the time periods so that their 4 utility functions could be combined into a single utility function representing all 5 attributes over all 4 time periods. For more information on the design of this experiment, see Atherton & French (1998). The distribution of attribute weights of each of these 5 attributes can be seen below in Figure 3.8 and an example utility function of a participant can be seen in Table 3.7.

| Attribute | Construction | Health | Environment | Operating | Accidents |
|---|---|---|---|---|---|
| Participant 14 | 0.09625 | 0.05919 | 0.06978 | 0.11068 | 0.66410 |

Table 3.7: An example of the normalised utility function for subject 14 (5 d.p.).

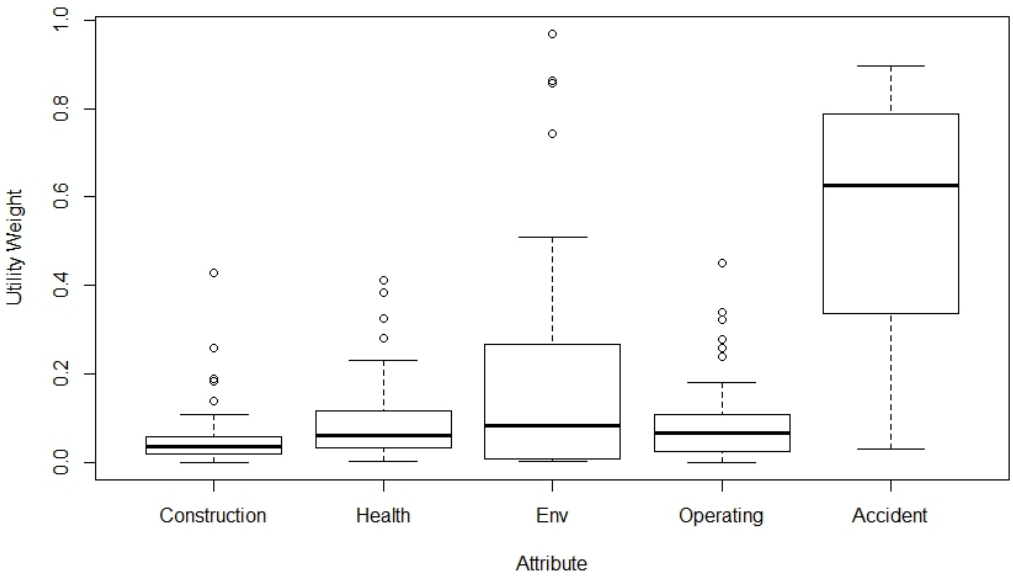



Figure 3.8: Box plots comparing the distributions of attribute weights assigned to each of the attributes for all participants.

46 participants were included in the study where most participants were between 20 and 30 (31 total), with the other participants being spread out between 30 and 50. Geographically, 33 participants were based in the UK, 8 from the EU, and the remaining 5 participants were non-EU. This shows that the biggest differences tended to be between the importance of 'accidents' or 'environment'. Keep in mind that increasing the weight of one attribute necessarily decrease the weight of the other due to the normalisation condition, and so many of the extreme values in one attribute have associated extreme weights for other attributes. In general it seems participants moved weight from 'accidents' to the attributes they felt were particularly important which accounts for the large variation of accident utility weights.

| Attribute | Construction | Health | Environment | Operating | Accidents |
|---|---|---|---|---|---|
| Mean | 0.05695 | 0.09422 | 0.18848 | 0.09631 | 0.56493 |
| Standard Deviation | 0.07716 | 0.09668 | 0.25064 | 0.10008 | 0.26303 |

Table 3.8: Summary statistics of the dataset. Note the group utility function is assumed to be the mean here.

There are some differences to my simulations that need to be considered. First, the number of participants is larger than any of the simulated studies but the scaling should compensate

for this. Second, as the participants did not collaborate, the utility functions are not as consistent as I would expect. Thirdly, zero utility weights have been replaced by a small value ($1 \times 10^{-9}$) to avoid numerical issues. Finally when considering sub-groups, I are unable to explore every possible sub-group due to the size of the power set ($2^{46}$), and while this is a more open problem, I have only explored sub-groups of size 6 (roughly 10 million sub-groups).

I also need to be clear about what the influence means in the given context. In this case the participants were not involved in group discussions, and so had no chance to influence the views of the other participants so all influence they wish to exert is contained in their utility function. Therefore I might expect 'potentially influential' participants to be one of two things; they may not understand the utility elicitation method as there was no human interaction for when participants may have had problems, or they may have an extremist view about a certain issue and so inflate their attribute weights for this issue. Using group utilities here also makes sense due to the significance of the issue, as any recommendation put forward for nuclear waste disposal should have a clear source.

### 3.5.2 Results

For the analysis of these results I used the Cosine Divergence, with $\alpha = 1$, as it showed better performance than the other distance measures during the simulations. As there are 5 attributes, I consider an individual as potentially influential if their adapted Cook's Distance is greater than $\delta = 0.12029$. Figure 3.10 shows why the participants were flagged in Figure 3.9; they are all far from the group's average. In particular all individuals that weight environment highly in Figure 3.8 were flagged as potentially influential. Also I can see that the accident weight is generally reduced when other attributes are weighted more heavily.

Some expected patterns are shown in Table 3.9. For instance, the younger people demonstrating more concern for the environment and the Assistant Director weighting operating cost very highly. This gives me more confidence that the results fit the context. Unexpected values could also be useful. For example, I could investigate participant 41 to see if they understood the utility elicitation process as they weighted construction costs very highly, when it was usually a very minor cost in the long term (even when participants weight immediate effects highly).

While I identified the students with high environmental weights, I did not consider other students. To answer this question I can appeal to my sub-group identification method. I only consider sub-groups of size 6 due to computational limitations. Comparing the adjusted $R^2$ values to my tolerance of 0.995, I found 1215 reported sub-groups. This number

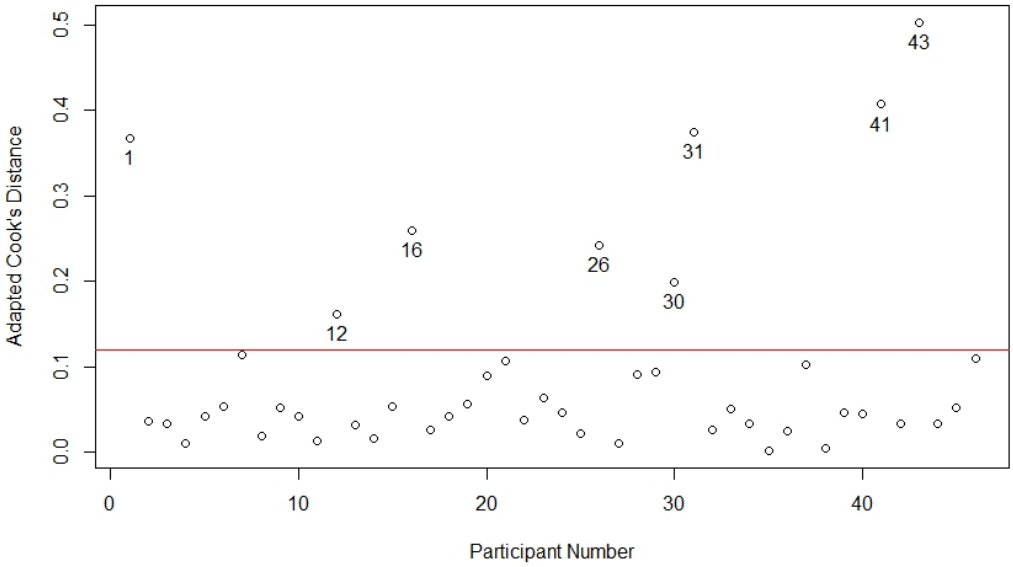



Figure 3.9: Scatter plot of the adapted Cook's Distance values for all participants, with a $\delta$ line (red).

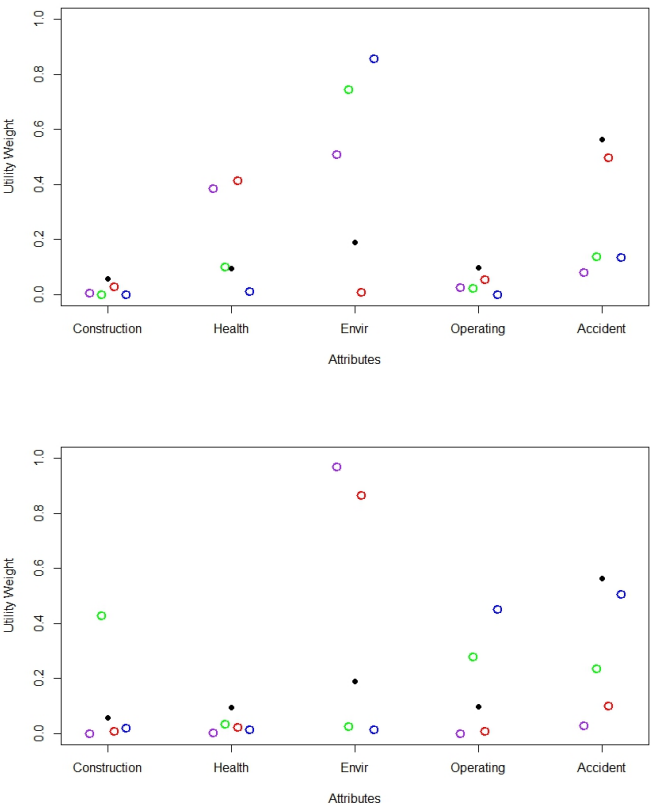



Figure 3.10: The attribute weights for participants 1 (blue), 12 (red), 16 (green) and 26 (purple) in the top plot and 30 (blue), 31 (red), 41 (green) and 43 (purple) in the bottom plot with the group utility function (black).

| Participant | Age | Country of Origin | Job Title | Sex |
|---|---|---|---|---|
| 1 | 23 | UK | Student | M |
| 12 | 28 | Belgium | Researcher | M |
| 16 | 20 | UK | Student | F |
| 26 | 42 | UK | PhD Student | M |
| 30 | 45 | Australia | Assistant Director | M |
| 31 | 26 | UK | PhD Student | F |
| 41 | 32 | UK | Research Fellow | M |
| 43 | 28 | Norway | Post Doctoral | M |

Table 3.9: Information about each of the participants that were flagged as potentially influential.

is still large, and work must be done on recommending the most likely sub-groups, however for now I consider those with particularly large adjusted $R^2$ values (over 0.998). This then the returns 19 sub-groups given in Table 3.10.

| Sub-group Number | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 9 | 9 |
| 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 15 | 15 | 15 | 15 | 18 | 15 | 18 |
| 15 | 15 | 15 | 15 | 15 | 15 | 15 | 18 | 18 | 18 | 18 | 19 | 18 | 18 | 18 | 18 | 19 | 18 | 19 |
| 18 | 18 | 18 | 18 | 18 | 19 | 19 | 19 | 19 | 22 | 39 | 39 | 19 | 19 | 19 | 39 | 39 | 19 | 39 |
| 19 | 19 | 22 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 40 | 40 | 22 | 39 | 39 | 40 | 40 | 39 | 40 |
| 39 | 40 | 39 | 40 | 42 | 40 | 42 | 40 | 42 | 40 | 42 | 42 | 39 | 40 | 42 | 42 | 42 | 40 | 42 |

Table 3.10: Sub-groups of size 6 which have an adjusted $R^2$ value of over 0.998. Each column is a reported sub-group, with the elements being the participant number.

From Table 3.10 I see the same participants are being included in many of these groups. In particular, participants 6, 9, 15, 18, 19, 39 and 40 all appear in at least 12 of these sub-groups, so if I look at this specific sub-group I see an adjusted $R^2$ value of 0.998483, which is also very high. Comparing the elicited utilities from these participants I can see all of them weighted accidents very highly (between 0.83 to 0.9), and so I have been successful in identifying a group that shares similar beliefs. I can also see a very strong trend demographically with these participants, as they were all students between the ages of 20 and 29. This shows that between applying my influence measure, and a simple application of my sub-group identification, I have been able to identify two distinct groups within the younger participants from just 11 of the participants.

## 3.6 Discussion and Extensions

### 3.6.1 Diagnostics Performance and Usage

In Sections 3.4 and 3.5 I explored the behaviour of my proposed methods in both large-scale simulated studies and a case study concerning nuclear waste disposal. The data set that was used proved a good test for the robustness of my methods to group size, and the results were consistent with what I may expect. My simulated results for influence detection were promising and quite useful in selection of the most suitable distance measure. The Cosine Divergence was chosen due to its empirical performance, giving the lowest false positive rate(2.7%) coupled with just as strong a true positive rate (93.4%) as any of the other distance measures.

When applying the influence measure to my case study, I identified some interesting behaviour showing the influence measure works in larger scenarios. If my influence measure had been applied at the time of the study, the on-line elicitation process could have been improved as there was some evidence that one participant did not understand the elicitation. Also expected behaviours were identified, such as the younger participants generally giving more extreme environment attribute weights. This could have been politically driven or influenced by parties such as Greenpeace. The influence measure could have been used to flag these participants for a follow-up study. It was also interesting to see that participants would usually increase one weight at the expense of just one other weight (usually accidents).

**Scenario 1: Boardroom style meetings**

This is the scenario where my proposed diagnostics has the least impact. This is due to individuals being more likely to influence the group by changing the beliefs of the other group members. Therefore an individual's influence can more easily be divided amongst the whole group's individual utility functions. I would expect my influence measure to be less useful here due to a lower true-positive rate, although it can be used to detect group members that misreport their beliefs. The sub-group identification could be more useful as it can check specific sub-groups the group may be worried about while also detecting sub-groups that remain undetected. Due to the difficulty of influencing a group decision individually, it is likely group members would form sub-groups to increase their influence over the group.

**Scenario 2: Chat room meetings**

In this scenario I would expect group members to exaggerate some of their beliefs (particularly when they can remain anonymous), which my influence measure can detect so that

the truth of their reported utilities can be investigated. Also group members are generally less malleable to other group members because of less trust in this setting. However, group members may be more open to working with other group members to manipulate the outcome due to the ease of hiding these discussions from other group members. My sub-group identification diagnostic should allow me to detect a selection of sub-groups that could be working together to allow the group to use this information to re-assess the truth of the group utilities.

**Scenario 3: Non-discussion decision making**

In this scenario I have no discussion between group members, meaning individuals influence the group utilities only through their own beliefs. I would expect exaggeration of group member's beliefs to be more extreme than in scenario 2 as people may feel they need to 'pull' the group towards their beliefs. My influence measure can detect these extreme views (as I saw in the case study), so that follow up studies or slight adaptations to the decision process could be made. Particularly high influence values could also correspond to individuals not understanding the system of utility elicitation well (which they likely would have had more help with in the other scenarios), and so it could be used as a diagnostic to test for how good the implemented elicitation process is.

The sub-group identification method can be useful for detecting group members with similar backgrounds or affiliations (for example political interests on environment as in my case study), and so could be useful for helping to identify demographics that tend to share the same beliefs. This could be useful in deciding how representative the sample was of the general beliefs of the target population of the decision (in my case study, the sample is not very representative of the general UK population due to the majority of participants being students in their 20s).

### 3.6.2 Influence in Dynamic Utilities

The assumptions I have made thus far have allowed me to create a basic influence measure in a specific scenario. However when applied to the real world I might expect that removing a group member from the discussions would have more impact than just on the given utility functions. Thus I can move from having static individual utilities to dynamic individual utilities, which change in response to which group members are being removed. This allows me to drop the more unrealistic assumption that individuals are unaffected when another group member is removed. This also gives me more flexibility on how I define influence in the group, as while I can still consider influence over a group utility function in the same way as before, I can also consider the influence of group members on each other and on

particular attribute weights. The problem that comes from using these dynamic utilities is that I must know the utility functions of each individual in all feasible group set-ups to do a comprehensive analysis. This makes this method quite difficult to apply in the traditional utility sense, both due to the time it would take, and the lack of co-operation from group members which must rerun the same situation many times with different people being removed. However, as I see later, it may be particularly useful in models that contain utility-like behaviour.

#### 3.6.2.1 Group Utilities

I first consider using dynamic utilities in a setting identical to before where the group has an agreed upon combination rule that defines the group utility function. Fortunately very few changes are required here, as I need to alter several definitions to include the fact that the individual utilities are no longer static for the whole process. So I define the utility weights of individual i, when individual i* has been removed from the group, to be $\mathbf{u}_{i,-(i*)} = (u^{(1)}_{i,-(i*)}, u^{(2)}_{i,-(i*)}, ..., u^{(K)}_{i,-(i*)})$. This definition allows me to change an individuals utility in different ways when different group members are being removed from the process. Next I update the definition of $\mathbf{u}_{G_{-i*}}$ to be $\mathbf{u}_{G_{-i*}} = G(\mathbf{u}_{-i*})$ where $\mathbf{u}_{-i*} = (\mathbf{u}_{i,-i*})^{N}_{i=1,i\neq i*}$, which allows my previous influence measure to be applied to this.

When I still have a group utility function involved, I are still concerned about how this changes when group members are removed, and so the definition of influence in this case does not need to be changed. $C_i(\mathbf{u}, G) = K^{-1}D(\mathbf{u}_G, \mathbf{u}_{G_{-i*}})$ would still measure the influence that individual i has over the group utility function, which is used to make the final decision in this case. I could change from static to dynamic utilities when considering the impact on the group utility function. However the process becomes far harder to implement and the influence of an individual starts to come both from their immediate removal (which is likely to be lessened from before) and the impact on the other individuals, which may result in relatively small changes.

#### 3.6.2.2 Individual Utilities

The more interesting extension comes when I are not considering a group utility function, simplifying the scenario to just having $N$ individual utility functions which dynamically change when individuals are removed. Due to the removal of the group utility function, I can no longer use this to measure the influence of an individual, however I no longer have static utilities and so can start to look at the affect that removing a group member has on the other group member's utilities. This then has the same format as comparing the change in group utility functions, so I are able to continue using the influence measure that was

defined earlier. I must think carefully about how I define influence here though, and my definition is more free to change in response to the scenario.

I considered two types of influence; influence over other group members, and influence over specific attributes. Alongside this I should also consider the detail of information I wish to produce. In single scenarios, I may want to keep the measure of influence very simple. For example, an average effect over all other group members. However when I start to have repeated scenarios with the same group, I can more comfortably explore the contributions to the influence of a group member from each other group member. For example I could start to look at the influence individual i* has over individual i, and then perhaps in more detail; the influence individual i* has over attribute j of individual i.

**Influence of individual i* over individual i.**

$$C_i(\mathbf{u}_{i*}, \mathbf{u}_i) = K^{-1} D(\mathbf{u}_i, \mathbf{u}_{i,-i*}) \tag{3.7}$$

**Influence of individual i* over attribute k.**

$$C_i(\mathbf{u}_{i*}, \mathbf{u}^{(k)}) = N^{-1} D(\mathbf{u}^{(k)}, \mathbf{u}^{(k)}_{-i*}), \text{ where } \mathbf{u}^{(k)} = (u_i^{(k)})_{i=1}^N \tag{3.8}$$

If I wish to get a single value for the influence of individual i*, then I can average the above values over all individuals or attributes respectively. This potentially allows me to get some very detailed analysis of how influential a group member is, although it would require a rather specific scenario. Also, in the case of influence over an attribute, I would need to be a little more careful of the usage of the distance measures as the values in each vector that is being compared will not generally sum to 1. The final version of influence I could consider would be influence over time. This is possible when I have a time series of utility weights, and could be useful to identify what events the influence of a group member responds to.

As before however, the usefulness of these measures depends entirely on the ability to get all of the utility weights that are needed for this analysis. One possible scenario where this could be the case is in a computer model of a discussion, where the interactions between group members are robust enough to not break down when a group member is removed.

### 3.6.3 Extensions

I considered three extensions to the methods developed in this paper. First, I could explore adaptations to the one-out restriction that the current method uses, as real scenarios could have complex interactions between group members. I may also be able to draw on more links to regression. For example stepwise forward selection in variable selection (Harrell

2001). Using this it may be possible to select the 'most important' group members to the decision. Exploration can also be done into effects of removing multiple group members, and whether the order and time of removals makes a significant impact on the group utility function. This could also help me understand how 'missing data' affects the process.

For my second extension, I could also use the developed diagnostic tests to attempt to identify deceptive individuals. This is a difficult problem as I need to use behavioural observations alongside the influence values for each individual. For example, I may expect that group members with much influence over the group utility function that interacts more than normal with the group could be a deceiver. This would be useful extension for scenarios 1 and 2. I should also keep in mind that false positives in this case could be far more common than for the influence measure, and so confidence in the diagnostic tools would drop substantially.

Finally, I could turn my focus to the detection of unwanted influence in a scenario where I expect group members to influence other member's beliefs instead of misreporting their own. I use the term 'unwanted' influence here because it is both expected and accepted by the group. The problem comes when group members do not realise they have been influenced. I may try to elicit each group member's utility function before any discussions to give an estimate of their 'prior' utility function. I may then need to draw on some more behavioural observations to estimate how malleable each individual is, although group hierarchy could also be used. This could then be used alongside the utility function elicited after the meeting (posterior) to lessen the effect of the meeting. However keep in mind there is a large difference between an individual's initial beliefs being corrected by the group and being influenced by a member within the group, despite both these cases giving similar outcomes.

## 3.7 Conclusions

Both the influence measure and sub-group identification methods developed showed promise, although improvements are needed to allow for more tailoring to specific scenarios. The influence measure can be particularly useful for identification of issues with an elicitation process in a large scale study, and also in identifying individuals with more extreme beliefs. This could be seen when exploring the data for the choice of nuclear waste disposal. More extreme beliefs were identified with ease, and also an example sub-group was identified with very similar beliefs, even when I could not explore all possible sub-groups due to the scale of the problem. In smaller scenarios, the influence measure needs to be adapted to account for group members attempting to influence the decision through other member's utilities. I hope that once some of these suggested improvements have been implemented,

that the described diagnostics would be a strong addition to a group's arsenal of diagnostic tests.

This Chapter has produced a selection of technologies for influence and sub-group identification when using a utility setting. This contributes to a gap in the previous utility theory literature, as the idea of influence has rarely been formally considered in such a way. This has also contributed, to some extent, to the opinion dynamics literature, as it gives a more formal way of measuring how influential an individual is. This may be useful for areas such as targeted marketing.

The production of these methods has been a worthwhile exercise and they have shown quite positive results. However, it became clear to me that continued work on these measures would be problematic to implement in the real world due to the very restrictive requirements for use. In particular, while they were quite useful in identification of interesting behaviour in the data set I used, collecting this data in future is unrealistic. While they could still be used to great effect in smaller scale decision making where the group can agree on a group decision rule, it still imposes quite a lot of restrictions on the group. I decided to stop pursuing a utility based approach to group decision making, and instead focused on usage of different modelling paradigms for the more specific example of the failed 2009-2013 Cumbrian siting process. I did however, still consider influence in this setting from a different viewpoint: influence of events and scenarios.

# Chapter 4

# Geological Disposal Facility Siting Case Study

## 4.1 Case Study

An initial consideration before proceeding with the case study of the Cumbrian GDF siting process, is to consider some of the methods for researching case studies (e.g. Gillham 2000). The first question is to propose a specific research question (or set of questions). In this case, the most specific case is: did the councils extension request at the end of the siting process change the final result (a quantitative and qualitative objective)? However, there is also a more generic objective which would be to understand some of the driving factors behind changing public opinion (a qualitative objective). Given this is a past process with limited data available, a variety of information needed to be collected from both the survey results throughout the process, and media/blogs/websites that were active at the time of the process. Additionally, it needs to be noted that the qualitative information taken from these sources has been initially interpreted by myself, and validated with experts in the area, such as experts within the nuclear industry, and emergency planning sector who are familiar with the Cumbrian siting process.

### 4.1.1 Problem Description

For several decades construction of a long-term nuclear waste disposal facility has been openly discussed by the UK government. Since the 2006 report of the Committee on Radioactive Waste Management (CORWM), the UK has openly adopted geological disposal as its preferred means of long term storage for its high-level waste (for more information on the CORWM analysis process see Morton et al 2009). The issue is now where to site the geological disposal facility (GDF). The UK government decided to adopt an approach

strongly focussed on public participation and volunteerism, which has had success in other countries for GDF siting (CORWM publications for details e.g. Sweden, Canada). The most recent siting attempt took place in Cumbria between 2009 and early 2013. The proposal to continue with the siting process was rejected by the Cumbrian County Council at the end of January 2013. As Cumbria had been the only county to volunteer for the siting process, this left the government with no more options and so it had to interrupt the siting process.

Following this, the government has indicated that it is still committed to using a GDF for the UK's high-level waste. The 2014 CORWM report shows they have assessed the failed Cumbrian siting process and plan to attempt the siting process again with a more significant focus on public participation. In particular, they are re-designing their methods of public participation. The government expects to release a report in 2016 on their progress on the siting process plans. The government is currently planning stakeholder engagement processes which will be defined more loosely to allow for more flexible deadlines. With public participation playing such a large role it is increasingly important that the government understands public responses. My model seeks a basis for exploring public responses, thus helping design the stakeholder engagement process.

A key step to improve the public participation process is to be able to learn from the previous siting process between 2009 and 2013. When communities were asked to volunteer to host the GDF, only Copeland and Allerdale in Cumbria showed enough interest to proceed with the siting process. It was planned that Copeland and Allerdale Councils, along with Cumbria County Council, would vote on whether to proceed with the siting process in October 2012. To maintain communication with the public and stakeholders through the process, the Managing Radioactive Waste Safely (MRWS) Partnership was set up. It provided links between the three councils making the decision (Copeland, Allerdale and Cumbria), representatives of various stakeholder groups and the public (see their website for more information).

When the deadline for the decision on whether to proceed drew close, the councils requested an extension until January 2013 due to uncertainty within the councils. However the MRWS Partnership had only been funded until the expected deadline in October 2012 and so stopped engaging with the public during this extension. It has been suggested that this extension may have biased the engagement process and so if I find that system dynamics could be a good tool for measuring public response, I can explore this suggestion to see that if the MRWS Partnership had been able to continue its activity, whether the voting results might have been different. Knowledge of any pitfalls such as these could help the government create more robust plans for the next siting process.

### 4.1.2 Previous Siting Attempts

The first major attempt at siting a geological disposal facility (GDF) was carried out by the Nuclear Industry Radioactive Waste Executive (NIREX) when in October 1992 it announced plans to build a GDF at Sellafield. NIREX met strong resistance, and the particular area in which they were planning to site the GDF was deemed by many to be geographically unsuitable. This lead to many people questioning if NIREX lacked the scientific expertise to guarantee a safe facility. The proposal was rejected in 1997. Following this CORWM was set up in 2003 to advise the UK government on the best options for nuclear waste management. Following a lengthy analysis of options and experiences overseas, CORWM suggested that a GDF would be the best method of waste disposal with a heavy focus on public participation, and the government adopted this recommendation.

The organisation set up to ensure that a wide variety of community interests were included in discussions was called the MRWS Partnership, introduced in 2009. The group met roughly every 6 weeks to discuss the current issues, and also organised stakeholder engagement events and data collection of the current public opinion. Throughout their 3 and a half year lifetime, they ran 3 major public and stakeholder engagement periods. These were usually between late Autumn to early Spring of each year. I call these engagement periods PSE1, 2 and 3. Full details can be found on the MRWS Partnership website.

The plan was that after PSE3 had finished, the Partnership would release a final report in August, giving an assessment of the different views of the proposal and their interpretation of the public opinion according to a survey taken at the end of PSE3. Note that this was the opinion of the partnership, not the community councils. However, when the deadline arrived to make a decision, the councils asked for an extension of the deadline to the end of January 2013 as they felt there was too much uncertainty in the process at the time. The Partnership could not continue its work during this extension period as it was not funded to do so.

Each stakeholder engagement period would usually involve public meetings and events throughout Copeland, Allerdale and the rest of Cumbria, information packs and leaflets, public awareness programs and many other events. Throughout the siting process there was also 4 public awareness surveys undertaken by Ipsos MORI (see MRWS survey links). For the first 3 surveys, responses were collected from roughly 1000 people living in Copeland, Allerdale or the rest of Cumbria, while the final survey had roughly 4000 responses. These surveys included demographics of those interviewed, their own assessment of their knowledge of the siting process and their opinions on the proposal.

Alongside the final vote of the councils, these 4 surveys formed the basis of my data. Unfortunately, with only 4 data points for each community, it is difficult to predict behaviours, and so I also appealed to the literature to get a general idea of publics responses to different events, with particular focus on their relative importance.

### 4.1.3 Cumbrian Siting Process

This section provides a summary of the data that has been used to produce the simulation models in both Chapter 5 and 6. There is a lack of significant quantitative data of the Cumbrian siting process between 2009 and 2013, however some of the key pieces of data from the 4 public awareness surveys (MRWS survey links) are summarised in Table 4.1 to 4.3 below. These survey results have been used to calibrate the strengths of relationships identified in other sources between groups and events and the public opinion.

| Survey | Positive | Negative | Neutral | Some Knowledge | No Knowledge |
|---|---|---|---|---|---|
| Survey 1 | 59% | 21% | 20% | 65% | 35% |
| Survey 2 | 63% | 19% | 18% | 60% | 40% |
| Survey 3 | 62% | 19% | 20% | 67% | 33% |
| Survey 4 | 68% | 23% | 9% | 74% | 26% |

Table 4.1: A summary of key data points from the 4 public awareness surveys for Copeland based on the 4 survey results documents downloaded from the MRWS Partnership's site.

| Survey | Positive | Negative | Neutral | Some Knowledge | No Knowledge |
|---|---|---|---|---|---|
| Survey 1 | 53% | 24% | 22% | 49% | 51% |
| Survey 2 | 47% | 25% | 28% | 48% | 52% |
| Survey 3 | 52% | 25% | 23% | 60% | 40% |
| Survey 4 | 51% | 37% | 12% | 65% | 35% |

Table 4.2: A summary of key data points from the 4 public awareness surveys for Allerdale based on the 4 survey results documents downloaded from the MRWS Partnership's site.

| Survey | Positive | Negative | Neutral | Some Knowledge | No Knowledge |
|---|---|---|---|---|---|
| Survey 1 | 47% | 26% | 27% | 36% | 64% |
| Survey 2 | 39% | 33% | 28% | 38% | 62% |
| Survey 3 | 44% | 30% | 26% | 42% | 58% |
| Survey 4 | 50% | 35% | 15% | 49% | 51% |

Table 4.3: A summary of key data points from the 4 public awareness surveys for the rest of Cumbria based on the 4 survey results documents downloaded from the MRWS Partnership's site.

Alongside this, there was a selection of literature, media and organisational (such as NGOs) articles dated during the Cumbrian siting process. Some of the primary conclusions that can be drawn from a selection of these sources has been summarised in Table 4.4 below. These sources provided the foundations of the relationships, with the strengths of these relationships being calibrated through a series of testing and validation steps.

| Source | Description | Conclusion |
|---|---|---|
| Brulle et al, 2012 | Public opinion & climate change | Contradictions ¿ economic factors ¿ media coverage ¿¿ scientific information ¿ weather incidents |
| Tanaka, 2004 | Nuclear facility siting issues | Perceived risks ¿¿ government trust ¿ perceived benefits |
| Benkert et al, 1997 | Public opinion & psychotropic drugs | media impact ¿ ideological attitudes |
| Tokushige et al, 2007 | Public acceptance & geological storage of greenhouse gases | Perceived benefits ¿¿ environmental interference ¿ perceived risks (benefits in this case could be seen as risk in nuclear facility siting) |
| Kunreuther & Easterling, 1996 | Compensation & hazardous facility siting | Compensation has serious limitations for a facility like a GDF, and could even increase opposition |
| Kunreuther et al, 1990 | Public opinion & nuclear disposal facility siting | Perceived risks ¿ safety standards ¿¿ compensation, also outlines that trust is very important for all factors |
| Jenkins-Smith et al, 2010 | Public acceptance & nuclear disposal facility siting | Perceived risks ¿ perceived benefits ¿ proximity ideological beliefs knowledge of nuclear industry trust |
| Kasperson et al, 1992 | Social distrust & hazardous facility siting | Provides a discussion of the importance of social trust and perceptions of the public |
| Sjberg & Drottz-Sjberg, 2011 | Risk & nuclear facility siting | Risk aversion ¿ economic benefits ¿ trust |
| Johnson, 1987 | Public opinion & nuclear facility siting | Provides a discussion about the benefits of risk mitigation in improving public opinion |
| Greenpeace, 2012 | Blog article on the GDF siting proposal | Shows significant resistance to the siting proposal. Suggests growing resistance locally to the proposal as well. |
| Friends of the Earth, 2013 | Discussion of the talks over the last few months of the siting process | Demonstrated the considerable negative shift over the final few months. |
| CORE, 2012 | Reactionary article to the final survey results | CORE suggested that the survey was invalid due to the methodology followed. Shows growing mistrust in the government/MRWS |
| No Ennerdale Nuclear Dump | Blogging site following the siting attempt | Portrays a significant reduction in governmental trust near the end of the process |
| Radiation Free Lakeland, 2012 | Set of articles following council discussions about the siting process | Large amounts of negativity towards the process, attempting to serve as a call to arms for local people |

Table 4.4: A summary of sources used to identify key drivers of public opinion. Greater than signs indicate significance of the factor in determining public opinion.

These sources have all been considered, alongside the information on the MRWS Partner-

ship website (for a more positive viewpoint), to define the relationships used in Chapters 5 and 6. In particular, there was a significant focus on the risks from the media, articles and Partnership in the final year of the process, which correlates to the findings from the literature that risk was, arguably, the most important factor in swinging public opinion. Additionally, several experts in the field were available to provide guidance when constructing the simulation models, and to provide face validity, some of which were directly involved in the Cumbrian siting process. While full information cannot be disclosed, a description of each expert is provided in Table .

| Expert Description | Expert Level | Contributions to model development |
|---|---|---|
| Decision support expert with considerable experience in the nuclear power industry, especially in emergency planning | Professor | Continuous support during model development. First point of call for validation tests. |
| Active engagement with nuclear waste management programs. Engagement with the Cumbrian siting process | Upper Management | Second point of call for model validation test. Provided additional background information on the siting process. Refined model assumptions. |
| Active engagement with nuclear waste management programs. Engagement with the Cumbrian siting process | Upper Management | Provided help with face validating the model. Refined model assumptions. |
| Active engagement with nuclear waste management programs. Engagement with the Cumbrian siting process | Senior Management | Provided help with face validating the model. |

Table 4.5: A summary the experts providing validation support.

### 4.1.4 Future Plans

Only rough guidelines have been given so far on the process that will be followed, with much of the specifics of exactly how the public will be participating in the process still to be decided (although they have formed a committee specifically to address this participation issue). These rough guidelines are shown in Figure 4.1 taken from the 2014 White Paper, which gives the expected flow of the process from now until the GDF is actively running.


Figure 4.1: Predicted timescales for the facility siting and construction of a GDF in the UK. Taken from the 2014 White Paper.

I have the most detail on what will be happening up to the end of 2016, where 3 actions are specifically listed. The first is bringing the development of a GDF in England within the definition of a 'Nationally Significant Infrastructure Project', which has been met since 27th March 2015[1]. Next, a national geological screening exercise will be put into place to assess suitability of geology across the country, which would be helpful when interacting with and considering interested communities. The progress of this is currently ongoing, and their draft National Geological Screening (NGS) Guidance is under public consultation until the 4th December 2015. The final action that was specified is to work with experts and stakeholders to develop the community representation mechanisms that will be employed. The call for evidence for this ended on 4th September[2].

With this in mind, it is unlikely the models produced would see use in this area until I at least have more information about how involved the community will be with the process, and exactly what methods they will have to bring issues to the developer. Fortunately I

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/444407/Implementing_Geological_Disposal_Annual_Report_14-15.pdf

[2] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/440014/Call_for_evidence__FINAL.pdf

can continue to develop the model under the expectations from previous White Papers, the public engagement in other countries, and from experts within RWM until I get more precise information.

### 4.1.5 Public Response Literature

There has been a broad range of case studies on public response across many different sectors such as climate change (e.g. Brulle et al 2012), psychotropic drugs (e.g. Benkert et al 1997), food technologies (e.g. Siegrist 2008) or, more relevantly, hazardous facility siting (e.g. Tanaka 2006, Kasperson et al 1992, Sjöberg & Drottz-Sjöberg 2001). These all tend to look at similar topics. In particular, what are the most important factors influencing public opinion? In most applications, there seems to be agreement that perceived risks are much more important than perceived benefits. One exception to this rule is suggested by Siegrist (2008) who argued that perceived benefits of new food technologies outweighed the perceived risks as long as the benefits were tangible.

Other than the relative weights of perceived risks and benefits, it is clear that trust plays a critical role in favourable public response (Kunreuther et al 1990, Tanaka 2006). For a discussion about social trust, see Jenkins-Smith et al (2010). In the setting of public opinion in geological CO2 capture, Tokushige et al (2007) argued that trust in government is very important in increasing perceived benefits while reducing perceived risks. This view is re-iterated by both Kunreuther et al (1990) and Tanaka (2006) in a nuclear facility siting setting. Alongside this, there have been various other sources of influence brought up which should be taken into account. For example, media (Benkert et al 1997, Brulle et al 2012), proximity (Jenkins-Smith et al 2010), risk mitigation (Kunreuther et al 1990, Johnson 1987) and compensation (Kunreuther et al 1990, Kunreuther & Easterling 1996).

### 4.1.6 Modelling in Public Response

There are several choices I have for modelling paradigms for this scenario. Systems dynamics appeared to be a strong paradigm for the general flow of the public's opinions over several years due to not needing information about each individual to understand the trends seen in a model that is produced. Additionally, systems dynamics is a very strong paradigm for heavy feedback systems, which I would expect to be the case. It also provides me with a strong deterministic framework to compare another paradigm to, and allows me to explore whether the additional stochasticity is required for a more accurate model.

In terms of a stochastic model, I could choose from either discrete event simulation, or agent-based modelling. Given the nature of my scenario (responses and interactions of

individuals), agent-based modelling should be a clear choice. However, the amount of information needed to develop individual behaviours and validate the model is not available to me. While a rudimentary model would be possible, there would be little difference in overall functionality to a discrete event simulation model. A discrete event model would also be far easier to validate and explain to users that are not modelling experts (due to their familiarity with discrete event simulation).

Hybrid modelling could also be an excellent way to explore this scenario. However, this would need to be an extension to work on the other paradigms so that I can fully understand the strengths and benefits of each paradigm in this specific scenario. I could also explore other methods of introducing stochasticity to the model, for example Bayesian networks, rather than a common modelling paradigm. I have discussed this possible extension in Chapter 8. Following this comparison of modelling paradigms, and my expectations of their performance in reproducing the trends I would expect to see in public deliberations, I used systems dynamics and discrete event simulation. However, there is potential to explore hybrid modelling in this setting in the future.

At this point it is also important to highlight the difference between group and societal decision making. I explored group decision making in Chapters 2 and 3. In group decision making I tend to focus on both the individuals making up a relatively small group (that are often in contact with other group members), and also the overall group decision. However, I would consider the scenario I have presented in this Chapter to be on a societal level, rather than the group level previously explored (at least for how I have constructed my models). This means that I are solely focussed on the societal level. While individuals may be modelled, they are usually not as important to society on an individual level as I have seen in group decision making. This change in focus is important to keep in mind when evaluating the results of each model as expectations have now shifted.

# Chapter 5

# Construction and Simulation of a Deterministic Model

## 5.1 Problem Articulation

### 5.1.1 Introduction to System Dynamics

Throughout this chapter, I use the system dynamics methodology to explore the unsuccessful Cumbrian siting process from 2009-2013, as described in Chapter 4. System dynamics is a field that was introduced by Forrester (1961, 1968). It has become a modelling method used in many areas. For example, politics, environmental studies and production lines. I only introduce the terminology and notation that are needed for my model. For a more detailed review of system dynamics, see Sterman (2000). System dynamics was chosen as my first modelling method because feedback loops and dependencies are central to this paradigm, and I would expect such behaviours to be common in the evolution of public opinion. Alongside this, system dynamics can be relatively easy to explain and so will help when presenting the model to those less familiar with the mathematical implications of such a complex system.

Traditionally system dynamics is used for large-scale scenarios where units of interest flow through a predefined system according to a set of rules used to define the process (Sterman 2000). These units can be anything that are considered measurable. For example, goods in a processing factory or people moving through the stages in a health system. My area of application fits these expectations of system dynamics; it is a large-scale scenario (opinion change over a four year period for over 100,000 people) and also, to some extent, has measurable units of interest (people holding each opinion), and policy design is not uncommon within system dynamics (Feng et al 2013, Onat et al 2016). The main problem of applying

system dynamics to my area though is the 'set of rules' used to define the process. Usually these rules are well defined in the real world, for example a production factory, and so can be translated into a model relatively easily. The set of rules I need to define this model are not so well-defined as it concerns the behaviour of individuals (who are often not entirely rational). This is a problem that I address later in this chapter.

### 5.1.2 Terminology

| | |
|---|---|
| Stock |  |
| Flow |  |
| Converter |  |
| Module |  |

Table 5.1: System dynamics terminology introduction with their relevant diagrams

#### Stock

The first commonly used component is called a 'Stock' and is represented by a square. These typically hold an object of interest. For example, in a production line you could have two stocks, one representing unprocessed goods, and one representing finished goods. There are several different forms of stock I could use, and have decided to define the majority of stocks as 'reservoirs', which is a pool of homogenous objects (and so I lose any history of each individual). In my model, I used stocks as my main measurement of support for the siting of the GDF. They represent the number of people in favour, or against the proposal. For each community there is a stock for each opinion of the proposal as seen in the MRWS Partnership's surveys.

#### Flow

While stocks are used to measure my object of interest, their values are static without flows that go into, and take from each stock. A flow is represented by a valve and directional arrow. The only flows I use are uni-directional to allow for different flow values into and out of a stock, allowing for more representative modelling. At each time unit, the values

of any stocks that a flow is attached to are updated according to the value of the attached flow. The value of the flow is set through constants and using the values of various converters, explained below, throughout the model. This allows the value of the flow to change dramatically to represent different situations. In my model, the value of a flow represents the rate at which people leave an opinion state to go to another. For example, a flow from the 'Neutral' stock to the 'Positive' stock, which has a value of 5, means that 5 people each time step move from the 'Neutral' to 'Positive' opinion.

**Converter**

Converters can be seen as the constants and variables of my model that are used to define the values of the flows, and initial values of the stocks. In the simplest cases they can represent constants that are independent of other values in the model. For example, the number of people in the community. Their power comes from the interactions they can have, as the value of one converter could be used to influence the value of another converter. This is typically where the feedback loops are introduced.

**Module**

The final component that I commonly use is called a 'Module', represented by a square with rounded edges. Modules contain their own stocks, flows and converters to become their own small scale models within the overarching model. Links can then be formed between different modules to allow values from one module to be used in another. While these technically will not impact the functionality of the model, they will greatly help in the presentation and organisation of the model. For example, in my model I have 2 modules for each community, which contains all the stocks, flows and converters associated with that community.

### 5.1.3 System Dynamics Literature

The unique contribution of system dynamics when it was first introduced was ease of including feedback loops in modelling by Forrester (1961, 1968). It saw increased use throughout the 1990s (alongside the increasing popularity and availability of simulation), e.g. Vennix 1996, 1999, Vennix et al 1990, Ford & Sterman 1998, Forrester 1994, Lane 1994, 1998, Lane & Oliva 1998. Just like discrete event simulation, SD had largely been developed independently from most other simulation methods, however there was some increased interest in bringing SD, soft operational research techniques and social theory (Forrester 1994, Lane 1994, 1998, Saeed 1994, Guo et al 2001). Sterman (2000) has provided a comprehensive review of SD, and also provides guidance on conducting a system dynamics study. This guidance ranged from the initial formulation of a hypothesis that SD could be used

to explore, through to the construction of SD models and identification of feedback loops, and interpretation of results. Also see Brailsford et al (2014) for a different perspective of SD, and for a comparison to DES, one of the other primary simulation techniques used, and Rahmandad & Sterman (2012) for guidance on simulation model reporting.

One of the primary areas of application of system dynamics is in environmental decision making and policy making (e.g. Ford 1996, Wu et al 1993, Saysel et al 2002, Stave 2002, Stave 2003). This is an ideal fit for system dynamics due to the lack of a need to simulate specific individuals. Instead the focus was on defining the overall trends and the feedback effects, allowing system dynamics to enhance understanding of the system. Ford (1999) provides a review of system dynamics, and specific applications to environmental modelling (e.g. water flow modelling). Other applications within environmental modelling and policy making include pollution modelling in Beijing (Feng et al 2013) for future city planning, a case study to show the impacts of commuter bicycling policies (Macmillan 2014) to help transportation policies within a car-dominated city and a study evaluating the introduction of electric vehicles on a variety potential economic impacts and measures (Onat et al 2016). Often there are multiple objectives that need to considered for such policies, which can require different integration techniques between modelling methods and multi-criteria decision making (Antunes et al 2006). System dynamics has also been used for siting problems, for instance modelling the impacts of constructing or demolishing landfill sites with respect to costs and emissions (Marzouk & Azab), who also highlight the need to provide a decision support tool for future developments.

While no model can be truly verified and validated as all models are wrong (Sterman 2000), building confidence through verification and validation techniques is invaluable to be able to convince others (e.g. policy decision makers) that the model can be useful in enhancing their understanding. Earlier attempts at validation were suggested by Wright (1972) and Mass & Senge (1978). A more comprehensive set of methodologies suggested by Forrester & Senge (1980), in which 17 tests were suggested to test structure and behaviour (the two areas of validation identified by the authors). These tests are qualitative and lack full mathematical rigour. There were also some promising methods suggested by Sterman (1984) and Barlas (1989). More recently, there have been many different, and increasingly rigorous, tests for both the structural and behavioural portions of the model (Huang et al 2009, Kampmann & Oliva 2009, Qudrat-Ullah & Seo Seong 2010, Hayward and Boswell 2014). Duggan & Oliva (2013) gave a special issue in 'System Dynamics Review' which collated many of the recent developments in model validation. For example, the Ford method (Ford 1999), public participation metrics (Mojtahedzadeh et al 2004) and eigenvalue elasticity analysis (Forrester 1982, Guneralp 2006). However, there is little consensus on which of

these methods (individually or as a combination) should be used, and work is continuing to be done in all three (e.g. Huang et al 2009), alongside newer methods (Hayward and Boswell 2014).

## 5.2 Formulation of a Dynamic Hypothesis

### 5.2.1 Aim

During the initial period of the study, I aimed to produce a more generic system dynamics model for GDF siting, that did not necessarily mimic the behaviour of the Cumbrian siting process. This was primarily to improve my own understanding of the problem, while collecting the information required for the final model of the Cumbrian siting process. It also allowed me to explore how influence and utilities could be incorporated into system dynamics modelling, which I explored in Chapter 3.

My primary aim was to explore the use of system dynamics as a modelling tool for public response. I built a model of the siting process between 2009 and 2013 based on data collected by the MRWS Partnership. In this model, I estimated the number of people in each community (Allerdale, Copeland or the rest of Cumbria) that are in support of, or opposed to, the proposal. I also considered the opinions of each member of the council that was involved in the final vote.

I modelled how the members of the public and council flow between different opinions on the proposal. This flow rate changes according to, among other things, recent events and current public support. One advantage of this is that it is straightforward to change how quickly people alter their opinions in the model by scaling these flow rates.

The events used to define these flow rates were defined by the actual events that the MRWS Partnership organised. This gave more flexibility to the model. To explore the effects of a different stakeholder engagement process, I redefined the events used by the model. This freedom allowed me to compare different stakeholder engagement plans. I also considered related worldwide events, and events that were put on by opposition stakeholder groups. Non-Governmental Organisations (NGOs) such as Greenpeace, Friends of the Earth and Cumbrians Opposed to a Radioactive Environment (CORE) were all openly opposed to the siting process (see Table 4.4).

In summary, my aim was first to explore if the use of system dynamics is suitable for modelling changes in public opinion. If so, this methodology could be used to provide an effective planning tool for stakeholder engagement. Having shown that the model can

indeed reflect what actually happened, I explored the suggestion that the extension to the council decision deadline could have biased the final vote.

**Hypothesis 1** *The deadline extension request by the Cumbrian councils, at the end of the intended siting process, biased the final result negatively. I hypothesise that the result may have been positive if the MRWS Partnership was funded to continue operation during these 6 months.*

Throughout this Chapter, multiple models are referenced. To avoid any potential confusion, these models are described in Table 5.2. Unless another model is clearly being referenced, 'model' refers to the 'Final Model 1' in Table 5.2.

| Model Name | Model Description | Model Introduction |
|---|---|---|
| First Iteration | The early model that was produced to better understand the area of application and software. This was not intended as a final model, and simply served as an initial testing base. This model was not directly based off the Cumbrian siting process. | Section 5.2.2 |
| Final Model 1 | This served as the baseline scenario for all alternative scenarios. It was constructed to mimic the Cumbrian siting process according to the MRWS Partnership website, and the sources identified in Table 4.4. | Section 5.2.3 |
| Final Model 2 | This is constructed in the same way as 'Final Model 1', however served as a sensitivity analysis to the speed of opinion change. | Section 5.4.2 |
| Deadline Extension | This is an alternative scenario of 'Final Model 1' which considers the situation where the Partnership was allowed to continue operation during the last 6 months of the process. | Section 5.5.1 |

Table 5.2: Description of each SD model and where it is first introduced in the Chapter.

### 5.2.2 First Model Iteration

The 'first iteration' model I have presented has had quite a long development through several different versions and modelling layouts, and throughout this subsection any reference to model refers to this 'first iteration' model. Here I introduce my earlier model which, while capable of including more detail, had a highly complex model and feedback structure which made validation infeasible. This has been introduced in a similar, but less detailed, way to my previous model.

#### 5.2.2.1 Model Introduction and Layout

For simplicity my initial model assumed there were 4 main groups of interest (local government, local industry, general public and the ECG) and the overall structure is presented in Figure 5.1. These are each described by two modules, for example; 'General Public' which

holds the stocks representing current public opinion on the proposal and 'Public Variables' which holds the information used to calculate the flows between stocks in the 'General Public' module. The model is split into 9 modules. The simplest modules are 'World Conditions', which stores most general constants used by the model and certain time-dependent variables, such as 'Radiation Incidents', and the 'Results' module, which collects information about the current state of the stakeholder groups.

The next module to consider is the 'General Variables' module, which is where general feedback and interactions are included. This module is used by all groups in a similar way (although slight group specific changes are added in the group variable modules). The converters contained here are used, alongside any group specific variables or interactions, to calculate the flow rates from the stocks in the group variable modules (e.g. 'Public Variables'). Figure 5.2 shows the structure of the stocks and flows of the 'General Public' module below.

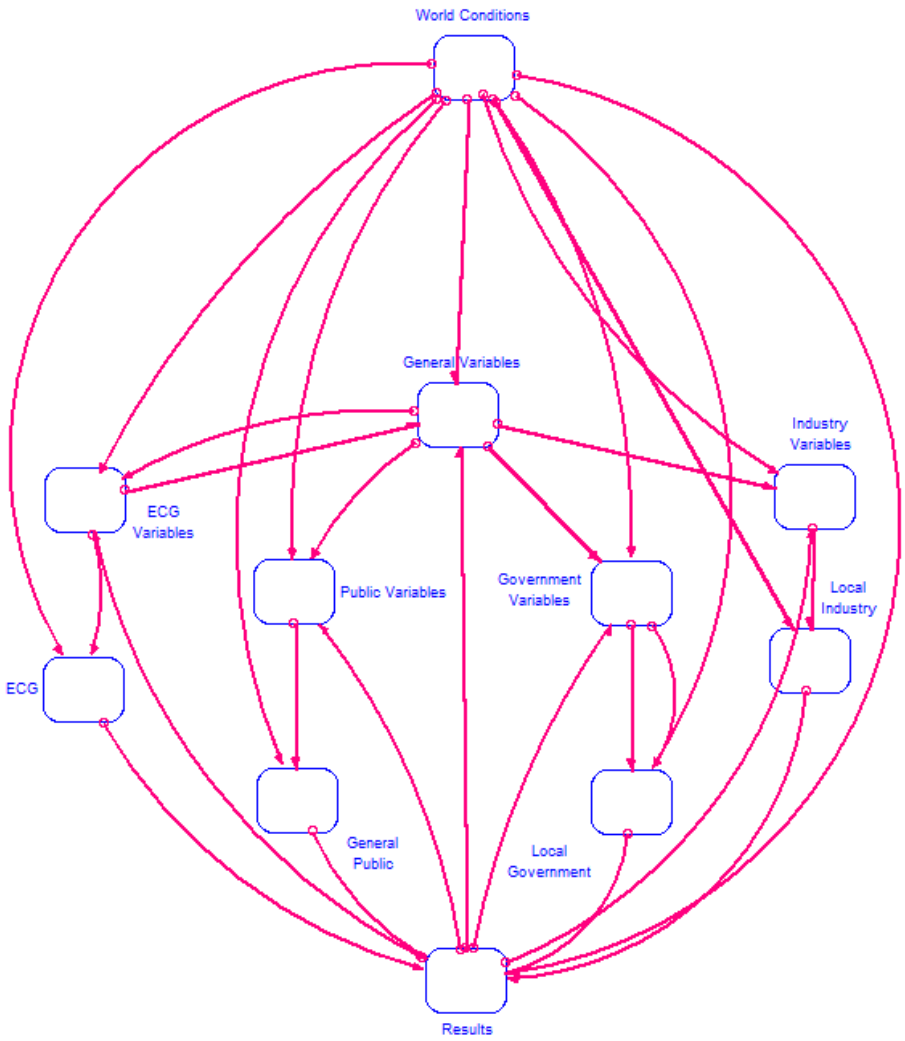



Figure 5.1: Top-Level display of the model from iThink. The directed red lines indicate interactions between modules.

Despite the apparent complexity in Figure 5.2 below, the basic structure is relatively simple. The 4 main converters in this module; 'Positive Flow', 'S Positive Flow', 'Negative Flow' and 'S Negative Flow' are being calculated from within the 'Public Variables' module. These are the main values used to calculate the flows between stocks. People flow between the states defined by each stock; 'strong positive', 'positive', 'negative' and 'strong negative' (this represents the number of people in each state of acceptance of the proposal). Of course other interactions between these flows exist, but for simplicity I will not discuss these at this stage.

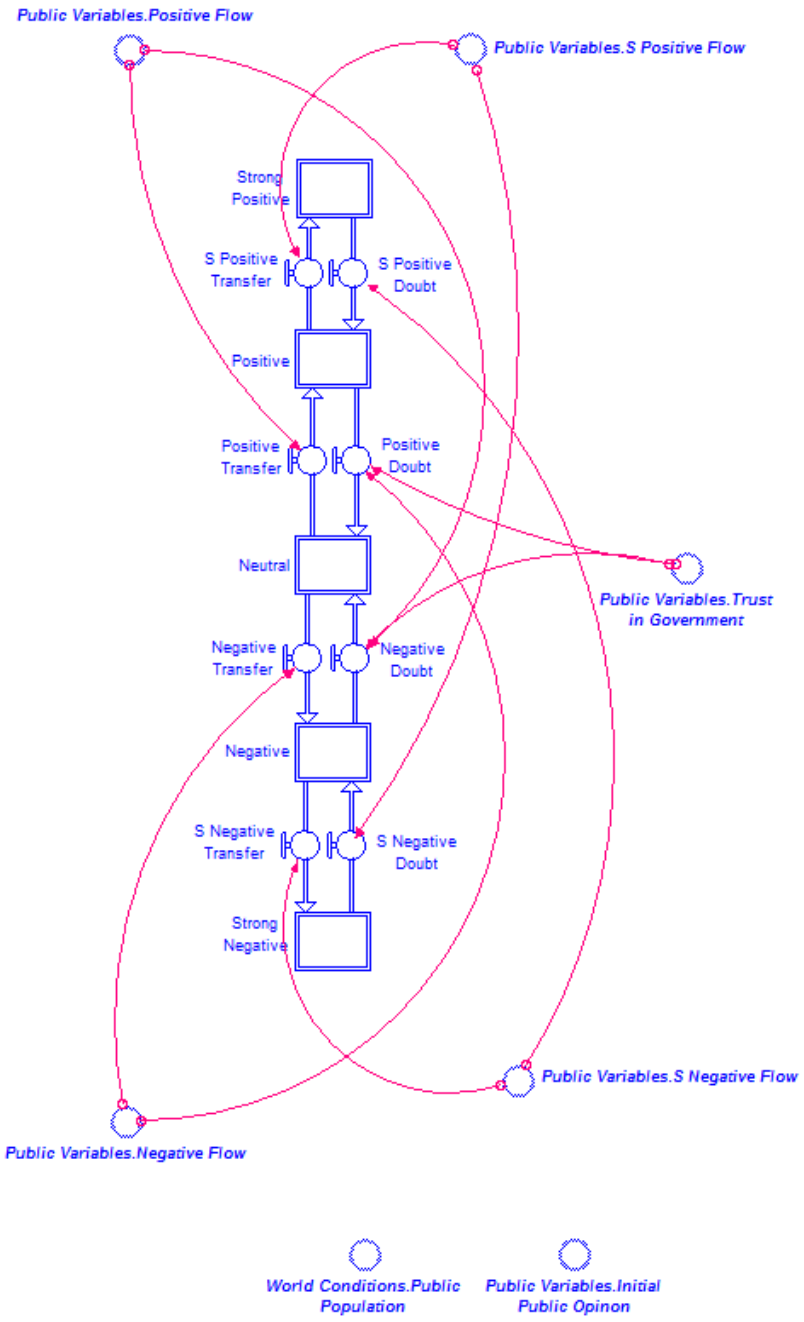



Figure 5.2: Detailed view of the 'General Public' module. This uses information from the 'Public Variables' module to calculate the flows.

**5.2.2.1.1 Flow Rates** Each group that has been modelled has 4 primary flow rates associated with them; 'Strong Positive', 'Positive', 'Negative' and 'Strong Negative'. These

flow rates are scaled according to the total population size. These 4 primary flow rates are used in the main group module, for example 'General Public' seen in Figure 5.2. In most cases the base values have been used, with the exception of arriving into the 'Neutral' stock, where the flow rates have been scaled by a converter representing the trust that the group has in Government.

The most interesting point about these primary flow rates is that they have been defined analogously to the way a linear utility function might be defined. Each group is given the relative importances of 4 main attributes; 'Perceived Benefit', 'Perceived Risk', 'Ideological and Political Attitudes' and 'Familiarity with Nuclear Industry'. These attributes are contained in each group's variables module (e.g. Public Variables), which is where the 4 primary flow rates referenced in the last paragraph are calculated, before being sent on the the group's main module shown in Figure 5.2. These have then been scaled according to their relative importance and combined into the 4 primary flow rates. The only exception to this is the two strong flow rates which have a slightly different relative importance set-up. These stronger opinion states in the model tended to favour evidence rather than popular opinion (e.g. reducing the effect of 'Ideological and Political Attitudes').

**5.2.2.1.2 Attributes** Given how the primary flow rates have been calculated, the definition and weighting of my 4 main attributes is important to how the groups will respond to different scenarios. These are, in the majority of cases, defined as a linear combination of other variables of interest, for example through word of mouth, media, government trust and predicted environmental damage. A linear combination was used to allow for more parallels to be drawn to work done in Chapter 3, which focussed on linear utility functions. The relative weightings of these variables, and of the attributes themselves, were defined according to the relative importance relationships derived from the literature. For example, the public had the following weightings for 'Perceived Benefit', 'Perceived Risk', 'Ideological and Political Attitudes' and 'Familiarity with Nuclear Industry' respectively: 0.3, 1, 0.1, 0.3. However, as this is not the final model that was used, and differed drastically in construction, the full definitions of the model has not been included. Although I have not included these definitions here as this was not used in the final model. (e.g. Kim et al 2013, Tokushige et al 2007, Kunreuther et al 1990, Jenkins-Smith et al 2010, Sjöberg & Drottz-Sjöberg 2001)

The most consistent of these relationships was that 'Perceived Risk' is more important than 'Perceived Benefits' (e.g. Tanaka 2004). Alongside this, trust in the government and experts played a key part, particularly in the assessment of benefit perception (e.g. Siegrist 2008). The group's familiarity with the nuclear industry and their ideological attitudes tended to play a much smaller role, but one of the key components to reducing the perceived risk of a

group was strong risk mitigation plans that the group can trust (e.g. Kunreuther et al 1990, Sjöberg & Drottz-Sjöberg 2001).

**5.2.2.1.3 Stocks** Each stakeholder group its opinions represented by 5 stocks. 'Strong Positive' through to 'Strong Negative' as seen in Figure 5.2. These represent the different states of mind that individuals of the group can have about the proposal (based on the categorisation used by the MRWS Partnership[1]). The initial population of the group is divided between the 'Positive' and 'Negative' state according to an adjustable variable representing the initial support for the proposal. The difference between a negative and positive state should be relatively clear, while the difference between, for example, 'Positive' and 'Strong Positive' is that an individual in the 'Strong Positive' state believes they have sufficient evidence to back up their support of the proposal. The flow rates to these stronger states have been developed to reflect this, placing a stronger emphasis on evidence and facts to get into or out of these states.

While the model is currently too complex to assess all feedback loops associated with the stocks (I are currently working on solving this complexity issue), the dominant feedback loops are all self-reinforcement loops of increasing (decreasing) support resulting in more positive (negative) media reporting and word of mouth effects. The other dominant feedback loop is between the positive (negative) states of the general public and the local government, which are tied together particularly on the government's side.

**5.2.2.1.4 Group Meetings** The last major component of the earlier model was that each group could have consistent meetings with other groups. In these meetings, it was assumed that the groups would try to influence members of the other groups involved. This would cause the overall opinions of each group involved in the meeting to move towards an 'average' opinion. This change in behaviour was reflected by short bursts of drastically increased flow rates during the meeting (although the overall opinion would only move a small amount). If there was a meeting between the 'ECG' and the 'General Public', then the extent to which the 'General Public' would move its overall opinion was dependent on two sets of variables; how influential the 'ECG' was, and how stubborn the 'General Public' are to changing opinions. This movement would then also be calculated for the 'ECG' group, using the 'General Public' influence and the 'ECG' stubbornness values.

[1] http://www.westcumbriamrws.org.uk/documents/Awareness_Tracking_Survey_1.pdf

#### 5.2.2.2 Simulation Specifications

I simulated public deliberations for 12 months, and one time unit is one month. The model was updated every 0.125 months.This duration and time step was chosen only as a testing case, and the model was not directly linked to the MRWS siting process at this time. The units for stocks were the number of people, and the units for flows were the number of people per month. Units for converters change depending on the context. While the units for stocks are numbers of people, I have not enforced these to be integers, primarily due to it limiting the model construction and not being necessary to understand the results as I use percentages for the public support results.

### 5.2.3 Final Model Layout

With the understanding and modelling experience gained from my first model attempt, I produced my final model (Final Model 1 in Table 5.2) that was specific to the Cumbrian siting process. My model is only concerned about the responses of Copeland and Allerdale boroughs, along with the 'Rest of Cumbria'. These are each described by two modules, for example; 'Copeland Public' which holds the stocks representing current public opinion on the proposal and 'Copeland Public Var' which holds the information used to calculate the flows between stocks in the 'General Public' module. This gave me 6 modules for the communities.

Alongside this I have several modules that are used for relevant events and how they are conveyed to the public. For simplicity, I have assumed that all positive events are attributed to the Partnership, and all negative events are attributed to the NGOs. These events have a direct affect on the behaviours of the public, and also affect how the media perceives and reports on the proposal. Therefore the modules 'NGOs', 'Media' and 'Partnership' contain the majority of the outside influence on the general public.

The module 'World Conditions' stores general constants used by the model, time-dependent variables such as 'Radiation and Government Media Incidents', and an estimation of the current trust in the government held by the public. The formula use to update the government trust can be found in Appendix B.1.1 and B.2.1, with an initial value of government trust of 0.3 (this value was selected due to the presence of active NGOs in the area (e.g. Friends of the Earth, CORE, NOEND), and the initial relative unfamiliarity with the process). When tested with initial government trust values between 0.2 and 0.4, relatively similar results, as for 0.3 were seen due to the first 6 months having little activity. The value was updated at each step according to the relative difference of Partnership and Media activity at the time, with an additional adjustment of 0, -0.01 or -0.025 depending on the

severity of the radiation and government media incidents at the time. The ‘Results’ module collects information about the current state of each community.

A detailed view of the ’Copeland Public’ modules is given in Figure 5.4. This module keeps track of the current opinions of the general public in Copeland, and is split into two sides of stocks. The left side is for members of the public that believe they know at least a little about the siting process, while the right side is for those that know less than a little. Each side then has 5 stocks to represent the different opinions people can have about the siting process (taken from the Partnership’s survey). The stocks are split in this way as from all 4 opinion surveys it seemed clear that people who considered themselves to know at least a little about the process had a more positive view than those who knew less. I go into more detail about what each of these stocks and flows mean later in this section.

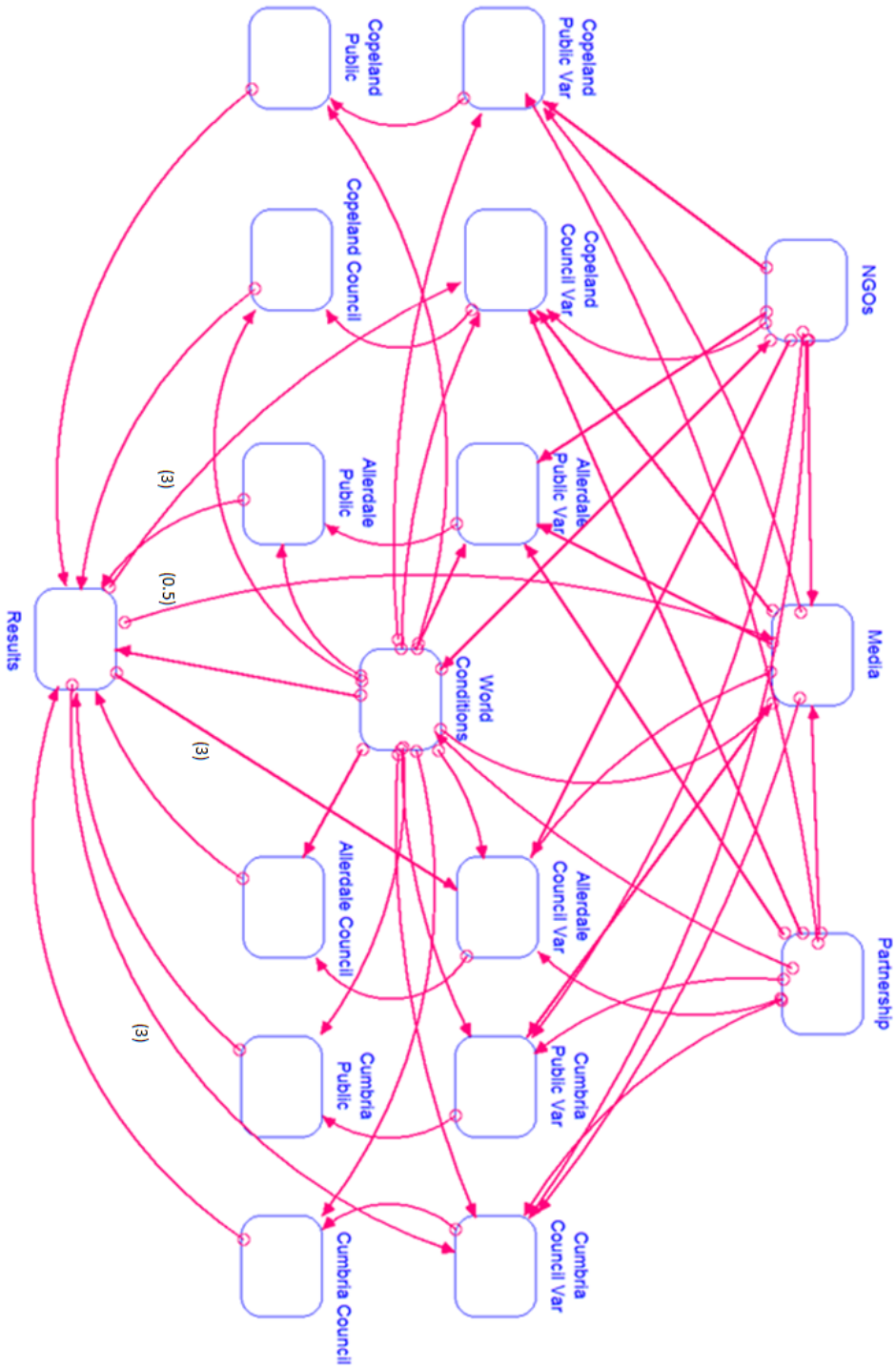



Figure 5.3: Top-Level display of the model from iThink. The directed red lines indicate interactions between modules. Time delays are included from the 'Results' module in weeks (bracketed numbers). There was a delay of 3 months to inform councils, and 0.5 months to adjust media activities.

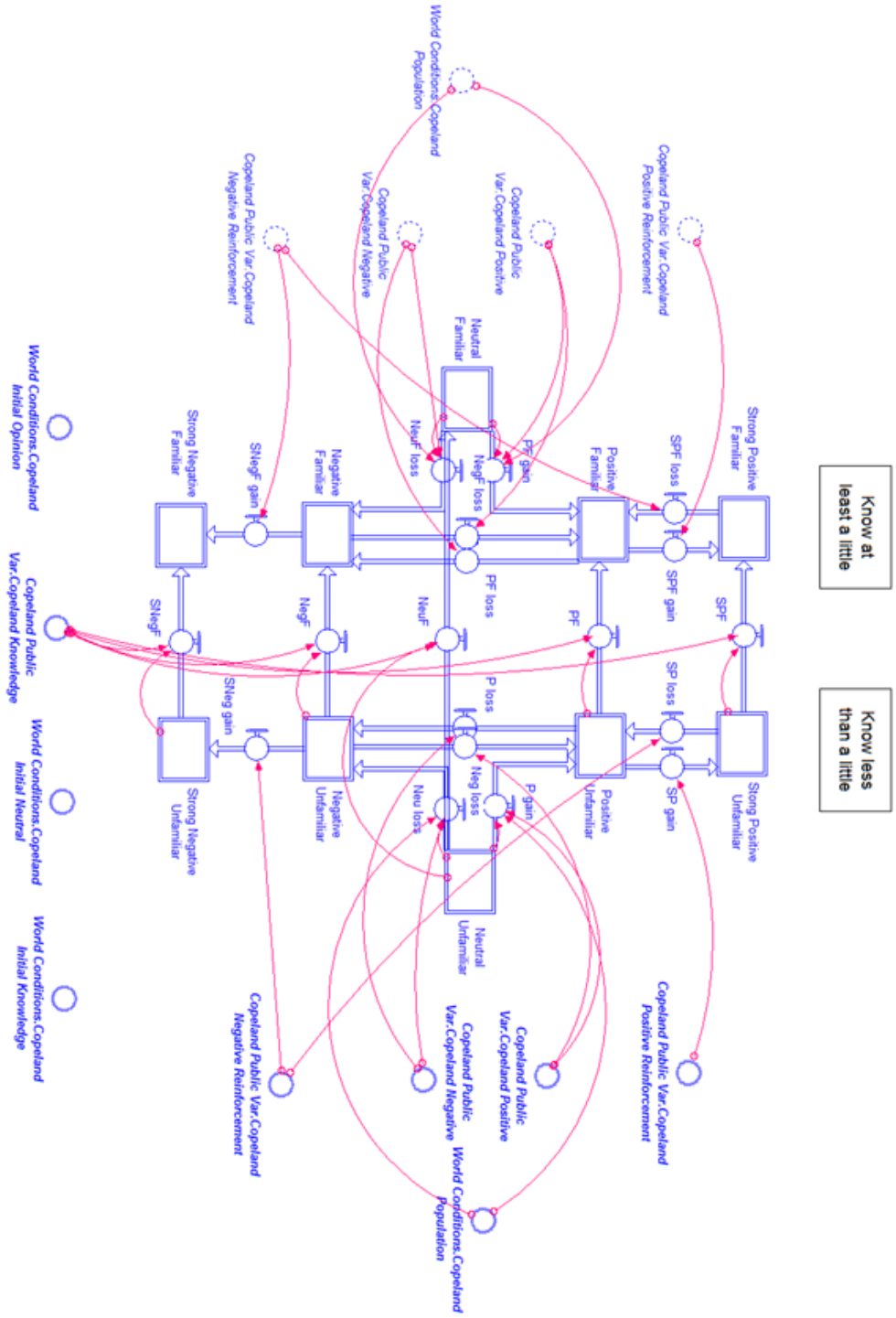



Figure 5.4: Layout of a community module, e.g. 'Copeland Public', showing the stocks representing each opinion and the flow rates between each stock. The community base flow rates have already been calculated in the respective communities 'Var' module (which is informed by the media, NGOs and Partnership).

The opinion survey data that was gathered by the partnership did not only show the support for the proposal against the demographics, but also against each person's own assessment of their knowledge of the siting process. I have simplified the categorisation used into people that think they know at least a little about the process, and those that think they know less than a little. How much 'a little' here varies from person to person, but I observed a positive bias if the individual felt they 'knew at least a little', and so this was included in my model. The percentage of those surveyed that felt they 'knew at least a little' increased over the duration of the siting process, and so I also modelled this behaviour, giving a larger transfer to the knowledgeable state when both the Partnership and the NGOs were active.

### 5.2.4 Cumbrian Siting Process Feedback

While there are many feedback loops that would be present in the Cumbrian siting process, most are one of three particular types (for this specific process). Keep in mind that while Figures 5.5 to 5.7 use the words 'positive' and 'negative' in labelling elements of the loop, these are just to reference actual nodes within the model with the same name. These names are not supposed to be indicative of the type of feedback loop. A type 1 loop is a simple reinforcing loop, where if the value of, for example, Allerdale Positive (know at least a little) increases, it causes an increase in the amount of positive media being presented which then further increases the flow rates to the Allerdale Positive stock. This has been represented in Figure 5.5 below. Keep in mind that the reinforcement is a little stronger than it appears, as the other communities positive stocks are also being reinforced.

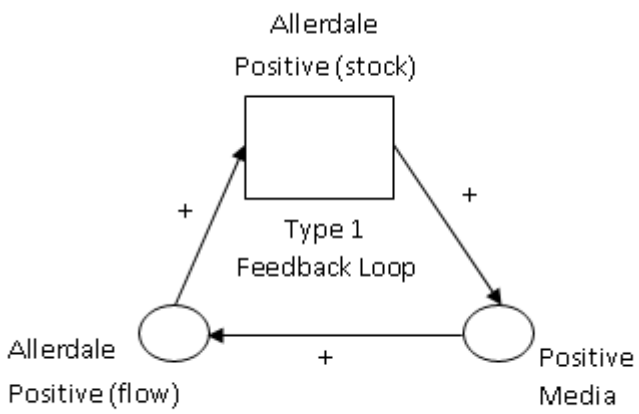



Figure 5.5: Simplified feedback diagram showing the reinforcing effect of a type 1 feedback loop.

A type 2 feedback loop in my model is a standard balancing loop. An increase in Allerdale Positive results in a decrease in negative media, this will then increase the relative support for the proposal in both Cumbria and Copeland, which increases the positive media impact similarly to the type 1 loop. This then reinforces all positive stocks for each community. An example type 2 feedback loop is given below.

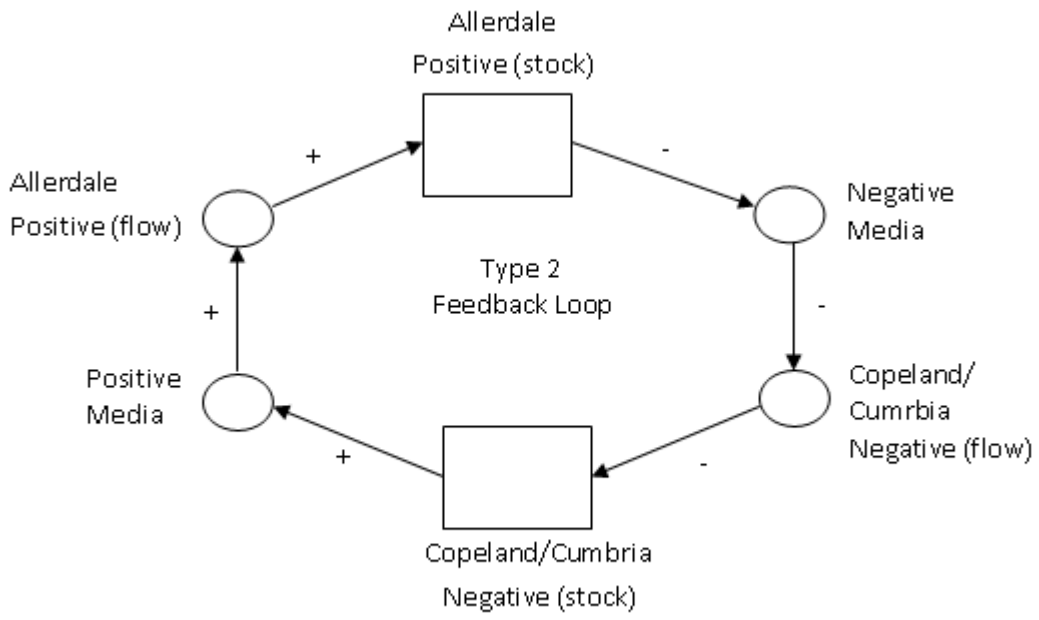



Figure 5.6: Simplified feedback diagram showing the balancing effect of a type 2 feedback loop.

Finally, a type 3 feedback loop instead focuses on the more positive effects of an increase on the other communities. Specifically it states that an increase in the Allerdale Positive stocks, will increase the Positive Media affect which in turn increases the Positive stocks of the other two communities. This then further increases the Positive Media, resulting in a slightly stronger reinforcement than the type 1 feedback loop. An example of a type 3 feedback loop is given below.

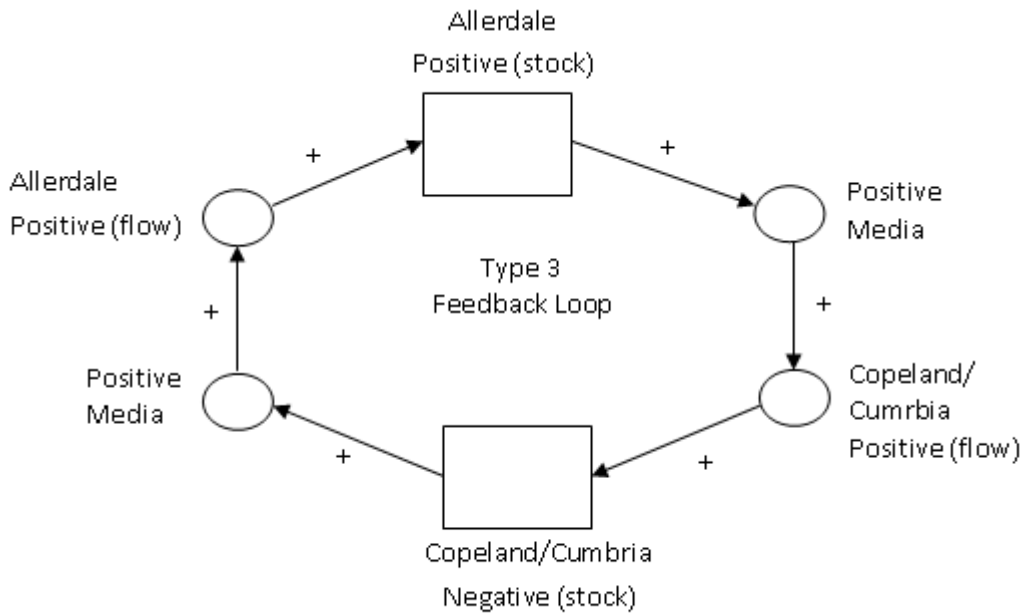



Figure 5.7: Simplified feedback diagram showing the reinforcing effect of a type 3 feedback loop.

## 5.3 Formulation of a Simulation Model

### 5.3.1 Assumptions

I need to make certain simplifying assumptions of the real world scenario. Here I go through the general assumptions that have been made when constructing the model.

**Assumption 1**: The views an individual in reference to the proposal can be described by exactly one of the five following states; Strong Positive', Positive', Neutral', Negative' and Strong Negative'.

Here I simplify the thought processes of the public which is necessary for this model to be able to model transitions between each of the states. There is also enough distinct states that the majority of the public would find themselves in one of them, and these states are based off the categorisation from my data (MRWS Partnership surveys). The main problem is those with contradicting views who do not see themselves as neutral, although this should have a fairly insignificant affect on the model due to my averaging of opinions.

**Assumption 2**: When individuals change their views, they must do so between the adjacent

states. For example, an individual in the Positive' state can only change states to Strong Positive' or Negative', however they cannot go straight to Strong Negative'.

This is another assumption that is necessary for a more parsimonious model. I can model any change from one state to another by going through the correct order of 'in-between' states, even if the individual only spends little time in these 'in-between' states.

**Assumption 3**: All individuals are contained in Copeland, Allerdale or the rest of Cumbria as a member of the general public, or as one of the council members.

While there would be an affect from those living outside of Cumbria, I are primarily concerned with the public response within the county as this would have a larger affect on the final vote of the councils.

**Assumption 4**: An individual cannot change between communities mid-simulation.

While this assumption does not mimic real behaviour, the effect of moving between two areas that are very close should be minimal. The populations of each of the communities has also remained relatively consistent during years I simulated.

**Assumption 5**: All individuals in the same community carry the same values and preferences about the proposal.

While there are going to members of a community that this is not true for, the group beliefs represent an 'average' belief of the group, and so, as long as I are considering sizeable groups the effects of any miss-matched beliefs should be counter-acted.

**Assumption 6**: There is no random error in reporting the support for, or against the proposal (although it may be time-lagged).

Here I have introduced another minor point of simplification to keep the model parsimonious. Any intentionally misreported numbers are another issue entirely that I have not be investigated in this model.

**Assumption 7**: An individual cannot lose knowledge of the process.

While this assumption was not strictly necessary, it followed the trends I observed from my data and so was included for the sake of parsimony.

**Assumption 8**: Once an individual enters the 'Strong Negative' state, they may never leave.

Here I aim to introduce 'Negative extremists' to the model that will never change their mind. This was again supported by the data, where at all times there was a proportion of

the community strongly against the proposal. This can be further observed from any of the NGO websites or open forums for the area. This behaviour was not mimicked by the strong positive opinion state, as there are fewer moral reasons to be stuck in the strong positive opinion (unlike anti-nuclear demonstrators for strong negative).

### 5.3.2 Simulation Specifications

I simulated public deliberations for 48 months (while the actual siting process was closer to 3.5 years, I included an additional few months at the start where nothing happened for more modelling flexibility if needed), and one time unit was one month. The model was updated every 0.25 months. The units for stocks were the number of people, and the units for flows were the number of people per month. Units for converters change depending on the context. While the units for stocks are numbers of people, I did not enforce these to be integers, primarily due to it limiting the model construction and not being necessary to understand the results as I primarily used percentages.

### 5.3.3 Data

For the remainder of this chapter, I are referring to my primary model that was initially introduced in Section 5.2.3 unless otherwise specified. I first checked that the model followed expected behaviour from the last siting process from 2009 to 2013. I built my model with a heavy consideration of the expected behaviours of the public and councils from the literature and calibrated the parameters and coefficients according to the limited data that is available from the MRWS Partnership's website.

The data has more detailed demographics of the survey's participants than I have used in this model. I focused on two main parts of the data; the knowledge people felt they had about the process, and their opinion of moving forward in the siting process. This left me with 4 data points over the timeline for each county. These are given below in Table 5.3. Unfortunately the councils did not report their current position on the proposal during the process in terms of council member votes, and so I only have the final vote count for each of the councils.

| Community | | Allerdale | | | | Copeland | | | | Rest of Cumbria | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Nov 09 | Feb 10 | Feb 11 | Mar 12 | Nov 09 | Feb 10 | Feb 11 | Mar 12 | Nov 09 | Feb 10 | Feb 11 | Mar 12 |
| Relative Support (%) | Strong Positive | 22 | 19 | 27 | 51 | 32 | 36 | 37 | 68 | 12 | 13 | 19 | 50 |
| | Positive | 31 | 28 | 25 | | 27 | 27 | 25 | | 35 | 26 | 25 | |
| | Neutral | 22 | 28 | 23 | 12 | 31 | 18 | 29 | 9 | 27 | 28 | 26 | 15 |
| | Negative | 8 | 7 | 8 | 37 | 9 | 4 | 5 | 23 | 10 | 12 | 8 | 35 |
| | Strong Negative | 16 | 18 | 17 | | 12 | 15 | 14 | | 16 | 21 | 22 | |
| Relative Knowledge (%) | Know at least a little | 49 | 48 | 60 | 65 | 65 | 60 | 67 | 74 | 36 | 38 | 42 | 49 |
| | Know less than a little | 51 | 52 | 40 | 35 | 35 | 40 | 33 | 26 | 64 | 62 | 58 | 51 |

Table 5.3: Data taken from the MRWS Partnership survey's which the model was evaluated against. The dates under each community are the dates for each of the four surveys.

The final survey in March 2012 only gave general support or resistance to the proposal instead of differentiating between strong positive and positive. This was also the largest survey (roughly four times larger than the others) and so I compare my model against general opinions to allow for more consistency. The final vote for each of the councils was 5-2, 6-1 and 3-7 for Allerdale, Copeland and Cumbria respectively (support-resistance). Full reports on each of these four surveys can be found on the MRWS Partnership's website. Given the final survey results are about a year before the end of the process, there is considerable uncertainty about the actual trends which should be displayed. However, I have a relatively good expectation of what to expect from my literature review presented in Chapter 4, and the opinions of the experts from Table 4.5.

### 5.3.4 Model Construction

Due to the size and complexity of my first model, I have not provided details of each individual interaction for the stocks, flows and converters in this section. However, I have given an overview of the general trends that the model has been built around. See Appendix B for full model details. Keep in mind that the values used are only loosely based on real data but rather a coarse measure of relative importance.

**5.3.4.0.1 Flow Rates** Each community has 4 primary flow rates associated with it; 'Strong Positive', 'Positive', 'Negative' and 'Strong Negative'. These flow rates are scaled according to the total population size. These 4 primary flow rates are used in the main community

module, for example 'Copeland Public' seen in Figure 5.4. In most cases the base values have been used, with the exception of some minor scaling to account for the two knowledge states (know at least a little and know less than a little), and the flows out of the neutral stocks which increases over the duration to account for the public taking a greater interest.

Each of the groups is defined similarly, with the main differences coming in minor adjustments to their preferences and an 'interest' variable for that community. This variable represents the community's relative openness to discussion about the process (or overall interest in discussing nuclear matters in an unbiased way, 0 represents a community where NGOs and Partnerships would have no effect), and scales the impact both the partnership and the NGOs have on the community.

This interest variable is assumed to be constant throughout the process (and is estimated from each communities familiarity and past resistance of the nuclear industry. Copeland had the highest interest of 0.5, as they housed the current nuclear waste facility and, as seen from their initial opinions in Table 4.1, were generally for the GDF, and Allerdale had the lowest of 0.25 due to being familiar with nuclear energy and having a more anti-nuclear representation in NGOs (e.g. CORE and NEEND)). The model results were, however, fairly sensitive to larger changes of these variables (0.1 or higher), however little information was available, and these values had been face validated by field experts.

The strong positive and strong negative flow rates are determined directly by the effects of the Partnership and NGOs respectively, with no contribution from the media. This is because it is assumed that people would feel far stronger about their position when they have met directly with the Partnership or NGOs, which is supported by the MRWS survey results that tend to show no increase in strong positive beliefs between PSEs, but strong negative beliefs do increase (due to NGOs being active during this time). This also means these two flow rates are noticeably lower, making it harder for people to get into the strong positive and strong negative states.

**5.3.4.0.2 NGOs, Partnership and Media** I modelled three key influencers of public opinion; the NGOs, the Partnership and the Media. The NGOs represent the general negative opinion of the proposal, and have a consistently increasing affect on the public as people begin to form more opinions, and the Partnership begins to push more aggressively to win the public's support. Alongside their own events and news releases, they will sometimes attend Partnership events, resulting in an increased affect during some of these events as well. The overall trend of the impact of the NGOs is consistently increasing.

The Partnership exerts the most influence when it is actively engaging with the public, rather

than relying on their online news releases and website. In particular, there are sharp spikes in the influence of the Partnership during each of the public stakeholder engagement periods (PSE), with the effects of PSE 2 being greater than PSE 1, and PSE 3 being greater than PSE 2. This results in a relatively steady increase in support during the stakeholder engagement periods. The overall trend of the impact of the Partnership is short spikes throughout the stakeholder engagement periods, with a minor increasing consistent effect.

The media is where the majority of the feedback is introduced in the process (with a delay of 0.5 months). The influence of the positive and negative media is scaled by the proportion of the public in support of, or against, the proposal respectively. The media will tend to report on recent events organised by the NGOs and Partnership but the influence will also be scaled by the current estimate of government trust. The positive media and negative media affects are scaled directly by the proportion of the public that are positive or negative about the proposal (with a 0.5 month delay).

Alongside this, the positive media is also scaled directly by current government trust, while negative media has an adjustment made to it of a scalar multiple of the inverse of government trust (this is done in the community variable modules). Full details of these equations can be found in Appendix B.1.2, B.2.1, B.2.4 and B.2.5. This results in more positive media when government trust is high, and more negative media when it is low. They will also report on any radiation or government incidents which are relevant. For example, after the Fukushima nuclear disaster in 2012 there is a significant increase in negative media. The overall trend of the media is relatively minor unless there are significant events happening, for example a stakeholder engagement period, nuclear incident or large scale events organised by the NGOs. Both positive and negative media also increases over time to account for the increasing interest as the decision deadline draws closer.

Alongside these direct effects, I also modelled government trust, which particularly affects the media (literature from Table 4.4). This increases or decreases over time depending on how active the Partnership and NGOs are, relative to each other. If the NGOs are far more active, then trust declines, while if the Partnership is far more active than the NGOs, then trust increases. Also there are sharp drops in trust around significant radiation or governmental incidents which are reported. Alongside the effect this has on the media, it also has a more direct (and relatively increasing over time) effect on the negative flow rates of the public and councils. A transformation of the variable representing government trust is directly applied to the negative flow rates, to provide a steady amount of resistance to the proposal throughout the process, with larger resistance when government trust is low.

**5.3.4.0.3 Stocks** Each community has its opinions represented by 2 lines of 5 stocks. 'Strong Positive' through to 'Strong Negative' as seen in Figure 5.3. These represent the different states of mind that individuals can have about the proposal (based on the categorisation used by the MRWS Partnership). The initial population of the community[1] is divided between the 'Positive', 'Neutral' and Negative' states according to model parameters indicating a community's initial support, neutrality and knowledge about the proposal (taken from Table 4.1 to 4.3, survey 1). The difference between a negative and positive state should be relatively clear. The difference between, for example, Positive' and Strong Positive' is that an individual in the 'Strong Positive' state believes they have sufficient evidence to back up their support of the proposal. The flow rates to these stronger states have been developed to reflect this, making any changes involving these states much slower.

The neutral stocks are transient to reflect more people in the community developing an opinion as the decision deadline comes closer. 'Neutral' can also mean one of two things about a person's opinion: either they have chosen to remain neutral in the discussion, or they do not feel like they have developed an opinion yet. The 'Strong Negative' stocks are absorbing (with the exception of an increase in knowledge to the same opinion) to reflect that it is far easier for an individual to remain in a state of extreme resistance than extreme support (it is difficult to define a positive equivalent of something like Fukushima).

**5.3.4.0.4 Knowledge** Assumption 7 refers to an individual being unable to feel like they have lost knowledge about the siting process. In other words, knowledge can only increase. I have distinguished between two cases; where the individual feels they know 'at least a little' or 'less than a little' about the process. This is purely based on that individual's own assessment of their knowledge, and has been implemented in the model due to the data collected by the Partnership showing a noticeable positive bias for those with 'at least a little' knowledge about the process. In my model, the rate at which people of a community gain knowledge is largely based upon the current activity of the NGOs and Partnership. When this activity is high, then people gain knowledge faster. This means the times where people gain the most knowledge is during the stakeholder engagement periods, especially closer to the decision deadline. Knowledge is also important for the councils, as the more knowledgeable the public of their community feels, then the more likely the council is to respond to the public's opinions. In particular, a high public knowledge means the council is more sensitive to changes in public opinion.

**5.3.4.0.5 Government Trust** My literature review provided the insight that implementing a measure of governmental trust was important for a more realistic model. There are two

[1] https://en.wikipedia.org/wiki/List_of_English_districts_by_population

places that this government trust has been used in my model to directly affect the behaviour of the public. Firstly, it has been used to scale the influence of positive media, which has a significant affect on the general public. This means that when government trust is high, more positive media will be released. Secondly, there is a direct effect on the negative flow rates of each community, which roughly increases over time and with low government trust. Full information for these effects can be found in Appendix B.2.4 and B.2.5. This is in place to represent the general opposition to the proposal that was in the community (e.g. the 'not in my backyard' argument), but has an increased affect on the councils (where media has a lower affect).

I define an initial value for Government trust in my model (at the start of the process), and then small changes are applied to this based upon the relative activities of the Partnership and the NGOs alongside any relevant external events (such as Fukushima). The relationship defining these changes is an estimation based upon the literature and my own experience in the area. When the NGOs are more active in comparison to the Partnership, government trust decreases and vice versa. Radiation and government media incidents also have a negative impact on government trust while they are still 'recent'. The decay rate is roughly 75% over 3 months, and full details can be seen in Appendix B.2.1. Finally, the government trust is measured on a 0-1 scaled, with 0 representing total lack of trust and 1 representing complete trust. It has been constructed such that it is difficult to approach the more extreme values (less than 0.3 and greater than 0.7) to reflect that there will always be individuals that support or resist the government, no matter what happens.

### 5.3.5 Model Parameter Definitions and Initial Values

All the values here are stored in the 'World Conditions' module, shown in Figure 5.3. These values were set using the sources presented in Tables 4.1 to 4.4 (initial knowledge and opinion), and with the help of area experts that were engaged with the previous process (Table 4.5).

| Parameter | Description | Initial Value |
|---|---|---|
| Copeland Population | Total number of people eligible to vote within Copeland. | 69800 |
| Allerdale Population | Total number of people eligible to vote within Allerdale. | 96000 |
| Cumbrian Population | Total number of people eligible to vote within the rest of Cumbria. | 329200 |
| Copeland Council | Total number of involved council members representing Copeland. | 7 |
| Allerdale Council | Total number of involved council members representing Allerdale. | 7 |
| Cumbrian Council | Total number of involved council members representing Cumbria. | 10 |
| Copeland Interest | The overall interest the Copeland population holds in the proposal. Scale from 0 to 1, with 0 representing no interest and 1 representing very high interest. | 0.5 |
| Allerdale Interest | The overall interest the Allerdale population holds in the proposal. Scale from 0 to 1, with 0 representing no interest and 1 representing very high interest. | 0.25 |
| Cumbrian Interest | The overall interest the rest of Cumbria's population holds in the proposal. Scale from 0 to 1, with 0 representing no interest and 1 representing very high interest. | 0.35 |
| Copeland Initial Knowledge | Proportion of people within Copeland that would consider themselves to know 'at least a little about the proposal & issue at the start of deliberations. | 0.65 |
| Allerdale Initial Knowledge | Proportion of people within Allerdale that would consider themselves to know 'at least a little about the proposal & issue at the start of deliberations. | 0.5 |
| Cumbrian Initial Knowledge | Proportion of people within the rest of Cumbria that would consider themselves to know 'at least a little about the proposal & issue at the start of deliberations. | 0.35 |

| | | |
|---|---|---|
| Copeland Initial Opinion | Proportion of people within Copeland that have a positive opinion on the proposal at the start of deliberations. | 0.57 |
| Allerdale Initial Opinion | Proportion of people within Allerdale that have a positive opinion on the proposal at the start of deliberations. | 0.55 |
| Cumbrian Initial Opinion | Proportion of people within the rest of Cumbria that have a positive opinion on the proposal at the start of deliberations. | 0.45 |
| Copeland Initial Neutral | Proportion of people within Copeland that are neutral, or do not know their positions on the proposal at the start of deliberations. | 0.2 |
| Allerdale Initial Neutral | Proportion of people within Allerdale that are neutral, or do not know their positions on the proposal at the start of deliberations. | 0.25 |
| Cumbrian Initial Neutral | Proportion of people within the rest of Cumbria that are neutral, or do not know their positions on the proposal at the start of deliberations. | 0.28 |
| Government Trust | The initial trust the public has in the government at the start of deliberations on a scale from 0 to 1, with 0 representing no trust in the government and 1 representing total faith. | 0.3 |
| Radiation and Government Media Incidents | Incident # - The scale of radiation incident # that is included in 'Radiation Incidents'. The scale runs from 1 to 5, with 1 being a very minor incident with little media attention, and 5 being a major incident that is heavily reported on. Time # - The start time since the beginning of deliberations of the associated radiation incident in months. | Incident A = 1 (Storage of German Plutonium), Incident B = 3 (Fukushima), Incident C = 1 (Deadline Extension). Time A = 43, Time B = 25.25, Time C = 44 |

Table 5.4: Table showing the initial values for SD model parameters, alongside a description of each parameter.

### 5.3.6 Model Formulae

To allow for simpler reporting on the formulae used in this SD model, they have been provided with as the direct change equation (the amount that actually moved at each time step), rather than as a differential equation. This is also more consistent with the display within the iThink software. Additionally, the formulae for the councils have not been included here as this could not be validated, and has no impact on the rest of the model (although it can be found in Appendix B). In the majority of cases, these formulae have been produced with area experts, alongside the set of preferences found in the literature, which has been summarised in Table 4.4.

Delay in the formulae is represented by D(). For example, D(RGMI,0.5) would refer to the value of RGMI 0.5 months previously. TIME refers to the current time of the SD model.

#### 5.3.6.1 World Conditions

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| Radiation and Government Media Incidents (RGMI) | Converter | Smoothed representation of information availability about radiation (such as radiation leaks) or government media (such as related controversial policies) incidents happening that could impact public approval | Third order exponential smoothed step functions at times A, B and C, of height, incident A, B and C respectively. Negative smoothed steps are applied 1 month after the event's time to start decaying the affect. |
| Trust incident Adjustment (TIA) | Converter | Tracks the adjustment to be made to government trust from incidents for the next time step. | If (RGMI ¿ 1.5) then -0.025 elseif (RGMI ¿ 0.5) then -0.01 else 0 |
| Government Trust (GT) | Converter | Provides an estimation of the current trust the public of the area has in the governments ability to fairly represent and follow through with the proposal. | max(min(D(GT,0.25)*((1+ PPI/50)/(1+NNI/50))+TIM, 1), 0). The scaling factors for PPI and NNI are adjusted if GT falls below 0.3 or above 0.7 to (50,100) and (100,50) respectively. |
| NIBY | Converter | Demonstrates a general aversion to the proposal, with the strength of this aversion being directly correlated to the current government trust. | IF(TIME¿20) THEN (1-GT)/2 ELSEIF (TIME¿9) THEN (1-GT)/3 ELSEIF (TIME¿6) THEN (1-GT)/4 ELSE 0 |

Table 5.5: Table showing the formulae for the 'World Conditions' module.

#### 5.3.6.2 Partnership

The information used to populate all of the news releases and events was taken from the MRWS Partnership website.

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| Minor News Releases (MNR) | Converter | Records the impact of news releases such as e-bulletins and local advertisements | Step(0.1,16)+Step(0.05, 21)+Step(-0.05,26)+Step(1,33)+Step(-1,38)+step(-0.1,42)+Step(0.1,23)+Step(-0.1,25.5)+Step(0.25,33)+Step(-0.25,34)+Step(0.25,35)+step(-0.25,36) |
| Major News Releases (MJR) | Converter | Records the impact of high-traffic news releases, usually related to significant events such as government statements or plans. | STEP(1,9.5)+STEP(-1,9.75)+STEP(1,10.5)+STEP(-1,10.75)+STEP(1,11.5)+STEP(-1,11.75)+STEP(1,21)+STEP(-1,21.5)+STEP(1,22)+STEP(-1,22.5)+STEP(1,23)+STEP(-1,23.5)+STEP(2,33)+STEP(-2,37) |
| Information Packs (IP) | Converter | Records the impact of newsletters, leaflets and final reports for each of the stakeholder engagement phases. Also includes the impact of the citizens panels held in PSE1. | STEP(1,9.5)+Step(-1,10)+STEP(1,21)+STEP(-1,21.5)+Step(1,23.5)+Step(-1,24)+STEP(0.5,23)+Step(-0.5,24.5)+Step(1,35)+Step(-1,35.5)+Step(1,37)+step(-1,37.5)+STEP(0.25,15.5)+Step(-0.25,16.5)+STEP(0.5,27.5)+Step(-0.5,28.5)+STEP(0.5,40.5)+Step(-0.5,41)+Step(0.5,42)+step(-0.5,44)+Step(0.25,9.75)+step(-0.25,10.75) |
| Major Events (MJE) | Converter | Records the impact of larger events organised by the Partnership such as residents panels and organisation workshops. | Step(0.75,12)+Step(-0.75,12.5)+Step(0.75,10.25)+Step(-0.75,10.75)+Step(0.75,23)+Step(-0.75,23.5)+Step(0.75,23.25)+Step(-0.75,23.75)+Step(1.5,37.25)+Step(-1.5,37.75) |
| Minor Events (MNE) | Converter | Records the impact of smaller scale local events during the stakeholder engagement phases. | STep(0.15,9.25)+step(-0.15,10)+step(0.15,10.25)+step(-0.15,10.5)+step(0.15,11.5)+step(-0.15,11.75)+step(0.15,12.25)+step(-0.15,22.75)+Step(0.15,21.5)+step(-0.15,22)+Step(0.15,22.25)+step(-0.15,25.5)+Step(0.5,35.75)+step(-0.5,36.5) |

| | | | |
|---|---|---|---|
| Partnership Positive Influence (PPI) | Converter | Totals the positive impact the Partnership is having on the public at that time. | MNR+MJR+IP+MJE+MNE+ if(TIME¿6) 0.25 else 0 |

Table 5.6: Table showing the formulae for the 'Partnership' module. The Step function is inbuilt into iThink, and is the format of (magnitude, time). E.g. Step(1,10) means increase value by 1 at month 10.

#### 5.3.6.3 NGOs

The information used to populate all of the news releases and events was taken from the MRWS Partnership website, the sources in Table 4.4, and was validated with experts.

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| News Releases (NR) | Converter | Records the impact of news releases and articles produced by the NGOs | Step(1,22.25)+step(-1,22.75)+Step(1,25.75)+step(-1,26.25)+step(1,27.5)+step(-1,28)+step(1,38)+step(-1,38.5)+step(1,39.75)+step(-1,40.25)+step(1,41.5)+step(-1,42)+step(1,44)+step(-1,44.5) |
| NGO Events (NE) | Converter | Records the impact of NGO events. | Step(0.05,7)+Step(0.15,15)+step(1,23) +step(-0.9,24)+step(0.25,35) |
| Partnership Event Attendance (PEA) | Converter | Describes the increased resistance to the proposal by the NGOs during stakeholder engagement phases | Step(0.5,12)+step(-0.5,12.5) +Step(0.5,23)+step(-0.5,23.5) |
| NGO Negative Influence (NNI) | Converter | Totals the negative impact the NGOs is having on the public at that time. | NR+PEA+NE |

Table 5.7: Table showing the formulae for the 'NGO' module. The Step function is inbuilt into iThink, and is the format of (magnitude, time). E.g. Step(1,10) means increase value by 1 at month 10.

#### 5.3.6.4 Media

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| Media Positive Influence (MPI) | Converter | Provides an overall measure of the current amount of positive attention the proposal is receiving from both the media and the general public. This is also scaled by current government trust. | (MJR+MJE+Step(0.05,6) +Step(0.1,8)+Step(-0.1,13) +Step(0.15,20)+Step(-0.1,25) +Step(0.2,32)+Step(-0.2,42)) *GT*D(Current Overall Positive Opinion,0.5) |
| Media Negative Influence (MNI) | Converter | Provides an overall measure of the current amount of positive attention the proposal is receiving from both the media and the general public. This also has additional influence directly from Radiation and Government Media Incidents. | (2*NR+NE+RGMI+Step(0.4,42)) *D(Current Overall Negative Opinion, 0.5) |

Table 5.8: Table showing the formulae for the 'Media' module. The Step function is inbuilt into iThink, and is the format of (magnitude, time). E.g. Step(1,10) means increase value by 1 at month 10.

#### 5.3.6.5 Community Public Variables

The table below provides information for the formulae contained in the 'Copeland Public Var' module. The other two communities also had a similar module, that worked in a very similar way. CI refers to 'Copeland Interest' and CP refers to 'Copeland Population', both of which are in the 'World Conditions' module.

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| Copeland Knowledge (CK) | Converter | Contains the current rate of knowledge gain within Copeland. | (NNI+PPI)/400 |
| Copeland Positive Reinforcement (CPR) | Converter | Current level of reinforcement of positive opinion, adjusted for population level. | CI*PPI*CP/100 |
| Copeland Positive (CP) | Converter | Current level of transfer to positive opinion from a negative opinion, adjusted for population level. | (MPI+CI*PPI)*CP/100 |
| Copeland Negative (CN) | Converter | Current level of transfer to negative opinion from a positive opinion, adjusted for population level. | (NIBY+MNI+CI*NNI)*CP/100 |
| Copeland Negative Reinforcement (CNR) | Converter | Current level of reinforcement of negative opinion (or doubt of strong positive opinion), adjusted for population level. | (CI*NNI)*CP/100 |

Table 5.9: Table showing the formulae for the 'Copeland Public Var' module.

#### 5.3.6.6 Community Public

**5.3.6.6.1 Stocks** CIP refers to 'Copeland Initial Opinion', CP refers to 'Copeland Population', CIN refers to 'Copeland Initial Neutral' and CIK refers to 'Copeland Initial Knowledge', all of which are in the 'World Conditions' module.

| Formula | Usage Type | Description | Initial Value |
|---|---|---|---|
| Strong Positive Familiar | Stock | Current number of people who believe they know at least a little in Copeland that feel strongly positive about the proposal. | 0 |
| Positive Familiar | Stock | Current number of people who believe they know at least a little in Copeland that feel slightly positive about the proposal. | CIK*CP*CIO |
| Neutral Familiar (NF) | Stock | Current number of people who believe they know at least a little in Copeland that have no strong opinion about the proposal. | CIK*CP*CIN |
| Negative Familiar | Stock | Current number of people who believe they know at least a little in Copeland that feel slightly negative about the proposal. | CIK*CP*(1-CIO-CIN) |
| Strong Negative Familiar | Stock | Current number of people who believe they know less than a little in Copeland that feel strongly negative about the proposal. | 0 |
| Strong Positive Unfamiliar (SPU) | Stock | Current number of people who believe they know less than a little in Copeland that feel strongly positive about the proposal. | 0 |
| Positive Unfamiliar (PU) | Stock | Current number of people who believe they know less than a little in Copeland that feel slightly positive about the proposal. | (1-CIK)*CP*CIO |
| Neutral Unfamiliar (NU) | Stock | Current number of people who believe they know less than a little in Copeland that feel slightly negative about the proposal. | (1-CIK)*CP*CIN |
| Negative Unfamiliar (NegU) | Stock | Current number of people who believe they know less than a little in Copeland that feel slightly negative about the proposal. | (1-CIK)*CP*(1-CIO-CIN) |
| Strong Negative Unfamiliar (SNU) | Stock | Current number of people who believe they know less than a little in Copeland that feel strongly negative about the proposal. | 0 |

Table 5.10: Table showing the formulae for the stocks of the 'Copeland Public Var' module.

**5.3.6.6.2 Flows** CP refers to 'Copeland Population', which is in the 'World Conditions' module

| Formula | Usage Type | Description | Value |
|---|---|---|---|
| SP gain | Flow | The flow rate from Positive Unfamiliar to Strong Positive Unfamiliar | CPR |
| SP loss | Flow | The flow rate from Strong Positive Unfamiliar to Positive Unfamiliar | CNR |
| P gain | Flow | The flow rate from Neutral Unfamiliar to Positive Unfamiliar | IF(TIME¡24) THEN CP*NU/(2*CP) ELSE CP*2*NU/CP |
| P loss | Flow | The flow rate from Positive Unfamiliar to Negative Unfamiliar | 1.25*CN |
| Neu loss | Flow | The flow rate from Neutral Unfamiliar to Negative Unfamiliar | IF(TIME¡24) THEN 1.25*CN*NU/(2*CP) ELSE 1.25*CN*2*NU/CP |
| Neg loss | Flow | The flow rate from Negative Unfamiliar to Positive Unfamiliar | CP |
| SNeg gain | Flow | The flow rate from Negative Unfamiliar to Strong Negative Unfamiliar | CNR |
| SPF gain | Flow | The flow rate from Positive Familiar to Strong Positive Familiar | CPR |
| SPF loss | Flow | The flow rate from Strong Positive Familiar to Positive Familiar | CNR |
| PF gain | Flow | The flow rate from Neutral Familiar to Positive Familiar | IF(TIME¡24) THEN 1.25*CP*NF/CP ELSE 1.25*CP*4*NF/CP |
| PF loss | Flow | The flow rate from Positive Familiar to Negative Familiar | CN |
| NeuF loss | Flow | The flow rate from Neutral Familiar to Negative Familiar | IF(TIME¡24) THEN CN*NF/CP ELSE CN*4*NF/CP |
| NegF loss | Flow | The flow rate from Negative Familiar to Positive Familiar | 1.25*CP |

| | | | |
|---|---|---|---|
| SNegF gain | Flow | The flow rate from Negative Familiar to Strong Negative Familiar | CNR |
| SPF | Flow | The flow rate from Strong Positive Unfamiliar to Strong Positive Familiar | SPU*CK |
| PF | Flow | The flow rate from Positive Unfamiliar to Positive Familiar | PU*CK |
| NeuF | Flow | The flow rate from Neutral Unfamiliar to Neutral Familiar | NU*CK |
| NegF | Flow | The flow rate from Negative Unfamiliar to Negative Familiar | NegU*CK |
| SNegF | Flow | The flow rate from Strong Negative Unfamiliar to Strong Negative Familiar | SNU*CK |

Table 5.11: Table showing the formulae for the flows of the 'Copeland Public' module.

## 5.4 Testing

### 5.4.1 Model Validation

To assess the model's suitability for its intended purpose (to develop understanding of the behavioural responses of each community) I applied validation tests from a selection of papers (e.g. Forrester & Senge 1980, Barlas 1994, Khazanchi 1996, Martis 2006, Kampmann & Oliva 2009). These included extreme-conditions tests for the adjustable parameters, time-step sensitivity and structural verification against the known format of the last proposal attempt in Cumbria. I performed structural and behavioural face-validity tests with experts knowledgeable of the process shown in Table 4.5.

Whenever any significant changes were made to the model, I revisited these validation and verification tests to ensure that the new changes did not compromise the integrity of model structure. Alongside this I have also conducted a large number of scenario-based validation tests as a final robustness test for the model once it had been completed. However, some of these had also been considered during the construction phase as well. These tests included (but were not limited to) large population differences, slower and faster opinion changes, sensitivity testing towards initial values (e.g. government trust, community assumptions, etc), different deliberation and engagement procedures for both the NGOs and the Partnership and stronger and weaker feedback effects. A summary of the validation and verification tests are provided in Appendix D.

### 5.4.2 Primary Results

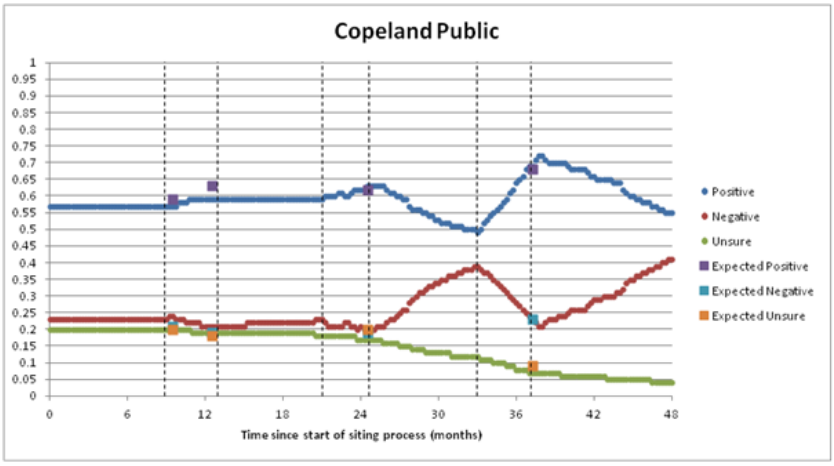
After calibration of the flow rates for each community, I had more confidence in the model's ability to represent the previous siting process. Due to the lack of data, I was uncertain about exactly how much opinion is changing between any two survey time points. In particular, it is difficult to assess how quickly the public change their opinions. To test the robustness of the model to this, I have produced two very similar additional models. The first has members of the public changing opinions relatively quickly, while the second scales the flow rates back (along with some minor calibrations to account for this flow rate change) so that opinions change more slowly.

Finally, when I refer to the model's robustness to a specific change, I are considering how closely the model results or trends (should be clear from the circumstance) remain to the original model's results and trends shown in Figure 5.8 (or another model if the scenario is being compared against say the decision deadline extension). The model is considered robust if the results are within 3% of original values after the change, and if the trends displayed are similar enough, according to the modeller (and experts) interpretation.

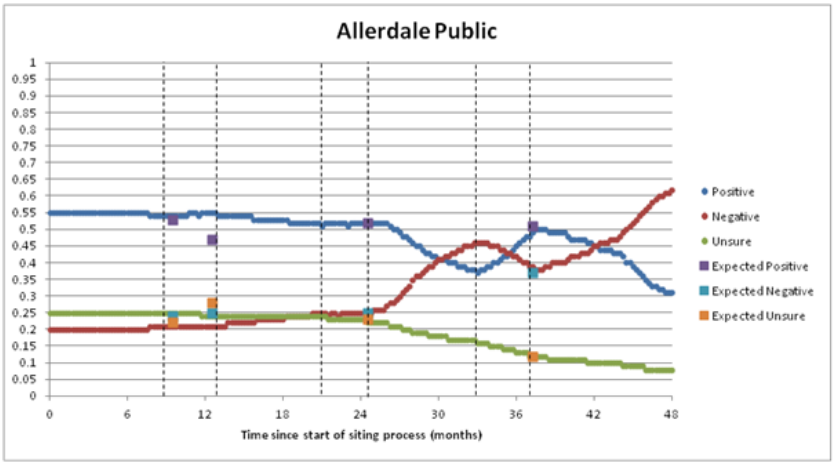
**5.4.2.0.1 Model 1** Each community showed similar trends as I may expect from geographically close counties, although the initial opinion varies according to how familiar each community was with the nuclear industry. For example, Copeland is the current borough hosting much of the nation's nuclear waste, and so are initially more acceptant of the proposal. The increasing resistance at the end of the timeline is what I would expect when the Partnership no longer engages with the public, while NGOs have increased activity. While I have not included a timeline of perceived knowledge of each community, this has also been evaluated against the data and shows a slow but relatively steady increase in knowledge over time.

The model's predications are very close to each of my data points for all communities. However, the behaviour between PSE 2 and PSE 3 (month 24-33) may lead to uncertainty about the model's validity. During this period public support decreases drastically in line with the Fukushima disaster in 2011. While I expect a decrease in support in response to such a significant event, it leads me to question whether the Partnership would be able to change public opinion so drastically during PSE 3. The change in support during PSE 3 seems excessive, although I must keep in mind that the Partnership engaged with the public much more actively than in the other stakeholder engagement periods and that this period was getting close to the council's planned decision point at month 44. This possible mismatch lead me to develop 'final model 2' which has slower changing opinions.

5.8a.




5.8b.




5.8c.

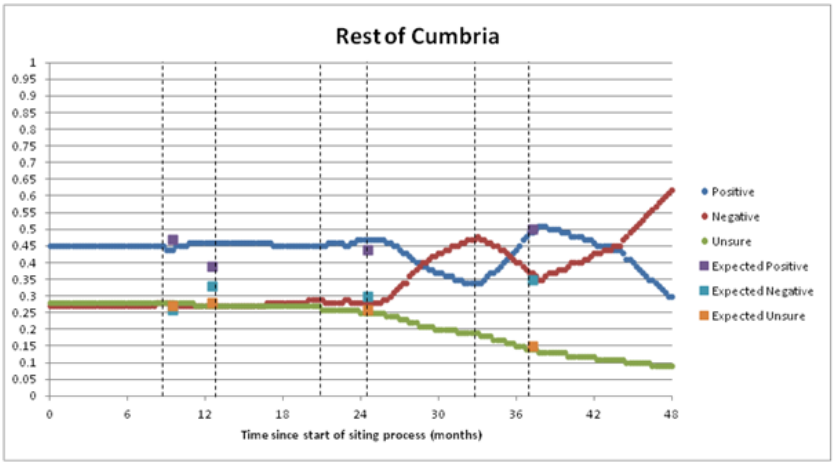
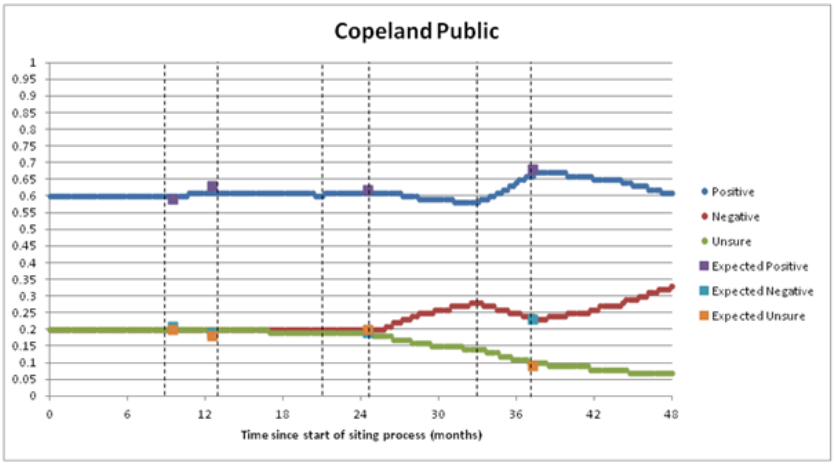
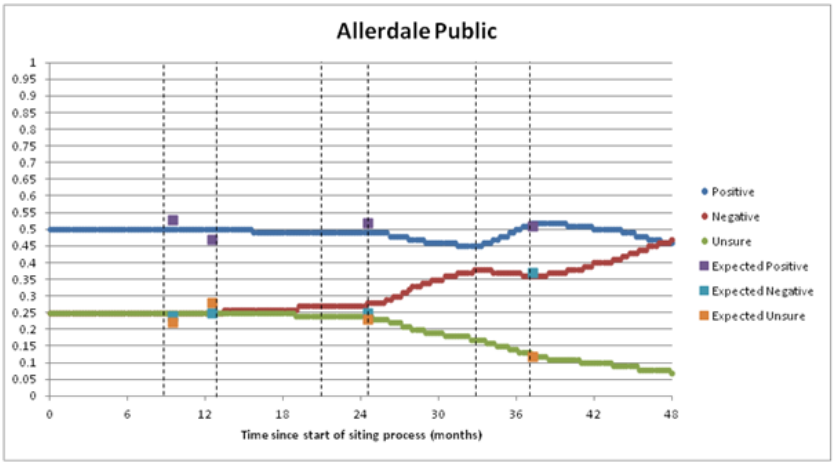



Figure 5.8: 5.8a, 5.8b and 5.8c shows the public support for proceeding with the siting process over the 4 year lifespan of the proposal for final model 1. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organise, and the squares show the survey results for that community for each of the four surveys.

5.9a.




5.9b.




5.9c.

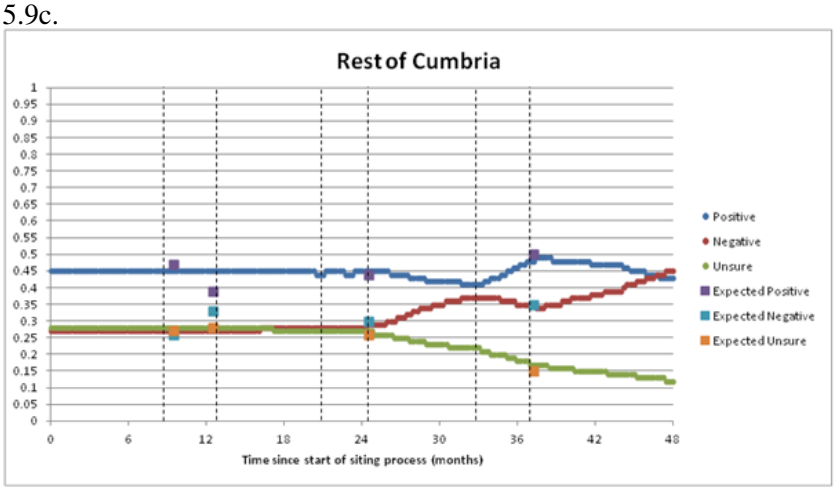



Figure 5.9: 5.9a, 5.9b and 5.9c show the public support for proceeding with the siting process over the 4 year lifespan of the proposal for final model 2. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organise, and the squares show the survey results for that community for each of the four surveys.

**5.4.2.0.2 Model 2** Contrasting the trends to those seen in final model 1, I can see that while the opinions of the public change noticeably slower, it does not affect the overall trends of final model 2. Fukushima has a noticeable impact but does not cause a swing of opinion both ways in this model. Also the public has slightly higher support of the proposal in all communities at the end of the process under this model, although it is clear that support is dropping relatively quickly. Seeing these trends repeat under different flow conditions while still being close to all data points does however give more confidence in the robustness of final model 1.

I conclude that systems dynamics has been an effective tool to simulate public opinion in a GDF siting process such as this (although this method could be extended to other proposals). My model seems robust to the choice of parameters defining flow rates, and manages to predict support values well at the survey points. Also in both models I can see the increasing resistance to the proposal which lead to the eventual rejection from the Cumbrian council despite the positive opinions from the last opinion survey. It would be possible to create a model using a similar structure to model public opinion in the upcoming siting attempt.

## 5.5 Policy Design and Evaluation

### 5.5.1 Deadline Extension

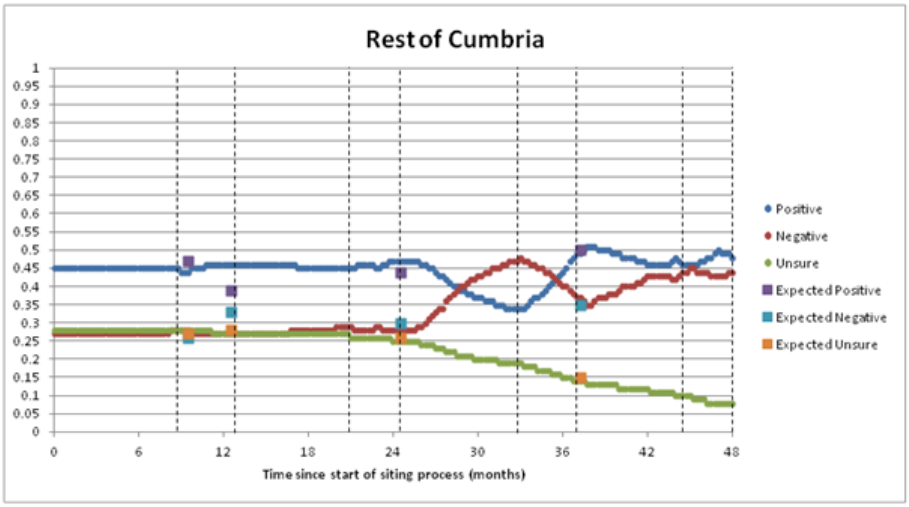
It may have came as a surprise to the government when the Cumbrian council decided to withdraw from the siting process given that their last formal feedback from the public was positive (2012 survey). Many reasons were suggested for this swing in opinion and I pay special attention to one of these; the deadline extension biased the engagement process and changed decision outcome.

I investigated this by allowing the partnership to continue to operate past the initial decision deadline in my model, where they would go into a fourth stakeholder engagement period (I call this PSE4) that is active up until the decision is made at the end of January 2013. During PSE4 I assume the partnership would carry out similar activities as they did in PSE3, which is not a far-fetched assumption given the increasing partnership activity. I also assumed slightly increased activity from the NGOs that would actively try to combat some of the events organised by the Partnership. The model produced for this subsection is the 'Deadline Extension' model from Table 5.2.

As the Cumbrian Council was the sole council to reject the proposal, I focused on the differences in the public and council opinion in the 'rest of Cumbria' as both Allerdale and

Copeland already had a positive vote (made more positive by the change to Partnership activity). The final vote of the Cumbrian Council was 3 for and 7 against the proposal and if the deadline extension biased the result, I may expect that this final vote would change to more in favour of proceeding with the proposal when the Partnership is active in the final few months. The results are given below in Figures 5.10 and 5.11.

5.10a.




5.10b.

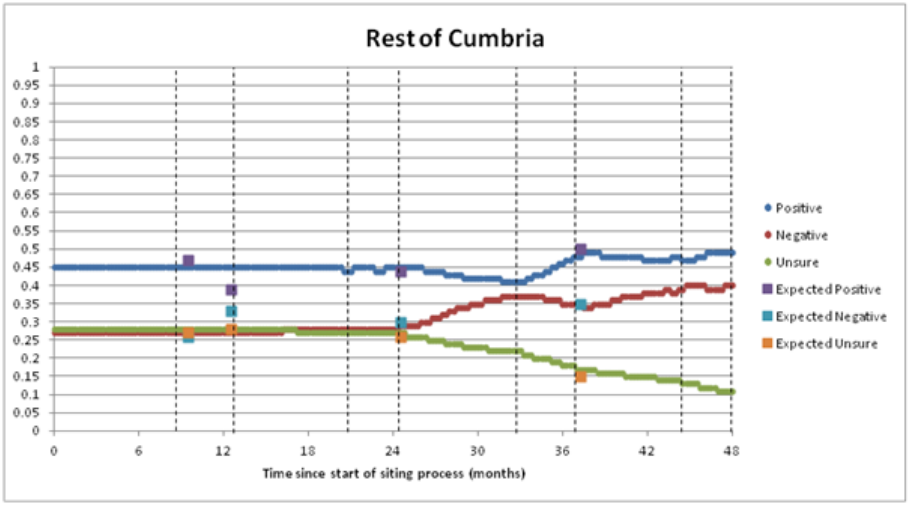



Figure 5.10: a and b shows the Cumbrian public support for proceeding with the siting process over the 4 year lifespan of the proposal for models 1 (top) & 2 (bottom) when PSE4 is included. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organised.

Figure 5.10 shows that the public has responded in the way I may expect, and that the introduction of PSE4 has largely stopped the rapid decline in support observed near the end

of the siting process. However, given PSE4 has been designed such that the Partnership is just as active as it was in PSE3, it is a little surprising to see that there is only a very minor increase in public support during PSE4. This can be explained by the Partnership being roughly on par with the NGOs in their influence on the public at this stage. However, PSE4 has at least been enough to maintain support of the proposal. Keep in mind that very similar patterns are shown for both Allerdale and Copeland.

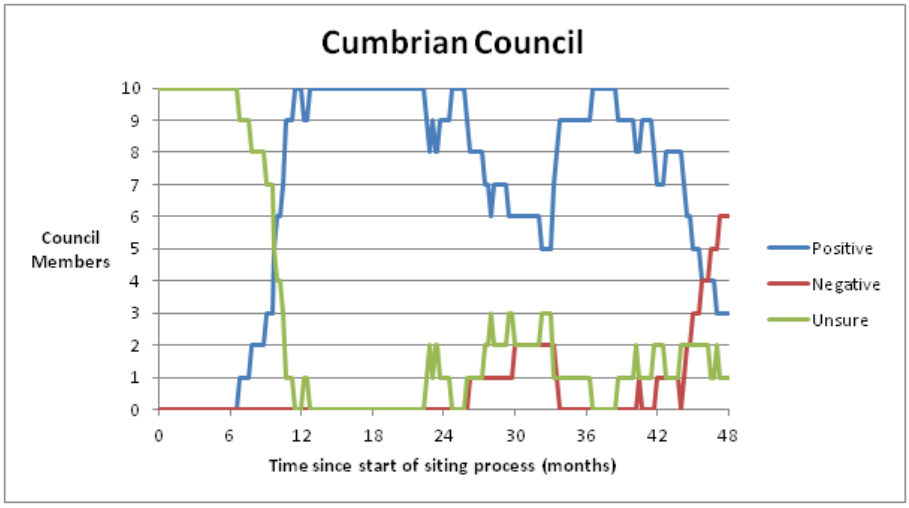
Sensitivity tests were carried out, such as those seen in Appendix D, to check how much these changes depended on a variety of factors, and the same trends were observed as for the original model with no deadline extension. Additionally, I are primarily interested in the overall trends rather than using the model for accurate predictions, and so it is likely that the displayed results are to some extent already biased. However, this bias has been consistent throughout models, allowing for a fairer comparison of trends.

From Figure 5.11, I can see a more dramatic difference than was observed in the public. In the original process, the Cumbrian Council was losing more and more support for the government's proposal over the last few months, resulting in the negative vote that was given at the end of January 2013. However when the partnership has been allowed to continue its activity with PSE4, I see that this loss of support is quickly reversed. While only the results for model 2 have been shown, model 1 shows a very similar trend. One conclusion I could draw from this is that the quickly declining support for the proposal in the public had a significant effect on the council's decision in the original process. However, when the Partnership is allowed to continue activity to possibly prevent this decline, it meant that the Cumbrian Council had little reason to change their opinions so drastically.

The behaviour of the councils are purely conjecture given the lack of any significant data, and while I have performed sensitivity analysis to attempt to calibrate the councils better, and understand how changing model parameters affects them, it is unknown if they follow the historical process of what happened. Additionally, the experts used in validation of the model were also uncertain. However, the results of the council had no impact or feedback to the rest of the model, they were an isolated module. They have been designed roughly to follow the opinions that could be found on the MRWS Partnership's website. However, given the lack of insight into how the council members would have voted earlier in the process it is difficult to validate this. It must also be considered that the vote on whether to continue now occurs directly at the end of a stakeholder engagement period, which is where support is generally highest. If the decision had been delayed by until at least 3 months after the end of PSE4 I could have seen a similar loss of support as in the original process, despite the Partnership being more active. My overall conclusion I can draw from the experiment

of introducing PSE4 to the process is that the extension of the decision deadline could have biased the engagement process. However, some care should be taken when interpreting these graphs, especially those concerning council opinions.

5.11a.




5.11b.

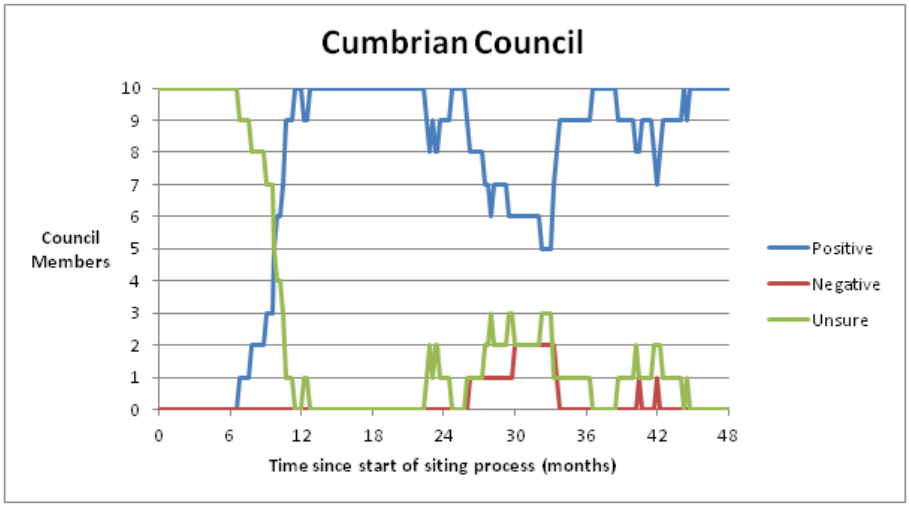



Figure 5.11: a and b shows the Cumbrian Council support for proceeding with the siting process over the 4 year lifespan of the proposal for model 2 when PSE4 is excluded (top) or included (bottom).

### 5.5.2 Influence in System Dynamics

#### 5.5.2.1 First Iteration Model

My first iteration model was functional enough to be used to predict acceptance rates of different groups over the 1 year period. However, I needed to be a little more creative with how

to measure the influence of each group. When defining the feedback loops in my model, the majority of the interactions were included on the variables directly used to calculate flow rates for each group (largely in the 'General Variables' module). This means that the most obvious utility weights would be static throughout the simulation, and as there is no clear group utility function, I are unable to directly apply my first influence measure that was introduced in Chapter 3. In order to analyse influence in my model, I decided to measure the influence of one group over each of the other groups behaviour (measured through differences in flow rates) once it had been removed (essentially as a scenario-based sensitivity analysis).

As I have a time series of points for the flows, I should also be able to go into more detail on specific flows. For example, showing that the removal of the 'Greenpeace' group has reduced the negative flows, but had relatively little impact on the positive flows on the 'General Public' group may be useful for users of the system to know. For this reason, I provide my results in the following format for a group being removed from the process.

| Greenpeace | General Public | Local Government | Overall |
|---|---|---|---|
| S Positive Flow | inf, avg, sd | inf, avg, sd | inf, avg, sd |
| Positive Flow | inf, avg, sd | inf, avg, sd | inf, avg, sd |
| Negative Flow | inf, avg, sd | inf, avg, sd | inf, avg, sd |
| S Negative Flow | inf, avg, sd | inf, avg, sd | inf, avg, sd |
| Overall | inf, avg, sd | inf, avg, sd | inf, avg, sd |

Table 5.12: Table showing the suggested layout for presenting the influence of Greenpeace when it has been removed from the model. Averages and standard deviations were calculated according the the differences of flow rates before and after Greenpeace's removal across all time steps sampled.

This style of table should contain all of the information you would need about the removal of a group from the process. The contents of cell i,j with respect to the removal of Greenpeace are; average influence on flow i of group j over time, average difference between flow i values for group j over time and standard deviation of differences between flow i values for group j over time. The 'Overall' row is the average influence over all flows for each group, and the 'Overall' column is the average influence over all groups for each flow.

To be able to do this, I must draw the links to my work on utilities seen in Chapter 3. First, let $s = sp, p, n, sn$ denote the types of flow I can have. Let $i = gr, pu, lg$ represent the group

being referred to (Greenpeace, General Public and Local Government respectively) and finally let $t = 1, ..., T$ be the point in the time series I are sampling at. Then define $f_{s,i,t}$ to be the flow value of type $s$ for group $i$ at time $t$. Additionally define $\mathbf{f}_{s,i,-i*}$ to be a vector of all flow values of type $s$ for group $i$ when group $i*$ has been removed from the model.

Following this I can use my distance measures that were introduced earlier on normalised values of the flow values to give a measure of how far a group's removal will impact another group's flows. For example, $D(\mathbf{f}_{p,pu}, \mathbf{f}_{p,pu,-gr})$ gives the average distance between the positive flow of the 'General Public' in the standard model, and in a model where 'Greenpeace' has been removed. While the vector $\mathbf{f}$ is defined over 3 indices (flow rate type, group, removed group), it is simplified to just two indices (flow rate type, group) if no group has been removed, i.e. for the base scenario. This is purely for simplicity of notation, and to better differentiate between the baseline and the group removal scenario. It is also worth noting that at this stage, the flow values were normalised, although when presenting results give summary statistics of the average distances to show direction, magnitude and consistency of the change. I used several influence measures for each type of influence that I are concerned with, which were inspired by the influence measure described in Section 3.3.3. The objective of these equations is to produce a non-negative measurement for how much the flow rates change between two scenarios. These are described below.

#### 5.5.2.1.1 Influence over a flow of a group

$$C_{i*,i,s}(\mathbf{f}_{s,i}) = T^{-1} D(\mathbf{f}_{s,i}, \mathbf{f}_{s,i,-i*}) \tag{5.1}$$

#### 5.5.2.1.2 Influence over a group

$$C_{i*,i}((\mathbf{f}_{s,i})_{s=sp,p,n,sn}) = (T)^{-1} \Sigma_{s=sp,p,n,sn} D(\mathbf{f}_{s,i}, \mathbf{f}_{s,i,-i*}) \tag{5.2}$$

#### 5.5.2.1.3 Influence over a flow

$$C_{i*,s}((\mathbf{f}_{s,i})_{i=gr,pu,lg}) = (T)^{-1} \Sigma_{i=gr,pu,lg} D(\mathbf{f}_{s,i}, \mathbf{f}_{s,i,-i*}) \tag{5.3}$$

These have rough estimates for their normalising constants. However, in the specific case where they are used, there should not be a large change in set-up. For the second two influence types, I have used the arithmetic mean of the outputs from the distance measure. I may also be interested in the change of influence over time, which was plotted separately.

#### 5.5.2.2 First Iteration Results

My main objective here was to assess the impact that removing the ECG would have on the behaviours of the other parties involved. The influence measures given in the last section was applied to my preliminary model where an ECG was considered with 80 members. In this model, the general public has 500 members and the local government had 50 members. The number of time points considered is 25, to allow for a comparison to be made each half month, for the full 12 months. The influence measures were then applied to the flow rates at each of these time points according to Section 5.2.2 and the results of this have been given in the table below.

| ECG | General Public | Local Government | Overall |
|---|---|---|---|
| S Positive Flow | 0.0713 | 0.3342 | 0.2028 |
| Positive Flow | 0.1204 | 0.2998 | 0.2101 |
| Negative Flow | 0.3136 | 0.4352 | 0.3744 |
| S Negative Flow | 0.1699 | 0.1793 | 0.1746 |
| Overall | 0.1688 | 0.3121 | 0.2405 |

Table 5.13: Table showing the comparison of the two cases where an ECG has been included and excluded in the model. Each cell contains the influence value given from using the influence measures in Section 5.5.2.1.

Keeping in mind that each of the influence values above is an 'average' influence over the time points considered, the 'Negative Flow' has the largest influence value and so has been the most affected by the removal of the ECG. Also, the high influence for the Local Government implies they have been impacted far more than for the General Public, due to more direct communication with the ECG. It is worth noting that the removal of the ECG decreased the scaled flow rates in all cases meaning that the change of opinion had slowed. However, the Negative flow rate decreased far more than any others, resulting in relatively less people entering the negative states. Another interesting feature is that the removal of the ECG has affected the negative rate noticeably more than the Strong Negative rate. This could be due to the evidence required to move an individual from the 'Neutral' to 'Negative' states being quite different to moving an individual from the 'Negative' to 'Strong Negative' states.

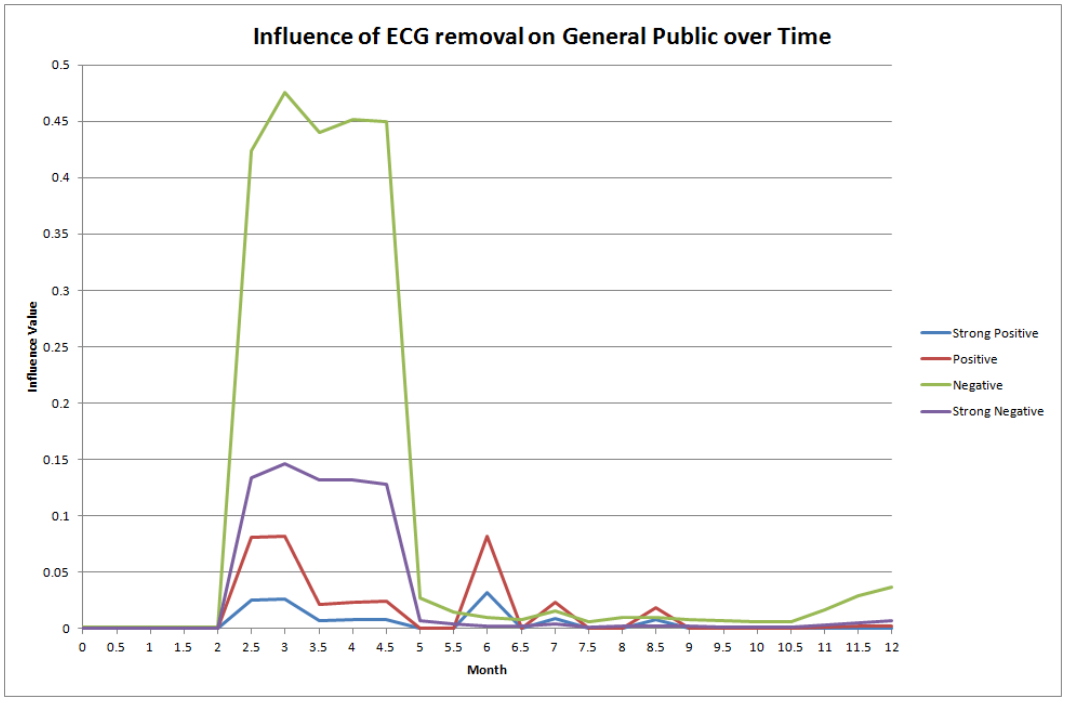



Figure 5.12: Time series showing the influence values of the ECG removal on the flow rates of the general public at each time point considered. Influence values are calculated according to Section 5.5.2.1 from the difference in flow rates. Note that values are often small but non-zero.

Figure 5.12 gives me more insight about the time intervals for which the removal of the ECG has most impacted the flow rates of the General Public. I can visualise the time points that have contributed the most to the calculation of influence value shown in Table 5.5.2.2. Immediately it is clear that the majority of the influence of the flow rates comes between months 2 and 5 for all flows. It is between these months that the ECG releases an information pack to the public to reduce support (this is the only information pack released during the simulation), and so the removal of the ECG caused this pack to never be released. Using both Figure 5.12 and Table 5.5.2.2 would therefore allow me to better understand where groups are exerting influence, and what is the driving force behind this influence.

While the removal of an entire ECG from the process may not be realistically possible, this method could still be used to compare different scenarios of interest. For example, I may be interested in the influence of world events, or restrictions on the media over the different stakeholder groups, so I are not limited to removing entire groups. This could be used for two primary purposes. The first would be to explore the scenario to develop better understanding of the stakeholder groups involved, and how they respond to changing world

conditions and the various feedback loops they are involved in. Secondly, it could help in event planning, to explore any possible bias that could be introduced through different debate structures, and how much they could affect the support of the proposal. The results have been promising overall, and exploring the idea of influence is a rather novel addition to system dynamics. Unfortunately, I could not continue to develop this style of model due to the complexities involved.

#### 5.5.2.3 Final Model 1

While my initial thoughts for designing a suitable measure of influence for system dynamics revolved around the style of measure in Chapter 3 (measuring the influence of a group by removing it from the process), my final model would not support this as well as my first iteration model. This is because I have removed some of the direct links between the different stakeholder groups, and so removing say an ECG from the process would now involve removing all events associated with that ECG from the NGOs module. This is possible in my current model but is too restrictive in the cases I could consider with the set-up of my current model.

So at this point I decided to move away from a one-out style of influence, and instead applied influence to specific scenarios. In my area of application, a scenario could represent a different set of events for the NGOs or Partnership (e.g. a public deliberation structure), or different defining characteristics of each group. I can then apply the same influence measures to the flow rates for each community that I had used for stakeholder groups in the preliminary model. I would expect that highly influential scenarios to change the flow rates (and hence behaviours) of the communities a large amount when compared to a base scenario. The base scenario I compare with, is the set of events and characteristics used for the results presented in Section 5.4.

#### 5.5.2.4 Final Model 1 Results

I compared my base scenario (the deliberation process as observed between 2009-2013) with my hypothesised extension of the Partnership's function during the last few months. By doing this, I can better understand how my model has reacted to the continued operation of the Partnership. Results shown in this section are for Copeland only, although the other communities showed similar behaviour. Additionally, the values of influence are considerably higher than demonstrated for my preliminary model as the influence measure does not scale for the number of people yet. The Cumbrian siting process included considerably more people, and so the flow rates were much higher (preliminary model had a few hundred people, while the current model contains almost 500,000 people). This caused the

influence values to become very inflated, although I are much more interested in the shape of the graph at this stage. If this is an issue in the future, scaling can be introduced to account for the magnitude of the flow rates.

| Base Flow Rates | Copeland |
|---|---|
| S Positive | 298.23 |
| Positive | 399.62 |
| Negative | 63.89 |
| S Negative | 0 |
| Overall | 190.43 |

Table 5.14: Table showing the overall influence that allowing the Partnership to continue functioning has had on the base flow rates for Copeland. I used the influence measures in Section 5.5.2.1. The values represent how much each flow rate changes over the course of the process with the new scenario, relative to the other flow rates.

I can see the difference that having a larger number of people in my model had on my original influence measures in Table 5.14. The extension of the Partnership's functions has had a much more dramatic impact on the positive base flow rates than their negative counterparts. Additionally, I can see that there has been no impact on my 'Strong Negative' base flow rate at all. This is because at the stage when the base flow rates were calculated, there was no effect from either the Partnership or downscaling due to feedback as with positive and negative. Details of this can be seen in Appendix B. While it may appear that this is an issue with the model, it can be described as the consistent negative trend which the Partnership cannot control. Changes to this consistent trend must be made by combating the NGOs directly to reduce their influence rather than increasing the Partnership's influence.

Figure 5.13 shows the development of influence over time. For the first 42 months of the process, there has been no changes to the model. All changes to the model only affected past month 42, so the flows would not change before that point. Between months 42 and 48 though I see the significant impact of the change to my positive base flow rates, with 'Strong Positive' often falling behind the 'Positive' base flow rates. This is what I would expect from making such changes. Additionally, I can see that the 'Negative' flow rate starts to increase with a few months delay to the positive flow rates. This is the effect of feedback within the system, which has a more direct affect on the negative flow rate due to word of mouth (which does not affect the strong positive flow rate).

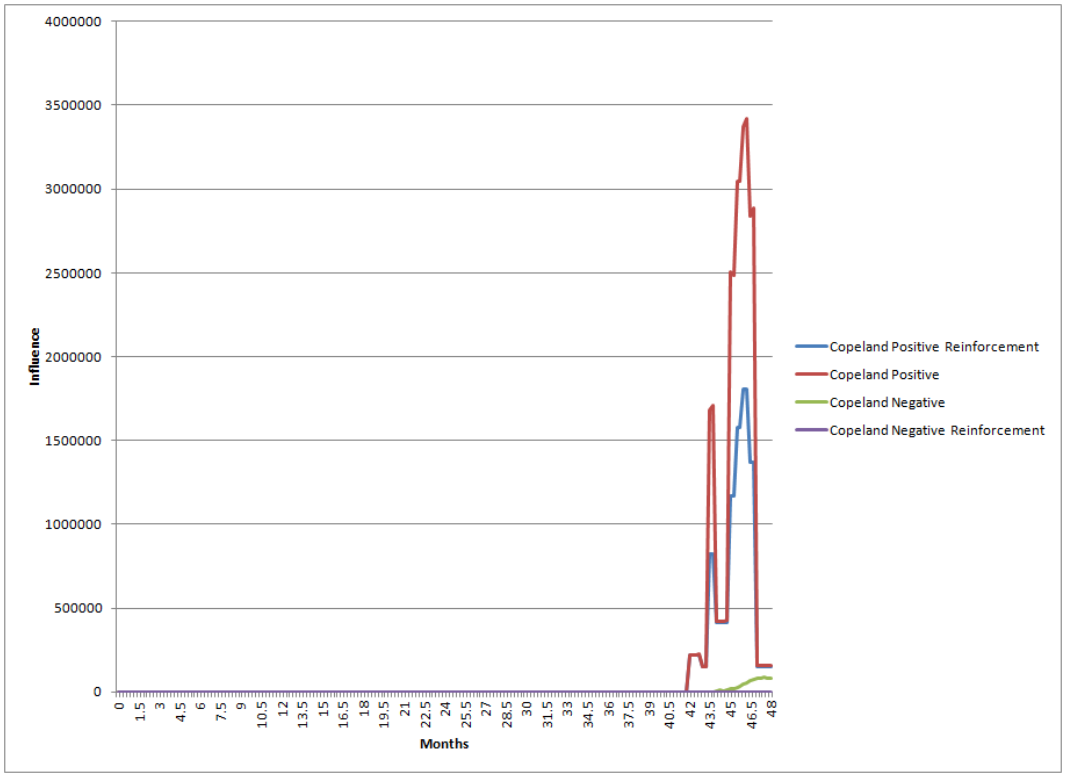



Figure 5.13: Time series showing the influence that allowing the Partnership to continue functioning has had on the base flow rates for Copeland at each time point considered. Influence values are calculated according to Section 5.5.2.1 from the difference in base flow rates.

#### 5.5.2.5 Discussion

The results from both my first iteration and final models can be considered interesting in their own right. Although having expanded my basic influence measures into my model for the Cumbrian siting process, it appears that the original aims of my work on influence cannot be met in this model setup (and in my DES model presented in Chapter 6). This is because the original aim of Chapter 3 was to measure how influential each member of a group is, but in the final model, it is no longer possible to define single individuals in a way that makes sense to measure influence over (e.g. I could measure influence of the removal of Copeland from the process, but that would result in an entirely different siting process). However, it can still be used to better understand how a particular scenario may influence the behaviour of the public within my models. In particular, I could draw from Figure 5.13 that while increasing the Partnership's activity has had a dramatic effect on the number of people moving to the positive states, it does not reduce the amount of support they lose

significantly. To combat this, they would have to focus on reducing NGO influence directly. It is likely that a balance of increased Partnership activity, while attempting to reduce NGO activity may be a more effective strategy to gaining and keeping supporters for the proposal.

## 5.6 Contributions

### 5.6.1 System Dynamics

One often difficult problem when constructing a SD model is defining the relationships and flow rates between stocks. This could be due to a lack of information, or uncertainties in the impact. The model produced in this chapter describes the construction of a SD model, with flow rates almost solely based on the relative importance of several attributes (e.g. media, perceived risks & benefits, trust, knowledge), and as such used the attribute weights traditionally used in utility theory to provide a foundation to calibrate the strength of preference from.

The chapter also provides an additional example that trend identification is possible when full system information is not known, or cannot be known. There are also more contributions to the SD literature in terms of potential new verification and validation techniques, however this is discussed in more detail in Chapter 8.

### 5.6.2 Opinion Dynamics and Nuclear Siting

The other main contribution from this chapter is in the areas of Opinion Dynamics and Nuclear Siting. To be able to define flow rates, the strengths of relative importance for a variety of attributes needed to be considered, quantified, and tested for sensitivity. The collation of the literature theory, combined with the calibration of this model, provides additional evidence towards the importance of certain key driving factors of public opinion. For example, perceived risk and governmental trust is an important driving factor in the model. This links with expectations from the literature reviewed in Chapter 4.

# Chapter 6

# Construction and Simulation of a Probabilistic Model

## 6.1 Introduction to Probabilistic Modelling

I have shown that system dynamics has strong potential in predictive modelling of public opinion in this area. However, there are several drawbacks to this deterministic method (see Brailsford et al 2014 for an example review of the strengths and weaknesses of DES and SD). Primarily, I lose all information about how a specific individual changes their opinion. While it is an important aspect of a produced DES model, it is not required as a reporting tool, but as a validation tool for the experts assisting with the construction of the model. The results requirements of the DES model are still the same as the SD model.

Tracking an individual through the system, and exploring how an individual is affected by changes made to the public deliberation structure within the model is particularly important to users who are less familiar with the model. In particular, such an analysis can be expected to improve trust in the model (as they can see expected behavioural responses). Alongside this, there is the important issue of how unpredictable an individuals behaviour can be, and the ramifications that could have on a heavily feedback-based model. Including some measure of this uncertainty would then also be very important both for model accuracy and for building model trust.

My system dynamics model was not able to address these two potential issues. So I first explored the probabilistic modelling paradigm of discrete event simulation (DES). I have also consider applications of dynamic Bayesian networks (DBN) to both my system dynamics and discrete event simulation models in Chapter 8. DES allowed me to relax several behavioural assumptions from my system dynamics model. One example is modelling the

way individuals change their opinions through a probability distribution, calculated from current events within the model, rather than modelling aggregate movements as in SD. This improvement also allows for users to track an individual's opinion over the four year period, and includes a measure of the uncertainty in my model. Moving towards this probabilistic system would also make it easier to implement the activity from the Partnership, and particularly the NGOs, where the deliberation structure could be uncertain. For example, I could define distributions for how often the NGOs host events within Cumbria. This would be particularly useful if the model was used for planning a future deliberation structure.

Another major probabilistic modelling paradigm I considered exploring was agent-based modelling. This would be ideal for my scenario of interest due to the high amount of individuality each entity can have within the model. In particular, I could define many more demographic and topographic interactions than would be feasible in a SD or DES model, potentially improving trust external users have in the model. However, in this particular application I lacked the more detailed data required to construct an in depth agent-based model. It was therefore less useful to explore this modelling paradigm in this instance. However, should more detailed data be collected, an agent-based model would be a suitable choice for simulation of public opinion.

### 6.1.1 Discrete Event Simulation Literature

Discrete event simulation has been a discipline that developed at a similar time to system dynamics. This is heavily linked to the consistent improvements to computing power since the 1950s. Arguably, one of the first influential methods was presented by Gordon (1961). He presented his general purpose simulation system (GPSS), which was designed to model work flows between activity centres in a business (or similar). This methodology gained some interest from others in the field (Schriber 1974, Kwak et al 1976). Another modelling method, developed slightly later than GPSS, was Simula (developed by Dahl & Nygaard at the Norweigen Computing Centre). This was considered a more difficult methodology to learn. There were also other methodologies presented for different scenario types during this early period, for example GASP and Simscript were both designed for event scheduling tasks. See Nance (1993) for a full account of the development of discrete event simulation programming languages up to 1986.

It was during these first 30 years that the foundations for modelling methods were laid down. However, it was not until the 1990s, when computing power became more accessible, that the DES discipline became more widely used. During this time DES became the standard for business applications. In particular, it became easier to tie together modelling software with a suitable graphical user interface (GUI). This enabled DES to be more

accessible to potential users (Swain 2011). The most common early uses for DES was process optimisation. For example, logistics, supply chain and transportation. These were natural applications because it was a relatively simple task to move the real-world system into a simulation model, as the systems would often have well defined rules (e.g. Legato & Mazza 2001, Detty & Yingling 2000, Spedding & Sun 1999). These applications have stayed relevant to this day, with simulation tools being specifically designed for logistical problems such as Plant Simulation[1].

The increasingly popularity of DES has seen more publications attempting to steer modellers towards formalising their process. For example, Brailsford et al (2014) provide a comprehensive review of both DES and SD techniques. The writers also make the point that it is important that the system to be modelled 'can be understood as a set of interconnected activities and queues that are subject to random variation', which follows from my own suggestions of essentially choosing the correct tool for the job. If this is not the case, then DES should not be seen as a useful modelling technique in this circumstance. This DES modelling style is also supported by others such as Tako & Robinson (2010) and Tako (2009). Robinson (2014) also provides another, similar, perspective on DES methodology. A standardisation of methodology in this way could help build trust in DES model from a user's perspective.

Additionally, there has been increasing interest over the past two decades on the application of DES to healthcare (e.g. Jun et al 1999, Swisher & Jacobson 2002, Duguay & Chetouane 2007, Gnal & Pidd 2010). However, more recently the focus of healthcare simulation has appeared to switch to using either agent-based modelling (Taboada et al 2013) or hybrid modelling (Brailsford et al 2010). While validation and verification of models is a very important step in the process of simulation, it has received less attention in DES than in SD. This is perhaps due to the less abstract 'feel' of DES models which makes validation a more natural step of the process during model development. More general approaches such as the tests that I mentioned for SD validation purposes are still applicable to DES models.

## 6.2 Conceptual Model & DES

### 6.2.1 Introduction

Discrete event simulation is a popular modelling paradigm that has been widely used within businesses, especially for supply chain management, production planning and queueing systems. The paradigm has become so popular that there are an increasing number of

[1] http://www.simsol.co.uk/products/plant-simulation/

DES consultancies (that often also produce DES software). Examples include: SIMUL8[1], PMC[2], Systems Navigator[3], Plant Simulation[4] and many more. DES is also seen as one of the easier modelling paradigms for users to understand. Outside users tend to be more familiar with DES. Additionally, DES simulates system behaviour in a clearer way than a paradigm such as system dynamics which requires a higher level of abstraction (Borshchev & Filippov 2004). This familiarity can also be seen through how much more software is available for DES than SD. DES has grown to be the 'go-to' simulation method for companies to use when they have little knowledge of other modelling paradigms. The general familiarity and popularity of DES were some of the reasons I used this paradigm and, while feedback is less common in DES systems, it is still supported by the paradigm.

In order to ensure comparability of my models, I constructed my DES model in a similar way to the system dynamics model. In particular, I included the five states of opinion as activities in the DES model. Furthermore, probability distributions for transitions between these states are defined according to variables and events within the model. The model was run for the full duration of the MRWS siting process in Cumbria. It was expected that my DES model may be more believable to outside users (as they can track individual changes of opinion) than the system dynamics model. However, it may be more difficult to validate due to the inclusion of significant stochastic elements. An initial issue was the exact definition of the 'true' behaviour that drives the model and what this might depend on. One particular concern was that the behavioural changes observed in the failed Cumbrian siting process could have been an outlier to the 'true' average behaviour.

### 6.2.2 Terminology

I have provided the general terminology I used, specific to DES, in this section. This is useful to distinguish between components within my SD model, and my DES model. The main exception to this is 'Individual' which has the same meaning in both models. While this terminology is general to DES, it is important to separate my terminology from that used in my SD model. So in this chapter I use the more general terminology of the paradigm, rather than terminology specific to my scenario (which could refer to my SD or DES model). However, keep in mind the meaning each statement can have for the scenario itself.

*Individual*: When I say individual I refer to a single person living in one of the communities included in the study.

[1] http://www.simul8.com/
[2] http://www.pmcorp.com/Home.aspx
[3] http://www.systemsnavigator.com/sn_website/
[4] http://www.simsol.co.uk/products/plant-simulation/

*Work Item*: These are the basic entities that travel through the model. In most cases, a work item represents 100 individuals of a community that travel through opinions together.

*Entry/Start Point*: These nodes are where work items enter the system according to some specified distribution. I have entry points for the individuals I are modelling, and for various events (e.g. NGO and Partnership news releases) relevant to the scenario.

*Inter-arrival time*: This is the time between consecutive work items arriving to the system. I usually assume an negative exponential inter-arrival distribution for the consistent effect of the NGOs and Partnership. I assumed a negative exponential distribution rather than fixed times (like in my SD model), as the aim of this DES model was to consider how the scenario would be modelled from a DES modeller's perspective, rather than a direct translation from SD. A deterministic distribution is used for important NGO and Partnership events and the individuals to the system.

*NGO/Partnership event*: These are represented by work items arriving at their relevant entry points representing the current activity of the NGOs or Partnership.

*Activity Centre*: This refers to a node in the model that services work items that arrive,which takes a certain amount of time (the service time) before being released to their next destination. An activity centre can only service as many work items as it has servers, and so I assume infinite servers.

*Servers*: This refers to the number of work items which can be serviced at the same time in a queue. Infinite servers means that all entities are served immediately on arrival.

*Queue*: This refers to a node in the model where work items wait until there is a space to be serviced in their next activity centre. As I assume infinite servers, no work items will have to queue but the nodes have still been used to improve model performance.

*Service time*: This is the time that a work item stays in the activity centre while it is being serviced. I assume exponential service time distributions (for the same reasons as in the inter-arrival time case) or instant service (0 service time).

*Opinion State*: Some activity centres in the model represent opinions that individuals can have about the proposal. These are referred to as opinion states. The service time at an opinion state represents the time the work item keeps that opinion before re-evaluating their position (and possibly changing opinion state).

*Decision Point*: When a work item finishes its service time at an opinion state it enters the decision point. This is where the work item decides whether to keep its current opinion for a while longer, or change its opinion.

*Label*: These are used to keep track of work items that represent different parts of the community demographics. Typically I track the community the work item originates from, whether they have knowledge of the process and their last opinion state.

*Knowledge*: If a work item has knowledge of the process, it is assumed that all individuals contained within the work item feel they 'know at least a little' about the siting process.

### 6.2.3 Aim

As in my system dynamics model, I aimed to explore the use of discrete event simulation as a modelling tool for public response. I explored the same process as in my SD model, with a focus on comparing how introducing probabilistic components to the system has affected modelling accuracy, structure and plausibility. I modelled the support or resistance to the government siting proposal each week over the four year period. However, due to the lack of data available for each community council's opinions over the period, and difficulty validating the council votes in my SD model, I decided to not include this in my DES model. I note that in the future it may be possible to include council votes if I are able to collect more information about the support and resistance within the community councils over the period.

I modelled how the public changed between different opinions of the proposal using a dynamic probability distribution. Each opinion had a base probability assigned to it according to the current activity from the NGOs and Partnerhip, support of the proposal and government trust. Unlike with flow rates in my SD model, changing this probability distribution had a much slower impact on the model. This is because individuals are not immediately affected by changes to the probability distribution, but only after they decide to change their opinion. I also included the events documented by the MRWS Partnership and NGOs as I did in the SD model. However, my DES model has the potential to include random events. This makes it more flexible for future predictions when there are more unknowns. For example, when I are uncertain about the number of events the NGOs will organise in response to the government proposal.

In summary, my DES model was constructed from the same basis and data as my SD model. Nevertheless, I have included more flexibility and stochasticity for events and how individuals react within the system. Primarily, I aimed to explore whether the introduction of more stochastic elements was a significant improvement over my deterministic SD model. In particular, I modelled the scenario where the MRWS Partnership were allowed to continue operation past the extension request. While my secondary aim was to contrast my two models to explore suitability for modelling public response.

### 6.2.4 Model Introduction

I represent the population moving around the system with work items. These enter the system through an arrival point. They are then serviced by activity centres according to the service time distributions. Each work item has a list of labels associated with them to describe differences between sections of the population (for example if the work item has gained knowledge of the process). These labels allow work items to respond differently to the current situation according to their characteristics stored in the labels.

#### 6.2.4.1 Arrival Points

Arrival points are used in two ways for my model: the initial batch arrival of the population for each community (with no more arrivals after), and for the arrival of NGO and Partnership events. For the arrival of the population to the system, I allowed all work items to enter the system through their corresponding arrival point (where knowledge of each work item is randomised) at the start of the simulation. This is a fairly simple application, and these arrival points become irrelevant after the start. More interestingly, I have used arrival points to model each type of NGO and Partnership event. These arrivals follow a strict schedule of when the events occurred during the MRWS siting process. However, it is simple to allow these events to arrive at random intervals according to some specified distribution. This means that the model can be generalised trivially should the model be used for future predictions where, for example, the NGO activity is unknown.

#### 6.2.4.2 Queues

Queues are used several times in my model. However, they have little functional value. They have been included between some activity centres and arrival points to allow hidden variables to be updated in a simple way. In particular, it allows easier construction of visual logic between transitions, and so can slightly improve run-time.

#### 6.2.4.3 Activity Centres

Activity centres were the backbone of my model where work items spend time according to a specified distribution. This is both where work items reside over the 4 simulated years, and where they make their decisions. I have included two basic types of activity centre: instant activities and timed activities. The instant activities have a service time fixed to be 0. These are primarily used to make changes to work items, or route them according to the hidden variables within the model. Timed activities consist of the opinion states (where the time spent represents the time between considering change of opinion), and the NGO and

Partnership events (where time spent represents how long the event has an affect for). The service time distributions for the opinion states change relative to the current activity of the NGOs and Partnership.

#### 6.2.4.4 Labels

Labels are used throughout the model to denote the history and demographics of individuals in a work item. These factors are important in describing aspects of their behaviour. Introducing more flags would increase the realism of the model, but also make the model far more complex and difficult to validate.

*Community*: Describes which community the work item originated from. It is set at the community reservoir on exit.

*Knowledge*: Describes whether or not a work item has knowledge of the process. On model initiation, an initial proportion of work items are set to 1 according to community (has knowledge). The proportion of each community that had knowledge of the process was defined as the respective value from Tables 4.1 to 4.3 for the first survey. All other entities are set to 0 and may gain knowledge through travelling to the knowledge node.

*Last opinion*: This shows the most recent opinion state the work item visited. It is set when an individual considers a change of opinion and leaves their current opinion state.

*Event type*: This label is only used for NGO and Partnership events to denote the type of event. This is used to specify the events service time and affect on current activity.

### 6.2.5 Assumptions

As in my system dynamics model, I needed to make certain simplifying assumptions of the real world scenario. Here, I explore the general assumptions that were made when constructing the model.

**Assumption 1**: Individuals contained in the same work item share the same stochastic process.

This assumption is to allow me to group individuals together and have people move around as batches, which was required for more realistic simulation run-times. While this means I cannot follow specific individuals through the process, I can follow a smaller group of people that are assumed to have the same thoughts on the process. Despite this batching, there is still all the different behaviours demonstrated within the model as I have roughly 5000 of these batches of individuals in the model. Additionally, initial testing done by the modeller, and checked by the first expert in Table 4.5, to ensure that the batch sizes did not

have a significant impact on results. The only cause of concern would be groups that are too large (resulting in very variable behaviour between scenarios), however for the chosen group size, the results were stable.

**Assumption 2**: Individuals cannot change between work items.

Similarly to assumption 1, this was included to simplify my batching of individuals.

**Assumption 3**: Each work item (and so individual) can only be in a single opinion state at a time.

Similarly to my system dynamics model, I must assume that each individual can only hold a single opinion at a time. My opinion states are based off the MRWS Partnership's categorisations in their opinion surveys, and so while more opinion states would improve accuracy, they would be far too difficult to validate at this stage.

**Assumption 4**: An individual cannot change between communities mid-simulation.

Just as in the system dynamics model I assume that there are no movements between communities. While not strictly necessary for a DES model, it improves the parsimony of my model greatly.

**Assumption 5**: A work item (and so individual) cannot lose knowledge of the process.

While this assumption was not strictly necessary, it followed the trends I observed from my data and so was included for the sake of parsimony.

**Assumption 6**: There is no random error in reporting the support for or against the proposal (although it may be time-lagged).

Here I have introduced another minor point of simplification to keep the model parsimonious. Any intentionally misreported numbers are another issue entirely that I will not be investigating in this model.

**Assumption 7**: Work items cannot enter the Neutral state if their last opinion state was not Neutral.

This behaviour was also included in the system dynamics model. It allows for a more parsimonious model, and the survey data showed that the number of people with a 'Neutral' stance only declined throughout the process.

**Assumption 8**: Work items (and so individuals) are only influenced by the current support/resistance in their own community.

This assumption was included to introduce community-based feedback, although I also explore the model where this assumption has been relaxed.

**Assumption 9**: Service times for opinion states and non-scheduled inter-arrival times have an exponential distribution.

From this point of view of a DES modeller, this was a natural assumption to make, due to the memoryless property of the exponential distribution. I would naturally assume an event causes an individual to consider changing opinion and that event would happen regardless of previous events.

**Assumption 10**: Work items travel between nodes instantly.

Again this was a natural assumption for a DES model, as individuals would not take a set time between deciding to change opinion and actually changing opinion.

### 6.2.6 Simulation Specifications

I simulated the public deliberations for 4 years starting from the 1st of February 2009. The time unit used was 1 day, which differed from the SD model to allow more control over event timings. The opinion weights for each community were updated every 7 days, and those weights were used for the following 7 days until the next update. At present, each work item represents 100 individuals from that community to improve simulation speeds. The number of arrivals to the NGOs/Partnership/Incidents at one time represents the relative significance of the event at that time.

### 6.2.7 Conceptual Model

Before construction of the simulation model in my chosen software, a conceptual model was created from the model assumptions, requirements and plans. This is to understand how the different components of the model interact with each other, and provides a presentation of the basic model logic that will be included. The conceptual model was constructed off the same 5 opinion state base that the SD model was built off.

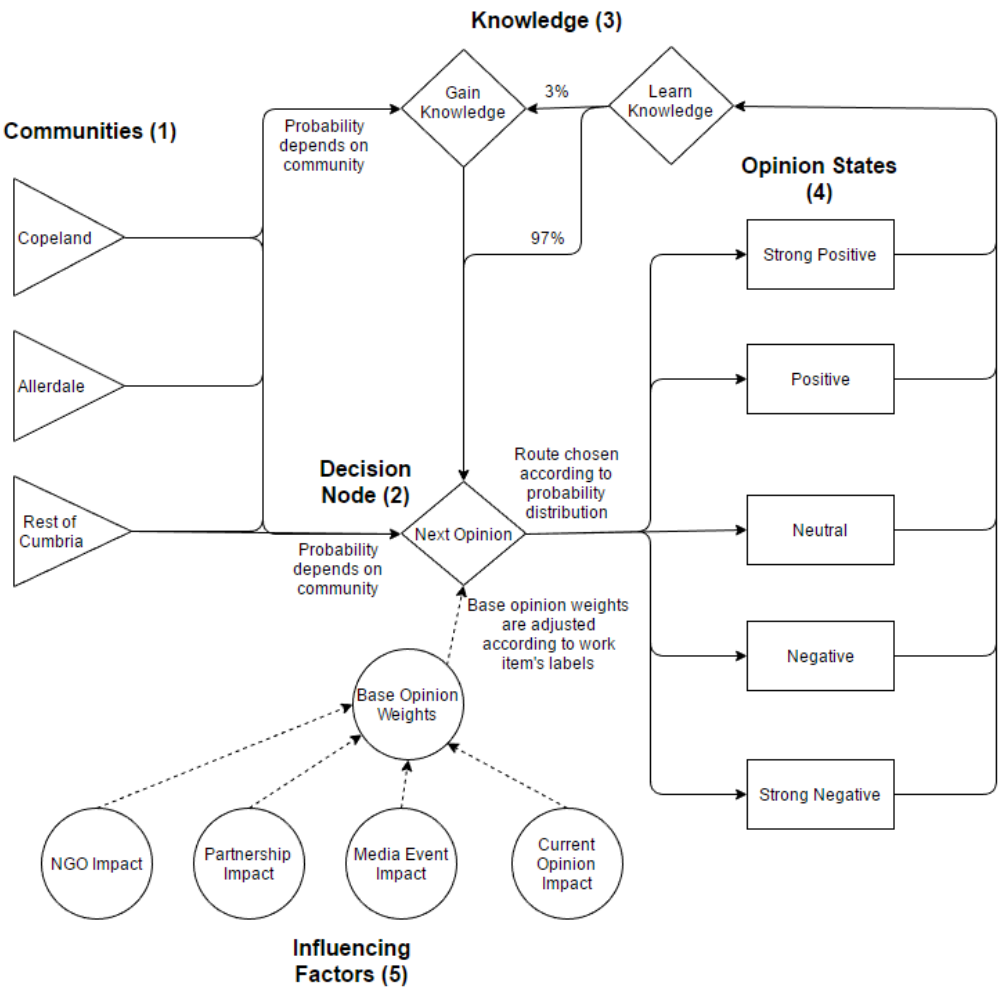



Figure 6.1: This shows the conceptual model, with labels for each major section explained below (given in the dashed boxes).

(1) Each community has a corresponding arrival point that has a restricted number of maximum arrivals it can provide according to the community population. The work items leaving these arrival points have labels set according to their origin community and whether they start in the simulation with process knowledge.

(2) When work items arrive at the decision node they move on to an opinion instantly because they have a fixed service time of zero. The work item moves to an opinion state according to a probability distribution dependent on the current base opinion weights the model and the work item's labels. This node has the most complexity of any node in my model, as it allows different behaviours for the different labels I use.

(3) When a work item decides to gain knowledge, they proceed to the 'Gain Knowledge' node to have a flag set denoting this change in behaviour. Each time a work item leaves an opinion state, there is a small chance they will gain knowledge of the process if they are not already knowledgeable. If they are already knowledgeable, they cannot gain additional knowledge.

(4) These opinion states are M/M/ activity centres. When work items arrive here, they are serviced for a random amount of time (according to an exponential distribution, which would be a natural selection from a DES point of view) until they proceed back to the decision node. When the work item leaves, its last opinion label is updated to the opinion state they are leaving and they have a small chance to become knowledgeable. A service time is higher when there is little activity from the NGOs and Partnership.

(5) These four nodes represent current activity of the NGOs, Partnership, any currently active media events (and governmental trust) and the current opinion distribution of the public. For NGOs, Partnership and media events, several types of activity are modelled that have a label according to the type of event which defines how much they contribute to current influence and the duration the influence is active for. These are combined with the current opinion distribution to update the base opinion weights according to the equations in Appendix C.

## 6.3 Model Creation & Coding

### 6.3.1 Software Description: SIMUL8

| Component Name | Symbol |
|---|---|
| Arrival Point |  |
| Queue |  |
| Activity Centre |  |
| Exit Point |  |

Table 6.1: Legend for model component symbols used in the SIMUL8 software package.

The four primary model components I used for my model are given above in Table 6.1. Alongside these components, Visual Logic was used to make the model more flexible and enable dynamic behaviour. Full details of the visual logic I included has been given in Appendix C.

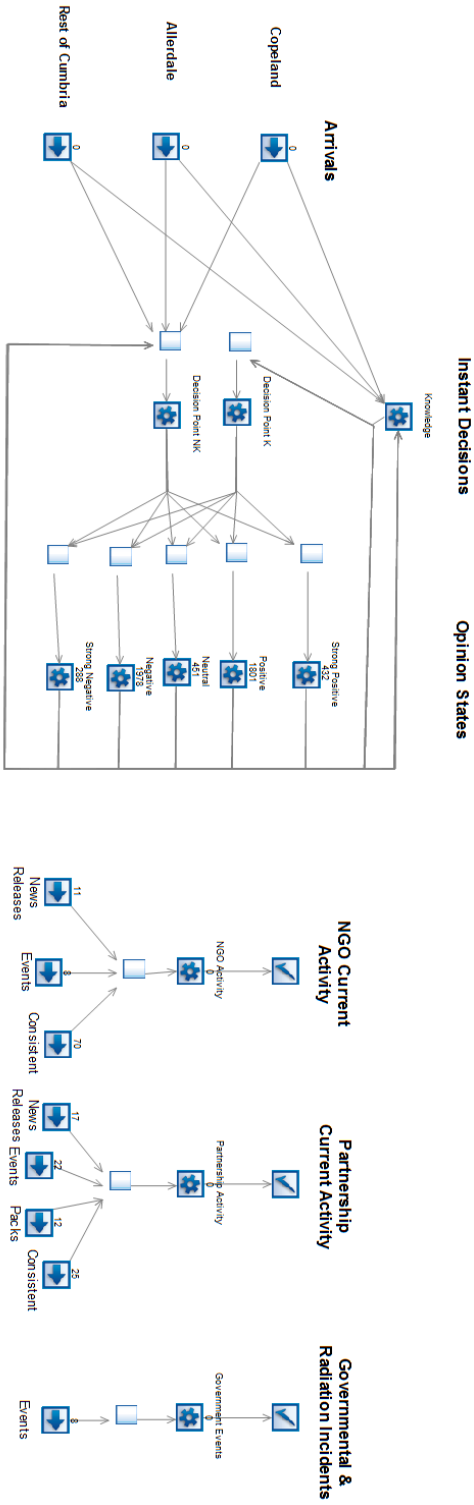



Figure 6.2: Layout of the SIMUL8 model. The thicker routing lines do not represent any difference to thinner lines. The consistent nodes for both the NGOs and the Partnership represent a consistent increase in their influence over time (using an exponential distribution for inter-arrival times)

Figure 6.2 shows my current model, constructed in SIMUL8, for the public response to siting a GDF in Cumbria. This model follows my initial model plans quite closely, but there are significant portions of the model that are contained within the visual logic, which can be found in Appendix C. In particular, the current activity for the NGOs, Partnership and government incidents have very strong impacts on the probability distribution used for routing from the decision points. Each of these are used to calculate the current weights of the opinion states for each community. These weights are then used to calculate the routing probabilities from the decision points, taking into account the label values of the work item (multipliers are applied to the weights according to the label value). Also keep in mind that every work item in the Opinion States represents 100 like-minded individuals.

### 6.3.2 Model Construction

While this section contains information on how the model was constructed, I do not give specific details of every element of the model. However, Appendix C contains a detailed description of every important node included in the model.

#### 6.3.2.1 Opinion Weight Variables

To introduce feedback into my model while taking into account the current events of the system, I decided to use base opinion weights for each of the opinion state. These base opinion weights are to some extent like the base flow rates that were introduced for my system dynamics model. Each community has an opinion weight for each of the five opinions, totalling 15 weights for all three communities. These reflect how visible the overall support for each opinion within the community is to the rest of the community according to the current events. For example, when the NGOs are more active than the partnership, the negative opinion weights receive slightly higher 'event scaling' than the positive opinion weights. Each of the opinion weights would also be scaled by the current government trust.

These opinion weight variables were updated every week and only change at the end of the week. This means that the opinion weights were fixed for each week according to the events active in the model at the start of that week. Ideally, I would update this whenever an individual arrives at the decision point to change their opinion but this would be far too costly for the simulation. The scaling factors I used here were based off the same literature my system dynamics model used, and calibration according to the survey results from the MRWS Partnership. For example, the 'Strong' opinion weights were defined the same as the positive or negative opinion weights, with an additional scaling constant to represent less people holding these stronger opinions in the surveys. The DES model was designed in

this way, as it was a more natural way to model the scenario in DES, from the perspective of a DES modeller, rather than the opinion movements of my SD model.

#### 6.3.2.2 Time-check Logic

As mentioned before in Section 6.2.6, the opinion weights were updated every 7 days and that update is done through the time-check visual logic in SIMUL8. This repeated a set of commands every 7 days. The details of the opinion weight updating, constant values, and other updating rules can be found in Appendix C. Alongside the opinion weights, other variables were also updated on this time cycle. For example, the measurement of government trust was slightly altered from its previous value, and the relative NGO and Partnership activity were stored. Results were updated in an in-built spreadsheet, and finally the service time distributions were updated for each of the opinion states. As mentioned previously in the chapter, these service time distributions were all exponential, and so the parameter of this distribution changed on each time-check. Each opinion state had a defined constant for the exponential parameter, which may be scaled by the current NGO and Partnership activity. These constants were derived from the literature and calibrations of the model to promote realistic behaviour.

In particular, if the NGO and Partnership were inactive, the parameters remain at the constant level. However, if there was a large amount of NGO and Partnership activity, then the service time distribution parameters were reduced according to the amount of activity. This was done to promote more uncertainty for individuals as the process continues (as the NGOs and Partnership are becoming more active), making individuals visit the decision point more often later in the process. This behaviour was supported by the MRWS Partnership survey results, which suggested individual activity increases as the process progressed. The precise definition of the service time distribution can be found in Appendix C, although the amount of time between arrivals tended to be, on average, between 1 change every 3 months (late in the process with high engagement) to 1 change every 1.5 years (early in the process with low engagement).

#### 6.3.2.3 Decision Node

The decision node was where much of the model complexity was contained. When a work item arrived at the decision node, they must make a decision on whether to change their opinion. This decision was made according to a probability distribution that is derived from both the current labels of the work item, and the current opinion weights of that work item's community. This adjustment to the current opinion weights were made according the work item's labels, so that each probability was better characterised to each work item's current

circumstance (e.g. knowledge level, last opinion). In summary, when a work item decides to change opinion, the current base opinion weights are noted, and then adjusted according to the work item's situation to create the probability distribution used to select the next opinion state.

The work item's labels adjusted the base opinion weights as follows: the community label was used to select the correct base opinion weights for the work item's community. The knowledge label was used to scale up the positive base opinion weights by 25%, if the work item was knowledgeable, else it increased the negative base opinion weights by 25% (this change is supported by the MRWS survey data). The last opinion label was used to increase the chance that the work item stays in the same opinion state they were last in. As time progresses, the chance that a work item remains in the same state decreases. This was to represent that individuals would get more involved with the process as time went on.

### 6.3.3 Feedback

Feedback played a significant role in determining the base opinion weights in my DES model, but the feedback loops were simplified slightly for this modelling paradigm. In particular, the only feedback loop is between the opinion states and the base opinion weights. This feedback loop is self-reinforcing, and applies to all opinion states, and is shown in Figure 6.3.

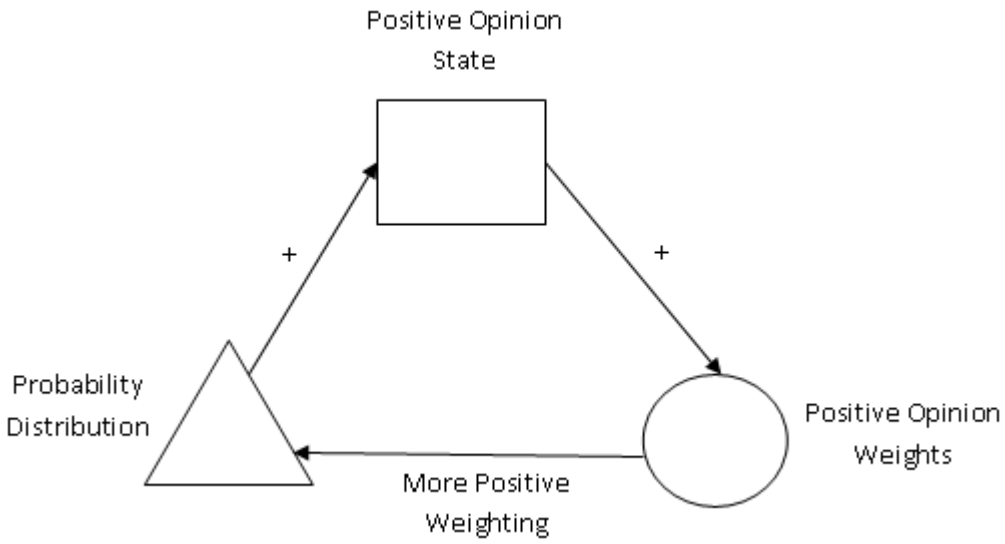



Figure 6.3: Simplified feedback diagram showing the self reinforcing effect of a positive feedback loop.

There is also another difference between feedback in my DES model and my system dynamics model. The DES feedback has no delay, while the system dynamics feedback loops could have delays of up to several months. While it would be possible to implement delay, it would be far more expensive than it was in system dynamics, as SIMUL8 is unable to access previous values of a node directly. This does impact the performance of my DES model slightly as it makes the public more responsive to changes in opinion, although this has not had a noticeable detrimental effect on my results.

### 6.3.4 Model Validation

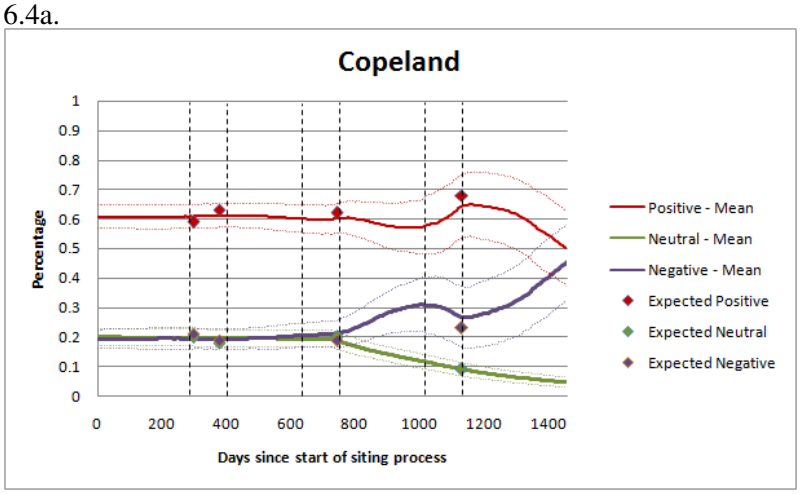
As in my SD model, I have conducted thorough validation tests for my DES model with respect to the purpose of prediction of public opinion. Some examples of validation and verification methods can be seen in Sargent (2013), Law (2008) and Wang & Lehmann (2007). I have conducted thorough sensitivity analysis and bounds testing to ensure the model remains realistic for less predictable circumstances. Additionally, analogous validation steps to those used for my SD model (Section 5.4.1) were conducted where possible, as seen in Appendix D.

### 6.3.5 Initial Results

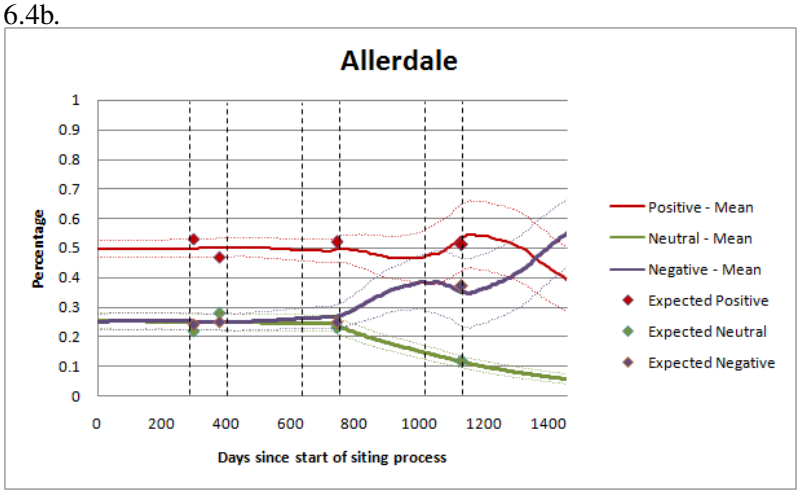
This model has used the same data that was used for my system dynamics model, so for an analysis of the data used for model calibration see the relevant section in Chapter 5. I decided to exclude the council from my DES model due to the difficulty in validating behaviour. As for my previous model, minor calibrations were made so that the model can more accurately reflect the data collected by the MRWS Partnership. This calibration was less strict due to the inclusion of stochastic components than for my SD model. I also used rough 95% confidence intervals for each of my objects of interest. The assumption of a normal error at each time point (not over the entire time interval) should not be unreasonable. I repeated the simulation 100 times, which was deemed sufficient (when considering the variability of the system) to produce suitable 95% intervals. A confidence interval such as this was not possible in my SD model due to the deterministic nature of the scenario (there is no variation between iterations).

My results in Figure 6.4 show variability within my model for the support and resistance for each community (although neutral was quite consistent). However, I expect this sort of variability from a system so dependent on feedback. Initial differences can have long-reaching ramifications, and the feedback effect can be amplified strongly in a probabilistic model. Despite this variability, my model showed consistent overall trends. The population actively responds to the NGO and Partnership activity, alongside pre-defined world events.

6.4a.




6.4b.




6.4c.

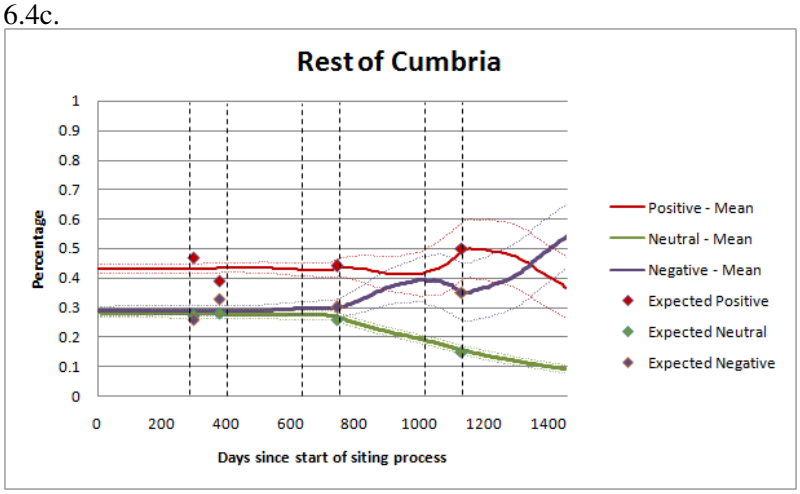



Figure 6.4: a, b and c show the public support for proceeding with the siting process over the 4 year lifespan of the proposal. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organise, and the diamonds show the survey results for that community for each of the four surveys.

Even if the same siting process was repeated under similar circumstances, the result may still be a rejection the vast majority of the time. This would imply that the deliberation structure is a primary determinant of public opinion in my model. Therefore exploring possible changes to this deliberation structure within the model could help users better understand the real world system and aid future planning of similar deliberation structures.

I are uncertain where the true mean of the process should lie in each community if the process was repeated many times, and so had to calibrate my model to the single repetition I had. Although this is a common problem where the process cannot be easily repeated. This means that my model has been biased by the previous process' results. So if public response from the previous process was a more extreme realisation of opinion than the norm, then this specific model would not be suitable for future predictions. However, I have explored the model's sensitivity to my defining constants, and in all cases similar responses are shown. Thus this model could still be used to plan future public deliberations, whose relative impacts are consistent, even if the past siting process was an extreme realisation of public response.

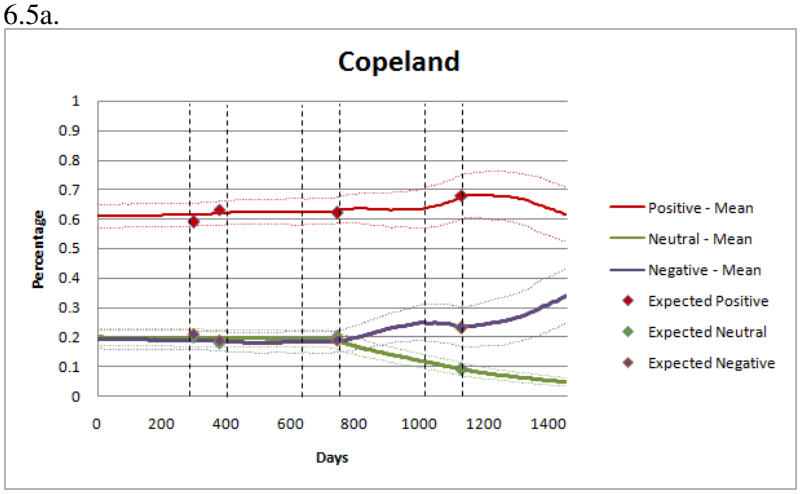
## 6.4 Experimentation

### 6.4.1 Sensitivity

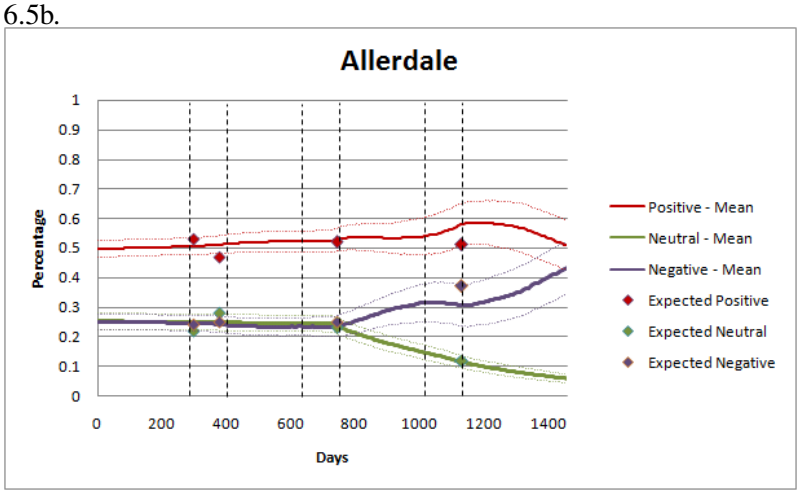
One question I may ask specific to my DES model would be: how does increasing and decreasing the number of decisions work items make impact the results of my model? I explored a similar question for my SD model when I asked how the model changed when individuals flowed through the states (and so changed opinions) at a faster rate. My base model had most work items arrive at the decision point roughly according to an exponential distribution with a mean of one year. Although this mean generally reduced throughout the 4 year process according to the current NGO and Partnership activity. I explored the change in behaviour when the base exponential mean was increased to two years (halving the average number of decision points), or decreased to a half year (doubling the average number of decision points). I call these two cases slow and fast opinion changes respectively.

#### 6.4.1.1 Slow Opinion Changes

6.5a.




6.5b.




6.5c.

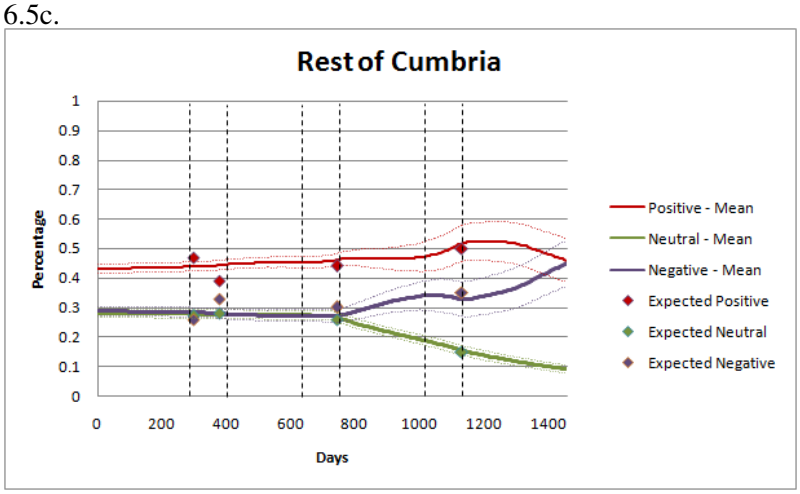



Figure 6.5: a, b and c show the public support for proceeding with the siting process over the 4 year lifespan of the proposal for slower opinion change. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organise, and the diamonds show the survey results for that community for each of the four surveys.

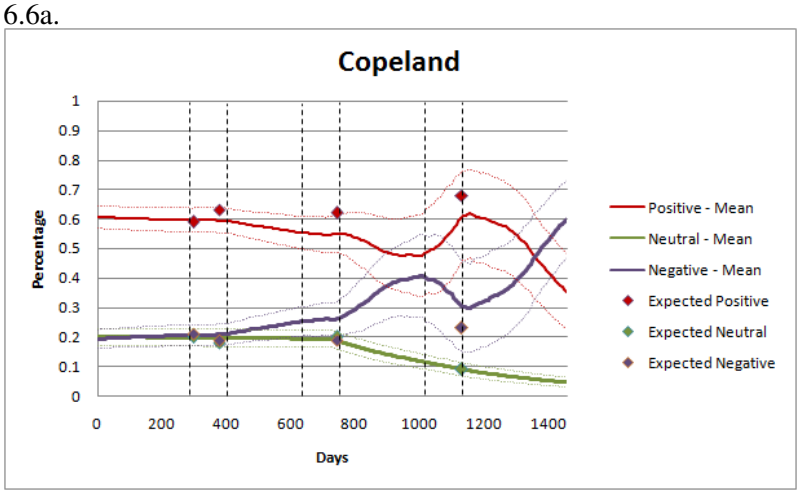
I first explored how behaviour changes when individuals took twice as long to make a decision about changing their decision. In this case, the base exponential distribution had a mean of roughly 2 years (those holding a positive/negative state have a slightly lower mean than those holding stronger views). This distribution was still altered dependent on the current activity of the NGOs and Partnership resulting in individuals taking generally less time between decision points as the process continues. My results are shown in Figure 6.5.

I can see that my model has been quite sensitive to increasing the time between decision points. The public in all three communities now change their opinions far less quickly and are much less responsive to current events. In the final year of the process I can see some changes in opinion, particularly in increasing resistance to the proposal. Although, even for the 'Rest of Cumbria', the final support and resistance percentages were very similar (resistance to the proposal was increasing). The main reason to increase the time between decision points is to improve model runtime, however this is at the expense of reducing the public's sensitivity to key drivers of opinion change. I concluded that, while I see similar trends to my original model, increasing the time between decision points for individuals within the system has reduced the sensitivity of my model far too much. Smaller increases could be considered, but there would be little benefit to doing this as run time of the model would not improve substantially.

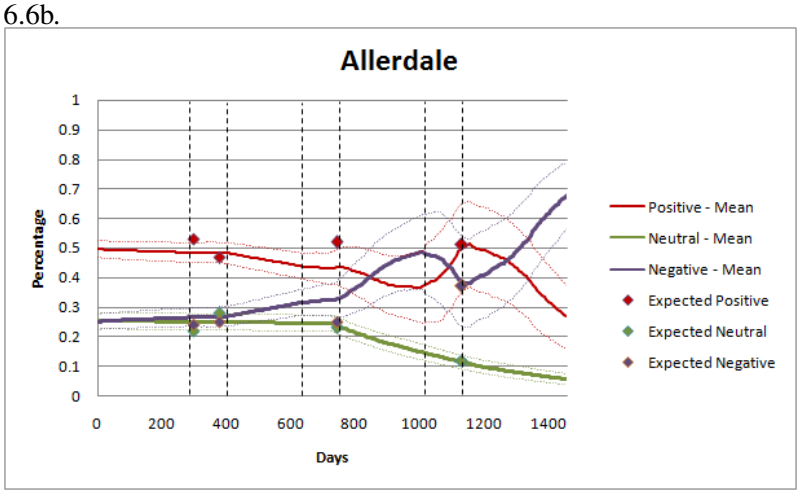
#### 6.4.1.2 Fast Opinion Changes

From my exploration of slower changing opinions, I asked the question of whether faster changing opinions could help improve model accuracy at the cost of model runtime. To explore this, I reduced the time between decision points to be sampled from base exponential distribution with a mean of 6 months. As before this mean is adjusted according to the opinion state they enter, and the current NGO and Partnership activity within the model. In this case, I would expect individuals in the system to be far more sensitive to current events such as the lulls in Partnership activity between stakeholder engagement periods. My results are shown below in Figure 6.6.

6.6a.




6.6b.




6.6c.

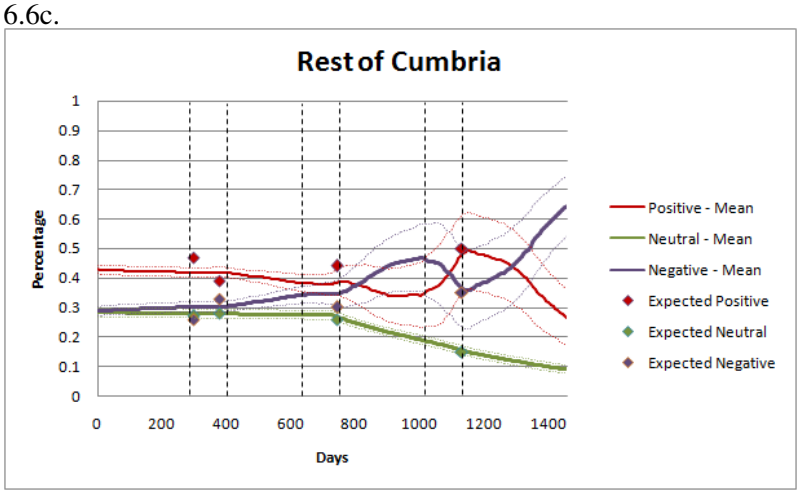



Figure 6.6: a, b and c show the public support for proceeding with the siting process over the 4 year lifespan of the proposal for faster opinion change. The vertical dashed lines indicate the start and end point of each stakeholder engagement period the partnership organise, and the diamonds show the survey results for that community for each of the four surveys.

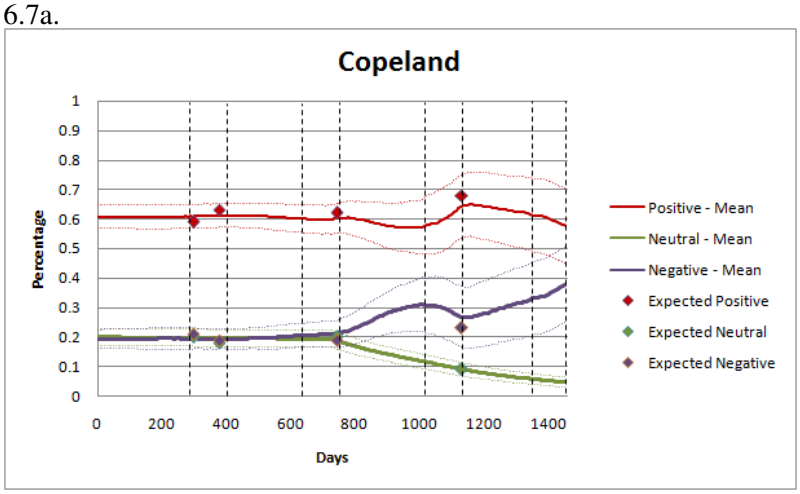
These results confirmed what I might have expected: that individuals change their opinions far quicker and are much more sensitive to current events. This seems to have the biggest affect between PSE1 and PSE2 where support is declining for all communities due to the activities organised by the NGOs when there is very little Partnership presence. However, the most variable part of the process is the time between Fukishima (after PSE2) and when the decision deadline extension request (after PSE3). This period showed the largest deviation between repetitions because of the strong feedback effect coupled with individuals in the system being far more sensitive to change. However, during the final few months the deviation of results starts to significantly decrease due to the very similar trend being shown in each run of my model.

If I was to decide to reduce the time between decision points in this way, I would also need to be careful to increase the chances of an individual keeping their current opinion. This would allow my model to simulate individuals being far more pro-active about updating their current beliefs of the siting process, while ensuring individuals are not changing opinions rapidly for the entire duration of the process. The comparison of these two adjustments suggests the question of including more individual differences between individuals. Some members of each community would seek information about the siting process actively and would be best modelled by the faster opinion change system, while others could demonstrate very little interest and so would be better represented by a slower opinion change system. This style of modelling would be possible in a DES model such as this, but would be best suited to an agent-based model. This would be a model I would like to pursue should I be able to collect more data on individual responses rather than large-scale survey results of overall support.

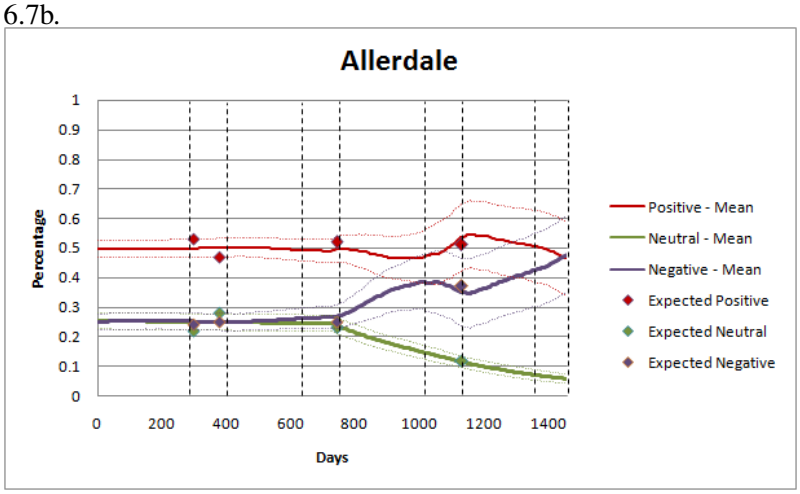
### 6.4.2 Deadline Extension

As in my SD model, I asked the question of whether the deadline extension near the end of the siting process had unfairly biased the final vote. My SD model showed that, had the Partnership been allowed to continue their activity and enter a fourth stakeholder engagement phase, PSE4, then the outcome may have been more positive. In particular, while support was not growing for the proposal, its decline had been reduced considerably. This would have significant impacts on the council's final vote as they would be under less pressure from the now relatively stable public (although the councils were not directly modelled in the DES model due to difficulty in validation of results). I considered the question: does this behaviour still happen in my DES model? I leave the discussion of the differences between my SD and DES models to Chapter 7.

6.7a.




6.7b.




6.7c.

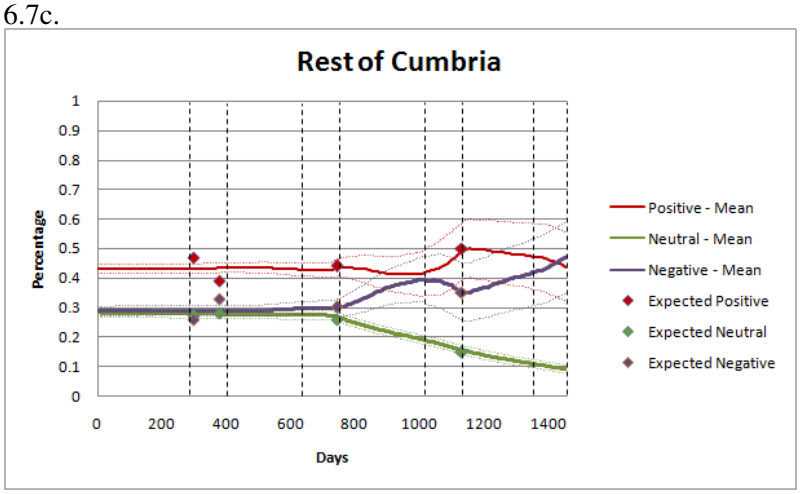



Figure 6.7: a, b and c show public support for proceeding with the siting process when the Partnership is allowed to continue operation after the deadline extension. Vertical dashed lines indicate the start and end points of each stakeholder engagement period, and diamonds show the survey results for each of the four surveys.

To test this question, I modelled the partnership continuing their activity past the deadline extension and entering PSE4 as I defined for my SD model. To keep comparability between my models, I defined PSE4 for my DES model similarly to in my SD model by keeping partnership activity and events consistent between models. The key factors I looked for to answer this question was how public opinion changed near the end of the process, in comparison to the results shown in Figure 6.4. In particular, I are interested in the differences in the last several months of the process (as the behaviour in early years of the process has not changed). These results are shown in Figure 6.7.

The inclusion of PSE4 has had a positive affect on public opinion in comparison to the baseline scenario shown in Figure 6.4. My SD model showed that PSE4 held public support steady at the end of the process. However, my DES model showed that resistance grows even with PSE4. Despite this, I can still see that the increase in resistance is far slower than in my original model, seen in Figure 6.4. These difference likely stems from how PSE4 was defined in each model (for example general NGO activity grew faster in my DES model nearer the end, while my SD model had a more consistent high activity state for the NGOs), and from the differences between individuals behaviour. Including PSE4 in my SD model had a forced impact on the number of people in each stock, whereas in my DES model the difference is only felt by those that considered changing their opinion during the last few months of the siting process. If I allowed a faster change of opinion, as seen in Figure 6.6, then I see more similar behaviour to my SD model.

## 6.5 Understanding and Conclusions

### 6.5.1 Discussion

First, I consider my DES model independently of my previous SD model. The model seemed successful as a predictive tool. For instance, my model was well calibrated against the available data, and follows expected trends (different expected trends were explored when validating the model, e.g. world events, starting opinions, NGO activity structures, moving the deadline extension request, etc). However, the purpose of my model is as a tool to help structure public deliberations. In particular, I can identify specific trends within the model. For example, Fukushima, the stakeholder engagement periods and when the Partnership stopped operations. This allows potential users of the model to explore public deliberation structures that are particularly robust to uncertain or unexpected events. Potential users could also identify weaknesses in current deliberation structures. For instance, the deliberation structure may be unsuitable for areas with low support. My model could be used as a preliminary analysis tool to explore issues when designing public deliberations.

If I now compare my DES model to my SD model, I see that there is more individuality within my DES model as might have been expected. This is key in building user trust, as they can begin to see how individuals within the model change their opinions over time and the key factors that influence them, as opposed to the more abstract view of my SD model. The ability to see individuals in this way was a key suggestion by the experts given in Table 4.5 when validating my SD model, even if it would have no real benefit on the model's ability to represent the siting process. However, that is not to say that my DES model is entirely individualised. Unfortunately, I lack enough data to validate building more information into the model to represents different behaviours within the communities.

### 6.5.2 Contributions

#### 6.5.2.1 DES modelling

While discrete event simulation is often focussed on processes rather than systems, this chapter has sought to apply a DES model to a more systems focussed thinking. Translating a SD model naturally brings more of a focus towards the system aspect of the scenario, and this Chapter has combined and adapted this aspect into a DES framework. For example, moving a stock representation into the queue in a DES model, or the addition of stochastic elements into a previously deterministic model.

Additional contributions are made to DES by adapting some of the principles behind Bayesian networks into the probability calculation. In particular, the probability distribution that individuals use to choose their next opinion is being consistently updated as new information becomes available, resulting in significant feedback loops. This also opens to door to more types of hybrid modelling that can be considered. For instance, it would be relatively simple to include a Bayesian network as a sub-model to update these probabilities. Implementing this style of hybrid model would allow additional validation methods. Some of these methods are discussed in Chapter 8.

#### 6.5.2.2 Opinion Dynamics and Nuclear Siting

The other main contribution from this chapter is in the areas of Opinion Dynamics and Nuclear Siting. The definitions behind how the probabilities are updated each week is based on an array of literature, past data, and media information. The probability updating rules therefore contribute to a better understanding of how public opinion can shift with both external (e.g. media & NGOs) and internal (word of mouth) factors to the community. This is particularly valuable for nuclear siting, allowing better planning of future public deliberation processes.

# Chapter 7

# Modelling Paradigm Comparison

## 7.1 Introduction

In Chapters 5 and 6 I introduced my two models used to explore the MRWS facility siting process relating to objective 3. These used the system dynamics paradigm (deterministic model) and the discrete event simulation paradigm (probabilistic model). Both these models provided promising results and could potentially be used to assist planning a public deliberation structure in the future. However, my fourth objective leads me to ask two important questions: which model is more suited to this scenario and what are the primary differences between the two modelling paradigms?

The first question is concerned specifically with my models, rather than the general paradigms: which model is more suited to this scenario? I introduced a scale for five relevant characteristics to compare each model against. These characteristics included: construction, flexibility, ease of use, validation and complexity. Each characteristic was ranked on a 1 to 5 scale, with 1 representing the lowest value. See Section 7.3.1 for a comprehensive analysis of these five characteristics. I also considered how the model adapted to different scenarios, for instance if Fukishima had not happened. These scenarios are explored in Section 7.4. I finally offer my own suggestions taking these aspects into account in Section 7.5.

My second question was a more general question for the paradigms as a whole: what are the primary differences between the two modelling paradigms? As such, I applied my characteristics scale for the first question to a much wider spectrum of scenarios and applications. In particular, I considered the benefits and drawbacks of each paradigm in common applications, such as process management and logistics, rather than just public deliberations. When exploring the impact of different scenarios on my MRWS siting process application, I also considered how any differences between the paradigms that were highlighted could affect

more general modelling with the paradigm. Alongside this, I provide commentary throughout the chapter on differences between the paradigms, and issues that can arise from these differences.

The rest of this chapter is structured as follows. Section 7.2 reviews the literature comparing the SD and DES paradigms, along with some considerations of agent based modelling and hybrid modelling. Section 7.3 provides an overview on system dynamics and discrete event simulation, along with comparisons between the two paradigms. Special attention is paid to how the scenario was represented in the paradigm. Section 7.4 explores how each paradigm reacts to several different scenarios, and explains the differences between these reactions while providing some general observations. Section 7.6 discusses extensions and improvements of my current models. Finally, Sections 7.5 and 9 state my conclusions and suggestions for use of each modelling paradigm.

## 7.2 Literature Review

### 7.2.1 System Dynamics and Discrete Event Simulation

Both System Dynamics and Discrete Event Simulation have a long history, as seen in Chapters 5 and 6, however have largely developed independently. Understanding where each paradigm has traditionally been used, and opinions of the benefits and weaknesses of each provides strong foundation for the comparison in this Chapter. This allows more focus on the modelling differences experienced for this specific scenario, rather than the more general differences between paradigms (although there is some discussion of experienced differences on a paradigm level).

Much of the comparison of the literature has been done in the past 2 to 3 decades, which falls in line with the increasing interest in hybrid modelling shown in Chapter 7.2.2. Mak (1992) suggests in his Thesis that often the choice of modelling technique depends on the modellers preference and technique rather than the nature of the problem. However, ideally the paradigm chosen should depend on which is best for the problem being modelled.

Some of the key differences between the modelling techniques are discussed in Sweetser (1999). When only considering the definitions of the two paradigms, some major differences are identified: SD is focussed mostly on systems modelling, with a preference towards continuous processes, while DES is focussed more on discrete processes. The writer does not that these are only the overall expectations of the paradigm, and each is flexible enough to model situations outside of these generic expectations. The author also discusses SD's strengths for high feedback scenarios, which the paradigm is ideal for (although DES

can also model these scenarios).

A comparison has been done by Morecroft and Robinson (2005) of a DES and SD model being produced independently to model a fishery. They first discuss comparisons made by other authors such as Brailsford & Hilton (2001), Mak (1992) and Lane (2000). They then discuss the iterations of the produced SD and DES model and compare the evolution of these models. The main conclusions are that the models can provide complementary insights and that more should be done to consider using multiple modelling techniques, or focussing more on the specific insight required. This view is supported by Hoad & Kunc (2015). Lane (2000) provides a comparison between DES and SD for 8 different modelling aspects. This is presented in Table 7.1. Tako & Robinson (2009) have conducted a more empirical study exploring a similar question to Morecroft and Robinson (2005).

| | **DES** | **SD** |
|---|---|---|
| *Perspective* | Analytic, emphasis on detail complexity | Holistic, emphasis on dynamic complexity |
| *Resolution* | Individual entities, attributes, decisions and events | Homogenised entities, continuous policy pressures and emergent behaviour |
| *Data sources* | Numerical with some judgmental elements | Broadly drawn |
| *Problems studied* | Operational (?) | Strategic (?) |
| *Model elements* | Physical, tangible plus some information | Physical, tangible, judgmental and information links |
| *Human agents* | Decisions | Policies |
| *Clients find the model* | Opaque, "dark grey box": convincing | Transparent, "Fuzzy glass box"; compelling |
| *Outputs* | Point predictions, performance measures | Understanding of structural source of behaviour modes |

Table 7.1: Comparison of DES and SD provided by Lane (2000). Taken from Morecroft & Robinson (2009), page 15.

### 7.2.2 Hybrid Modelling and Agent-Based Simulation

Hybrid modelling (occasionally called multi-paradigm modelling) received some attention for more complex applications in the 90s and early 2000's. For example, De Azevedo et al (1997) highlighted some of the benefits they saw when comparing a hybrid modelling approach to a conventional approach when applied to biochemical processes. In particular they stated that hybrid modelling could be particularly affective when there is 'limited theoretical knowledge'. A more general introduction to hybrid modelling (and simulation

in general) is provided by Vangheluwe et al (2002), where they do particularly focus on its application to systems dynamics. They also introduce meta modelling which is another related area, but I have not explored in this literature review. More recently there has been a considerable amount of work done for hybrid modelling as it can be considered a natural next step for simulation as a whole (e.g. Chen et al 2013, Sadsad 2014, Shamim et al 2015).

Agent-based modelling also started to receive attention from academics in operational research during the 90s, although it has been an important area within computer science for a longer time. For instance, Kreft et al (1998) produced an agent based model for bacterial colony growth, while Schelhorn et al (1999) produced an agent-based model to investigate pedestrian movement in urban areas. This paradigm has been of particular interest to social scientists due to its clear parallel to modelling individuals (e.g. Gilbert & Terna 2000). For an introduction to agent-based modelling as a paradigm, see Macal & North (2005, 2009) or van Dam et al (2012). More recently it has been used for a wide variety of application (e.g. Macklin et al 2012, Murray-Rust et al 2013, Berger & Troost 2014) and has received increased attention, especially with regards to hybrid modelling (Cilfone et al 2015).

## 7.3 Modelling Paradigms

I have produced both a deterministic, and probabilistic model from system dynamics and discrete event simulation respectively. However, these were not the only modelling paradigms that could have been used. Another prime candidate for modelling change in public opinion would be to use agent based modelling (ABM). This would have the benefit of providing more individuality to entities in the model (see Macal & North 2009), and so would be more believable to outside users. However, this would also require more data than I had available to produce a suitable model (although a basic model would still be possible). Due to this limitation, I decided not to use ABM. Should more information become available (through surveys or expert judgements), an ABM model could be considered.

For my deterministic model, system dynamics was used. Modelling change of opinion and public deliberations was a less common application of the paradigm, and so I was careful with how each aspect of the system was going to be included. However, I hoped that the simple modelling of the feedback loops within the system (which is a major strength of SD, Sterman 2000) would offset the more complicated modelling for individuals. This was also the model that I constructed first and so many of the interactions, dependencies and feedback I identified for the scenario were specific to system dynamics. This may have introduced some bias into my DES model, as that was constructed from the same interactions

that I identified.

For my probabilistic model, I used discrete event simulation. After production of my SD model, I wanted to explore if introducing more stochasticity to my model would improve predictive power. I was also aware that I would be able to follow individuals as they travel through different opinion states. While feedback is less common (at least with how I was using feedback) in DES models, I included a strong feedback interaction with the base probability distribution for opinion state selection. However, I decided not to include time delay to drastically reduce model runtime (this would involved manually storing the information). I also took inspiration from my SD model for the general structure of my DES model, for both ease of implementation, and to allow simpler comparisons. Although other layouts could be just as suitable for my scenario.

### 7.3.1 Paradigm Comparison

To allow for easier comparison of the two paradigms, from my own perspective rather than those shown in Section 7.2, I made comparisons against 5 characteristics. These are construction, flexibility, ease of use, validation and complexity. Construction refers to how easy modelling my specific scenario was in the paradigm. Flexibility is concerned with how easily I can model different types of scenarios and systems with each paradigm. Ease of use compares how simple it is for newer users to alter the model, both for slight changes such a deliberation structure or more significant structural changes. Validation refers to how easy the model may be to validate. Finally, for complexity, I was interested in how much benefit is gained from constructing a more detailed model.

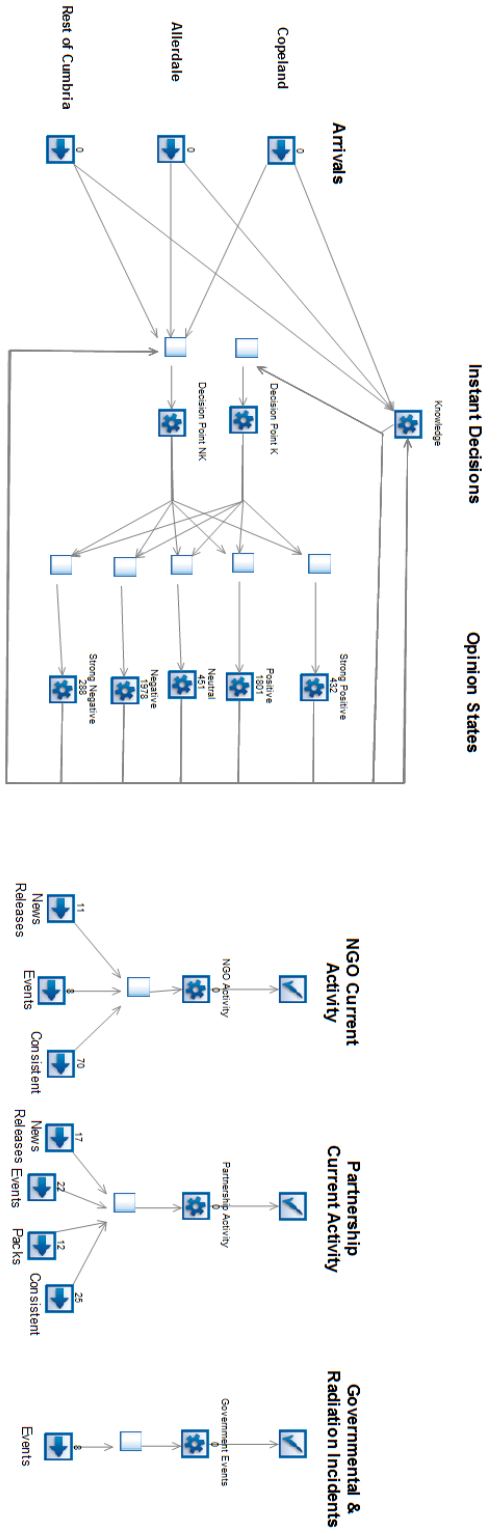



Figure 7.1: Layout of the SIMUL8 model. The thicker routing lines do not represent any difference to thinner lines.

However, I first consider some of the more general differences. In both cases, the model's predictive power could be heavily biased by the data used to construct it. In this case, a model's predictive power is its ability to predict qualitative behaviour, rather than quantitative outcomes, and so each model has been compared with this in mind. A deterministic model may suffer more from bias than a stochastic one due to the mitigation the inherent stochasticity of DES provides. In particular, I are concerned with my data falling within my confidence intervals for DES, but for SD I are attempting to more closely match the data. This can result in calibration being too specific. It is for this reason that model purpose is very important. The data bias would be less important in a SD model when the SD model is being used for exploration of different scenarios rather than prediction. Thus a DES model may be more useful for prediction than a SD model.

In terms of the differing behaviour of the models in my scenario, I found my SD model to be more sensitive to events than my DES model. This behaviour is likely observed due to the differences in how the SD and DES models were constructed, resulting in more direct impacts to stock levels in the SD model. While in my DES model, events alter a probability distribution for each of the opinion states rather than forcing a small number of individuals to change state. To have an effect in the DES model, it also requires individuals to consider changing opinion during the event, which is not always be the case. This can be seen as a different assumption in each model: SD assumes all individuals see all events while DES assumes individuals see events only when they change opinions. Ideally, my model would take an approach somewhere between these two extremes. Where events do not necessarily directly affect an individual, but they could reduce (or increase) the time until their next decision if the event opposes (or is in support of) their opinions.

#### 7.3.1.1 Construction

While I modelled my scenario in a similar way for both SD and DES, I certainly had more options for my DES model. I could easily include additional categories for individuals in the system, and different usage of Visual Logic would have allowed me to produce a similar model with an entirely different structure (for instance the base probability distribution being more directly incorporated into the model and individuals having a label for an opinion rather than an activity centre). With my SD model, incorporating these additional categories was very cumbersome, requiring additions to each of the community modules. However, SD allowed for easier uses of delayed feedback, which was quite inconvenient in my DES model. SD also had the benefit of the entire model being readily available with less happening 'behind the scenes', which was quite common in my DES model.

#### 7.3.1.2 Flexibility

From Chapter 6, it is clear that DES has become a widely used modelling technique, and so is generally considered to be very flexible. However, the difference in this category is in the original purpose of the paradigm. SD is associated with more aggregate flows between several states, which provide a good high-level summary for many systems. While SD has a strong advantage in this category, it is difficult to simulate lower-level systems due to being unable to follow specific items through the system. On the other hand, DES is designed for these more low-level systems, and can provide basic aggregate movement for higher-level views in the same model. So I can say DES is more flexible than SD, but the purpose of the model must be strongly considered when choosing a paradigm.

#### 7.3.1.3 Ease of Use

This category has two components: scenario changes and structural changes. In terms of scenario changes, DES has a clear advantage as (and commonly in other models) making a small change to the system is relatively simple. For example, altering arrival times of events involves updating an internal spreadsheet with the times and number of arrival. It is also quite simple to set up pre-defined scenarios that users can select. SD on the other hand is more difficult to build a user interface for to make such changes, although this may have been due to the way the SD model has been constructed. For structural changes, SD has the advantage as while you still need to understand the system well, it is clear to see the overall structure of the system. DES on the other hand has much of the structure contained within the visual logic which is difficult to link to the system without much experience. There is also a consideration to pay towards the modellers bias, as I was already slightly familiar with the SIMUL8 software before deciding to use it for the DES model, and so would have perceived the DES model to be constructed easier (alongside the benefits of making an analogous model in SD before).

#### 7.3.1.4 Validation

Validation is a key concept in both models. In some circumstances, validating a SD model may be slightly easier due to two factors. First, as it is a deterministic system, it is common to accept the system is biased by the data and leave a discussion of data suitability for the data analysis rather than model analysis. Also, validation is a more common topic in SD than in DES, and new methods are commonly being suggested to help validate models, both structurally and behaviourally. DES on the other hand is slightly easier to perform face validation for, due to the less abstract nature of the model.

#### 7.3.1.5 Complexity

In both models, I can explore the system in more detail to provide a more realistic model. However, the extent of this improvement depends on both the paradigm selected, and the scenario. In particular, as SD is often selected for aggregate estimates, it is often considered a more rough analysis of trends rather than a detailed predictive model. This comes from the initial purpose of many SD models: to explore the overall movements of the stocks. As such, while more detail can be included, it often does not fit with the purpose of the model as it is rarely used for prediction. DES on the other hand can greatly benefit from increased model complexity, as it can help provide more accurate confidence intervals for predictions. However, a significant drawback is higher run times, and so optimisation is a core concept to consider.

#### 7.3.1.6 Summary

Overall there are many benefits for using each of the modelling paradigms, but the purpose of the model is incredibly important. Models which are more concerned with general trends than predictive power may find SD a better choice. While those that are more focussed on the details of a system and high predictive power may find DES to be a better choice. A summary of the rankings of each paradigm is given in Table 7.3.1.6. However, if the purpose of the model was known, these rankings would likely change.

| Paradigm | Construction | Flexibility | Ease of Use | Validation | Complexity |
|---|---|---|---|---|---|
| System Dynamics | +++ | ++ | ++ | ++++ | + |
| Discrete Event Simulation | ++++ | ++++ | +++ | ++ | +++ |

Table 7.2: Summary of each paradigm against the five characteristics for an unknown purpose model. + denotes low characteristic, while +++++ denotes high characteristic.

## 7.4 Scenario Comparisons

### 7.4.1 Scenarios to Consider

In this section I explored three slight changes to the MRWS siting process, modelled using SD and DES. My objective is to demonstrate how each model responds to each type of change, and to provide explanations on why there may be differences between the model responses. I do not provide full results for each model and scenario to provide a more condensed overview of the scenario responses, and instead highlight points of importance in each case. I considered three scenarios: Fukushima removal, a shift in the stakeholder engagement periods and Hinkley Point construction plan cancellation. Note that I used

‘Model 1’ for my SD model, as shown in Chapter 5. The difference between using the two models is how quickly the public responds to events, and so I used the more sensitive model to make changes between paradigms clearer.

#### 7.4.1.1 Fukushima

My first scenario explores how my models would respond if I removed the direct effect of the Fukushima accident that occurred in March 2011 (roughly half way through the engagement process). This event had a large amount of exposure to the public through papers and online news websites, and so caused a noticeable reduction in trust in the government and nuclear projects. To explore this scenario, I removed the event entirely from my model (which has a direct affect on public trust). This is an important scenario to consider, as the likelihood of an event of this magnitude occurring during the public deliberations is quite small. Future public deliberation plans would likely proceed under the assumption that this sort of event does not happen (with exploratory analysis into alterations to the deliberation structure should an event occur).

#### 7.4.1.2 Shift in Stakeholder Engagement Periods

The second scenario I considered was related to the decision deadline extension. In particular, I was interested in how the models responded when the whole public deliberation process was moved 6 months later than the original process. This synchronises the deliberation structure with different events and news releases by the NGOs and media. Although the NGO process would have changed slightly to accommodate this, in both models the majority of the influence from the NGOs came from a more consistent increase of pressure as the decision deadline approached, and so I did not alter NGO event times as well (a lot of NGO events I included were also not related to partnership actions).

#### 7.4.1.3 Hinkley Point

My final scenario was if the Hinkley Point construction plans had been cancelled during the stakeholder engagement process. This could be quite important for the outcome. One of the significant arguments from NGOs was the belief that, if the GDF was constructed, there would be more nuclear reactors built due to the increased waste storage capacity. I introduced this event 3 months after the Fukushima accident (June 2011), to represent a government response to growing concerns about nuclear power. It was included as a ‘positive’ governmental incident, that instead improved government trust slightly. However, I have not reduced the number of NGO events in response to this as it is assumed that events would have had a slightly different focus should this cancellation have happened.

### 7.4.2 Practical Expectations

Given my discussions in Section 7.3, I made several predictions for how each modelling paradigm would respond to these scenarios. For instance, I believed that SD would have a clearer response on each of the three scenarios as it was a deterministic model. In particular, I expected the Fukushima and Hinkley Point events to have a larger impact than the shift of the deliberation process. Shifting the deliberation process would cause people to move stocks at a different time, but the overall number of people moving should be similar. However, I was uncertain how strong an impact this would have on the feedback within the system, particularly as the shift causes PSE3 to occur during and shortly after Fukushima and so could have a mitigating effect. I also expected Fukushima and Hinkley point to have a more noticeable impact as the SD model had been designed to be slightly more sensitive to world and government events than my DES model.

I expected a lessened impact with my DES model. As the stochastic nature of the model may obscure the trends slightly, but may also have a chance to identify trends that fall outside the abilities of a deterministic model (e.g. swing points in opinion). The Fukushima and Hinkley Point events would also have a noticeable impact in the DES model. However, this affect may diminish due to the number of individuals who consider changing their opinion when these events are active. Overall howeve,r I would expect to see more changes in my SD model than my DES model, as the SD model is more sensitive to changing scenarios due to the direct affect flow rates can have (which guarantees individuals change opinion states).

### 7.4.3 Fukushima

To explore the responses of each model to the removal of the Fukushima event, I compared public acceptance and government trust for both models. It is clear what I mean by public acceptance, as it has been my standard evaluation tool so far. However, government trust has received less focus so far. It is an underlying variable within each model that estimates how trustworthy the public perceives the government to be. So while it is not directly visible, I are able to understand some of the differences between the models by comparing how government trust has responded (as both models have slightly different definitions to better fit the paradigm, such as the more continuous updating of government trust and introducing a stochastic element to Partnership & NGO influence growth).

#### 7.4.3.1 Public Acceptance

I was most interested in how the removal of Fukushima affects overall public acceptance near the end of the process. I start with a more quantitative comparison, and provide qualitative remarks in the summary for the scenario. Throughout this section I only presented results for the Copeland community, however both Allerdale and the rest of Cumbria displayed similar trends. The results for my DES model are shown in Figure 7.2.

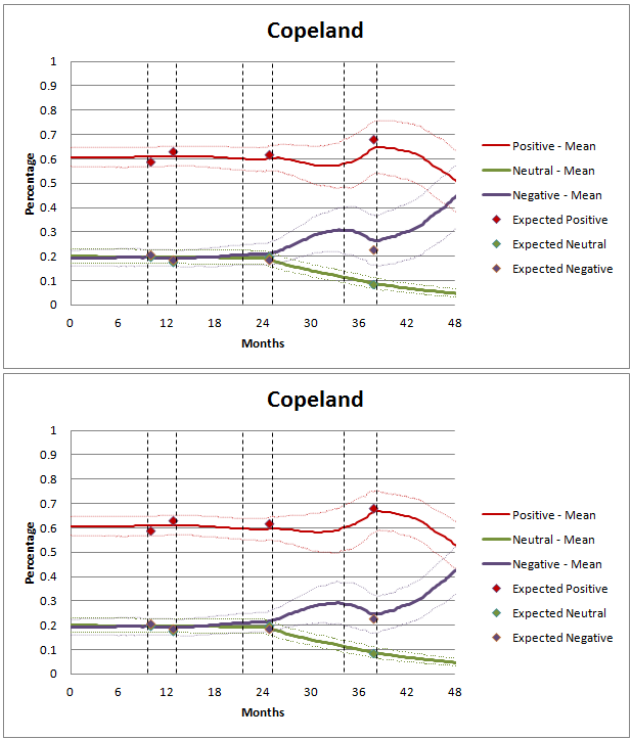



Figure 7.2: DES model results for Copeland with (top) and without (bottom) Fukishima.

I can see that removing Fukushima has had an overall positive effect. This stems from the public acceptance dropping much slower between PSE2 and 3, when Fukushima was removed. Additionally, the feedback effect within my model caused the end acceptance value to be roughly 2% higher. I initially found this quite surprising that there was such a minor change. However, if I take into account that PSE3 happened after Fukushima and absorbed much of the negativity, it makes sense that the lasting impact would be through smaller changes to feedback within the model.

A more clear difference between the two scenarios is shown in the narrower confidence intervals. This also makes a lot of sense in my DES model, as I have removed one element of stochasticity within the model. Thus while the overall increase to public acceptance

was quite small, the removal of Fukushima improved the consistency of my DES model noticeably.

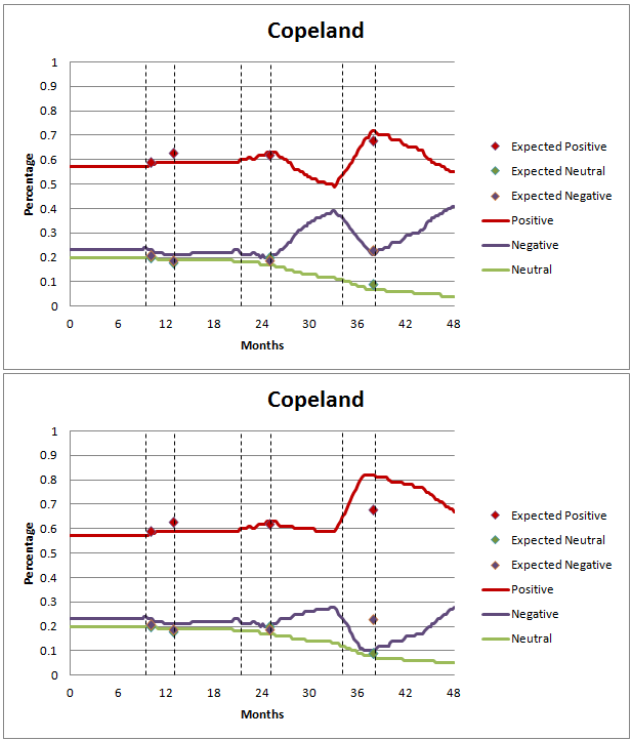



Figure 7.3: SD model results for Copeland with (top) and without (bottom) Fukishima.

My SD model was more sensitive to the removal of Fukushima in terms of public acceptance. The drop in public support between PSE2 and 3 is now far smaller, and has had a strong impact on how effective PSE3 was. This contrasts to the responses seen in my DES model. This difference comes from how directly feedback was included within each model. In my DES model feedback was introduced as scaling for the base probability distribution that work items would use to decide which opinion to change to. However, my SD model had feedback which affected the flow rates of each stock directly. The SD feedback system therefore had a stronger reaction to the change in scenario.

#### 7.4.3.2 Government Trust

In both models, government trust has been modelled in a similar way. Every 7 days (DES) or 0.25 months (SD) the current value is scaled up or down slightly according to the current prevalence of the NGOs and Partnership. Additionally, a small value may be deducted according to other events that are not directly related to one of these two sides (such as

Fukushima). Despite this similarity, the introduction of various stochastic elements in the DES model resulted in a slightly less sensitive government trust variable (due to the more stochastic approach). So my DES mode had slightly higher weighting on NGO and Partnership activity rather than other incidents. Figure 7.4 shows how these different sensitivities have affected government trust in each paradigm.

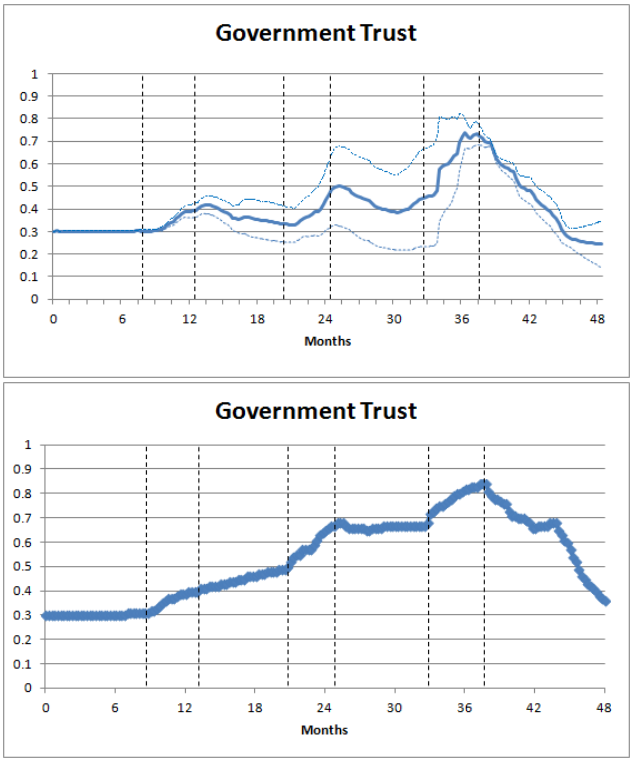



Figure 7.4: DES (top) and SD (bottom) model results for government trust on a scale between 0 (low trust) and 1 (high trust). The DES model presents a rough 95% confidence interval over the duration of the process.

A quick comparison of government trust in each paradigms begins to explain the difference in public acceptance. Government trust in my SD model is noticeably higher than in my DES model when Fukushima has been removed. In particular, government trust does not decrease much between PSE2 and 3, while it does in the DES model due to the relatively higher NGO activity. This difference has been reflected in public support where particularly high government trust, combined with a strong feedback effect within the SD model, increased public acceptance.

Keep in mind that while government trust decreases quite quickly between PSE2 and 3 in my DES model, the amount that it decreases is still lower than in my original model

where Fukushima was included. Both paradigms do however agree that my measure of government trust reduces drastically during the last 6-12 months of the process, which can be considered as a prime reason for the loss of public support within my models. In other words, the removal of Fukushima does not affect the overall outcome. The near inevitability of this fall in government trust is reinforced by the confidence intervals shown for my DES model. During the last 12 months (with the exception of the very last month) the confidence intervals were very tight no matter how high or low government trust has been before this stage.

#### 7.4.3.3 Summary

My first scenario has highlighted some significant differences between my models, and the paradigms as a whole. For instance, my SD model responded more to the removal of Fukushima than my stochastic DES model. In particular, the affects of feedback appeared stronger in my SD model. This, coupled with the slightly higher sensitivity to world events, drove my SD model to give a higher public acceptance rate at the end of the process. I also may begin to question whether the increase of public support seen in my SD model is realistic, as the reinforcing effect of increased positive feedback has increased public support much more than in my original SD model.

Despite all of this, the trends displayed for each modelling paradigm remained consistent. In both cases, government trust and public acceptance were noticeably higher between PSE2 and 3 when Fukushima has been removed. This was followed by the increase in support from PSE3 (where feedback played an important role) followed by the significant drop in government trust, resulting in a sharp decrease of public support near the end of the process. From this, I can conclude that while each modelling paradigm has slightly different sensitivities to elements in my model, the overall trends have remained the same.

In summary, it appears that the robustness of my DES model is a strong benefit over my SD model. This increased robustness is inherited from the stochasticity included in the model that can absorb smaller shocks to the system, which can have a strong effect on a SD model with strong and direct feedback loops. I can however, begin to question whether my DES model is actually too resilient to changes, and this is a topic I revisit for my following two scenarios. However, each modelling paradigm has displayed the same trends, with differing magnitudes. Each paradigm could therefore be considered as suitable. Choosing between the paradigms has been a matter of how much stochasticity and sensitivity should be included in the model.

### 7.4.4 Shift in Stakeholder Engagement Periods

My second scenario explored the responses of my two models when I moved each of the stakeholder engagement periods 6 months later than their original timing. There are two main reasons why I considered this. The first was to explore whether the impact of each stakeholder engagement phase change according to the time of year they are planned for. Secondly, this was a more realistic alternate scenario to explore the affect of the deadline extension than the inclusion of PSE4. This is because the Partnership would need time to write their final report, which would not be possible with PSE4. However, the fact that the deadline extension was an unexpected request would make this deliberation structure unlikely. In other words, PSE4 could be an emergency reaction, however with forward knowledge, shifting the deliberation structure could have a similar effect.

#### 7.4.4.1 Public Acceptance

For this scenario, I only present the results on public acceptance for Copeland and Allerdale. However, the shift of deliberation structure had the expected effect within my model on variables such as government trust, as I explored in scenario 1 (e.g. increases in trust according to the new PSE times). The rest of Cumbria was excluded, as it showed the same trends as the other two communities I had considered. My results for the DES model are shown in Figure 7.5.

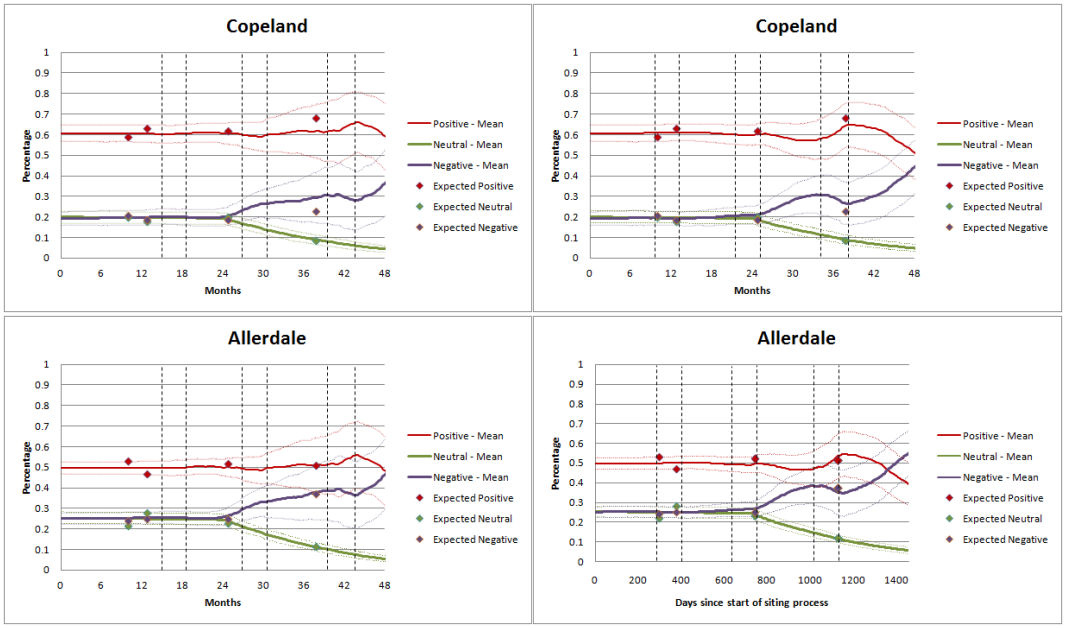



Figure 7.5: DES model results for Copeland (top) and Allerdale (bottom) when the public deliberation structure is moved by 6 months (left) compared to the original process (right).

The most immediate conclusion I can draw from is that shifting the deliberation structure has had a positive impact on the final outcome. Positive support is near 60% for copeland, which showed almost a 10% increase over the original model. However, should this simulation continue for another few months, I would see support dropping rapidly again due to the lack of Partnership presence. The same trend can be seen for Allerdale. A byproduct of this shift in timing however, has resulted in more variance near the end of the process than in my original model. This is due to large differences in how quickly public support begins to lower following PSE3. The overall trend shifting met my expectations for the DES model.

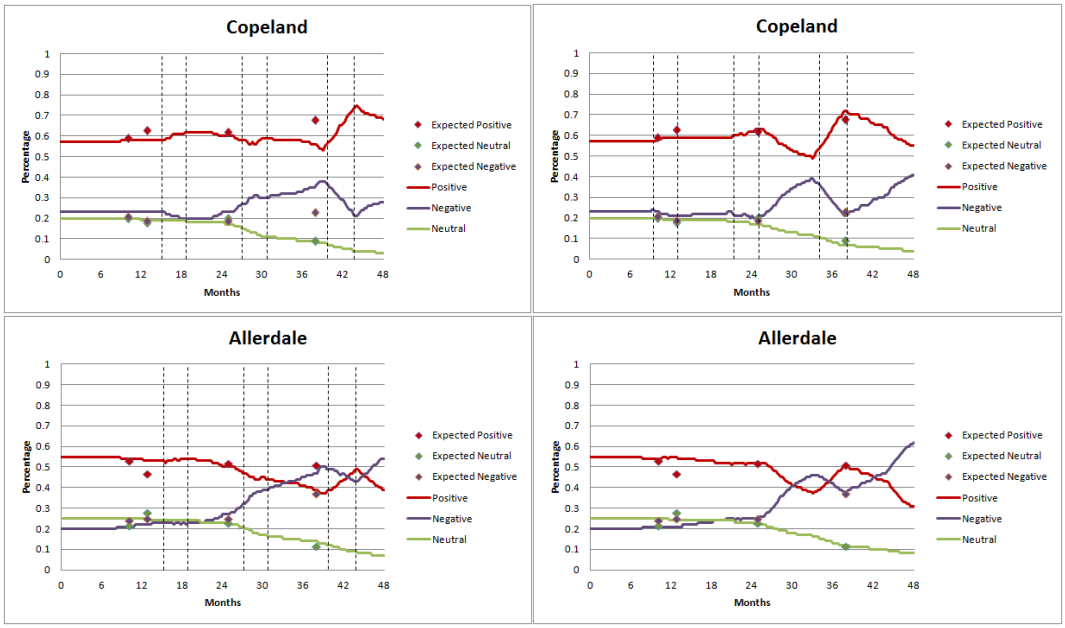



Figure 7.6: SD model results for Copeland (top) and Allerdale (bottom) when the public deliberation structure is moved by 6 months (left) compared to the original process (right).

My SD model on the other hand showed a similarly positive result for Copeland. Although the Copeland's support in my SD model decreases at a slower pace initially due to the stronger feedback effect. Allerdale on the other hand shows a noticeably different trend than I saw in my DES model. Allerdale was originally designed in my model to be slightly more negatively minded than Copeland (this was supported by the data from the MRWS Partnership). This difference caused Allerdale to see a more dramatic increase in resistance following PSE2 (and Fukushima) when there was less Partnership presence. Due to the feedback effect in my SD model, it was difficult for public support to increase during PSE3, resulting in a negative outcome from Allerdale.

When comparing both models, I see a similar issue to Scenario 1 where my SD model was particularly sensitive to changes. In this scenario, the models were slightly less sensitive than when I removed Fukushima, but the affect the deliberation structure shift had on Allerdale was quite significant. If I compare how much public support increases for both Copeland and Allerdale in my SD model, I may begin to question if this increase is too dependent on public support levels at the start of PSE3 (due to the strong feedback effect). While my DES and SD models showed the same trends for Copeland, they did not for Allerdale and the rest of Cumbria.

#### 7.4.4.2 Summary

This scenario has highlighted my first significant difference between the two models in terms of trends. My SD model has shown unexpected behaviour for the lower public support levels that happen due to the delayed PSE3. While this is likely due to the SD model being slightly too sensitive (as seen in Scenario 1 as well), it does suggest that the deliberation structure should ensure that less supportive areas receive more attention than more supportive areas. This kind of behaviour was not very common in the previous siting process.

Despite this, exploring a shift in public deliberations has shown a strong positive effect in my DES model, where all 3 communities were far more positive near the end of the process than in the original process. It is also likely I would have seen similar behaviour in my SD model for Allerdale and Cumbria if several smaller scale events had been included between PSE 2 and 3. This would have kept Partnership presence in areas with higher resistance, hopefully keeping the public support level a little more stable until PSE3. However, I can also see that the uncertainty of support levels has increased quite substantially, especially nearer the end of the process. This means I must take care when drawing any conclusions, although identification of the general trends would still be useful.

In conclusion, I can see that the strength of feedback within my SD model has led to my first large performance difference between the two models. While this difference may be due to this difference in feedback structures between my two models, it does highlight the importance of keeping public support as high as possible at all times. In particular, it may suggest that short bursts of activity may not be the best use of resources when planning a deliberation structure. For example, having more persistent presence throughout the process (at the expense of smaller stakeholder engagement periods) could help mitigate the affect feedback can have on a system. In other words, while my SD results for Allerdale and the rest of Cumbria may have been extreme, they do show how important it can be to maintain public support throughout the entire process.

### 7.4.5 Hinkley Point

My final scenario has some similarity with scenario 1. I considered how each model responds to an external positive event. In this case, I considered a government announcement to cancel their Hinkley Point construction plans several months after Fukushima. One of the reasons for considering this was to explore implementations of external positive events in each model, as originally they only considered negative events. Note that by events, I refer to world or UK incidents that are not directly sourced from NGOs or the Partnership.

I was also able to consider how significantly each model responded to a mitigating effect, following a significant negative event (in this case Fukushima). I could then compare this with scenario 1 where I assumed Fukushima did not happen.

#### 7.4.5.1 Public Acceptance

Similarly to Scenario 2, I only present results for Copeland and Allerdale. I assume that the announcement to cancel the Hinkley Point construction plans happened in June 2011, which would be 3 months after Fukushima. I implemented this positive event as a negative modifier to my usual government trust adjustments. This negative modifier was smaller than Fukushima's modifier to represent the difference in significance of the two events. However, there was an additional allowance that government trust can increase slightly from these events if there have only been positive events recently. My results for the DES model are shown in Figure 7.7.

The overall trend of my DES model followed what was seen in scenario 1 for Copeland. However, the mitigating effect of a positive event increased public support. This could be considered interesting, as the Hinkley Point cancellation was a smaller event than Fukushima, and yet had a more positive affect compared to when Fukushima was removed altogether. A similar trend can be seen in Allerdale. The average positive support exceeded levels seen in the data at the end of PSE3. While the support is dropping quickly at the end of the process, all three communities were positive or neutral about the proposal overall. However, support would drop should the process be extended further. My DES model also became more consistent due to the balancing affect of the two events. Including the Hinkley Point cancellation has restricted confidence intervals to similar levels seen in scenario 1 when the stochasticity introduced by Fukushima was removed altogether.

The mitigating effect of the Hinkley Point announcement can be seen from my SD model results in Figure 7.8. For all three of the communities, public support dropped quite quickly following Fukushima. However, once Hinkley Point had been cancelled, public support held steady until PSE3. Unlike my DES model, my SD model was slightly more negative due to this initial decline. Despite this, the results were still positive overall, and does show a similar (but more exaggerated) trend to my DES model. This was a clearer demonstration that the significance of the Hinkley Point announcement was lower than the Fukushima event.

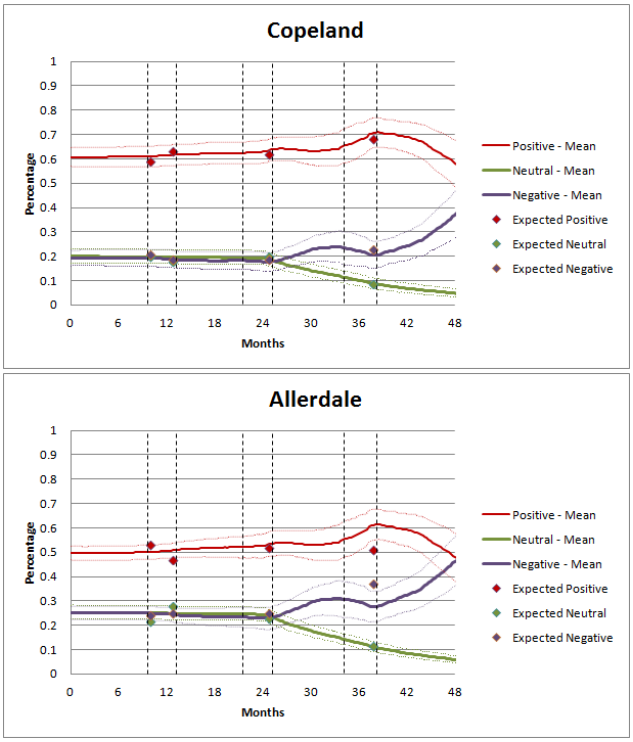



Figure 7.7: DES model results for Copeland (top) and Allerdale (bottom) when Hinkley Point construction plans were cancelled.

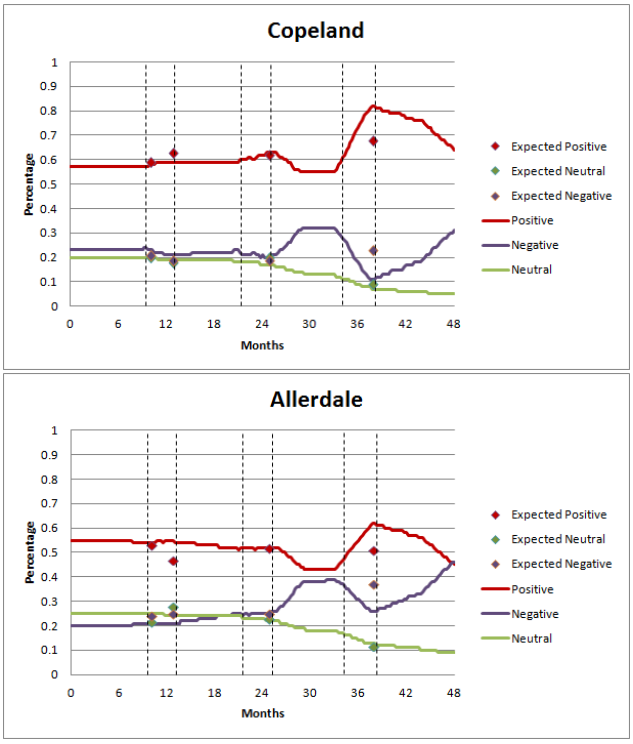



Figure 7.8: SD model results for Copeland (top) and Allerdale (bottom) when Hinkley Point construction plans were cancelle.

If I compare the results of my SD and DES models, it is clear that the sensitivity of my SD model separates them in terms of behaviour. Despite the different behaviour of my two models, each model displays similar trends and also arrives at comparable results for the end of the process. This further reinforces the suggestion that the modelling paradigm that should be used would heavily depend on the perceived sensitivity of the process to these changes (although the SD model can be constructed in a less sensitive manner).

#### 7.4.5.2 Summary

My third scenario has perhaps been the most promising in showing similar responses from both modelling paradigms. In both cases, the Hinkley Point cancellation served as a strong mitigating factor following the Fukushima accident. In particular, the feedback effect from both models has propagated this mitigation factor and resulted in noticeably higher support at the end of the process for both models, and for all communities. When compared to my results from removing Fukushima entirely, this could suggest that the proper response to a significant negative event could be to provide a more positive response than if the negative event had never happened. Unfortunately, the Partnership did relatively little to

ease concerns stemming from the Fukushima accident. Had more been done then a more positive result may have been more likely.

To conclude, this scenario has certainly highlighted the importance of mitigating events that could reduce the public's trust in the government. While my SD model was more sensitive, it still showed the same trends as my DES model. Despite this difference in sensitivity, both models (and modelling paradigms) could be considered suitable. However, care must be taken to ensure that model choice reflects the expected sensitivity of the real system through thorough validation steps. The improvement of consistency seen in my DES model is also a strong benefit for a stochastic model, and this does again suggest that my DES model is more robust to changes than my SD model.

### 7.4.6 System Dynamics Model 2

Throughout all three scenarios, there was the common theme that my SD model responded more sensitively to changes. While this is not necessarily a negative aspect of my SD model, it does give further reason to explore how my alternative SD model, model 2, responds to the same changes. Model 2 was designed to respond in the same way as my original models with the exception that all flow rates between stocks had been reduced. These lower flow rates indicates that individuals in model 2 change opinion slower than in my original model (see Chapter 5 for a full review). I initially decided to use model 1 to ensure that any changes were clearly displayed to better contrast behavioural changes with my DES model. For the remainder of this section, keep in mind that model 1 refers to my original SD model, while model 2 refers to my alternative, slow opinion change, SD model shown in Chapter 5.

My original SD model showed many of the same trends to my DES model throughout the scenarios, although they were often more exaggerated. Some of this exaggeration can be attributed to stochasticity in my DES model absorbing some extreme behaviour, however it was a consistent aspect of my SD model. Because of this, I then compared my DES model to model 2 of SD. My hope was to show that my less sensitive SD model still shows similar trends to model 1. In particular, I was interested in how close this sensitivity reduction brought my SD to my DES public support values.

#### 7.4.6.1 Scenarios

To compare the different behaviours of models 1 and 2, I implemented each scenario into model 2. I then contrasted the differences of the two models (see Sections 7.4.3 to 7.4.5 for model 1 results). The most significant difference was for Allerdale and the rest of Cumbria

in scenario 2 (shifted deliberation structure). In this case, the public support levels did not drop enough to have a strong feedback effect going into PSE3, as can be seen from Figure 7.9.

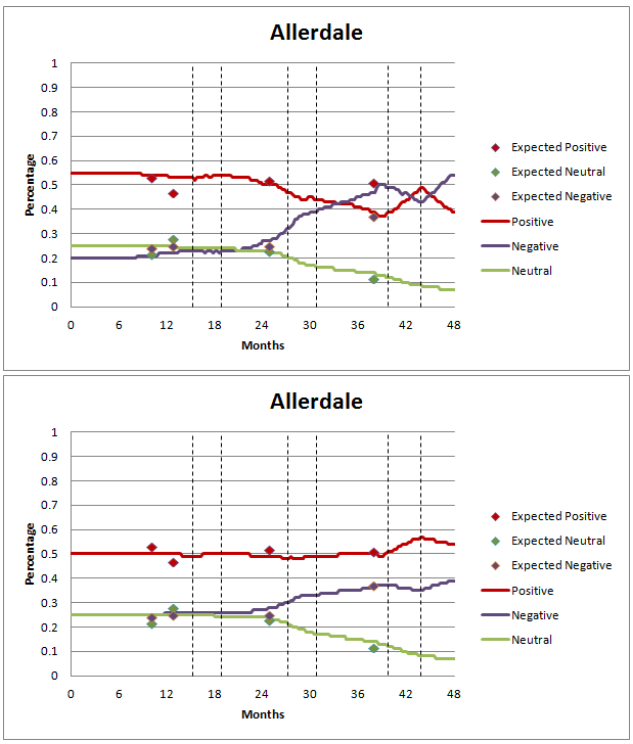



Figure 7.9: SD model results for Allerdale for final model 1 (top) and final model 2 (bottom) for the shifted deliberation structure.

The reasoning behind this difference should be clear. Model 2 responds in a similar way to model 1, however not enough people become negatively minded during PSE2 and 3 to initiate a strong feedback effect. This is due to the reduced flow rates of the model. From this, I may begin to question whether another SD model may have been more suitable. In particular, a model whose sensitivity to these changes (and so flow rate scaling) was in between model 1 and 2. This balance could improve the overall performance of my SD model. Figures 7.10 to 7.12 show the model 2 results compared to my DES results.

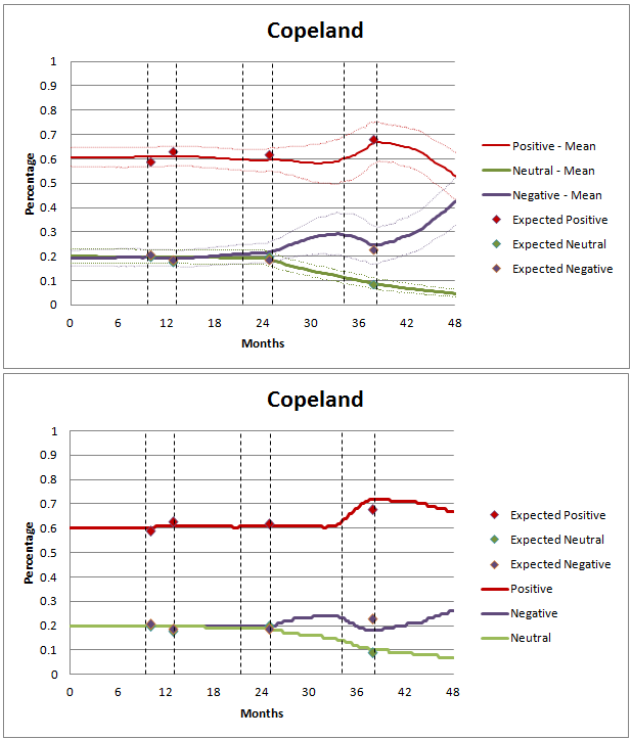



Figure 7.10: Model results for Copeland for DES (top) and SD final model 2 (bottom) for removal of Fukishima.

The first observation I can make from Figures 7.10 to 7.12 is that the reduced sensitivity in model 2 has caused it to mimic behaviour seen in my DES model more closely in all cases. However, the common theme in each of these cases is that public support is quite high at the end of the process. This is due to the lower flow rates seen in model 2. This further suggests that an additional SD model could be beneficial, which is a balance of models 1 and 2. This was particularly the case for scenario 2, where the shift in deliberation structure has left too little time at the end of the process for the public to adapt to the increasing resistance that should be present.

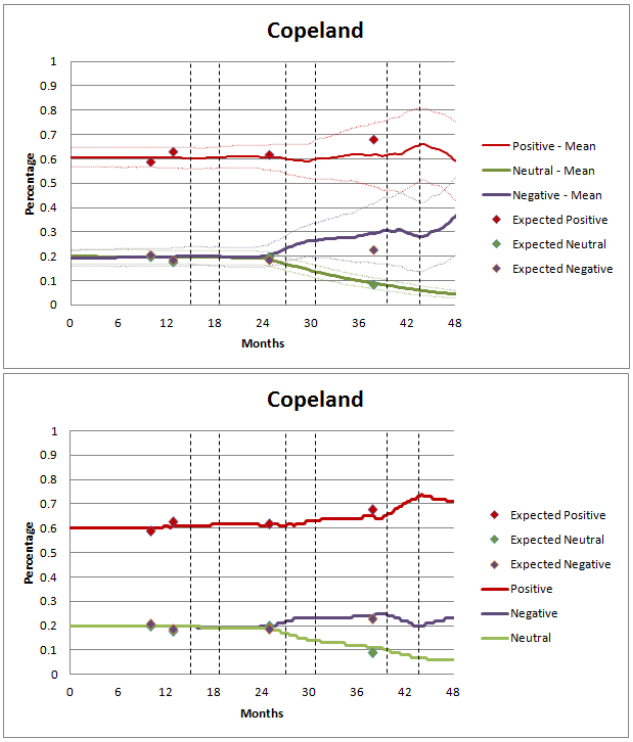



Figure 7.11: Model results for Copeland for DES (top) and SD final model 2 (bottom) for the shifted deliberation structure.

My DES model has consistently shown that while it is sensitive to changes in scenario, it does not over-express these changes like model 1 did. It also shows each change clearly, which can sometimes be difficult to see in model 2. My conclusion is that model 2 seems more suitable for this setting than model 1 in terms of adaptability to different scenarios. However, the most suitable SD model would demonstrate sensitivity somewhere between that shown in models 1 and 2. This does demonstrate how flexible SD can be, and while my DES model can demonstrate similar flexibility, it is less simple to implement (and can also be computationally costly).

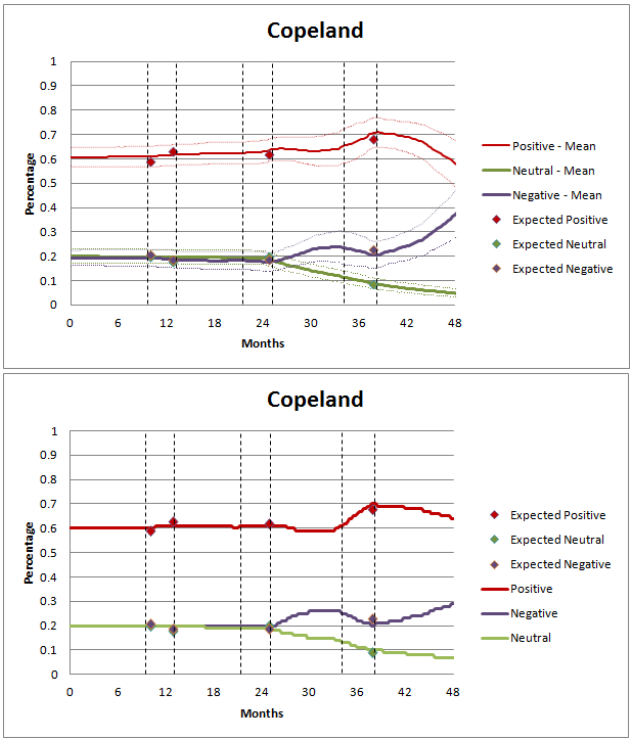



Figure 7.12: Model results for Copeland for DES (top) and SD final model 2 (bottom) for Hinkley Point cancellation.

### 7.4.7 Expectations Evaluation

In sections 7.3.1 and 7.4.2, I outlined some of the differences I expected to see before implementing any scenarios into each model. In particular, I expected that my SD model would 'have a clearer response' to each of the three scenarios. This has certainly been the case due to the sensitivity of my deterministic model. Even in the case of model 2, where individuals changed opinions slower, the response to each scenario was still quite clear. I initially proposed that Fukushima and Hinkley Point would have a larger impact on my SD model, however my results showed that shifting the deliberation structure also had a large impact on the model results. My uncertainty on the strength of the feedback in this scenario was also well founded, as I saw the largest deviation of results in this scenario. For example, the negative feedback effect was far stronger in model 1 than in model 2 which resulted in very different final outcomes.

On the other hand, my DES model performed as I had expected in most cases. The main exception to this was how positive an affect the Hinkley Point scenario had on the final results. Despite this, my DES model showed the most consistent responses, and seemed to repre-

sent an excellent middle ground in sensitivity between models 1 and 2. A minor point is that the removal of the Fukushima incident perhaps had too small of an impact on my DES model. This could have been due to the slightly different weightings of government trust in each paradigm (these slight weighting changes were chosen to better suit the paradigm, for instance DES updated government trust more frequently with smaller changes, which caused Fukushima had less of a 'shock' factor which could have swung opinion). My conclusion from exploring each of these scenarios with my DES and SD models was that both modelling paradigms could be used. However, care must be taken in constructing a model which is sensitive enough to detect scenario changes, but not too sensitive to exaggerate any responses. This was most well represented by my DES model.

## 7.5 Suggestions

I provided a comparison of DES and SD on the paradigm level in Section 7.3, and on the practical level of my scenario in Section 7.4. I now bring these two comparisons together to give general comments and recommendations for modelling my specific scenario. In Section 7.3, I gave a ranking of each paradigm on 5 characteristics: construction, flexibility, ease of use, validation and complexity. However, this table of rankings was for a generic scenario where no details were known. Following my results from Section 7.4, I can revise these rankings for my specific scenario.

I altered SD model rankings for the construction, flexibility and complexity characteristics. Ease of use kept the same score, as my SD model was below average when implementing scenario and structural changes. In particular, changes to the deliberation structure were quite cumbersome due to defining size, time and duration of each event individually. Validation kept its higher ranking due to the wide variety of validation techniques commonly used for SD models, that were less restricted by my limited data. Construction had its score reduced as my specific scenario had a strong reliance on discrete events, which were cumbersome to include in my model. This also increased the complexity score as this required a large number of additional interactions that would not usually be required. Finally, I increased the flexibility score in this scenario as SD fits quite well with the aggregate movements that are of interest when planning deliberation structures.

My DES model only had the score for flexibility altered. Due to computational limitations, I was required to batch together similar individuals in my DES model to groups of size 100. This reduced the expected benefit of being able to follow each individual around the system, and so I reduced the flexibility score to account for this. None of the other characteristic

scores were changes, as my scenario was closer to my expectations for the DES paradigm.

| Paradigm | Construction | Flexibility | Ease of Use | Validation | Complexity |
|---|---|---|---|---|---|
| System Dynamics | ++ | +++ | ++ | ++++ | +++ |
| Discrete Event Simulation | ++++ | +++ | +++ | ++ | +++ |

Table 7.3: Summary of each paradigm against the five characteristics for an unknown purpose model. + denotes low characteristic, while +++++ denotes high characteristic.

My paradigm suggestion for my scenario would be to use DES modelling, if only DES or SD was available. When constructing my SD model, I encountered many more complications than I had expected when implementing certain features which were better suited to a DES model. This made it more difficult to explore the sensitivity of my SD model and to explain to potential users. However, the higher score SD kept in validation cannot be understated. This is a key component of any model, and can be more challenging in DES models. If more varied data had been available then validation in a DES model becomes far easier.

## 7.6 Extensions and Contributions

### 7.6.1 Contributions

The results from this Chapter primarily contribute towards the Opinion Dynamics literature. In particular, the trends identified throughout the Chapter provide a further link between the theory of opinion dynamics, and practical examples of these systems. Also it has reinforced some of the notions, that are present throughout the literature, that risk mitigation appears to be an effective strategy. Additionally, the benefits of persistent engagement with the public, especially during periods with a large amount of negative outcry (e.g. around Fukushima). This can be seen in the deliberation shift scenarios, where the mitigating effect of the Partnership has been delayed by 6 months resulting in a noticeable improvement in public opinion. There is also contributions towards the simulation methodologies literature, by offering a case study that has been done in both System Dynamics and Discrete Event Simulation, offering an additional perspective on the differences between these two paradigms.

### 7.6.2 Extensions

Both my models have been successful in regards to their initial objectives, and either could be used to assist plans for a new deliberation structure. However, I have only considered

two specific paradigms (with a single model structure each) for my scenario. I mentioned earlier in this chapter, and in Chapter 6 that a better paradigm to use could have been agent based modelling (ABM). While ABM is a relatively new modelling technique, it has been successful in a wide range of applications (e.g. Pahl-Wostl 2002, Matthews et al 2007 and Berger 2001). It would be particularly suitable for my scenario of public deliberations. A common question when exploring models of deliberation structures is: what could I do to change this person's vote?

While DES can answer this question to some degree, there is relatively little learning from those in the system, which is an area ABM excels at. In particular, it would be possible to have each individual develop an opinion over time in more detail than I had included in my DES or SD models, which involved very distinct opinion states. It would also be simpler to introduce more types of people to the model that react differently according to their history. Because of these reasons, ABM appears to be an ideal candidate for a suitable modelling paradigm for my scenario. However, there are several reasons I could not utilise this paradigm. The first was that computational run time could be very high for such a detailed model, where each person is modelled individually. It may be possible to combine individuals into like-minded groups such as in my DES model. However, this would defeat the purpose of individual histories. The more important problem was that I lacked the data required to construct such a model. I could have built a rudimentary model, validation would become extremely difficult. While users may prefer the paradigm and the model, it is unlikely they would be able to build enough confidence in the model to consider using it as an assistive tool.

This lack of data renders ABM an unlikely option, however improvements could be made by including more spatial-based responses to my models. In particular, certain towns and villages were hotspots of resistance to the proposal, and so I could include these in my model. While my limited data does provide some information about these areas, much of the validation would still need to come from expert opinions which was why this was not included in my initial models. However, this would be an area of improvement for my current models. One benefit from including this level of feedback would be that I could produce a spatio-temporal map which could be very useful and convincing for potential users of the model.

My final extension I considered was the use of hybrid modelling. I have contrasted the SD and DES paradigms and stated that each is better used for slightly different objectives and situations. While each model is quite strong on its own, it could be stronger if it worked alongside another modelling paradigm, combining strengths and mitigating weaknesses of

each paradigm. For instance, I could combine my SD and DES models such that SD defines how many people change opinions at each time point, and a smaller DES model takes those individuals and changes their opinions according to probability distributions similar to those I used in my original DES model. This would combine the power of SD on an aggregate level with a lower level DES system that introduces stochasticity.

# Chapter 8

# Extensions

## 8.1 Issues Facing Model Construction

Throughout the last four chapters, I have introduced several different modelling paradigms. I constructed a model using two of these paradigms for the unsuccessful Cumbrian siting process. The results of each of these were promising, and Chapter 7 provides a comparison of the behaviours of these models to a set of alternate scenarios. However, both the modelling paradigm and application area can be faced with a variety of problems when constructing a suitable model. Examples of these problems could include; unrealistic links to the real scenario (for instance probabilistic relationships, levels of abstraction, etc), model validation issues or inconsistencies between the theoretical expectations of the model and the practical expectations of the user.

For example, both my system dynamics and discrete event models were defined from attributes and objects which can be difficult to quantify. This made validation a more difficult task, as I must infer interactions from more qualitative statements made by experts in the area. While techniques to allow clearer elicitation can be used, it would still be beneficial to make questions posed to experts more quantifiable. For instance, when validating model structure, it may be simpler to provide a list of conditional independence statements between elements of the model for the expert to evaluate, rather than attempting to explain the model structure directly.

This leads me to my fifth original objective. To provide a foundation for additional validation methods, I require a strong probabilistic framework such as a Bayesian network (BN). This chapter explores potential applications of a probabilistic framework such as this, in the hopes of alleviating some of the issues facing model construction. This section directly addresses objective 5 of this thesis, and will hopefully spark discussion on the potential

benefits of incorporating less known modelling paradigms into a standard model. I have considered the conversion of a standard system dynamics model to an analogous BN, hopefully allowing for additional insight and validation options.

## 8.2 Introduction to Bayesian Networks

I first provide a brief introduction to BNs. I can then consider how these could be used to help address the issues I highlighted earlier. In particular, I focus on dynamic Bayesian networks (DBNs) as they share more similarities with the traditional expectations of modelling paradigms. However, I suggest Smith (2010) or Nielsen & Jensen (2009) for a deeper review of the BN and other graphical models.

Given I am looking to use DBNs to assist with validation of SD model, and as a potential hybridisation tools, it is important to consider how incommensurable each of these paradigms are with each other. SD is of course an inherently deterministic system, while DBNs are used specifically to evaluate the stochastic nature and probability distributions. This clear difference between the two paradigms poses considerable problems in trying to move from one paradigm to another. For example, moving from exact stock levels from a SD model into discrete probabilistic intervals that a probability distribution can be defined over in a DBN. Therefore it is important to keep in mind that there are some leaps that need to be made in order to attempt to link these two paradigms in such a way that would allow for useful validation techniques.

### 8.2.1 Bayesian Networks

One of the simplest descriptions of a BN is as a probabilistic graphical model, that describes the conditional dependencies of a set of random variables (RV) using a directed acylic graph (DAG). A DAG is a graph with directed edges between its nodes with no directed cycles, i.e. once you have left a node you can never return there. I revisit this observation when providing a link between system dynamics (heavily feedback dependent) and a BN (requires no feedback by definition). There are a variety of uses of BNs, although some of the most well known uses would be to describe the relationships between diseases and symptoms, or for weather predictions based on a set of predictor variables. A BN may allow a user to clearly understand the interactions between all of the RVs included, and can provide probability estimates throughout the network.

To introduce Bayesian networks, I have provided a commonly used example in Figure 8.1. This describes a situation where I are interested in whether the grass is wet in an area on

a specific day, according to a set of RVs that are believed to affect the outcome. Each random variable can only have an outcome of true or false, and the directed lines indicate dependencies between the probability structures of variables. Even without knowledge of the probability distributions of the RVs I can still draw useful conclusions from the basic structure of the BN. For example, BNs are commonly used to define a set of conditional independency statements.

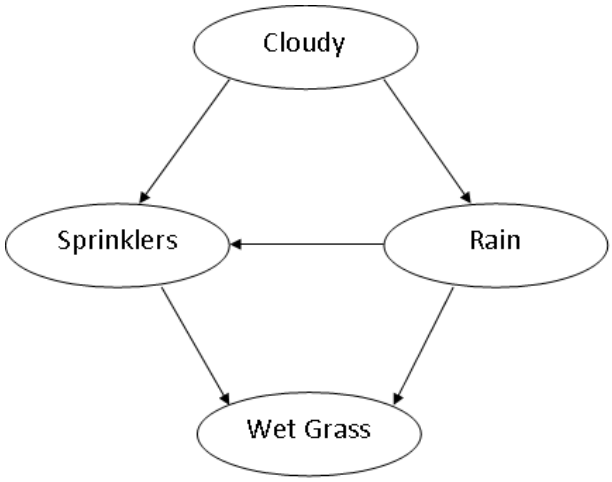



Figure 8.1: A common example of a Bayesian Network with 4 random variables defining whether grass is wet on a particular day.

Given that a BN essentially describes the conditional relationship between a set of RVs, it is a natural extension to explore both dependence and independence from the DAG. The diagram in Figure 8.1 shows the relationship between 4 random variables, and from this I can understand what information is needed to fully describe the probability distribution of each RV. For example, if I wish to know the probability distribution of whether the grass will be wet, and I know the states of all three other RVs then the realisation of the 'Cloudy' RV provides no additional information on the 'Wet Grass' RV. This is because I already know the states of both the 'Sprinklers' and 'Rain' RVs.

This can be described by the following conditional independence statement.

$$\text{'Wet Grass'} \perp\!\!\!\perp \text{'Cloudy'} \mid \text{'Rain', 'Sprinklers'} \tag{8.1}$$

Conditional independence statements can be useful when validating and constructing models, as it provides a simple basis to test model assumptions. In this case, I could check with an expert that they believe that if you know if it has rained and if the sprinklers are on, then knowing if it is cloudy does not provide any additional information on whether the grass is

wet. If they do not believe this statement, then the dependency structure of the BN needs to be re-evaluated. For example, this could happen when the expert believes cloudy weather causes grass to remain wet for longer and so could still provide additional information.

I have so far only discussed the structural conclusions that can be drawn from the DAG. However, BNs are also a powerful tool for understanding different scenarios. I can explore realisations of each random variable and analyse the impact it can have on the probability distribution of the RV of interest. For instance, I can assume that there has been no rain on the day. This fixes the value of the 'Rain' RV, resulting in a different probability distribution for other RVs that are dependent (in this case both 'Sprinklers' and 'Wet Grass'). The ease of exploring scenarios can greatly help enhance understanding of the problem, and help discover the main determinants of the outcome of interest. It also allows additional information to be incorporated in the model in a natural and easy way.

### 8.2.2 Dynamic Bayesian Networks

One of the most common uses for a standard BN is to understand the dependencies of RVs at a single snapshot in time. While this is all that is required if I use a BN as part of a hybrid model, as the other modelling paradigm would be able to move between time steps and 'activate' the BN when it is needed. However, if I wish to produce an analogous model for comparison and validation purposes, I must be able to move between these time steps in the BN itself. This is done through using a dynamic Bayesian network (DBN). A DBN is constructed from multiple copies of a BN that are linked together in the DAG. These links enforce that RV's can only go forward in time and can use information from any RVs that have already happened. This also allows feedback within a BN as long as there is at least one time step delay between feedback steps.

I expand my example from Figure 8.1 earlier to demonstrate how a DBN interacts between its time steps. For example, I assume that the only dependencies between time steps are between the two weather RVs 'Cloudy' and 'Rain'. In particular, I assume that if the weather was cloudy or rainy the day before, this changes the likelihood of the next day being cloudy or rainy respectively. The dashed lines in Figure 8.2 represent these time dependencies, and the number within the loop describes the time length between dependencies. In this case, the 'Cloudy' and 'Rain' RVs each only affect the probability distributions of themselves one step into the future. This time-dependent structure can be expanded to as many time steps as required, and allows exploration of the impact on later days when the realisations for each RV is known from preceding days. For instance, how much does the probability distribution change for whether the grass is wet in 5 days, if I know that today is both cloudy and rainy.

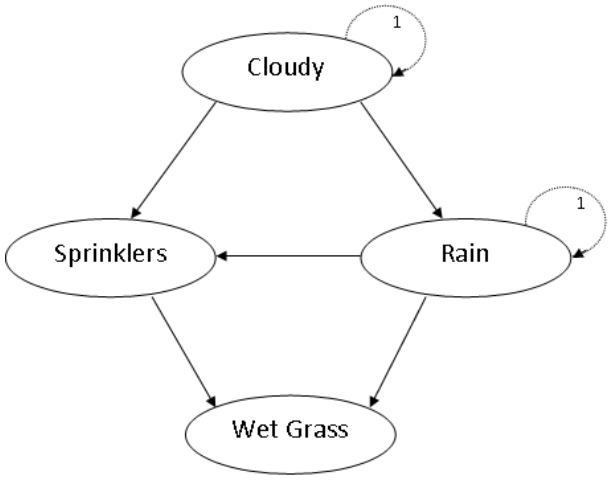



Figure 8.2: An expansion of Figure 8.1 into a Dynamic Bayesian Network. The dashed lines indicate the temporal relationship, and the numbers represent the length of time between these dependencies.

## 8.3 The link between System Dynamics and Dynamic Bayesian Networks

The main extension I considered was to draw a direct link between system dynamics models and dynamic Bayesian networks. There are several reasons I may consider doing this. For instance, better understanding of system structure, assistances with system dynamics model validation, or to introduce probabilistic aspects to standard system dynamics models. However, the similarities between the two modelling structures are quite superficial. For example, each is initially developed from a set of formulae (difference equations for system dynamics, and conditional independencies for BNs) and each can be represented in a similar graphical way. However, the similarities stop quickly when you consider each modelling method in detail. In particular, in system dynamics feedback is a vital component, whereas standard BNs use a directed acyclic graph which forbids any feedback within the system.

Due to this strict restriction on BNs, I cannot create a direct link between a 'standard' BN and a system dynamics model. However, I can use a dynamic Bayesian network (DBN) to change the feedback loops in a system dynamics model into a BN by introducing a time dimension. As I can see from Section 8.2.2, a DBN creates a BN for each time point, and provides links between these different BNs as time progresses. With this structure, I can begin to see how to create a link between these two modelling methodologies given system dynamics also works on time steps in a similar way.

As I are assessing the validity of linking these two methodologies at this point, I focussed primarily on their more graphical links. If work is to be continued, more substantial work would need to be done on linking the flow rates in a SD model to the probability changes in a DBN. Although, I have begun to explore how this would be done. Additionally, I have focussed on transferring a SD model to a DBN at this stage as I already have a SD model I can work with. Transferring a DBN to a SD model would also be an interesting extension. I first considered how to convert each SD component to a DBN framework, followed by a simple example and finally demonstrate one way I can attempt to transfer my SD model from Chapter 5 to a DBN.

### 8.3.1 Structural Conversion of System Dynamics Components

My first step in defining a conversion from a SD model to a DBN was to understand the types of RVs that will be present in the DBN. I considered three types of RVs to form a direct link with the three primary components in a SD model. Although each type of RV would be represented by its own nodes in the DBN. I define these three types of variable to be primary, secondary and tertiary RVs. While they are characterised by conditional independence statements in the same way, they have very different meanings for the behaviour of the system. Each SD model component (stocks, flows and converters) are associated with a single type of RV. These associations are described below.

#### 8.3.1.1 Primary Random Variables

My first type of random variable are the objects of interest for the model. Each stock in a SD model would be assigned a corresponding primary random variable within the DBN. These primary RVs would be discrete, where the value the RV would take would be a short interval of possible values in the range of the original stock in the SD model. For instance, a SD stock that can take values between 0 and 100 could be split into 10 equal intervals of length 10. It is these intervals that the primary RV would be discrete over. The size of interval would depend on how accurate the model is required to be, but in most cases 10 to 100 intervals should be enough for an informative model.

These primary RVs should be consistent throughout every time step the DBN is defined over (even if the stock is inactive at some points of time), and these form the basis of the DBN. Primary RVs are, or can be, observed in the process. For instance, in my SD model for siting a GDF, the primary RVs would be the number of people holding each opinion in each community (resulting in 30 primary RVs overall - 10 for each community). Define $M$ to be the maximum number of time steps in the DBN (or SD model), then for some

$n \in \{1, ..., M-1\}$ I have that a primary RV at time step $n$ would be connected to the same primary RV at time $n+1$. This allows the previous value of the stock to be remembered.

#### 8.3.1.2 Secondary Random Variables

The next type of random variable defines how likely the primary RVs are to change their current interval. They are essentially the extra information I need to go from time step $n$ to $n+1$, and so would be related to the flow rates from a SD model. Thus each flow from, or into, stocks in the SD model would have an associated secondary RV in the DBN. The secondary RVs would generally be constants defined by additional information in the system (tertiary RVs explained in the next subsection). The precise form of the secondary RVs depends on the level of stochasticity that is introduced to the system.

If the DBN is kept deterministic, as is the case in the SD model, then the secondary RVs would state the associated stock level change precisely. However, if I wanted to introduce stochasticity to the SD model, a secondary RV would contain the information required to define a probability distribution over the state space of the primary RV it is connected to. In practice, secondary RVs are generally not directly observed, as they denote the rate of change of my objects of interest which can often be difficult to measure directly.

#### 8.3.1.3 Tertiary Random Variables

The final type of random variable I introduce to DBNs are tertiary random variables. These contain the extra information required by secondary RVs. Each converter in the SD model would have an associated tertiary RV in the DBN. The form of these tertiary can vary drastically, some could be constants or have defined values at specific time steps (which would be reflected in the DBN), others could be probability distributions. There are likely to be dependencies on primary or tertiary RVs from previous time steps. The tertiary RVs of such a DBN could be a mix of both observable and unobservable RVs. If a converter (or flow and stock) holds a constant value throughout all time steps in the SD model, it is possible to create a less complex DBN by characterising the component by a single 'global' RV as a single node in the DBN which feeds into all time steps from one place. This could help reduce computation issues, given how large a DBN constructed like this could be. Most of the complexity of the system would involve the interactions between tertiary RVs with other tertiary RVs, and the secondary RVs.

Even at this stage I can begin to make some statements about the conditional independencies within a DBN constructed from a SD model. All primary RVs at time step n must be independent from all tertiary RVs given the values (or distributions) of the secondary RVs

at time step n and the primary RVs at time step $n - 1$. There would be far more statements I could make given an actual DBN, but this broad statement characterises the hierarchy of the RVs I have included along the time line of the DBN. How each RV is defined in the DBN would depend on how it is defined in the SD model. However, it may be required to have external input in providing state spaces for some of the primary and tertiary RVs. In particular, where such a state space is not directly clear from the design of the SD model.

### 8.3.2 A Simple Example

To demonstrate how this conversion can be used, I applied it to a very simple system dynamics model where people can only become supportive of the proposal if they are not already. This was a significant simplification of my scenario, and I only use this for illustrative purposes. For this example, I assume that there is a positive influence on those against the proposal from two sources; word of mouth from supporters of the proposal, and consistent positive events from the MRWS Partnership. These two sources define how quickly people move from the 'Against' stock to the 'Support' stock, as seen in Figure 8.3.

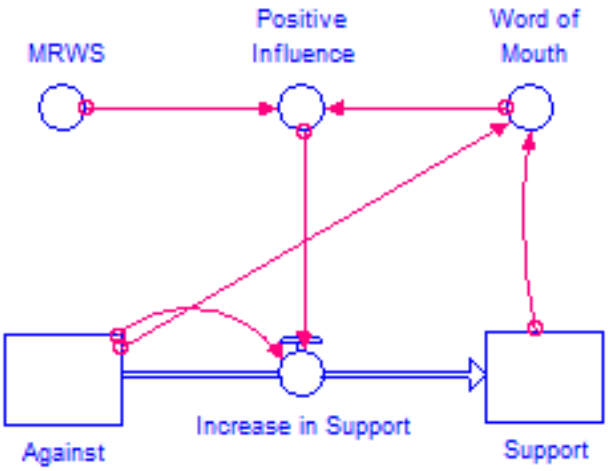



Figure 8.3: Simple system dynamics model for the movement of people according to their opinion of the government GDF siting proposal.

At this point, I are only concerned with the structural conversion to a DBN, and so have not provided additional information on each of these elements. The conversion of flow rates to random variables is explored in the next section. For now, I only consider the movement from the first to second time step. From my definitions in Section 8.3.1, I define 4 primary RVs (2 for each time step), 1 secondary RV (the increase in support flow) and 3 tertiary RVs (the converters in the SD model used to define the flow). The links between these RVs are

consistent with their links in the SD counterparts in Figure 8.3. These RVs are represented in the BN shown in Figure 8.4.

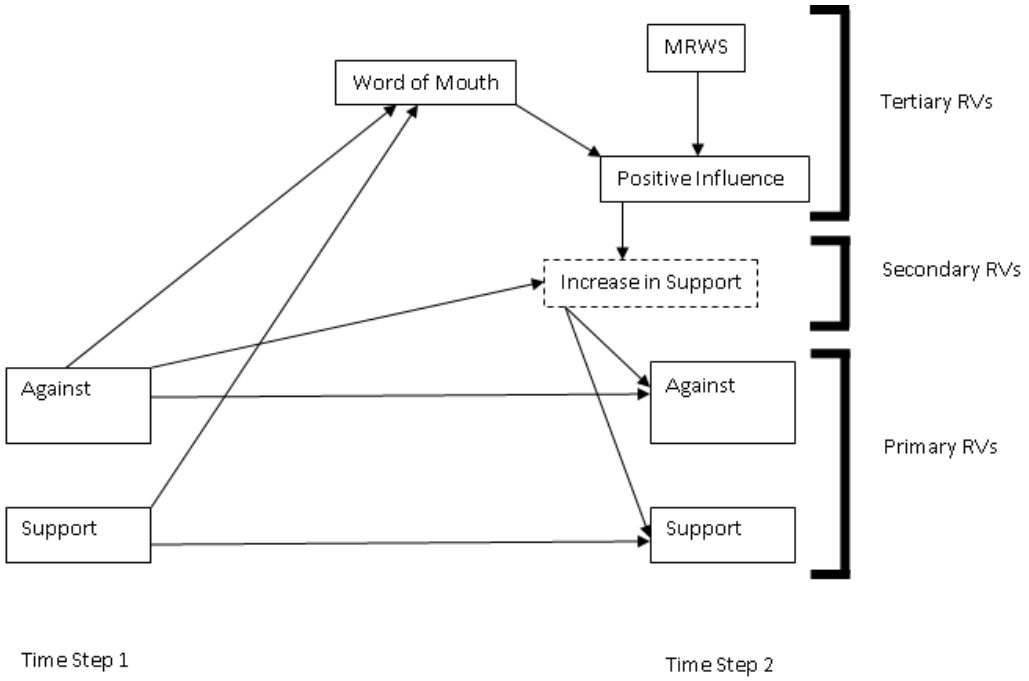



Figure 8.4: The conversion of the SD model shown in Figure 8.3 to a DBN. This DBN has only been shown over two time steps.

Extending Figure 8.4 to the higher number of time steps I considered in my original SD model can be achieved by repeating this same set of RVs for each time step, while keeping the links consistent between time steps with those seen between time steps 1 and 2. Despite this structural conversion being quite simple, I can draw several statements from Figure 8.4 that could be useful to provide to experts when validating the SD model. For instance, I could check the conditional independency statements on the 'Word of Mouth' and 'MRWS' RVs. One such question for an expert could be 'If I have a current estimate for the positive word of mouth effect, does knowing the current support levels of the proposal provide no additional information on the overall current positive influence?'. I would expect the answer to this question to be yes (according to the links shown in Figure 8.4). However, if the expert suggests this statement is not correct. I would need to consider adding links directly between the 'Positive Influence' and current support levels. These are the types of statements that are easy to identify from such BNs.

### 8.3.3 Functional Conversation of System Dynamics Equations

The structural conversion of a system dynamics model was relatively simple to implement. This simple translation to BN highlights clearer methods of validation. However, I considered extending the trend identification and predictive capabilities of system dynamics models. One of the most significant problems with this conversion is the movement from a purely deterministic system, to a probabilistic set of random variables and distributions. Additionally, as I demonstrate later in this section, using discretised intervals to represent a continuous RV (or a near-continuous, e.g. current support level) poses some significant problem either in terms of accuracy or complexity of the model.

My first step is to identify the different ways I can convert the deterministic SD model to a more stochastic setting. If I consider the relationship between stocks and flows (or primary and secondary RVs), the primary RVs must be deterministic in relation to their associated secondary RVs to ensure that flow values are mirrored in both stocks the flow is connected to. This is to help prevent a different amount people moving from one stock as is being received into the destination stock (this problem has also been considered in flow graphs, see Smith & Figueroa 2007). This means that if I are going to introduce additional stochasticity to the system, it must be applied directly to the secondary or tertiary RVs. In the case of tertiary RVs, this would depend on each RV's individual meaning, and its relations within the BN. However, a natural place to introduce stochasticity would be on the secondary RVs (which represent the flow values). This would allow slight randomisation of how many people are moving between stocks while maintaining consistency between stock movements. There are several ways this may be done, and I have presented three of these below.

#### 8.3.3.1 Deterministic

The first method I have considered would be to allow the RV in the BN to behave similarly to its component counterpart in the SD model. In other words, have a nearly entirely deterministic system. I cannot have an entirely deterministic system due to the restrictions required to use RVs with extremely large state spaces. This is because I must create intervals of values instead of recording specific values, and track the movements between these intervals. Doing this does lose the information of where in the interval the current support level is, and so introduces some uncertainty from this. I can reduce this uncertainty by increasing the number of intervals, but this also drastically increases the state space size of the RV which can be difficult to explain to potential users of the model.

If this method is used, then the primary use of the BN model would be providing additional clarity for structural validation, rather than validation of the underlying difference equations

in the SD model. This would also be the simplest type of BN model to build, and could still allow for stochasticity to be introduced in the tertiary RVs to explore the affects they may have (for instance randomised impact of a radiation incident). The relationships between RVs within this type of model would be directly related to the difference equations (and relationships) within the original SD model.

#### 8.3.3.2 Discrete Triangular Distribution

My next method of introducing stochasticity to the secondary RVs would be to use a triangular distribution (or some other higher point distribution) to provide a set of discrete scaled outcomes that are defined from the original flow value. These would represent chances for lower or higher flows than expected to be applied to the stock movements. Suppose that $F_1$ is a secondary RV at time step 1, and that $\mu_1$ is the flow rate at time step 1. An example of how $F_1$ could be defined is given below.

$$F_1(\mu_1) = \begin{cases} \frac{1}{2}\mu_1 \text{ w.p. } \frac{1}{4} \\ \mu_1 \text{ w.p. } \frac{1}{2} \\ \frac{3}{2}\mu_1 \text{ w.p. } \frac{1}{4} \end{cases} \tag{8.2}$$

While the specifics of this type of definition can change on a case by case basis (e.g. the scaling factors or probabilities for each state of the RV), the overall structure allows me to implement some of the unexpected behaviour that cannot be represented well in a SD model. Additionally, these types of distributions are simple to explore theoretically, allowing me to potentially create conditional distributions for experts to assess, providing another method of validation for the original SD model. Although in this case, it must be made clear that the BN has deviated from the SD model in definition. This would need to be explained to any experts presented with probabilities or distributions from the BN representation of the original model.

#### 8.3.3.3 Continuous Distribution

The final type of distribution I considered was to use a continuous distribution to describe the secondary RVs. In particular, I could use a bounded normal distribution (just to ensure non-negativity), and adjustments to stock values can be made using this distribution. Other example distributions that could be used are continuous triangular, gamma or Weibull distributions, although the selection of distribution could be done according to the scenario. The majority of these distributions require more than just a single parameter to define.

How I define a distribution from the single parameter would also depend on the scenario. I would recommend one of three choices: get an expert's opinion on the distribution, approximate the other parameters from the first parameter (e.g. $\sigma_1^2 = \frac{\mu_1}{5}$ or similar), or approximate the other parameters from the distribution of differences between consecutive flow values in the original SD model (this would give an indication of how much the flow value deviates at a time step, however with no indication of the cause of this deviation).

$$F_1(\mu_1) = N_{>0}(\mu_1, \frac{\mu_1}{5}) \tag{8.3}$$

While this method may be a strong choice in terms of capturing stochastic behaviour, it may become difficult to explain to experts when validating the model (e.g. each parameter of the distribution would have its own distribution of values). Thus I have not explored any of my models using continuous distributions. It may add more to the models that must be validated, alongside the original validation tests that are required, without providing much benefit over the simpler discrete triangular distribution.

### 8.3.4 A Simple Example: Revisited

I now continue to explore the example introduced in Section 8.3.2 in more detail. Specifically, exploring how introducing stochasticity has affected the predictive ability of the model, and highlighting and issues from this introduction. I first summarise some of the details of the SD model in Table 8.1. Keep in mind that this example is purely for illustrative purposes and is not meant to be accurate.

| **Component** | **Description** |
|---|---|
| Support (Stock) | 105000 (Initial Value) |
| Against (Stock) | 75000 (Initial Value) |
| Increase in Support (Flow) | Positive Influence$*$Against |
| Word of Mouth (Converter) | $0.5 * (\frac{Support}{Support+Against})$ |
| MRWS (Converter) | 1 (Constant) |
| Positive Influence (Converter) | $(MRWS$ + Word of Mouth$)/100$ |

Table 8.1: Summary of the definitions for the SD model introduced in Figure 8.3.

Using this information, I mapped my SD model to a DBN constructed using the Netica software package, and continued the model for 10 time steps. The discretised intervals I used for each RV was dependent on the purpose of the RV and its range, although I kept

all RVs below 13 intervals each. Additionally, I used the discrete triangular distribution described in Section 8.3.3 to describe stochastic flow rates. The first time step is shown in Figure 8.5.

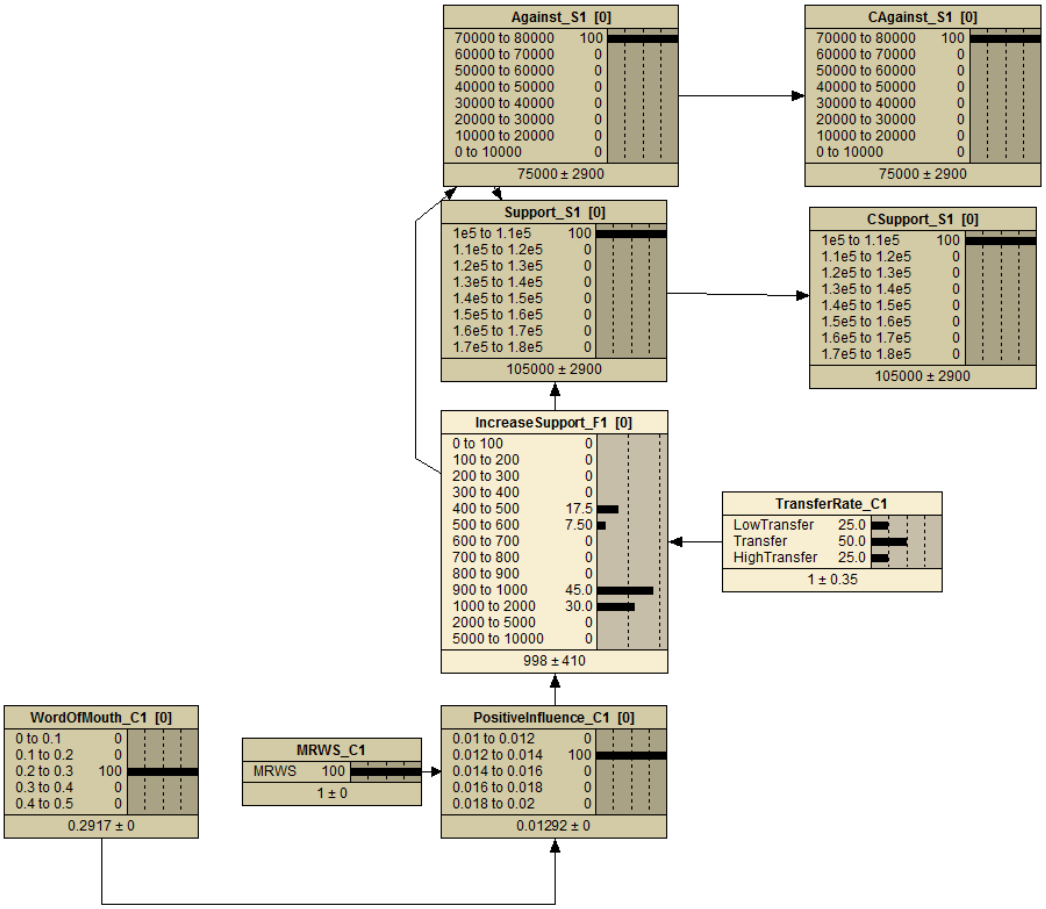



Figure 8.5: The Bayesian Net adaptation of the SD model shown in Figure 8.3. The initial time step is shown.

Each RV I introduced in Figure 8.4 has been allocated a set of intervals which describes the distribution of its current value with the largest number of intervals coming from the secondary RV describing the flow rate (IncreaseSupport). Each interval has a probability next to it representing how likely the RV is to have a value in that interval. At the start of the process, this is fairly simple, but as I progress through time these distributions expand over the possible intervals. The only variability shown at the initial stage is from the flow value (as the discrete triangular distribution is applied at this stage). Note that the 'Against', 'CAgainst' and analogous support RVs are a minor addition to allow Netica to expand the

BN over time more easily (the functionally of the DBN is not changed). This BN is then propagated over an additional 10 time steps to arrive at the conclusion shown in Figure 8.6.

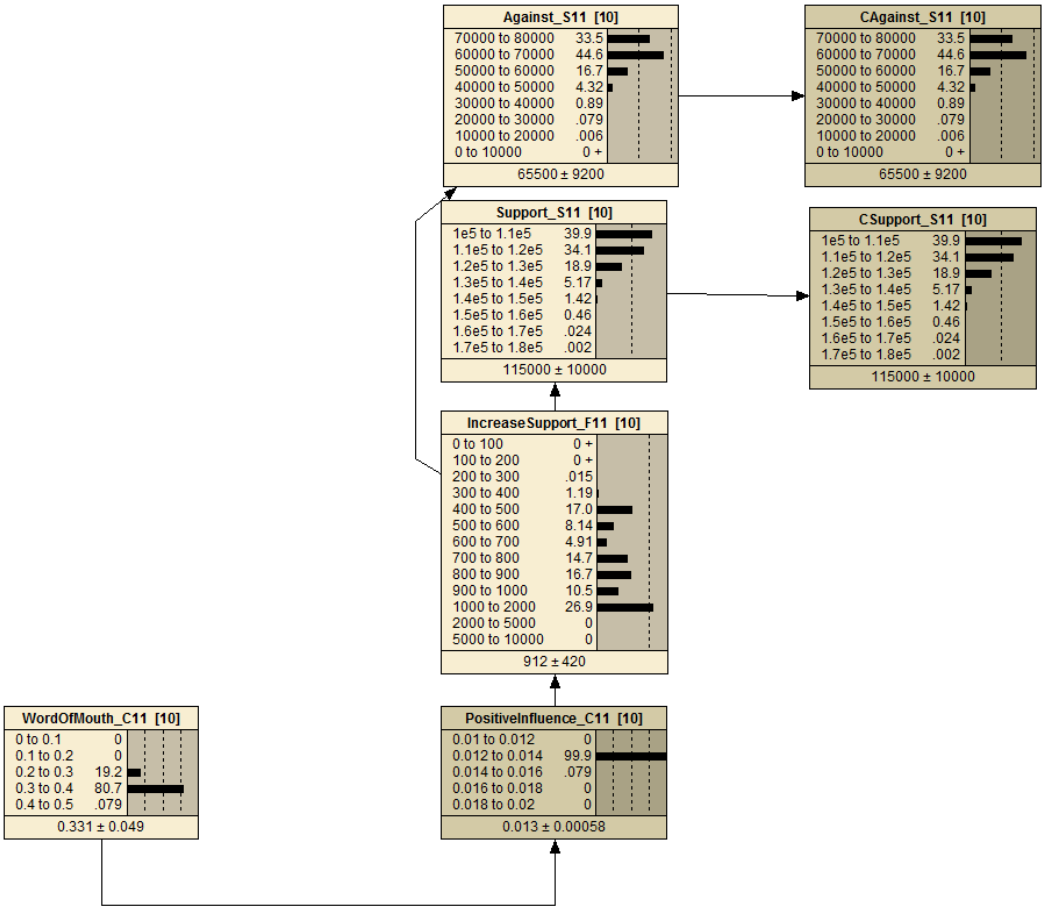



Figure 8.6: The Bayesian Net adaptation of the SD model shown in Figure 8.3. The last time step is shown. Note that the affect of the 'MRWS' RV has been accounted for despite not being shown.

First, I note that my SD model ended with a final value of 113345 in support of the proposal, and 66655 against the proposal. So with this consideration the BN appears to have done a relatively good job of mimicking the behaviour of the SD model given the relatively higher probability of being in the correct interval. However, the inherent uncertainty introduced through using intervals to represent the stock value has had a significant negative affect. In particular, the mean of the support and against distributions in this BN at the final time step are 115000 and 65500. This means the mean total population has grown by 500 due to this uncertainty, and often the exact same changes are not applied to both the Against and Support RVs to keep the total population constant.

This is certainly an issue, particularly when attempting to get experts to validate the model because this sort of inaccuracy would reduce trust in the model. However, a BN model could still spark a discussion of how important it is to include stochasticity in the model and whether it is necessary for their purpose. This is particularly relevant when a model is being used to enhance understanding, rather than as a predictive tool, as this may be able to begin to answer questions on how important stochasticity is to the user's understanding. Additionally, converting a SD model to a BN also allows many conditional independence statements to be identified easily. This can be an invaluable tool to both enhancing understanding, and for structural validation.

This has been a promising start to linking system dynamics and Bayesian networks. However, there were difficulties surrounding the discretisation of near-continuous variables. Even with this drawback, some useful conclusions (and conditional independence statements) could be drawn from the resulting Bayesian network of my system dynamics model presented in Chapter 5. While I have done a basic translation of this model to a Bayesian network, doing a full conversion would be a substantial task due to the number of nodes included in my SD model (30 stocks, 57 flows and a large number of converters). As this task would be better suited to at least one chapter of its own I decided to leave this as potential future work.

### 8.3.5 Dynamic Discretisation of Continuous Random Variables

My work done on translating a simple system dynamics model into a Bayesian network highlighted a major problem for automation of this process moving forwards in the software available to me. This was the problem of taking a continuous (or near-continuous) RV and translating it into discrete intervals for use in a BN. This is not a problem if I only wish to use the BN to draw conditional independence statements (which can be a useful validation tool). However, if I wish to use the strong theoretical structure of a BN for more numerical validation (through providing probability distributions of the changes between stock levels and flow rates), I need to be able to describe each RV accurately enough throughout the process, while maintaining a suitable level of parsimony.

The problem I encountered was that the intervals used for each RV was unsuitable to describe early movements between stocks within the model. Each RV had been limited to 10 intervals to describe its distribution (I thought this was a suitable amount of information for the end of the process). However, as these intervals had to describe all possible values of each stock/flow then much detail of the movements between adjacent time steps was lost, as the intervals are far too large. For example, suppose a number of people holding an opinion is described by the interval (70000, 80000) while the flow value is around 1000 for this time

step. Then in the vast majority of cases no movement will be recorded, as the adjusted value still remains within the large interval of length 10000. This presents difficulty recording the smaller changes of stock levels if I are to keep a relatively low number of intervals for each RV.

A natural step would be to have different intervals for the same random variable at different time steps. For instance, the first movement between opinions is known to have a value less than 5000, and so I could construct 10 intervals between 70000 (the lowest possible number in the against RV after the first time step) and 75000. This reduces interval length from 10000 to 500, giving far more detail with the same number of intervals. This could then be adjusted according to the maximum flow value for each subsequent time-step. Implementing a method such as this is certainly possible by hand (especially when I know the maximum number of people changing opinions given the current system state), however it was not supported by current free software for Bayesian networks available to me, and so was outside of the scope of this thesis. As such there is still a need to implement an automatic version of the dynamic discretisation scaling to these types of software. This would assign shorter intervals where needed in a DBN, while generally increasing intervals size as the total number of movement possibilities increases.

This is a problem that is not new to Bayesian networks, and a variety of work has been done. For instance, Friedman & Goldszmidt (1996) and Friedman et al (1998) suggest methods involving discretised learning in standard BN and parametric and semi-parametric conditional probabilities. Additionally, Kozlov & Koller (1997) suggest a data structure aimed towards reducing information loss from discretisation, and Sudderth et al (2010) explored extensions using non-parametric representations in belief propagation. Norman Fenton has also done a variety of work on dynamic discretisation methods directly (e.g. Fenton et al 2006, Marquez et al 2010, Fenton & Neil 2012). However, sadly none of his results have been incorporated into current free software.

## 8.4 Contributions to System Dynamics

The primary reason to consider BNs in relation to SD is to provide additional verification and validation options for both structural and predictive aspects of the SD model. Verification and validation of models is a vital component to model creation, and having more options may make it easier to perform and report on comprehensive verification and validation studied, and to explain to the uninitiated. Alongside this, I have provided an exploration of ways to evaluate uncertainty and stochastic behaviour in a SD model (which could be used alongside standard analysis using SD models).

The most common link between SD models and BNs is their use of causal loop diagrams for structural definitions. However, there has still been relatively little that actually considers linking the two paradigms (potentially due to the incommensurability between them). For example, Warren (2007) provides a passing remark about the usage of SD for time dependent systems and thus dynamic Bayesian networks could be used for such a system as well. There have also been several constructions of BNs from causal loop diagrams (e.g. Nadkami & Shenoy 2004, 2001), and it a method has also been proposed to construct SD models from similar diagrams (Binder 2004), although the authors do also state the need for additional information to fully characterise the SD model or BN.

This chapter has sought to expand on these current links, and provide a foundation for more in depth studies that seek to explore the benefits of using SD models and DBNs together. I have provided a basic algorithm for the conversion of a SD model into a DBN, along with relevant terminology, and also have provided discussions of how flow rates could be included in the conditional probability distribution dependencies. Additionally, I stated how this transformations from SD to DBN may be useful for structural verification. Finally, I have also identified some areas that would be important to address to be able to explore this link in more detail. For instance, the issue of dynamic discretisation of continuous random variables.

# Chapter 9

# Conclusion

## 9.1 Overview

This thesis sought to explore the area of group and societal decision making, and some of the common modelling paradigms used to assist decision makers (either to enhance understanding or serving as a vehicle to compare potential alternatives). My first area of exploration was utility theory. More specifically, I investigated measurements of influence within groups that have used both individual utilities and group utility functions for decision making. I adapted results used to measure influence in regression (Cook's Distance), and explored the suitability of a set of distance measures between vectors that can resemble discrete probability distributions. This exploration led me to suggest the cosine divergence measure for use in my influence measure. This was selected after comparing the false positive and true positive rates in a large-scale randomised study of hypothetical groups. I also adjusted my influence measure to take account of the number of attributes and size of the group, which allowed for a more generalisable measure.

Additionally, I explored a sub-group identification method on groups under the same assumptions. I adapted the well known $R^2$ value from regression, to indicate how well the sub-group's beliefs can explain the whole groups beliefs. This was also tested on similar large-scale randomised studies to ensure a generalisable method. Finally, I applied both my influence measure and sub-group identification method to a data set collected on the siting of a new nuclear facility. The results were promising, as it identified behaviour such as misunderstanding the elicitation method used, biases from demographics and could relatively accurately group together participants with similar demographics from their individual utility functions. However, I decided that the assumptions required for this type of paradigm are unrealistic given the amount of independent elicitation required from each group member.

This led me to explore modelling paradigms from simulation (system dynamics and discrete event simulation) in a more specific scenario on a societal level. I modelled the geological disposal facility siting process in Cumbria between 2009 to 2013 (introduced in Chapter 4). The first simulation modelling paradigm explored was system dynamics, and my initial plans for the model were altered after a discussion with field experts, who felt it was not truly representative of how they viewed the process. These suggestions were used to construct my current system dynamics model for the Cumbrian siting process. Both of these models can be seen in Chapter 5. I found that my current model was robust to changing assumptions of the system, such as how quickly people changed opinions. Also the model was predictively quite accurate for public support. However, system dynamics was quite an abstract application for this area, and could be difficult to explain to potential users. Additionally, the nature of system dynamics makes it extremely difficult (or impossible) to track individuals through the system, which would be of great interest. This, along with its deterministic nature, led me to explore how to best introduce stochasticity to my model.

I constructed an analogous model using discrete event simulation, as seen in Chapter 6. There were a variety of components that saw an introduction of stochastic behaviour. The most important of these areas was how long an individual would hold a specific opinion, and the probability distribution they would use to choose a new opinion. The overall structure, however, remained similar to my system dynamics model to allow for a simpler comparison of the two paradigms. This stochastic model also proved to be robust a variety of assumptions on individual behaviour and starting states of the three communities. Additionally, the ability to provide a measure of uncertainty for predictions (which continued to be relatively accurate for the data available) was a significant improvement over system dynamics. In particular, it would be simpler to explain this discrete event model to a potential user. This is because it appears closer to their view of the system, and the higher familiarity with discrete event simulation over system dynamics for potential users.

Each of these models have their strengths and weaknesses, both when building the model initially and for explanation to an audience less familiar with modelling techniques. I sought to explore these differences in the hopes of providing a recommendation of which model to use in this specific scenario, and some more general comments on the comparison of each of these paradigms. This can be seen in Chapter 7. I ranked each paradigm both more generally, and for this scenario, according to a set of attributes I considered important when selecting a paradigm (construction style, flexibility, ease of use, validation and complexity). Additionally, I explored how each model responded to a selection of scenarios that could have been of interest to potential users of the model. I highlighted how each model had been constructed differently, and to what extent this was based on the paradigm used.

Finally, I provided a recommendation for the discrete event simulation model to be used for the scenario I reviewed, although the purpose of the model would need to be taken into account (for example prediction versus trend identification).

In Chapter 8 I introduced another modelling paradigm known as Bayesian networks, and explored how these could be linked to system dynamics models in the hopes of providing additional methods of validation. The strength of Bayesian networks was with the clarity of statements that could be produced, that can be checked by experts. In particular, I can structurally validate a system dynamics model by presenting experts with a set of conditional independence statements to ensure no dependencies had been included in the model which should not have been. I encountered a problem when attempting to provide similar statements for the functional validation of a system dynamics model. More specifically, the discretisation of near-continuous stock and flow levels for the Bayesian network resulted in too much information loss. This has been an open problem within Bayesian networks, and while solutions have been suggested for dynamic discretisation, they have not been implemented into automatic procedures for the software available to me yet. The main insights by chapter are summarised in Table 9.1 below.

| Chapter | Insight & Contributions |
|---|---|
| 3 | Techniques were presented for identifying influential group members and sub-groups in a group decision making setting. These were tested against large randomised studies, and for a specific scenario seeking public opinion for future Nuclear facility siting. |
| 4 | The unsuccessful Cumbrian siting process between 2009 and 2013 was discussed. Literature and sources were reviewed to provide a foundation that the SD and DES models of Chapters 5 and 6 could be built from. |
| 5 | A SD model was constructed and documented for the Cumbrian siting process. The deadline extension was explored, and it the model supported the hypothesis that this extension could have biased the process. |
| 6 | A DES model was constructed and documented for the Cumbrian siting process. Additional sensitivity analyses and tests for robustness were performed given the more stochastic nature of the DES model. The conclusions of the DES model further supported the conclusions from Chapter 5. |
| 7 | The SD and DES models were compared according to 3 alternate scenarios: no Fukushima, shifted deliberation structure, and Hinkley Point construction cancellation. Both models showed similar trends for each scenario, and it was concluded that the DES model was preferable due to the inherent stochasticity. |
| 8 | Bayesian networks are considered as an extension to standard simulation methodologies. Foundational work is performed to use DBNs as an additional validation tool for SD models, and initial problem structure is discussed. Also, issues were identified when moving from a deterministic SD to the stochastic DBN. |

Table 9.1: Summary of the main insights by chapter.

## 9.2 Objectives

In Chapter 1 I provided a set of five objectives to explore throughout the thesis. Each of these objectives was broadly focussed on enhancing understanding of a selection of modelling paradigms. In general, I believe this thesis has met each of these objectives. Although I have recalled each objective in this section and provided a description of how I met the objective and any issues that arose when exploring associated topics.

**Objective 1** *Explore past structures of decision support processes and several potential decision structure candidates for application to my area of interest in modelling public participation.*

The aim of my first objective was to provide a strong foundation of knowledge required for my other objectives and aiding my modelling choices. I explored the history of decision support processes (and some of the issues facing their use) in Chapter 2, and analysed a selection of candidates for decision structures both in Chapter 2 (utility theory) and in Chapter 4 (system dynamics, discrete event simulation, agent-based modelling and hybrid modelling). I found the research done in these areas very helpful in the selection of modelling paradigms, and mitigating against common issues that arise when providing decision support to groups (for instance group characteristics and influential members).

Examples of this can be seen in both my measures for utility-based decision making (through normalising for group characteristics such as size and attribute number), and in the initial construction and adaptation of my simulation models (ensuring a clear objective for each model and understanding the limitations of each paradigm). While a more substantial review of the literature is always possible, in my opinion I have comfortably met what I set out to do with this objective through both the breadth and depth of the literature reviewed primarily in Chapters 2 and 4. I have enhanced my knowledge of the area to the point where I can compare a set of modelling paradigms (and the models produced) in Chapter 7. This allowed me to provide a recommendation and ranking of each paradigm according to a set of attributes I considered important.

**Objective 2** *Understand where the ideas of influential individuals, groups or scenarios would fit into each of these decision structures, and where appropriate develop new methodologies to provide a measure of this influence.*

With the strong foundation of knowledge provided through my first objective, I considered influence in the methodologies that I had identified and decided to pursue in more detail. The most natural application of this was to groups that decided to use a mix of both individual and group utility functions to assist the decision making process. In particular, I

developed a measure that, when applied to the individual attribute weights (and group decision rule), would provide a value indicating how much potential influence an individual could have exerted over the group. My definition of potential influence is key here, see Chapter 3 for review. This was found to be effective at identifying individuals that were attempting to influence the group in my randomised studies, and in my real data set. However, there was a problem in that influence is often exerted over other individual's utilities rather than their own, and assuming the group functions the same with an individual removed is far-fetched in many scenarios. It did however provide a start to measuring influence in this area, and could be used ad hoc to analyse such decisions.

Additionally, I explored the identification of sub-groups under the same assumptions. This proved to be quite effective at identifying a selection of individuals in the group that could be secretly collaborating. This can also be seen when it was applied to the data set on nuclear facility siting. I could identify groups of people with similar demographics by their individual utility functions. These two measures were my primary work towards meeting this objective. I also considered influence in the simulation modelling paradigms. However, my original measures were unsuitable to be adapted to these paradigms due to the assumptions of a probability distribution (and the lack of utilities). I did, however, explore if changes in flow rates between scenarios could be used as a proxy to identify influential scenarios in my original system dynamics model. While it could to some extent, this type of result was not particularly useful in practice. So, while I attempted to explore this objective in simulation modelling paradigms, I considered it not worth the additional work at the time to develop an entirely new influence measure and definition of influence. Often users of a model would explore the influence of a scenario by observing the simulation rather than consulting a numerical value.

**Objective 3** *Apply each decision structure considered to data or a real-life scenario related to public participation in nuclear facility siting.*

My third primary objective aimed to explore the potential applications of each decision structure to the specific case of nuclear facility siting. In particular, I wanted to understand which would be most applicable to a real-world scenario. To help answer this question for my simulation modelling paradigms, I appealed to the specific example of the Cumbrian siting process introduced in Chapter 4. I found that my measures in utility theory could have been used to enhance the design of the survey conducted (for instance a lack of understanding of the elicitation methods) and could identify groups of people with similar demographics. This could be useful for exploring potential outliers or for follow up studies. However, the main problem was that this type of survey is quite rare, and requires a lot of

engagement and understanding on the side of the participant.

Applications of simulation modelling paradigms were quite reassuring in terms of potential future applications and ease of use. In particular, I explored how changing the public participation process during the Cumbrian siting process could have biased the process. My models provided a vehicle to do a variety of scenario analysis to understand the 'best' participation process design, and each model could be easily generalisable to a variety of public opinion based scenarios. Additionally, I explored a question that had been hypothesised surrounding the Cumbrian siting process: had the council decision deadline extension at the end of the process biased the result? My models were able to explore a variety of scenarios surrounding this question, and can begin to provide some evidence towards the deadline extension having biased the process. Each of these applications has been insightful to me, and I hope can demonstrate some of the versatility of each of these decision structures considered.

**Objective 4** *Evaluate the differences of these decision structures with regards to these applications.*

For my fourth objective, I aimed to explore some of the differences observed between the decision structures considered. Most of my exploration focussed on the differences between system dynamics and discrete event simulation, as seen in Chapters 4 and 7. However, I have considered some of the benefits for using simulation methodologies over utility theory at the end of Chapter 3 and in Chapter 4. In Chapter 7, I considered the differences between the paradigms on two levels. The first was a more general level, considering the common uses of each paradigm and how suitable they are for these uses. This initial comparison highlighted the differences in levels of abstraction between the two paradigms. System dynamics tended to be at a higher level of abstraction and was more concerned with aggregate movements. Discrete event simulation was usually more focussed on the behaviour of individual units within the model rather than aggregate movements.

The second was more specific to my models, where I considered how each model responded to differing scenarios. For instance, I explored a scenario where Fukushima did not happen during the Cumbrian siting process, or if the public deliberation process had been shifted by 6 months. From this, I found that the deterministic nature of my system dynamics model made it more sensitive to these types of changes, although the same changes were generally reflected in both models. Both of these comparisons highlighted the importance of understanding the requirements for the model. Predictive power is not always the primary goal (which discrete event simulation appeared to have the edge in). Sometimes other characteristics can be more important such as trend identification (which both models could be used

for). The understanding of these different goals was one of the main conclusions I drew from this objective.

**Objective 5** *Consider evolutions of these decision structures that use a strong probabilistic model such as a Bayesian Network.*

My final objective was quite open-ended as I wanted to leave room for further work in this area. I decided to consider using Bayesian networks due to their strong theoretical underpinnings, perhaps opening the way to either some more informative models or additional validation methods. My contributions towards this objective are given in Chapter 8. I sought to link system dynamics models to an analogous Bayesian network. With the link established, I hoped that I could draw various conditional independence statements and probability distributions from the Bayesian network that could be presented to experts. This gives benefits over working directly with the system dynamics model, due to the clarity that the theoretical structure of a Bayesian network can provide.

There would hopefully be less misinterpretation of such conditional independence statements (particularly relevant when validating independently with several experts), and so making validation a slightly easier process at the cost of having to move between two different modelling paradigms. My initial results on this were promising on the structural level. However, when I considered the conditional probability distributions defining the Bayesian network, the discretisation of near-continuous variables caused a large amount of information loss. While this problem could be addressed by hand, the procedures had not been automated in the software I had available to me. If the process was automated, I could also automate the translation of a system dynamics model to a Bayesian network.

## 9.3 Further Work

While I have conducted research into several areas throughout this thesis, there are always places that more research could be done. In this section, I present a selection of extensions that I would be interested in pursuing given more time. Each of these avenues are generally quite broad in scope and show some of the further work that could be done in this area.

### 9.3.1 Bayesian Networks in Hybrid Models

The first extension to my work is to incorporate Bayesian networks in a natural way in the common simulation methodologies as a hybrid model. Ideally the characteristics of a Bayesian network would lead it to be a fully incorporated model within a simulation model. When the simulation model needs to identify or resolve a probability distribution,

it could evaluate this using a Bayesian network. Not only would this make construction of complex stochastic elements simpler (due to considering conditional probabilities), it would have significant benefits in terms of model validation and clarity. This is due to the very structured nature of Bayesian networks, which can produce statements that are relatively easy to understand and check.

An example of how I could have used this is for my discrete event simulation model. When an individual leaves an opinion state, they must choose their next opinion state according to some probability distribution. The selection of this probability distribution could have been done via a Bayesian network. This would make it easier to demonstrate the variables that determine an individual's probability distribution for their next opinion state. However, the main problem I saw was that a hybrid model created in such a way was considerably slower than the original model, particularly in my case where there were a large number of opinion changes occurring during the simulation. This could be improved in some cases by implementing the defining equations of a Bayesian network directly into the original simulation model, thus reducing any interfacing between two pieces of software. However, this could be an interesting avenue of research that is particularly relevant at the moment with the growing interest in hybrid modelling.

### 9.3.2 Continuous Variable Discretisation

Another potential extension of my work is to continue to improve the link between system dynamics models and Bayesian networks. Chapter 8 suggested a major roadblock that discretisation caused to be able to create a automated link between these two paradigms. In particular, it would be of interest to develop an automatic discretisation method that scales dynamically with the need of the Bayesian network. This could be done by fixing the number of discretisation intervals for each random variable. However, the length of each interval would dependent on the maximum possible number at that time step for the random variable. This would be calculated from the maximums and minimums of all variables that affect the value of the original variable. While this would be a relatively rudimentary method, it would encapsulate the majority of the behaviour I would expect from the Bayesian network while keeping information loss to a bare minimum.

If this was done, it could be possible to provide additional validation options for the original system dynamics model based on the probability distributions of its associated Bayesian network. Additionally, dependent on how the Bayesian network was defined, it could introduce an uncertainty measure to a previously deterministic system. For example, I could have a probability distribution over a pre-defined number of intervals that represents how much public opinion may have changed over the four year period.

### 9.3.3 Agent Based Modelling

As mentioned in Chapter 4, agent based modelling would have been a natural paradigm to choose for modelling opinion change. However, I did not have enough data to validate a model constructed in this way. Using agent-based modelling would be a natural choice, as I could allow each individual use their own history to influence their decisions rather than a set of pre-defined rules in either of the models I presented in this thesis. It could therefore be worthwhile to take the time to collect the additional data needed to produce an agent based model that could be validated fully.

This would also naturally link to my first extension on including Bayesian networks in standard simulation paradigms. Agent based modelling would fit well with using Bayesian networks to model the stochastic nature of individuals in the system, while the over-arching agent based model keeps track of each individual and their history. The process of data collection and model construction would likely be quite lengthy, however could lead to an insightful model that would closely align with any potential user's interest in individual behaviour. One question that could be answered by a model such as this would be: how much do I need to spend on the deliberation structure to change the opinion of this specific person?

## 9.4 Concluding Remarks

Throughout this thesis I explored a variety of modelling paradigms, and some of the strengths and weaknesses of each. Utility theory has a very strong theoretical basis, however is generally difficult to do in practice. The idea of hidden influence or deception can hold back the success of a group meeting, especially when there are competing parties involved in the decision making process. I have suggested two new technologies in this area that can help build trust in this decision structure and reduce uncertainty when making decisions in groups. The main drawbacks of this decision structure is the requirement of a large amount of interaction and participation from each group member individually.

Alongside this, I explored a set of models for the Cumbrian siting process. These were built using system dynamics and discrete event simulation. Each models performed well according to the data available to me, and can provide a basis to explore the impacts of different deliberation structures. Each of my models is generalisable to other scenarios where public opinion is of concern, and could be used to aid in the planning for long and costly processes, such a facility siting. Additionally, I could explore the question of whether the previous Cumbrian siting process had been biased due to the deadline extension. In this

case it looks like the deadline extension may have indeed biased the process. This is useful to know moving forward given the UK government is currently in the process of planning another public deliberation for geological disposal facility siting.

My final contributions were to contrast the two simulation modelling paradigms that I considered, and have provided a set of scores for each on five characteristics. Additionally, I explored these differences in practice by conducting a explorative analysis of each model's response to a variety of scenarios of interest. Finally, I have suggested additional validation methods for system dynamics models that could be used by creating a link to Bayesian networks. Currently only structural validation is possible using the work presented. However, functional validation may also be possible in the future with more developments in dynamic discretisation of continuous random variables. The work done in preparation of this thesis has been invaluable to me, and has given a much greater understanding of the variety of modelling paradigms available, alongside the common problems and strengths seen in each paradigm.

# Appendix A

# Chapter 3 Proofs

## A.1 Theorem 1

First consider the permutability of any two individuals $i_1$ and $i_2$ and assume that $\mathbf{u}*$ is another set of utilities where $\mathbf{u}_{i_1} = \mathbf{u}_{i_2}*$, $\mathbf{u}_{i_2} = \mathbf{u}_{i_1}*$ and $\mathbf{u}_i = \mathbf{u}_i*$ for $i = 1, ..., N$ with $i \neq i_1, i_2$.

From the permutability of $i_1$ and $i_2$ it should not matter where one of the individuals are within the group before being removed, so we have that;

$$D(\mathbf{u}_G, \mathbf{u}_{G_{-i_1}}) = D(\mathbf{u}_G*, \mathbf{u}_{G_{-i_2}}*) \tag{1.1}$$

Where $\mathbf{u}_G = \sum_{i=1}^{N} w_i \mathbf{u}_i$ and $\mathbf{u}_{G_{-i_1}} = \sum_{i=1, i\neq i_1}^{N} \tilde{w}_i \mathbf{u}_i$ with $w_i$ and $\tilde{w}_i$ being the weight and adjusted weight (different group size) assigned to individual i respectively.

**Case 1: Equal weights**

Assume $w_i = N^{-1}$ and $\tilde{w}_i = (N-1)^{-1}$. Then from (1.1) we require;

$$D(N^{-1} \textstyle\sum_{i=1}^{N} \mathbf{u}_i, (N-1)^{-1} \sum_{i=1, i\neq i_1}^{N} \mathbf{u}_i) = D(N^{-1} \sum_{i=1}^{N} \mathbf{u}_i*, (N-1)^{-1} \sum_{i=1, i\neq i_2}^{N} \mathbf{u}_i*) \tag{1.2}$$

Considering each summand separately we know from our definition of $\mathbf{u}*$ that $\mathbf{u}_i = \mathbf{u}_i*$ holds for $i \neq i_1, i_2$, so for (1.2) to hold we need that $\mathbf{u}_{i_2} = \mathbf{u}_{i_1}*$ which is true from the definition of $\mathbf{u}*$.

**Case 2: Unequal weights**

We proceed through proof by contradiction. Assume that $w_{i_1} \neq w_{i_2}$. By the permutability of $i_1$ and $i_2$ we know that;

$$D(\textstyle\sum_{i=1}^{N} w_i \mathbf{u}_i, \sum_{i=1, i\neq i_1}^{N} \tilde{w}_i \mathbf{u}_i) = D(\sum_{i=1}^{N} w_i \mathbf{u}_i*, \sum_{i=1, i\neq i_2}^{N} \tilde{w}_i \mathbf{u}_i*) \tag{1.3}$$

Similarly to in (1.2) we know that each summand for $i \neq i_1, i_2$ must be equal, and so we only need to show that $w_{i_2}\mathbf{u}_{i_2} = w_{i_1}\mathbf{u}_{i_1}*$. We know that $\mathbf{u}_{i_2} = \mathbf{u}_{i_1}*$ from the definition of $\mathbf{u}*$, however our assumption was that $w_{i_1} \neq w_{i_2}$ and so we arrive at a contradiction. Therefore we cannot have permutability with unequal weights.

## A.2 Theorem 2

Assume for two individuals $i_1$ and $i_2$ we have that $w_{i_2} > w_{i_1}$ and $\mathbf{u}_{i_1} = \mathbf{u}_{i_2}$. We want to show that;

$$C_{i_2}(\mathbf{u}, G) > C_{i_1}(\mathbf{u}, G) \tag{2.1}$$

Due to the construction of $C_i(.,.)$ we can remove any normalisation terms and the problem is simplified to showing;

$$D(\mathbf{u}_G, \mathbf{u}_{G_{-i_2}}) > D(\mathbf{u}_G, \mathbf{u}_{G_{-i_1}}) \tag{2.2}$$

As $D(.,.)$ is our distance measure and is increasing in divergent arguments, so it suffices to show that $\mathbf{u}_{G_{-i_2}}$ has moved further than $\mathbf{u}_{G_{-i_1}}$. Note that we mean moves further in all attributes here, as both $i_1$ and $i_2$ have the same utility functions and that $\tilde{w}_i = w_i \frac{N}{N-1}$ denotes the weight adjusted for group size.

$$\mathbf{u}_{G_{-i_1}} = \sum_{i=1, i\neq i_1}^{N} \tilde{w}_i \mathbf{u}_i = \sum_{i=1, i\neq i_1, i_2}^{N} \tilde{w}_i \mathbf{u}_i + \tilde{w}_{i_2}\mathbf{u}_{i_2}$$
$$\mathbf{u}_{G_{-i_2}} = \sum_{i=1, i\neq i_2}^{N} \tilde{w}_i \mathbf{u}_i = \sum_{i=1, i\neq i_1, i_2}^{N} \tilde{w}_i \mathbf{u}_i + \tilde{w}_{i_1}\mathbf{u}_{i_1}$$

We know that $\tilde{w}_{i_2}u_{i_2} > \tilde{w}_{i_1}u_{i_1}$ from our assumptions that $w_{i_2} > w_{i_1}$ and $\mathbf{u}_{i_1} = \mathbf{u}_{i_2}$ implying that $\mathbf{u}_{G_{-i_2}}$ has moved further from the group utility $\mathbf{u}_G$ than $\mathbf{u}_{G_{-i_1}}$, and so necessarily we have that (2.2) holds which implies (2.1) holds.

## A.3 Theorem 3

### Case 1

Suppose $\mathbf{u}_1 = (u_1^{(1)}, u_1^{(2)}, ..., u_1^{(K)})$ with $u_i^{(j)} > 0$ for $j = 1, ..., K$ and that $u_G^{(2)} < u_G^{(l)}$ for $l = 3, ..., K$. We wish to influence individual 1's utility for attribute 1 at the expense of attribute 2. Set $\mathbf{u}_{1,1}* = (u_1^{(1)} + L, u_1^{(2)} - L, ..., u_1^{(K)})$, where
$L < min(1 - u_1^{(1)}, u_1^{(2)})$. Then we have the group utility functions given by;

$$\mathbf{u}_G = \sum N^{-1} u_i$$

$\mathbf{u}_{G,1}* = \sum_{i=2}^{N} N^{-1}u_i^{(1)} + N^{-1}u_{1,1}*.$

Clearly the group utilities for attributes $3, ..., K$ will remain the same, so we only need to consider attributes 1 & 2. For attribute 1 we have that;

$u_{G,1}^{(1)}* = \sum_{i=2}^{N} N^{-1}u_i^{(1)} + N^{-1}(u_i^{(1)} + L).$

From this expression we can see that $u_{G,1}^{(1)}* = u_G^{(1)} + \frac{L}{N}$ and in a similar way we can derive that $u_{G,1}^{(2)}* = u_G^{(2)} - \frac{L}{N}$. Now consider the impact this has on the KL divergences when comparing the two group utilities.

$D(\mathbf{u}_G, \mathbf{u}_{G,1}*) = u_G^{(1)} log(\frac{u_G^{(1)}}{u_G^{(1)} + \frac{L}{N}}) + u_G^{(2)} log(\frac{u_G^{(2)}}{u_G^{(2)} - \frac{L}{N}})$

We now take the derivative of this with respect to L to give us a basis to compare against case 2;

$$\frac{dD(\mathbf{u}_G, \mathbf{u}_{G,1}*)}{dL} = -\frac{u_G^{(1)}}{(Nu_G^{(1)} + L)} + \frac{u_G^{(2)}}{(Nu_G^{(2)} - L)} \tag{3.1}$$

It is worth noting that we can see that the distance measure is increasing in L as we might expect.

**Case 2**

Now we repeat these same steps for case 2, where influence is introduced such that $\mathbf{u}_{1,2}* = (u_1^{(1)} + L, u_1^{(2)} - \frac{L}{K-1}, ..., u_1^{(K)} - \frac{L}{K-1})$, where $L$ is defined similarly as before. Redoing the same calculations we get that $u_{G,2}^{(1)}* = u_G^{(1)} + \frac{L}{N}$ as before and $u_{G,2}^{(j)}* = u_G^{(j)} - \frac{L}{N(K-1)}$ for $j = 2, 3, ..., K$. If we then consider the impact this has on the KL Divergence, we have;

$D(\mathbf{u}_G, \mathbf{u}_{G,2}*) = u_G^{(1)} log(\frac{u_G^{(1)}}{u_G^{(1)} + \frac{L}{N}}) + \sum_{j=2}^{K} u_G^{(j)} log(\frac{u_G^{(j)}}{u_G^{(j)} - \frac{L}{N(K-1)}})$

$$\frac{dD(\mathbf{u}_G, \mathbf{u}_{G,2}*)}{dL} = -\frac{u_G^{(1)}}{(Nu_G^{(1)} + L)} + \sum_{j=2}^{K} \frac{u_G^{(j)}}{(N(K-1)u_G^{(j)} - L)} \tag{3.2}$$

**Comparison of the cases**

The first point we note when comparing equations (3.1) and (3.2) is that first term (relating to attribute 1) is the same for both cases, and so we can ignore this term for now for the purposes of comparison of the two expressions. We aim to show that;

$\frac{u_G^{(2)}}{(Nu_G^{(2)} - L)} > \sum_{j=2}^{K} \frac{u_G^{(j)}}{(N(K-1)u_G^{(j)} - L)}$

Let $u_G^{(-)} = min(u_G^{(2)}, u_G^{(3)}, ..., u_G^{(K)}) = u_G^{(2)}$. Then when comparing each element of the summand in (3.2) to $u_G^{(-)}$, we know that;

$$\frac{u_G^{(j)}}{(N(K-1)u_G^{(j)}-L)} \leq \frac{u_G^{(-)}}{(N(K-1)u_G^{(-)}-L)} \text{ for all } j = 2, 3, ..., K.$$

As this holds for all elements of the summation, we have that;

$$\begin{aligned}\sum_{j=2}^{K} \frac{u_G^{(j)}}{(N(K-1)u_G^{(j)}-L)} &\leq \sum_{j=2}^{K} \frac{u_G^{(-)}}{(N(K-1)u_G^{(-)}-L)} = \frac{(K-1)u_G^{(-)}}{(N(K-1)u_G^{(-)}-L)} \\ &< \frac{(K-1)u_G^{(-)}}{(N(K-1)u_G^{(-)}-(K-1)L)} = \frac{u_G^{(2)}}{(Nu_G^{(2)}-L)}\end{aligned}$$

# Appendix B

# SD Model Description

Note that only the objects introduced in each module will be included in the listing, not when a module uses a value from another module.

## B.1 Module Descriptions

### B.1.1 World Conditions

This module records the starting settings for the model for each community and process, and also adjusts current government trust according to recent events.

#### Converters

- Copeland Population - Total number of people eligible to vote within Copeland (69800, 96000 and 329200 for Copeland, Allerdale and the rest of Cumbria respectively).
- Copeland Council  Total number of involved council members representing Copeland (7, 7 and 10 for Copeland, Allerdale and the rest of Cumbria respectively).
- Copeland Interest  The overall interest the Copeland population holds in the proposal. Scale from 0 to 1, with 0 representing no interest and 1 representing very high interest (0.5, 0.25 and 0.35 for Copeland, Allerdale and the rest of Cumbria respectively).
- Copeland Initial Knowledge  Percentage of people within Copeland that would consider themselves to know 'at least a little about the proposal & issue at the start of deliberations (0.65, 0.5 and 0.35 for Copeland, Allerdale and the rest of Cumbria respectively).
- Copeland Initial Opinion  Percentage of people within Copeland that have a positive opinion on the proposal at the start of deliberations (0.57, 0.55 and 0.45 for Copeland, Allerdale and the rest of Cumbria respectively).
- Copeland Initial Neutral  Percentage of people within Copeland that are neutral, or do not know their positions on the proposal at the start of deliberations (0.2, 0.25 and 0.28 for Copeland, Allerdale and the rest of Cumbria respectively).

- These converter related to Copeland are repeated for Allerdale and the Rest of Cumbria.
- Total Population  The total number of people eligible to vote from all three communities.
- Radiation and Government Media Incidents - Smoothed representation of information availability about radiation (such as radiation leaks) or government media (such as related controversial policies) incidents happening that could impact public approval
  - Incident # - The scale of radiation incident # that is included in 'Radiation Incidents'. The scale runs from 1 to 5, with 1 being a very minor incident with little media attention, and 5 being a major incident that is heavily reported on.
  - Time # - The start time since the beginning of deliberations of the associated radiation incident in months.
- Government Trust  provides an estimation of the current trust the public of the area has in the governments ability to fairly represent and follow through with the proposal.
- Initial Government Trust  The initial trust the public has in the government at the start of deliberations (0.3).
- Trust Incident Adjustment  Tracks the adjustment to be made to government trust from incidents for the next time step.
- NIBY  Demonstrates a general aversion to the proposal, with the strength of this aversion being directly correlated to the current government trust.

### B.1.2 Media

This module records the base positive and negative effects of the media, and of word of mouth, on the flow rates for each communitys flow rates.

#### Converters

- Positive  Records the overall percentage of the population that is currently in support of the proposal.
- Negative - Records the overall percentage of the population that is currently resist the proposal.
- Media Positive Influence  Provides an overall measure of the current amount of positive attention the proposal is receiving from both the media and the general public. This is also scaled by current government trust.
- Media Negative Influence - Provides an overall measure of the current amount of positive attention the proposal is receiving from both the media and the general public.  This also has additional influence directly from Radiation and Government Media Incidents.

### B.1.3 Partnership

This module details the positive impacts that the partnership has had on the publics perception of the proposal.

#### Converters

- Minor News Releases  Records the effects of news releases such as e-bulletins and local advertisements
- Major News Releases  Records the effects of high-traffic news releases, usually related to significant events such as government statements or plans.
- Information Packs  Records the effects of newsletters, leaflets and final reports for each of the stakeholder engagement phases. Also includes the effects of the citizens panels held in PSE1.
- Major Events  Records the effects of larger events organised by the Partnership such as residents panels and organisation workshops.
- Minor Events  Records the effects of smaller scale local events during the stakeholder engagement phases.
- Partnership Positive Influence  Totals the positive impact the Partnership is having on the public at that time.

### B.1.4 NGOs

This module details the negative impacts that the NGOs has had on the publics perception of the proposal.

#### Converters

- News Releases  Records the effects of news releases and articles produced by the NGOs
- Partnership Event Attendance  Describes the increased resistance to the proposal by the NGOs during stakeholder engagement phases
- NGO Events  Records the effects of NGO events.
- NGO Negative Influence - Totals the negative impact the NGOs is having on the public at that time.

### B.1.5 Copeland Public Var

Contains the converters describing the flow rates between opinions for Copeland community. There are analogous modules for both Allerdale and the Rest of Cumbria.

#### Converters

- Copeland Knowledge  Contains the current rate of knowledge gain within Copeland

- Copeland Positive Reinforcement  Current level of reinforcement of positive opinion, adjusted for population level.
- Copeland Positive - Current level of transfer to positive opinion from a negative opinion, adjusted for population level.
- Copeland Negative - Current level of transfer to negative opinion from a positive opinion, adjusted for population level.
- Copeland Negative Reinforcement - Current level of reinforcement of negative opinion (or doubt of strong positive opinion), adjusted for population level.

### B.1.6 Copeland Public

Contains all the flows and stocks describing the current opinions of the population of Copeland. Also accounts for the knowledge level in the community. There are analogous modules for both Allerdale and the Rest of Cumbria.

#### Stocks

- Strong Positive Familiar  Current number of people who believe they know at least a little in Copeland that feel strongly positive about the proposal.
- Positive Familiar - Current number of people who believe they know at least a little in Copeland that feel slightly positive about the proposal.
- Neutral Familiar - Current number of people who believe they know at least a little in Copeland that have no strong opinion about the proposal.
- Negative Familiar - Current number of people who believe they know at least a little in Copeland that feel slightly negative about the proposal.
- Strong Negative Familiar - Current number of people who believe they know less than a little in Copeland that feel strongly negative about the proposal.
- Strong Positive Unfamiliar  Current number of people who believe they know less than a little in Copeland that feel strongly positive about the proposal.
- Positive Unfamiliar - Current number of people who believe they know less than a little in Copeland that feel slightly positive about the proposal.
- Neutral Unfamiliar - Current number of people who believe they know less than a little in Copeland that feel slightly negative about the proposal.
- Negative Unfamiliar - Current number of people who believe they know less than a little in Copeland that feel slightly negative about the proposal.
- Strong Negative Unfamiliar - Current number of people who believe they know less than a little in Copeland that feel strongly negative about the proposal.

### Flows

- SP gain The flow rate from Positive Unfamiliar to Strong Positive Unfamiliar
- SP loss The flow rate from Strong Positive Unfamiliar to Positive Unfamiliar
- P gain The flow rate from Neutral Unfamiliar to Positive Unfamiliar
- P loss The flow rate from Positive Unfamiliar to Negative Unfamiliar
- Neu loss The flow rate from Neutral Unfamiliar to Negative Unfamiliar
- Neg loss The flow rate from Negative Unfamiliar to Positive Unfamiliar
- SNeg gain The flow rate from Negative Unfamiliar to Strong Negative Unfamiliar
- SPF gain The flow rate from Positive Familiar to Strong Positive Familiar
- SPF loss The flow rate from Strong Positive Familiar to Positive Familiar
- PF gain The flow rate from Neutral Familiar to Positive Familiar
- PF loss The flow rate from Positive Familiar to Negative Familiar
- NeuF loss The flow rate from Neutral Familiar to Negative Familiar
- NegF loss The flow rate from Negative Familiar to Positive Familiar
- SNegF gain The flow rate from Negative Familiar to Strong Negative Familiar
- SPF The flow rate from Strong Positive Unfamiliar to Strong Positive Familiar
- PF The flow rate from Positive Unfamiliar to Positive Familiar
- NeuF The flow rate from Neutral Unfamiliar to Neutral Familiar
- NegF The flow rate from Negative Unfamiliar to Negative Familiar
- SNegF The flow rate from Strong Negative Unfamiliar to Strong Negative Familiar

## B.1.7 Copeland Council Var

Contains all the flows and stocks describing the current opinions of the council of Copeland. There are analogous modules for both Allerdale and the Rest of Cumbria.

### Converters

- Copeland Positive Records the support of the Copeland population, with a 4 month delay
- Copeland Negative Records the resistance of the Copeland population, with a 4 month delay
- Copeland Trust in Populace Estimates how well the Copeland council believes the community population understands the proposal.

- Council Positive Reinforcement - Current level of reinforcement of positive opinion (or doubt of strong negative opinion), adjusted for council size.
- Council Positive - Current level of transfer to positive opinion from a negative opinion), adjusted for council size.
- Council Negative - Current level of transfer to negative opinion from a positive opinion), adjusted for council size.
- Council Negative Reinforcement - Current level of reinforcement of negative opinion (or doubt of strong positive opinion), adjusted for council size.

### B.1.8 Copeland Council

#### Stocks

- Strong Positive - Current number of council members of Copeland that feel strongly positive about the proposal.
- Positive - Current number of council members of Copeland that feel slightly positive about the proposal.
- Neutral - Current number of council members of Copeland that are undecided or neutral about the proposal.
- Negative - Current number of council members of Copeland that feel slightly negative about the proposal.
- Strong Negative - Current number of council members of Copeland that feel strongly negative about the proposal.

#### Flows

- SP gain The flow rate from Positive to Strong Positive.
- SP loss The flow rate from Strong Positive to Positive.
- P gain The flow rate from Neutral to Positive.
- P loss The flow rate from Positive to Neutral.
- Neu gain The flow rate from Negative to Neutral.
- Neu loss The flow rate from Neutral to Negative.
- SN gain The flow rate from Negative to Strong Negative.
- SN loss The flow rate from Strong Negative to Negative.

The set-up for 'Allerdale Public Var' and Cumbria Public Var' is the same as for Copeland Public Var'. Similarly, the set-up for 'Allerdale Council Var' and Cumbria Council Var' is the same as for Copeland Council Var'.

## B.2 Component Values and Interactions

A general note is that all of the specific values used in the model at the moment are representative of the relative importance of one factor over another (or some slight scaling factors), and so if variable 1 is weighted by a scalar of 2, then that means that assuming the scale of the variable 1 is the same as variable 2 which has a scalar multiplier of 1, then variable 1 should be more important than variable 2 (In that specific model, it is exactly 2x more important, but these values need to be validated first).

### B.2.1 World Conditions

- Radiation and Government Media Incidents - This is given as a smoothed function with increases whenever an incident occurs (as defined by incident # and time #). The increase associated with an incident will take just over a week to get to its full value, and after this, the value will decrease by roughly 75% of its current value for that incident over 3 months, until it eventually hits 0. Note that the effect of multiple incidents can stack up.

- Trust Incident Adjustment holds the value to be subtracted from the government trust converter according to the current value of Radiation and Government Media Incidents. If the value of Radiation and Government Media Incidents is greater than 1.5, then the adjustment value is set to -0.025. Else if the value is greater than 0.5, then the adjustment values is set to -0.01, else the adjustment value is set to 0.

- Government Trust On start-up of the simulation, this converters value is set to equal Initial Government Trust. This is then adjusted multiplicatively by the relative difference between the Partnership and NGO activity at the time (e.g. Initial Government Trust * ((1+Partnership.Partnership Positive Influence/50) / (1+NGOs.NGO Negative Influence/50)). Scaling is also introduced according to the current value of the converter to prevent extreme trust cases that cannot be recovered from (Partnership is weighted heavier when trust is less than 0.3, and NGOs are weighted heavier when the trust is greater than 0.7). Additionally there are checks in place to ensure this value remains between 0 and 1.

- NIBY For the first 6 months, this is 0. After this period, it records as a scaled value of 1-Government Trust. The scaling value depends on the current time in the model. When the month is 6, the value is multiplied by 0.25, whereas after the month is 20 the value is multiplied by 0.5. This demonstrates people becoming more worried as the decision deadline approaches.

### B.2.2 Partnership

- Partnership Positive Influence This is the sum of the 5 other converters in the Partnership module. After month 6, a constant value of 0.25 is also added to this summation.

### B.2.3 NGOs

- NGO Negative Influence This is the sum of the other 3 converters in the NGOs module.

### B.2.4 Media

- Media Positive Influence This is the sum of Partnership.Major Events, Partnership.Major News Releases and other separately defined positive media articles. This summation is then scaled multiplicatively according to the current values of World Conditions.Government Trust and Media.Positive (delayed by half a month).

- Media Negative Influence This is the sum of 2*NGOs.News Release and World Conditions.Radiation and Government Media Incidents. After month 42, a constant value of 0.4 is also added. This is then scaled multiplicatively according to the current value of Media.Negative (delayed by half a month).

### B.2.5 Copeland Public Var

- Copeland Knowledge This is the sum of NGOs.NGO Negative Influence and Partnership.Partnership Positive Influence, divided by 400. This represents the overall current activity in the area, used as a proxy to estimate the gain of knowledge.

- Copeland Positive Reinforcement This is the product of World Conditions.Copeland Interest, Partnership.Partnership Positive Influence and Copelands population, divided by 100.

- Copeland Positive - This is the sum of Media.Media Positive Influence and World Conditions.Copeland Interest*Partnership.Partnership Positive Influence. This is then multiplied by Copelands population, divided by 100.

- Copeland Negative - This is the sum of World Conditions.NIBY, Media.Media Negative Influence and World Conditions.Copeland Interest*NGOs.NGO Negative Influence. This is then multiplied by Copelands population, divided by 100.

- Copeland Negative Reinforcement - This is the product of World Conditions.Copeland Interest, NGOs.NGO Negative Influence and Copelands population, divided by 100.

### B.2.6 Copeland Public

#### Stocks

- Strong Positive and Strong Negative states all have their initial value set to 0.

- Positive Familiar and Unfamiliar The initial values of these states are set as the product of the Copeland population, World Conditions.Copeland Initial Opinion. This value is then multiplied by World Conditions.Copeland Initial Knowledge and (1- World Conditions.Copeland Initial Knowledge) for familiar and unfamiliar states respectively.

- Negative Familiar and Unfamiliar The initial values of these states are set as the product of the Copeland population, (1-World Conditions.Copeland Initial Opinion-World Conditions.Copeland Initial Neutral). This value is then multiplied by World Conditions.Copeland Initial Knowledge and (1- World Conditions.Copeland Initial Knowledge) for familiar and unfamiliar states respectively.

- Neutral Familiar and Unfamiliar The initial values of these states are set as the product of the Copeland population, World Conditions.Copeland Initial Neutral. This value is then multiplied by World Conditions.Copeland Initial Knowledge and (1- World Conditions.Copeland Initial Knowledge) for familiar and unfamiliar states respectively.

### Flows

- SP gain and SPF gain These are equal to Copeland Public Var.Copeland Positive Reinforcement.
- SP loss, SPF loss, SNeg gain and SNegF gain - These are equal to Copeland Public Var.Copeland Negative Reinforcement.
- P loss This is equal to 1.25*Copeland Public Var.Copeland Negative.
- Neg loss This is equal to Copeland Public Var.Copeland Positive.
- PF loss This is equal to Copeland Public Var.Copeland Negative.
- NegF loss This is equal to 1.25*Copeland Public Var.Copeland Positive.
- P gain Before 24 months, this equals Copeland Public Var.Copeland Positive * Neutral Unfamiliar divided by 2 times the Copeland population. After 24 months this expression is multiplied by 4.
- Neu loss - Before 24 months, this equals 1.25 * Copeland Public Var.Copeland Negative * Neutral Unfamiliar divided by 2 times the Copeland population. After 24 months this expression is multiplied by 4.
- PF gain Before 24 months, this equals 1.25 * Copeland Public Var.Copeland Positive * Neutral Familiar divided by the Copeland population. After 24 months this expression is multiplied by 4.
- Neu loss - Before 24 months, this equals Copeland Public Var.Copeland Negative * Neutral Familiar divided by the Copeland population. After 24 months this expression is multiplied by 4.
- SPF, PF, NeuF, NegF and SNegF These are all equal to Copeland Public Var.Copeland Knowledge multiplied by the current value of the stock the flow comes from.

## B.2.7 Copeland Council Var

- Copeland Trust in Populace This is set to Results.Copeland Familiar, delayed by 4 months, divided by the total population of Copleand. In other words, the percentage of knowledgeable people in Copleand 4 months prior.
- Copeland Positive Reinforcement This is the product of Partnership.Partnership Positive Influence, (0.5+Copeland Trust in Populace*Copeland Positive/2) and the number of council members, divided by 10.
- Copeland Positive - This is the sum of 0.5* Media.Media Positive Influence and 2*Partnership.Partnership Positive Influence. This is then multiplied by (0.5+Copeland Trust in Populace*Copeland Positive/2) and the number of council members, divided by 5.

- Copeland Negative - This is the sum of World Conditions.NIBY, 0.5*Media.Media Negative Influence and NGOs.NGO Negative Influence. This is then multiplied by (0.5+Copeland Trust in Populace*Copeland Negative/2) and the number of council members, divided by 5.
- Copeland Negative Reinforcement - This is the sum of 1.25*World Conditions.NIBY and 0.75*NGOs.NGO Negative Influence. This is then multiplied by (0.5+Copeland Trust in Populace*Copeland Negative/2) and the number of council members, divided by 10.

### B.2.8 Copeland Council

Stocks:

- Stong Positive, Positive, Negative and Strong Negative all have their initial value set to 0.
- Neutral The initial value of this stock is set to equal the number of council members.

Flows:

- SP gain and SN loss These are set to Copeland Council Var.Council Positive Reinforcement.
- SP loss and SN gain These are set to Copeland Council Var.Council Negative Reinforcement.
- P gain and Neu gain These are set to Copeland Council Var.Council Positive.
- P loss and Neu loss These are set to Copeland Council Var.Council Negative.

## B.3 Input Values

Initialisation values described earlier have been repeated here for clarity.

### B.3.1 World Conditions

- Copeland Population = 69800
- Allerdale Population = 96000
- Cumbrian Population = 329200
- Copeland Council = 7
- Allerdale Council = 7
- Cumbrian Council = 10
- Copeland Interest = 0.5
- Allerdale Interest = 0.25

- Cumbrian Interest = 0.35
- Copeland Initial Knowledge = 0.65
- Allerdale Initial Knowledge = 0.5
- Cumbrian Initial Knowledge = 0.35
- Copeland Initial Opinion = 0.57
- Allerdale Initial Opinion = 0.55
- Cumbrian Initial Opinion = 0.45
- Copeland Initial Neutral = 0.2
- Allerdale Initial Neutral = 0.25
- Cumbrian Initial Neutral = 0.28
- Radiation and Government Media Incidents
  - Incident = 1 (Storage of German Plutonium)
  - Incident = 3 (Fukushima)
  - Incident = 1 (Deadline Extension)
  - Time = 43
  - Time = 25.25
  - Time = 44
- Initial Government Trust = 0.3

## B.4 iThink Code

```
Allerdale Council:
Negative(t) = Negative(t - dt) + (Neu_loss + SN_loss - Neu_gain - SN_gain) * dt
INIT Negative = 0
INFLOWS:
Neu_loss = Allerdale__Council_Var.Council_Negative
SN_loss = Allerdale__Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
Neu_gain = Allerdale__Council_Var.Council_Positive
SN_gain = Allerdale__Council_Var.Council_Negative_Reinforcement
Neutral(t) = Neutral(t - dt) + (P_loss + Neu_gain - P_gain - Neu_loss) * dt
INIT Neutral = World_Conditions.Allerdale_Council
INFLOWS:
P_loss = Allerdale__Council_Var.Council_Negative
Neu_gain = Allerdale__Council_Var.Council_Positive
```

```
OUTFLOWS:
P_gain = Allerdale__Council_Var.Council_Positive
Neu_loss = Allerdale__Council_Var.Council_Negative
Positive(t) = Positive(t - dt) + (SP_loss + P_gain - SP_gain - P_loss) * dt
INIT Positive = 0
INFLOWS:
SP_loss = Allerdale__Council_Var.Council_Negative_Reinforcement
P_gain = Allerdale__Council_Var.Council_Positive
OUTFLOWS:
SP_gain = Allerdale__Council_Var.Council_Positive_Reinforcement
P_loss = Allerdale__Council_Var.Council_Negative
Stong_Positive(t) = Stong_Positive(t - dt) + (SP_gain - SP_loss) * dt
INIT Stong_Positive = 0
INFLOWS:
SP_gain = Allerdale__Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
SP_loss = Allerdale__Council_Var.Council_Negative_Reinforcement
Strong_Negative(t) = Strong_Negative(t - dt) + (SN_gain - SN_loss) * dt
INIT Strong_Negative = 0
INFLOWS:
SN_gain = Allerdale__Council_Var.Council_Negative_Reinforcement
OUTFLOWS:
SN_loss = Allerdale__Council_Var.Council_Positive_Reinforcement

Allerdale  Council Var:
Allerdale_Negative = Delay(Results.Allerdale_Negative, 3)/
World_Conditions.Allerdale_Population
Allerdale_Positive = Delay(Results.Allerdale_Positive, 3)/
World_Conditions.Allerdale_Population
Allerdale_Trust_In_Populace = Delay(Results.Allerdale__Familiar, 3)/
World_Conditions.Allerdale_Population
Council_Negative = (0.5*Media.Media_Negative_Influence+World_Conditions.NIBY+
NGOs.NGO_Negative_Influence)*(0.5+Allerdale_Trust_In_Populace*
Allerdale_Negative/2)*World_Conditions.Allerdale_Council/5
Council_Negative_Reinforcement = (NGOs.NGO_Negative_Influence+1.25*
World_Conditions.NIBY)*(0.5+Allerdale_Trust_In_Populace*Allerdale_Negative/2)*
World_Conditions.Allerdale_Council/10
Council_Positive = (0.5*Media.Media_Positive_Influence+2*
Partnership.Partnership_Positive_Influence)*(0.5+Allerdale_Trust_In_Populace*
Allerdale_Positive/2)*World_Conditions.Allerdale_Council/5
Council_Positive_Reinforcement = Partnership.Partnership_Positive_Influence*
(0.5+Allerdale_Trust_In_Populace*Allerdale_Positive/2)*
```

```
World_Conditions.Allerdale_Council/10

Allerdale  Public:
Negative_Familiar(t) = Negative_Familiar(t - dt) + (NeuF_loss + NegF +
 PF_loss - SNegF_gain - NegF_loss) * dt
INIT Negative_Familiar = World_Conditions.Allerdale_Initial_Knowledge*
World_Conditions.Allerdale_Population*(1-
World_Conditions.Allerdale_Initial_Neutral-
World_Conditions.Allerdale_Initial_Opinion)
INFLOWS:
NeuF_loss = IF(TIME<24) THEN
Allerdale__Public_Var.Allerdale_Negative*Neutral_Familiar/
World_Conditions.Allerdale_Population
ELSE
Allerdale__Public_Var.Allerdale_Negative*4*Neutral_Familiar/
World_Conditions.Allerdale_Population
NegF = Negative_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
PF_loss = Allerdale__Public_Var.Allerdale_Negative
OUTFLOWS:
SNegF_gain = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
NegF_loss = 1.25*Allerdale__Public_Var.Allerdale_Positive
Negative_Unfamiliar(t) = Negative_Unfamiliar(t - dt) + (Neu_loss +
P_loss - SNeg_gain - NegF - Neg_loss) * dt
INIT Negative_Unfamiliar = (1-World_Conditions.Allerdale_Initial_Knowledge)*
World_Conditions.Allerdale_Population*(1-
World_Conditions.Allerdale_Initial_Neutral-
World_Conditions.Allerdale_Initial_Opinion)
INFLOWS:
Neu_loss = IF(TIME<24) THEN 1.25*Allerdale__Public_Var.Allerdale_Negative*
Neutral_Unfamiliar/(2*World_Conditions.Allerdale_Population)
ELSE
1.25*Allerdale__Public_Var.Allerdale_Negative*2*Neutral_Unfamiliar/
World_Conditions.Allerdale_Population
P_loss = 1.25*Allerdale__Public_Var.Allerdale_Negative
OUTFLOWS:
SNeg_gain = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
NegF = Negative_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
Neg_loss = Allerdale__Public_Var.Allerdale_Positive
Neutral_Familiar(t) = Neutral_Familiar(t - dt) + (NeuF - NeuF_loss -
PF_gain) * dt
INIT Neutral_Familiar = World_Conditions.Allerdale_Initial_Knowledge*
World_Conditions.Allerdale_Population*
```

```
World_Conditions.Allerdale_Initial_Neutral
INFLOWS:
NeuF = Neutral_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
OUTFLOWS:
NeuF_loss = IF(TIME<24) THEN
Allerdale__Public_Var.Allerdale_Negative*Neutral_Familiar/
World_Conditions.Allerdale_Population
ELSE
Allerdale__Public_Var.Allerdale_Negative*4*Neutral_Familiar/
World_Conditions.Allerdale_Population
PF_gain = IF(TIME<24) THEN
1.25*Allerdale__Public_Var.Allerdale_Positive*Neutral_Familiar/
World_Conditions.Allerdale_Population
ELSE
1.25*Allerdale__Public_Var.Allerdale_Positive*4*Neutral_Familiar/
World_Conditions.Allerdale_Population
Neutral_Unfamiliar(t) = Neutral_Unfamiliar(t - dt) + (-P_gain - NeuF -
Neu_loss) * dt
INIT Neutral_Unfamiliar = (1-World_Conditions.Allerdale_Initial_Knowledge)
*World_Conditions.Allerdale_Population*
World_Conditions.Allerdale_Initial_Neutral
OUTFLOWS:
P_gain = IF(TIME<24) THEN
Allerdale__Public_Var.Allerdale_Positive*Neutral_Unfamiliar/(2*
World_Conditions.Allerdale_Population)
ELSE
Allerdale__Public_Var.Allerdale_Positive*2*Neutral_Unfamiliar/
World_Conditions.Allerdale_Population
NeuF = Neutral_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
Neu_loss = IF(TIME<24) THEN 1.25*Allerdale__Public_Var.Allerdale_Negative*
Neutral_Unfamiliar/(2*World_Conditions.Allerdale_Population)
ELSE
1.25*Allerdale__Public_Var.Allerdale_Negative*2*Neutral_Unfamiliar/
World_Conditions.Allerdale_Population
Positive_Familiar(t) = Positive_Familiar(t - dt) + (SPF_loss + PF_gain +
PF + NegF_loss - SPF_gain - PF_loss) * dt
INIT Positive_Familiar = World_Conditions.Allerdale_Initial_Knowledge*
World_Conditions.Allerdale_Population*
World_Conditions.Allerdale_Initial_Opinion
INFLOWS:
SPF_loss = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
PF_gain = IF(TIME<24) THEN
```

```
1.25*Allerdale__Public_Var.Allerdale_Positive*Neutral_Familiar/
World_Conditions.Allerdale_Population
ELSE
1.25*Allerdale__Public_Var.Allerdale_Positive*4*Neutral_Familiar/
World_Conditions.Allerdale_Population
PF = Positive_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
NegF_loss = 1.25*Allerdale__Public_Var.Allerdale_Positive
OUTFLOWS:
SPF_gain = Allerdale__Public_Var.Allerdale_Positive_Reinforcement
PF_loss = Allerdale__Public_Var.Allerdale_Negative
Positive_Unfamiliar(t) = Positive_Unfamiliar(t - dt) + (SP_loss +
P_gain + Neg_loss - SP_gain - PF - P_loss) * dt
INIT Positive_Unfamiliar = (1-
World_Conditions.Allerdale_Initial_Knowledge)*
World_Conditions.Allerdale_Population*
World_Conditions.Allerdale_Initial_Opinion
INFLOWS:
SP_loss = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
P_gain = IF(TIME<24) THEN
Allerdale__Public_Var.Allerdale_Positive*Neutral_Unfamiliar/(2*
World_Conditions.Allerdale_Population)
ELSE
Allerdale__Public_Var.Allerdale_Positive*2*Neutral_Unfamiliar/
World_Conditions.Allerdale_Population
Neg_loss = Allerdale__Public_Var.Allerdale_Positive
OUTFLOWS:
SP_gain = Allerdale__Public_Var.Allerdale_Positive_Reinforcement
PF = Positive_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
P_loss = 1.25*Allerdale__Public_Var.Allerdale_Negative
Stong_Positive_Unfamiliar(t) = Stong_Positive_Unfamiliar(t - dt) +
(SP_gain - SP_loss - SPF) * dt
INIT Stong_Positive_Unfamiliar = 0
INFLOWS:
SP_gain = Allerdale__Public_Var.Allerdale_Positive_Reinforcement
OUTFLOWS:
SP_loss = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
SPF = Stong_Positive_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
Strong_Negative_Familiar(t) = Strong_Negative_Familiar(t - dt) +
(SNegF_gain + SNegF) * dt
INIT Strong_Negative_Familiar = 0
INFLOWS:
SNegF_gain = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
```

```
SNegF = Strong_Negative_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
Strong_Negative_Unfamiliar(t) = Strong_Negative_Unfamiliar(t - dt) +
(SNeg_gain - SNegF) * dt
INIT Strong_Negative_Unfamiliar = 0
INFLOWS:
SNeg_gain = Allerdale__Public_Var.Allerdale_Negative_Reinforcement
OUTFLOWS:
SNegF = Strong_Negative_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
Strong_Positive_Familiar(t) = Strong_Positive_Familiar(t - dt) +
(SPF_gain + SPF - SPF_loss) * dt
INIT Strong_Positive_Familiar = 0
INFLOWS:
SPF_gain = Allerdale__Public_Var.Allerdale_Positive_Reinforcement
SPF = Stong_Positive_Unfamiliar*Allerdale__Public_Var.Allerdale_Knowledge
OUTFLOWS:
SPF_loss = Allerdale__Public_Var.Allerdale_Negative_Reinforcement

Allerdale  Public Var:
Allerdale_Knowledge = (NGOs.NGO_Negative_Influence+
Partnership.Partnership_Positive_Influence)/200
Allerdale_Negative = (1.25*World_Conditions.NIBY+
Media.Media_Negative_Influence+World_Conditions.Allerdale_Interest*
NGOs.NGO_Negative_Influence)*World_Conditions.Allerdale_Population/100
Allerdale_Negative_Reinforcement = (World_Conditions.Allerdale_Interest*
NGOs.NGO_Negative_Influence)*World_Conditions.Allerdale_Population/100
Allerdale_Positive = (Media.Media_Positive_Influence+
World_Conditions.Allerdale_Interest*
Partnership.Partnership_Positive_Influence)*
World_Conditions.Allerdale_Population/100
Allerdale_Positive_Reinforcement = World_Conditions.Allerdale_Interest*
Partnership.Partnership_Positive_Influence*
World_Conditions.Allerdale_Population/100

Copeland Council:
Negative(t) = Negative(t - dt) + (Neu_loss + SN_loss - Neu_gain -
SN_gain) * dt
INIT Negative = 0
INFLOWS:
Neu_loss = Copeland__Council_Var.Council_Negative
SN_loss = Copeland__Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
Neu_gain = Copeland__Council_Var.Council_Positive
```

```
SN_gain = Copeland__Council_Var.Council_Negative_Reinforcement
Neutral(t) = Neutral(t - dt) + (P_loss + Neu_gain - P_gain -
Neu_loss) * dt
INIT Neutral = World_Conditions.Copeland_Council
INFLOWS:
P_loss = Copeland__Council_Var.Council_Negative
Neu_gain = Copeland__Council_Var.Council_Positive
OUTFLOWS:
P_gain = Copeland__Council_Var.Council_Positive
Neu_loss = Copeland__Council_Var.Council_Negative
Positive(t) = Positive(t - dt) + (SP_loss + P_gain - SP_gain -
P_loss) * dt
INIT Positive = 0
INFLOWS:
SP_loss = Copeland__Council_Var.Council_Negative_Reinforcement
P_gain = Copeland__Council_Var.Council_Positive
OUTFLOWS:
SP_gain = Copeland__Council_Var.Council_Positive_Reinforcement
P_loss = Copeland__Council_Var.Council_Negative
Stong_Positive(t) = Stong_Positive(t - dt) + (SP_gain - SP_loss) * dt
INIT Stong_Positive = 0
INFLOWS:
SP_gain = Copeland__Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
SP_loss = Copeland__Council_Var.Council_Negative_Reinforcement
Strong_Negative(t) = Strong_Negative(t - dt) + (SN_gain - SN_loss) * dt
INIT Strong_Negative = 0
INFLOWS:
SN_gain = Copeland__Council_Var.Council_Negative_Reinforcement
OUTFLOWS:
SN_loss = Copeland__Council_Var.Council_Positive_Reinforcement

Copeland Public:
Negative_Familiar(t) = Negative_Familiar(t - dt) + (NeuF_loss +
NegF + PF_loss - SNegF_gain - NegF_loss) * dt
INIT Negative_Familiar = World_Conditions.Copeland_Initial_Knowledge*
World_Conditions.Copeland_Population*(1-
World_Conditions.Copeland_Initial_Opinion-
World_Conditions.Copeland_Initial_Neutral)
INFLOWS:
NeuF_loss = IF(TIME<24) THEN
Copeland_Public_Var.Copeland_Negative*Neutral_familiar/
```

```
World_Conditions.Copeland_Population
ELSE
Copeland_Public_Var.Copeland_Negative*4*Neutral_familiar/
World_Conditions.Copeland_Population
NegF = Negative_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
PF_loss = Copeland_Public_Var.Copeland_Negative
OUTFLOWS:
SNegF_gain = Copeland_Public_Var.Copeland_Negative_Reinforcement
NegF_loss = 1.25*Copeland_Public_Var.Copeland_Positive
Negative_Unfamiliar(t) = Negative_Unfamiliar(t - dt) + (Neu_loss +
P_loss - SNeg_gain - NegF - Neg_loss) * dt
INIT Negative_Unfamiliar = (1-World_Conditions.Copeland_Initial_Knowledge)*
World_Conditions.Copeland_Population*(1-
World_Conditions.Copeland_Initial_Opinion-
World_Conditions.Copeland_Initial_Neutral)
INFLOWS:
Neu_loss = IF(TIME<24) THEN
1.25*Copeland_Public_Var.Copeland_Negative*Neutral_Unfamiliar/
(2*World_Conditions.Copeland_Population)
ELSE
1.25*Copeland_Public_Var.Copeland_Negative*2*Neutral_Unfamiliar/
World_Conditions.Copeland_Population
P_loss = 1.25*Copeland_Public_Var.Copeland_Negative
OUTFLOWS:
SNeg_gain = Copeland_Public_Var.Copeland_Negative_Reinforcement
NegF = Negative_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
Neg_loss = Copeland_Public_Var.Copeland_Positive
Neutral_Familiar(t) = Neutral_Familiar(t - dt) + (NeuF - NeuF_loss -
PF_gain) * dt
INIT Neutral_Familiar = World_Conditions.Copeland_Initial_Knowledge*
World_Conditions.Copeland_Population*
World_Conditions.Copeland_Initial_Neutral
INFLOWS:
NeuF = Neutral_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
OUTFLOWS:
NeuF_loss = IF(TIME<24) THEN
Copeland_Public_Var.Copeland_Negative*Neutral_familiar/
World_Conditions.Copeland_Population
ELSE
Copeland_Public_Var.Copeland_Negative*4*Neutral_familiar/
World_Conditions.Copeland_Population
PF_gain = IF(TIME<24) THEN
```

```
1.25*Copeland_Public_Var.Copeland_Positive*Neutral_familiar/
World_Conditions.Copeland_Population
ELSE
1.25*Copeland_Public_Var.Copeland_Positive*4*Neutral_familiar/
World_Conditions.Copeland_Population
Neutral_Unfamiliar(t) = Neutral_Unfamiliar(t - dt) + (-P_gain -
Neu_loss - NeuF) * dt
INIT Neutral_Unfamiliar = (1-World_Conditions.Copeland_Initial_Knowledge)*
World_Conditions.Copeland_Population*
World_Conditions.Copeland_Initial_Neutral
OUTFLOWS:
P_gain = IF(TIME<24) THEN
Copeland_Public_Var.Copeland_Positive*Neutral_Unfamiliar/
(2*World_Conditions.Copeland_Population)
ELSE
Copeland_Public_Var.Copeland_Positive*2*Neutral_Unfamiliar/
World_Conditions.Copeland_Population
Neu_loss = IF(TIME<24) THEN
1.25*Copeland_Public_Var.Copeland_Negative*Neutral_Unfamiliar/
(2*World_Conditions.Copeland_Population)
ELSE
1.25*Copeland_Public_Var.Copeland_Negative*2*Neutral_Unfamiliar/
World_Conditions.Copeland_Population
NeuF = Neutral_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
Positive_Familiar(t) = Positive_Familiar(t - dt) + (SPF_loss + PF_gain +
PF + NegF_loss - SPF_gain - PF_loss) * dt
INIT Positive_Familiar = World_Conditions.Copeland_Initial_Knowledge*
World_Conditions.Copeland_Population*
World_Conditions.Copeland_Initial_Opinion
INFLOWS:
SPF_loss = Copeland_Public_Var.Copeland_Negative_Reinforcement
PF_gain = IF(TIME<24) THEN
1.25*Copeland_Public_Var.Copeland_Positive*Neutral_familiar/
World_Conditions.Copeland_Population
ELSE
1.25*Copeland_Public_Var.Copeland_Positive*4*Neutral_familiar/
World_Conditions.Copeland_Population
PF = Positive_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
NegF_loss = 1.25*Copeland_Public_Var.Copeland_Positive
OUTFLOWS:
SPF_gain = Copeland_Public_Var.Copeland_Positive_Reinforcement
PF_loss = Copeland_Public_Var.Copeland_Negative
```

```
Positive_Unfamiliar(t) = Positive_Unfamiliar(t - dt) + (SP_loss +
P_gain + Neg_loss - SP_gain - PF - P_loss) * dt
INIT Positive_Unfamiliar = (1-World_Conditions.Copeland_Initial_Knowledge)*
World_Conditions.Copeland_Population*
World_Conditions.Copeland_Initial_Opinion
INFLOWS:
SP_loss = Copeland_Public_Var.Copeland_Negative_Reinforcement
P_gain = IF(TIME<24) THEN
Copeland_Public_Var.Copeland_Positive*Neutral_Unfamiliar/
(2*World_Conditions.Copeland_Population)
ELSE
Copeland_Public_Var.Copeland_Positive*2*Neutral_Unfamiliar/
World_Conditions.Copeland_Population
Neg_loss = Copeland_Public_Var.Copeland_Positive
OUTFLOWS:
SP_gain = Copeland_Public_Var.Copeland_Positive_Reinforcement
PF = Positive_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
P_loss = 1.25*Copeland_Public_Var.Copeland_Negative
Stong_Positive_Unfamiliar(t) = Stong_Positive_Unfamiliar(t - dt) +
(SP_gain - SP_loss - SPF) * dt
INIT Stong_Positive_Unfamiliar = 0
INFLOWS:
SP_gain = Copeland_Public_Var.Copeland_Positive_Reinforcement
OUTFLOWS:
SP_loss = Copeland_Public_Var.Copeland_Negative_Reinforcement
SPF = Stong_Positive_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
Strong_Negative_Familiar(t) = Strong_Negative_Familiar(t - dt) +
(SNegF_gain + SNegF) * dt
INIT Strong_Negative_Familiar = 0
INFLOWS:
SNegF_gain = Copeland_Public_Var.Copeland_Negative_Reinforcement
SNegF = Strong_Negative_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
Strong_Negative_Unfamiliar(t) = Strong_Negative_Unfamiliar(t - dt) +
(SNeg_gain - SNegF) * dt
INIT Strong_Negative_Unfamiliar = 0
INFLOWS:
SNeg_gain = Copeland_Public_Var.Copeland_Negative_Reinforcement
OUTFLOWS:
SNegF = Strong_Negative_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
Strong_Positive_Familiar(t) = Strong_Positive_Familiar(t - dt) +
(SPF_gain + SPF - SPF_loss) * dt
INIT Strong_Positive_Familiar = 0
```

```
INFLOWS:
SPF_gain = Copeland_Public_Var.Copeland_Positive_Reinforcement
SPF = Stong_Positive_Unfamiliar*Copeland_Public_Var.Copeland_Knowledge
OUTFLOWS:
SPF_loss = Copeland_Public_Var.Copeland_Negative_Reinforcement

Copeland Public Var:
Copeland_Knowledge = (NGOs.NGO_Negative_Influence+
Partnership.Partnership_Positive_Influence)/400
Copeland_Negative = (World_Conditions.NIBY+Media.Media_Negative_Influence+
World_Conditions.Copeland_Interest*NGOs.NGO_Negative_Influence)*
World_Conditions.Copeland_Population/100
Copeland_Negative_Reinforcement = (World_Conditions.Copeland_Interest*
NGOs.NGO_Negative_Influence)*World_Conditions.Copeland_Population/100
Copeland_Positive = (Media.Media_Positive_Influence+
World_Conditions.Copeland_Interest*
Partnership.Partnership_Positive_Influence)*
World_Conditions.Copeland_Population/100
Copeland_Positive_Reinforcement = World_Conditions.Copeland_Interest*
Partnership.Partnership_Positive_Influence*
World_Conditions.Copeland_Population/100

Copeland  Council Var:
Copeland_Negative = Delay(Results.Copeland_Negative, 4)/
World_Conditions.Copeland_Population
Copeland_Positive = Delay(Results.Copeland_Positive, 4)/
World_Conditions.Copeland_Population
Copeland_Trust_In_Populace = Delay(Results.Copeland_Familiar, 4)/
World_Conditions.Copeland_Population
Council_Negative = (0.5*Media.Media_Negative_Influence+
World_Conditions.NIBY+NGOs.NGO_Negative_Influence)*
(0.5+Copeland_Trust_In_Populace*Copeland_Negative/2)*
World_Conditions.Copeland_Council/5
Council_Negative_Reinforcement = (0.75*NGOs.NGO_Negative_Influence+
1.25*World_Conditions.NIBY)*(0.5+Copeland_Trust_In_Populace*
Copeland_Negative/2)*World_Conditions.Copeland_Council/10
Council_Positive = (0.5*Media.Media_Positive_Influence+2*
Partnership.Partnership_Positive_Influence)*(0.5+
Copeland_Trust_In_Populace*Copeland_Positive/2)*
World_Conditions.Copeland_Council/5
Council_Positive_Reinforcement =
Partnership.Partnership_Positive_Influence*(0.5+
```

```
Copeland_Trust_In_Populace*Copeland_Positive/2)*
World_Conditions.Copeland_Council/10

Cumbria Council:
Negative(t) = Negative(t - dt) + (Neu_loss + SN_loss - Neu_gain -
SN_gain) * dt
INIT Negative = 0
INFLOWS:
Neu_loss = Cumbria_Council_Var.Council_Negative
SN_loss = Cumbria_Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
Neu_gain = Cumbria_Council_Var.Council_Positive
SN_gain = Cumbria_Council_Var.Council_Negative_Reinforcement
Neutral(t) = Neutral(t - dt) + (P_loss + Neu_gain - P_gain -
Neu_loss) * dt
INIT Neutral = World_Conditions.Cumbrian_Council
INFLOWS:
P_loss = Cumbria_Council_Var.Council_Negative
Neu_gain = Cumbria_Council_Var.Council_Positive
OUTFLOWS:
P_gain = Cumbria_Council_Var.Council_Positive
Neu_loss = Cumbria_Council_Var.Council_Negative
Positive(t) = Positive(t - dt) + (SP_loss + P_gain - SP_gain -
P_loss) * dt
INIT Positive = 0
INFLOWS:
SP_loss = Cumbria_Council_Var.Council_Negative_Reinforcement
P_gain = Cumbria_Council_Var.Council_Positive
OUTFLOWS:
SP_gain = Cumbria_Council_Var.Council_Positive_Reinforcement
P_loss = Cumbria_Council_Var.Council_Negative
Stong_Positive(t) = Stong_Positive(t - dt) + (SP_gain -
SP_loss) * dt
INIT Stong_Positive = 0
INFLOWS:
SP_gain = Cumbria_Council_Var.Council_Positive_Reinforcement
OUTFLOWS:
SP_loss = Cumbria_Council_Var.Council_Negative_Reinforcement
Strong_Negative(t) = Strong_Negative(t - dt) + (SN_gain -
SN_loss) * dt
INIT Strong_Negative = 0
INFLOWS:
```

```
SN_gain = Cumbria_Council_Var.Council_Negative_Reinforcement
OUTFLOWS:
SN_loss = Cumbria_Council_Var.Council_Positive_Reinforcement

Cumbria Council Var:
Council_Negative = (0.5*Media.Media_Negative_Influence+1.25*
World_Conditions.NIBY+1.25*NGOs.NGO_Negative_Influence)*(0.5+
Cumbria_Trust_In_Populace*Cumbria_Negative/2)*
World_Conditions.Cumbrian_Council/5
Council_Negative_Reinforcement = (1.5*NGOs.NGO_Negative_Influence+
1.25*World_Conditions.NIBY)*(0.5+Cumbria_Trust_In_Populace*
Cumbria_Negative/2)*
World_Conditions.Cumbrian_Council/5
Council_Positive = (0.5*Media.Media_Positive_Influence+2*
Partnership.Partnership_Positive_Influence)*(0.5+
Cumbria_Trust_In_Populace*Cumbria_Positive/2)*
World_Conditions.Cumbrian_Council/5
Council_Positive_Reinforcement =
Partnership.Partnership_Positive_Influence*
(0.5+Cumbria_Trust_In_Populace*Cumbria_Positive/2)*
World_Conditions.Cumbrian_Council/5
Cumbria_Negative = Delay(Results.Cumbria_Negative, 3)/
World_Conditions.Cumbrian_Population
Cumbria_Positive = Delay(Results.Cumbria_Positive, 3)/
World_Conditions.Cumbrian_Population
Cumbria_Trust_In_Populace = Delay(Results.Cumbria_Familiar, 3)/
World_Conditions.Cumbrian_Population

Cumbria Public:
Negative_Familiar(t) = Negative_Familiar(t - dt) + (NeuF_loss +
NegF + PF_loss - SNegF_gain - NegF_loss) * dt
INIT Negative_Familiar =
World_Conditions.Cumbrian_Initial_Knowledge*
World_Conditions.Cumbrian_Population*(1-
World_Conditions.Cumbrian_Initial_Opinion-
World_Conditions.Cumbrian_Initial_Neutral)
INFLOWS:
NeuF_loss = IF(TIME<24) THEN
Cumbria_Public_Var.Cumbrian_Negative*Neutral_familiar/
World_Conditions.Cumbrian_Population
ELSE
Cumbria_Public_Var.Cumbrian_Negative*4*Neutral_familiar/
```

```
World_Conditions.Cumbrian_Population
NegF = Negative_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
PF_loss = Cumbria_Public_Var.Cumbrian_Negative
OUTFLOWS:
SNegF_gain = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
NegF_loss = 1.25*Cumbria_Public_Var.Cumbrian_Positive
Negative_Unfamiliar(t) = Negative_Unfamiliar(t - dt) + (Neu_loss +
P_loss - SNeg_gain - NegF - Neg_loss) * dt
INIT Negative_Unfamiliar = (1-
World_Conditions.Cumbrian_Initial_Knowledge)*
World_Conditions.Cumbrian_Population*(1-
World_Conditions.Cumbrian_Initial_Opinion-
World_Conditions.Cumbrian_Initial_Neutral)
INFLOWS:
Neu_loss = IF(TIME<24) THEN
1.25*Cumbria_Public_Var.Cumbrian_Negative*Neutral_Unfamiliar/
(2*World_Conditions.Cumbrian_Population)
ELSE
1.25*Cumbria_Public_Var.Cumbrian_Negative*2*Neutral_Unfamiliar/
World_Conditions.Cumbrian_Population
P_loss = 1.25*Cumbria_Public_Var.Cumbrian_Negative
OUTFLOWS:
SNeg_gain = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
NegF = Negative_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
Neg_loss = Cumbria_Public_Var.Cumbrian_Positive
Neutral_Familiar(t) = Neutral_Familiar(t - dt) + (NeuF - NeuF_loss -
PF_gain) * dt
INIT Neutral_Familiar = World_Conditions.Cumbrian_Initial_Knowledge*
World_Conditions.Cumbrian_Population*
World_Conditions.Cumbrian_Initial_Neutral
INFLOWS:
NeuF = Neutral_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
OUTFLOWS:
NeuF_loss = IF(TIME<24) THEN
Cumbria_Public_Var.Cumbrian_Negative*Neutral_familiar/
World_Conditions.Cumbrian_Population
ELSE
Cumbria_Public_Var.Cumbrian_Negative*4*Neutral_familiar/
World_Conditions.Cumbrian_Population
PF_gain = IF(TIME<24) THEN
1.25*Cumbria_Public_Var.Cumbrian_Positive*Neutral_familiar/
World_Conditions.Cumbrian_Population
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ELSE
1.25*Cumbria_Public_Var.Cumbrian_Positive*4*Neutral_familiar/
World_Conditions.Cumbrian_Population
Neutral_Unfamiliar(t) = Neutral_Unfamiliar(t - dt) + (-P_gain -
Neu_loss - NeuF) * dt
INIT Neutral_Unfamiliar = (1-
World_Conditions.Cumbrian_Initial_Knowledge)*
World_Conditions.Cumbrian_Population*
World_Conditions.Cumbrian_Initial_Neutral
OUTFLOWS:
P_gain = IF(TIME<24) THEN
Cumbria_Public_Var.Cumbrian_Positive*Neutral_Unfamiliar/
(2*World_Conditions.Cumbrian_Population)
ELSE
Cumbria_Public_Var.Cumbrian_Positive*2*Neutral_Unfamiliar/
World_Conditions.Cumbrian_Population
Neu_loss = IF(TIME<24) THEN
1.25*Cumbria_Public_Var.Cumbrian_Negative*Neutral_Unfamiliar/
(2*World_Conditions.Cumbrian_Population)
ELSE
1.25*Cumbria_Public_Var.Cumbrian_Negative*2*Neutral_Unfamiliar/
World_Conditions.Cumbrian_Population
NeuF = Neutral_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
Positive_Familiar(t) = Positive_Familiar(t - dt) + (SPF_loss +
PF_gain + PF + NegF_loss - SPF_gain - PF_loss) * dt
INIT Positive_Familiar =
World_Conditions.Cumbrian_Initial_Knowledge*
World_Conditions.Cumbrian_Population*
World_Conditions.Cumbrian_Initial_Opinion
INFLOWS:
SPF_loss = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
PF_gain = IF(TIME<24) THEN
1.25*Cumbria_Public_Var.Cumbrian_Positive*Neutral_familiar/
World_Conditions.Cumbrian_Population
ELSE
1.25*Cumbria_Public_Var.Cumbrian_Positive*4*Neutral_familiar/
World_Conditions.Cumbrian_Population
PF = Positive_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
NegF_loss = 1.25*Cumbria_Public_Var.Cumbrian_Positive
OUTFLOWS:
SPF_gain = Cumbria_Public_Var.Cumbrian_Positive_Reinforcement
PF_loss = Cumbria_Public_Var.Cumbrian_Negative
```

```
Positive_Unfamiliar(t) = Positive_Unfamiliar(t - dt) + (SP_loss +
P_gain + Neg_loss - SP_gain - PF - P_loss) * dt
INIT Positive_Unfamiliar = (1-
World_Conditions.Cumbrian_Initial_Knowledge)*
World_Conditions.Cumbrian_Population*
World_Conditions.Cumbrian_Initial_Opinion
INFLOWS:
SP_loss = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
P_gain = IF(TIME<24) THEN
Cumbria_Public_Var.Cumbrian_Positive*Neutral_Unfamiliar/
(2*World_Conditions.Cumbrian_Population)
ELSE
Cumbria_Public_Var.Cumbrian_Positive*2*Neutral_Unfamiliar/
World_Conditions.Cumbrian_Population
Neg_loss = Cumbria_Public_Var.Cumbrian_Positive
OUTFLOWS:
SP_gain = Cumbria_Public_Var.Cumbrian_Positive_Reinforcement
PF = Positive_Unfamiliar*Cumbria_Public_Var.Cumbrian_Knowledge
P_loss = 1.25*Cumbria_Public_Var.Cumbrian_Negative
Stong_Positive_Unfamiliar(t) = Stong_Positive_Unfamiliar(t -
dt) + (SP_gain - SP_loss - SPF) * dt
INIT Stong_Positive_Unfamiliar = 0
INFLOWS:
SP_gain = Cumbria_Public_Var.Cumbrian_Positive_Reinforcement
OUTFLOWS:
SP_loss = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
SPF = Stong_Positive_Unfamiliar*
Cumbria_Public_Var.Cumbrian_Knowledge
Strong_Negative_Familiar(t) = Strong_Negative_Familiar(t - dt) +
(SNegF_gain + SNegF) * dt
INIT Strong_Negative_Familiar = 0
INFLOWS:
SNegF_gain = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
SNegF = Strong_Negative_Unfamiliar*
Cumbria_Public_Var.Cumbrian_Knowledge
Strong_Negative_Unfamiliar(t) = Strong_Negative_Unfamiliar(t -
dt) +
(SNeg_gain - SNegF) * dt
INIT Strong_Negative_Unfamiliar = 0
INFLOWS:
SNeg_gain = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement
OUTFLOWS:
```

```
SNegF = Strong_Negative_Unfamiliar*
Cumbria_Public_Var.Cumbrian_Knowledge
Strong_Positive_Familiar(t) = Strong_Positive_Familiar(t - dt) +
(SPF_gain + SPF - SPF_loss) * dt
INIT Strong_Positive_Familiar = 0
INFLOWS:
SPF_gain = Cumbria_Public_Var.Cumbrian_Positive_Reinforcement
SPF = Stong_Positive_Unfamiliar*
Cumbria_Public_Var.Cumbrian_Knowledge
OUTFLOWS:
SPF_loss = Cumbria_Public_Var.Cumbrian_Negative_Reinforcement

Cumbria Public Var:
Cumbrian_Knowledge = (NGOs.NGO_Negative_Influence+
Partnership.Partnership_Positive_Influence)/300
Cumbrian_Negative = (World_Conditions.NIBY+
Media.Media_Negative_Influence+World_Conditions.Cumbrian_Interest*
NGOs.NGO_Negative_Influence)*
World_Conditions.Cumbrian_Population/100
Cumbrian_Negative_Reinforcement = (
World_Conditions.Cumbrian_Interest*NGOs.NGO_Negative_Influence)*
World_Conditions.Cumbrian_Population/100
Cumbrian_Positive = (Media.Media_Positive_Influence+
World_Conditions.Cumbrian_Interest*
Partnership.Partnership_Positive_Influence)*
World_Conditions.Cumbrian_Population/100
Cumbrian_Positive_Reinforcement =
World_Conditions.Cumbrian_Interest*
Partnership.Partnership_Positive_Influence*
World_Conditions.Cumbrian_Population/100

Media:
Media_Negative_Influence = (2*NGOs.News_Releases+NGOs.NGO_Events+
World_Conditions.Radiation_and_Government_Media_Incidents+
Step(0.4, 42))*Delay(Negative, 0.5)
Media_Positive_Influence = (Partnership.Major_News_Releases+
Partnership.Major_Events+Step(0.05, 6)+Step(0.1, 8)+Step(-0.1, 13)+
Step(0.15, 20)+Step(-0.1, 25)+Step(0.2, 32)+Step(-0.2, 42))*
World_Conditions.Government_Trust*Delay(Positive, 0.5)
Negative = (Results.Cumbria_Negative+Results.Allerdale_Negative+
Results.Copeland_Negative)/World_Conditions.Total_Population
Positive = (Results.Copeland_Positive+Results.Allerdale_Positive+
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Results.Cumbria_Positive)/World_Conditions.Total_Population

NGOs:
News_Releases = Step(1, 22.25)+step(-1, 22.75) + Step(1, 25.75)+
step(-1, 26.25)+step(1, 27.5)+step(-1, 28)+step(1, 38)+
step(-1, 38.5)+step(1, 39.75)+step(-1, 40.25)+step(1,41.5)+
step(-1, 42)+step(1, 44)+step(-1, 44.5)
NGO_Events = Step(0.05, 7)+Step(0.15, 15)+step(1, 23)+
step(-0.9, 24) +step(0.25,35)
NGO_Negative_Influence = News_Releases+Partnership_Event_Attendance+
NGO_Events
Partnership_Event_Attendance = Step(0.5,12)+step(-0.5, 12.5)+
Step(0.5,23)+step(-0.5, 23.5)

Partnership:
Information_Packs = STEP(1, 9.5)+Step(-1, 10) + STEP(1, 21)
+STEP(-1, 21.5)+Step(1,23.5)+Step(-1, 24)+STEP(0.5, 23)+
Step(-0.5, 24.5)+Step(1,35)+Step(-1, 35.5)+Step(1, 37)+
step(-1, 37.5) +STEP(0.25, 15.5)+Step(-0.25, 16.5)+
STEP(0.5, 27.5)+Step(-0.5, 28.5)+STEP(0.5, 40.5)+
Step(-0.5, 41)+Step(0.5,42)+step(-0.5, 44)+Step(0.25, 9.75)+
step(-0.25, 10.75)
Major_Events = Step(0.75,12)+Step(-0.75, 12.5) +
Step(0.75, 10.25)+Step(-0.75, 10.75)+
Step(0.75,23)+Step(-0.75, 23.5) + Step(0.75, 23.25)+
Step(-0.75, 23.75)+Step(1.5,37.25)+Step(-1.5, 37.75)
Major_News_Releases = STEP(1,9.5)+STEP(-1,9.75)+
STEP(1,10.5)+STEP(-1,10.75)+STEP(1,11.5)+
STEP(-1,11.75)+STEP(1,21)+STEP(-1,21.5)+STEP(1,22)+
STEP(-1,22.5)+STEP(1,23)+STEP(-1,23.5)+
STEP(2,33)+STEP(-2,37)
Minor_Events = STep(0.15, 9.25)+step(-0.15, 10) +
step(0.15, 10.25)+step(-0.15, 10.5)+step(0.15, 11.5)+
step(-0.15, 11.75)+step(0.15, 12.25)+step(-0.15, 22.75)+
Step(0.15, 21.5)+step(-0.15, 22)+Step(0.15, 22.25)+
step(-0.15, 25.5)+Step(0.5,35.75)+step(-0.5, 36.5)
Minor_News_Releases = Step(0.1,16)+Step(0.05, 21)+
Step(-0.05, 26)+Step(1,33)+Step(-1, 38)+step(-0.1,42)+
Step(0.1,23)+Step(-0.1,25.5)+Step(0.25, 33)+
Step(-0.25, 34)+Step(0.25, 35)+step(-0.25, 36)
Partnership_Positive_Influence = IF(TIME>6) THEN 0.25+
Minor_News_Releases+Major_News_Releases+Information_Packs+
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Major_Events+Minor_Events
ELSE
Minor_News_Releases+Major_News_Releases+Information_Packs+
Major_Events+Minor_Events

Results:
Allerdale_Council_Negative = ROUND(
Allerdale_Council.Strong_Negative+
Allerdale_Council.Negative)
Allerdale_Council_Neutral = World_Conditions.Allerdale_Council-
Allerdale_Council_Negative-Allerdale_Council_Positive
Allerdale_Council_Positive = ROUND(
Allerdale_Council.Stong_Positive+
Allerdale_Council.Positive)
Allerdale_Familiarity = Allerdale__Familiar/
World_Conditions.Allerdale_Population
Allerdale_Negative = Allerdale__Public.Strong_Negative_Unfamiliar+
Allerdale__Public.Negative_Unfamiliar+
Allerdale__Public.Strong_Negative_Familiar+
Allerdale__Public.Negative_Familiar
Allerdale_Neutral = Allerdale__Public.Neutral_Unfamiliar+
Allerdale__Public.Neutral_Familiar
Allerdale_Positive = Allerdale__Public.Stong_Positive_Unfamiliar+
Allerdale__Public.Positive_Unfamiliar+
Allerdale__Public.Positive_Familiar+
Allerdale__Public.Strong_Positive_Familiar
Allerdale_Resistance = Allerdale_Negative/
World_Conditions.Allerdale_Population
Allerdale_Support = Allerdale_Positive/
World_Conditions.Allerdale_Population
Allerdale_Unfamiliar =
Allerdale__Public.Stong_Positive_Unfamiliar+
Allerdale__Public.Positive_Unfamiliar+
Allerdale__Public.Neutral_Unfamiliar+
Allerdale__Public.Negative_Unfamiliar+
Allerdale__Public.Strong_Negative_Unfamiliar
Allerdale_Unfamiliarity = Allerdale_Unfamiliar/
World_Conditions.Allerdale_Population
Allerdale_Unsure = Allerdale_Neutral/
World_Conditions.Allerdale_Population
Allerdale__Familiar = Allerdale__Public.Strong_Positive_Familiar+
Allerdale__Public.Positive_Familiar+
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Allerdale__Public.Neutral_Familiar+
Allerdale__Public.Negative_Familiar+
Allerdale__Public.Strong_Negative_Familiar
Copeland_Council_Negative = ROUND(Copeland_Council.Strong_Negative+
Copeland_Council.Negative)
Copeland_Council_Neutral = World_Conditions.Copeland_Council-
Copeland_Council_Negative-Copeland_Council_Positive
Copeland_Council_Positive = ROUND(Copeland_Council.Stong_Positive+
Copeland_Council.Positive)
Copeland_Familiar = Copeland_Public.Strong_Positive_Familiar+
Copeland_Public.Positive_Familiar+
Copeland_Public.Neutral_Familiar+
Copeland_Public.Negative_Familiar+
Copeland_Public.Strong_Negative_Familiar
Copeland_Familiarity = Copeland_Familiar/
World_Conditions.Copeland_Population
Copeland_Negative = Copeland_Public.Strong_Negative_Unfamiliar+
Copeland_Public.Negative_Unfamiliar+
Copeland_Public.Strong_Negative_Familiar+
Copeland_Public.Negative_Familiar
Copeland_Neutal = Copeland_Public.Neutral_Unfamiliar+
Copeland_Public.Neutral_Familiar
Copeland_Positive = Copeland_Public.Stong_Positive_Unfamiliar+
Copeland_Public.Positive_Unfamiliar+
Copeland_Public.Positive_Familiar+
Copeland_Public.Strong_Positive_Familiar
Copeland_Resistance = Copeland_Negative/
World_Conditions.Copeland_Population
Copeland_Support = Copeland_Positive/
World_Conditions.Copeland_Population
Copeland_Unfamiliar = Copeland_Public.Stong_Positive_Unfamiliar+
Copeland_Public.Positive_Unfamiliar+
Copeland_Public.Neutral_Unfamiliar+
Copeland_Public.Negative_Unfamiliar+
Copeland_Public.Strong_Negative_Unfamiliar
Copeland_Unfamiliarity = Copeland_Unfamiliar/
World_Conditions.Copeland_Population
Copeland_Unsure = Copeland_Neutal/
World_Conditions.Copeland_Population
Cumbrian_Council_Negative = ROUND(
Cumbria_Council.Strong_Negative+Cumbria_Council.Negative)
Cumbrian_Council_Neutral = World_Conditions.Cumbrian_Council-
```

```
Cumbrian_Council_Negative-Cumbrian_Council_Positive
Cumbrian_Council_Positive = ROUND(Cumbria_Council.Stong_Positive+
Cumbria_Council.Positive)
Cumbrian_Familiarity = Cumbria_Familiar/
World_Conditions.Cumbrian_Population
Cumbrian_Resistance = Cumbria_Negative/
World_Conditions.Cumbrian_Population
Cumbrian_Support = Cumbria_Positive/
World_Conditions.Cumbrian_Population
Cumbrian_Unfamiliarity = Cumbria_Unfamiliar/
World_Conditions.Cumbrian_Population
Cumbrian_Unsure = Cumbria_Neutral/
World_Conditions.Cumbrian_Population
Cumbria_Familiar = Cumbria_Public.Strong_Positive_Familiar+
Cumbria_Public.Positive_Familiar+Cumbria_Public.Neutral_Familiar+
Cumbria_Public.Negative_Familiar+
Cumbria_Public.Strong_Negative_Familiar
Cumbria_Negative = Cumbria_Public.Strong_Negative_Unfamiliar+
Cumbria_Public.Negative_Unfamiliar+
Cumbria_Public.Strong_Negative_Familiar+
Cumbria_Public.Negative_Familiar
Cumbria_Neutral = Cumbria_Public.Neutral_Unfamiliar+
Cumbria_Public.Neutral_Familiar
Cumbria_Positive = Cumbria_Public.Stong_Positive_Unfamiliar+
Cumbria_Public.Positive_Unfamiliar+
Cumbria_Public.Positive_Familiar+
Cumbria_Public.Strong_Positive_Familiar
Cumbria_Unfamiliar = Cumbria_Public.Stong_Positive_Unfamiliar+
Cumbria_Public.Positive_Unfamiliar+
Cumbria_Public.Neutral_Unfamiliar+
Cumbria_Public.Negative_Unfamiliar+
Cumbria_Public.Strong_Negative_Unfamiliar
Total_Familiar = (Cumbria_Familiar+
Allerdale__Familiar+Copeland_Familiar)/
(World_Conditions.Cumbrian_Population+
World_Conditions.Allerdale_Population+
World_Conditions.Copeland_Population)
Total_Unfamiliar = (Cumbria_Unfamiliar+Allerdale_Unfamiliar+
Copeland_Unfamiliar)/(World_Conditions.Cumbrian_Population+
World_Conditions.Allerdale_Population+
World_Conditions.Copeland_Population)
Total_Unsure = (Cumbria_Neutral+Allerdale_Neutral+
```

```
Copeland_Neutal)/(World_Conditions.Cumbrian_Population+
World_Conditions.Allerdale_Population+
World_Conditions.Copeland_Population)

World Conditions:
Allerdale_Council = 7
Allerdale_Initial_Knowledge = 0.5
Allerdale_Initial_Neutral = 0.25
Allerdale_Initial_Opinion = 0.55
Allerdale_Interest = 0.25
Allerdale_Population = 96000
Copeland_Council = 7
Copeland_Initial_Knowledge = 0.65
Copeland_Initial_Neutral = 0.2
Copeland_Initial_Opinion = 0.57
Copeland_Interest = 0.5
Copeland_Population = 69800
Cumbrian_Council = 10
Cumbrian_Initial_Knowledge = 0.35
Cumbrian_Initial_Neutral = 0.28
Cumbrian_Initial_Opinion = 0.45
Cumbrian_Interest = 0.35
Cumbrian_Population = 329200
Government_Trust = IF(TIME=0) THEN Initial_Government_Trust
ELSE
IF(previous(self, Initial_Government_Trust)<0.3)
THEN max(min(previous(self, Initial_Government_Trust)*((1+
Partnership.Partnership_Positive_Influence/50)/(1+
NGOs.NGO_Negative_Influence/100))+Trust_Incident_Adjustment, 1), 0)
ELSE
IF(previous(self, Initial_Government_Trust)>0.7)
THEN max(min(previous(self, Initial_Government_Trust)*((1+
Partnership.Partnership_Positive_Influence/100)/(1+
NGOs.NGO_Negative_Influence/50))+Trust_Incident_Adjustment, 1), 0)
ELSE max(min(previous(self, Initial_Government_Trust)*((1+
Partnership.Partnership_Positive_Influence/50)/(1+
NGOs.NGO_Negative_Influence/50))+Trust_Incident_Adjustment, 1), 0)
Incident_1 = 1
Incident_2 = 3
Incident_3 = 1
Initial_Government_Trust = 0.3
NIBY = IF(TIME>20) THEN (1-Government_Trust)/2
```

```
ELSE IF (TIME>9) THEN (1-Government_trust)/3
ELSE IF (TIME>6) THEN (1-Government_trust)/4
ELSE 0
Radiation_and_Government_Media_Incidents = SMTH3(STEP(Incident_1,
Time_1), 1)+SMTH3(STEP(-Incident_1, Time_1 +1), 3) +
SMTH3(STEP(Incident_2,Time_2), 1)+SMTH3(STEP(-Incident_2,
Time_2 +1), 3)+ SMTH3(STEP(Incident_3,Time_3), 1)+SMTH3(
STEP(-Incident_3,Time_3 +1), 3)
Time_1 = 43
Time_2 = 25.25
Time_3 = 44
Total_Population = Allerdale_Population+Copeland_Population+
Cumbrian_Population
Trust_Incident_Adjustment = IF(
Radiation_and_Government_Media_Incidents>1.5)
THEN -0.025
ELSE IF (Radiation_and_Government_Media_Incidents>0.5)
THEN -0.01
ELSE 0
```

# Appendix C

# DES Model Description

This section contains information on each element used in my DES model.Keep in mind that the arrival schedules for the NGO/Partnership/Government incidents are sourced from the Partnership's website, and various NGO and news websites from the period of time that the process was active.

## C.1 Start Points

For each of the population arrival points, people arrive in batches of 100, and so the total population numbers have been divided by 100.

**Copeland arrivals**

- A single arrival at time 0 with batch size equal to population size (698)
- Constrained so that no more than 698 work items can arrive.
- Sets community label to Copeland
- Percentage routing for knowledge (60% starts with knowledge, 40% does not)

**Allerdale arrivals**

- A single arrival at time 0 with batch size equal to population size (960)
- Constrained so that no more than 960 work items can arrive.
- Sets community label to Allerdale
- Percentage routing for knowledge (55% starts with knowledge, 45% does not)

**Cumbrian arrivals**

- A single arrival at time 0 with batch size equal to population size (3292)
- Constrained so that no more than 3292 work items can arrive.
- Sets community label to Rest of Cumbria
- Percentage routing for knowledge (35% starts with knowledge, 65% does not)

**NGO news/events**

- Follows NGO news or events arrival schedule.
- Sets event label to be 1 for news and 2 for events

**NGO consistent**

- Follows an exponential distribution initially with parameter 30.
- Sets event label to be 0

**Partnership news/events/packs**

- Follows Partnership news, events or information packs arrival schedule.
- Sets event label to be 1 for news, 2 for events and 3 for information packs.

**Partnership consistent**

- Follows an exponential distribution initially with parameter 45.
- Sets event label to be 0

**Government & Radiation incidents**

- Follows incidents arrival schedule.

## C.2 Queues

**Entry into opinion states (on exit)**

- Increments the current contents tracker by 1 for the community the current work item originated from according to the opinion they are travelling to.

**Entry into NGO and Partnership activity centres (on exit)**

- Adjustments are made to the current NGO or Partnership activity and the service time distribution of their related activity centres dependent on the event type.

  - If the label value is 0 (consistent arrival), then increase the current NGO or Partnership activity by 0.01 and set the service time distribution at the activity centre to be fixed 0.
  - Else if the label value is 1 (news arrival), then increase the current NGO or Partnership activity by 0.5 (or 0.25) and set the service time distribution at the activity centre to be average 15.
  - Else the label value is 2 or 3 (event or pack arrival), then increase the current NGO or Partnership activity by 0.5 (or 0.25) and set the service time distribution at the activity centre to be average 30.

- The amount current NGO or Partnership activity increases (0.5 or 0.25) depends on the current time of the simulation. For the first 450 days, increases are 0.25, and after this they are 0.5. This represents the increasing interest.

- Average distribution was used instead of exponential to represent the more consistent effects of these events.

**Entry into incidents activity centre (on exit)**

- Increase the government and incident value by 1.

## C.3 Activity Centres

**Opinion states**

- Service time distribution is exponential with parameter (for warm-up) 200 for strong positive/negative, 150 for positive/negative and 300 for neutral.

- (on exit) Sets last opinion label according to the opinion state.

- (before exit) Decrements the current contents tracker by 1 for the community the current work item originated from according to the current opinion state.

- (before exit) Sets routing percentages to knowledge to be 3% if their knowledge label is 0, or 0% if their knowledge label is 1.

**Knowledge (on exit)**

- Service time distribution is fixed at 0.

- Increments the current work items knowledge label by 1.

- Increments the current value of the variable tracking the number of knowledgeable people by 1.

**Decision Points K and NK (before exit)**

- Service time distribution is fixed at 0.
- Sets the routing out percentage for Neutral to be 0 (after initialisation).
- Sets routing out percentages for each of the other opinion states to equal the weight currently assigned to that state for the community the individual comes from (e.g. wgt_CumbSP is the strong positive weight for someone from the rest of Cumbria).
  - The positive weights are multiplied by 1.25 for decision point K (knowledgeable)
  - The negative weights are multiplied by 1.25 for decision point NK (not knowledgeable)
- Adjusts the routing out percentages for the individuals last opinion according to the current simulation time.
  - Multiply the weight by 80 in the first year
  - Multiply the weight by 15 in the second year
  - Multiply the weight by 5 in the final two years
- Finally the routing out percentages are adjusted to relatively sum to 100 percent.

**NGO/Partnership (on exit)**

- The service time distribution is set according to the visual logic in the queue before this activity centre.
- Whenever a work item leaves the activity centre, its label is checked to identify the type of event it was and an adjustment may be made to the current NGO/Partnership Activity.
  - If the label value is 0 (consistent arrival), then the work item leaves.
  - Else if the label value is 1 (news arrival), then decrease the current NGO or Partnership activity by 0.5 (or 0.25).
  - Else the label value is 2 or 3 (event or pack arrival), then decrease the current NGO or Partnership activity by 0.5 (or 0.25.

- The amount current NGO or Partnership activity decreases (0.5 or 0.25) depends on the current time of the simulation. For the first 450 days, decreases are 0.25, and after this they are 0.5. This represents the increasing interest.

**Government & Radiation incidents (on exit)**

- The service time distribution is exponential with parameter 60.
- Whenever a work item leaves the activity centre, reduce the government and incident value by 1.

## C.4 Time-check logic

The time check interval is set to 7 days, and the following commands are run at the end of each of these intervals.

**Results export**

- Here I simply export the current information I want about the simulation to an internal spreadsheet. I exported the following;
  - Simulation Time
  - Current population support values.
  - Government trust
  - Current NGO and Partnership activity.
- The row the information is exported to depends on the number of time checks that have completed so far (and at the end of the time check, the variable that records this increases by 1)

**NGOvsPart**

- Update the current NGOvsPart variable to be the current Partnership activity divided by the current NGO activity (a small addition is made to the NGO activity to avoid division by 0).

**Government Trust**

- I update the current government trust value (*govttrust*) according to the current activity of NGOs (*NGO*) and the Partnership (*Part*), and have an additional adjustment for current government incidents (*govt*).

- If *govttrust* is greater than 0.7, then:
  - Set $govttrust = govttrust * ((1 + Part/100)/(1 + NGO/25)) - govt/200$
- Else if *govttrust* is less than 0.3, then:
  - Set $govttrust = govttrust * ((1 + Part/25)/(1 + NGO/100)) - govt/200$
- Else *govttrust* is between 0.3 and 0.7, so:
  - Set $govttrust = govttrust * ((1 + Part/25)/(1 + NGO/25) + 0.005) - govt/200$
- There are also bounding conditions to ensure *govttrust* remains between 0 and 1.

**Community weights**

- These weights are adjusted according to the current level of activity of the NGOs and Partnership (high activity means the sum is greater than 0.5), and low activity otherwise.
- Additionally, each weight is updated according to the current support levels within that community, not for the whole population of all 3 communities unless specified with 'total.
- During low activity, the following weights are set for each community.
  - $wgt\_SP = 0.1 + ((SP + P)/population) * govttrust/4$
  - $wgt\_P = 0.25 + ((SP + P)/population) * govttrust$
  - $wgt\_Neu = (totalneutral)/totalpopulation) * govttrust$
  - $wgt\_N = 0.25 + ((SN + N)/population) * (1 - govttrust)$
  - $wgt\_SN = 0.1 + ((SN + N)/population) * (1 - govttrust)/4$
- During high activity (the majority of the time), the constant added to each weight is slightly different for different communities. These are given below in the order of (SP, P, N, SN).
  - Copeland is (0.11, 0.27, 0.25, 0.1)
  - Allerdale is (0.1, 0.25, 0.29, 0.11)
  - Rest of Cumbria is (0.1, 0.25, 0.25, 0.1)
- As before, the weights use the population and support levels of the specific community they are for unless otherwise specified.

- $wgt\_SP = 0.1 + ((SP + P)/population) * (0.5 + NGOvsPart/4) * govttrust/4$
- $wgt\_P = 0.25 + ((SP + P)/population)) * (0.5 + NGOvsPart/4) * govttrust$
- $wgt\_Neu = (totalneutral)/totalpopulation) * govttrust$
- $wgt\_N = 0.25 + ((SN + N)/population)) * (0.5 + (1/NGOvsPart)/4) * (1 - govttrust)$
- $wgt\_SN = 0.1 + ((SN + N)/population)) * (0.5 + (1/NGOvsPart)/4) * (1 - govttrust)/4$

**Opinion State service times**

- Each opinion state has an exponential distribution, with base parameters 300, 250, 400, 250, 300.
- When the sum of the current activity of the NGOs and Partnership is under 1, these service time distributions are reset to their base parameters.
- However if the sum of the current activity of the NGOs and Partnership is over 1, then these parameters are each divided by the sum of the NGOs and Partnerships current activity (NGO+Part).
- This represents quicker changes of opinions when there is more activity.

## C.5 Time Scheduled logic

**Partnership cut-off**

- This is activated at simulation time 1250 (1250 days have passed).
- Disables further Partnership consistent arrivals.
- Adjusts current activity of the Partnership by subtracting the amount that consistent arrivals have contributed to activity so far.

**NGO activity_early**

- This is activated at simulation time 300.
- Sets the inter-arrival time distribution of NGO consistent to be exponential with parameter 20.

**NGO activity_middle**

- This is activated at simulation time 900.

- Sets the inter-arrival time distribution of NGO consistent to be exponential with parameter 15.
- Sets the inter-arrival time distribution of Partnership consistent to be exponential with parameter 22.5.
- Adds 0.5 to the current activity of the Partnership.

**End of PSE3**

- This is activated at simulation time 1150.
- Sets the inter-arrival time distribution of NGO consistent to be exponential with parameter 10.

## C.6 Labels

**Area (string)**

- Records the community a population work item is part of.
  - Copeland = Copeland
  - Allerdale = Allerdale
  - Rest of Cumbria = Rest of Cumbria

**Event (numeric)**

- Records the type of event for the Partnership and NGO activity centres.
  - Consistent = 0
  - News Releases = 1
  - Events = 2
  - Support Packs = 3

**Knowledge (numeric)**

- Records whether a population work item has knowledge of the proposal.
  - No knowledge = 0
  - Knowledge = 1

**Last (numeric)**

- Records the last opinion a population work item has visited.
  - Strong positive = 1
  - Positive = 2
  - Neutral = 3
  - Negative = 4
  - Strong Negative = 5

## C.7 Arrival Schedules

**Partnership News**

| Arrival Time | Number of Arrivals |
|---|---|
| 287 | 1 |
| 317 | 1 |
| 324 | 1 |
| 348 | 1 |
| 485 | 1 |
| 638 | 1 |
| 638 | 1 |
| 668 | 1 |
| 699 | 1 |
| 1003 | 1 |
| 1003 | 3 |
| 1064 | 3 |
| 1100 | 1 |

Table C.1: Arrival schedule for Partnership News Releases (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) releases

**Partnership Events**

| Arrival Time | Number of Arrivals |
|---|---|
| 210 | 1 |
| 248 | 1 |
| 280 | 1 |
| 310 | 2 |
| 365 | 2 |
| 372 | 1 |
| 652 | 1 |
| 675 | 1 |
| 699 | 1 |
| 706 | 2 |
| 1000 | 2 |
| 1040 | 2 |
| 1060 | 3 |
| 1100 | 2 |

Table C.2: Arrival schedule for Partnership Events (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) events

**Partnership Information Packs**

| Arrival Time | Number of Arrivals |
|---|---|
| 287 | 1 |
| 294 | 1 |
| 468 | 1 |
| 638 | 1 |
| 699 | 1 |
| 713 | 1 |
| 933 | 1 |
| 1064 | 2 |
| 1090 | 2 |
| 1250 | 1 |

Table C.3: Arrival schedule for Partnership Information Packs (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) packs

**NGO News**

| Arrival Time | Number of Arrivals |
|---|---|
| 675 | 1 |
| 772 | 1 |
| 833 | 1 |
| 1155 | 2 |
| 1206 | 2 |
| 1260 | 2 |
| 1338 | 2 |

Table C.4: Arrival schedule for NGO News Releases (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) releases

**NGO Events**

| Arrival Time | Number of Arrivals |
|---|---|
| 212 | 1 |
| 365 | 1 |
| 454 | 1 |
| 640 | 1 |
| 699 | 2 |
| 1064 | 2 |

Table C.5: Arrival schedule for NGO Events (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) events

**Govt Incidents**

| Arrival Time | Number of Arrivals |
|---|---|
| 420 | 1 |
| 765 | 5 |
| 1308 | 1 |
| 1338 | 1 |

Table C.6: Arrival schedule for Governmental and Nuclear Incidents (the label is set on exit). Arrival time is the number of days since the start of the process and larger numbers of arrivals denote more significant (or combined) incidents

# Appendix D

# Verification and Validation Tests

This section contains information on the validation and verification tests that were performed on the SD model. Results are provided for the final model, although many of these tests were assessed in earlier iterations as well. When experts are referenced, then I am referring to those in Table 4.5. There were also less formal tests that were carried out throughout the model construction process.

## D.1 Verification

The following tests are more behavioural tests of the software and modelling style to ensure that expected behaviour was reproduced in the model.

| Test Description | Testing Method | Result |
|---|---|---|
| Type 1, 2 and 3 feedback loops | Intervention in size of stocks and flow rates relevant to each loop, comparing the changes to without any intervention | Each type of feedback loop followed the expected behaviour (e.g. increasing a positive stock resulted in a quicker increase of the same positive stock after 0.5 months, the time delay). A type 3 feedback loop showed a stronger effect (by 3x) over an isolated type 1 feedback loop, which is expected. |
| Overall model structure & relationships | Isolated relationships and overall structure verified with experts in Table 4.5 and against literature provided in Chapter 4 | The overall structure was consistent with expert expectations, taking into account the lack of information for more external factors, and the relationships observed when isolating sections of the model matched those identified from the literature in Chapter 4. |
| Feedback delays & time steps | Run the model over 5 time steps and compare each time step's results (and delay-based changes) against mathematical calculations for just these time steps | The model produced identical results to those calculated over all 5 time steps. |
| Government trust behaviour & | Comparison of how the government trust in the model compared to the timings of each PSE | Peaks of trust at the end of each PSE, and reductions of trust between PSEs. Government trust was being correctly bounded between 0 and 1. |

Table D.1: A summary of the formal SD verification tests. All tests were passed in the final SD model.

## D.2 Validation

The following tests are a mixture of results comparison tests and sensitivity analyses.

| Test Description | Testing Method | Result |
|---|---|---|
| Extreme conditions: Initial values | Change the following initial values to their lowest possible value and then their highest to see what impact it has on the model results: Government trust & community characteristics (interest, starting opinion, knowledge) | Reducing each initial value to 0 (as separate scenarios) being significantly more negative than the baseline process ( 70% negative for copeland). Knowledge had much less of an effect. Increasing each value to 1 (as separate scenarios) resulted in the opposite extreme behaviour. Nothing observed was unexpected by the modeller or experts. |
| Extreme conditions: Speed of opinion change | Run a scenario for a very large (40) and very small (0.025) scalar to current flow rates and evaluate impact | Model behaved as expected, slow opinion change (with 0.025 scalar) showed extremely small changes, ending near the start opinions for each community, while the very fast opinion change resulted in dramatic swings, and far more negativity due to entering the strong negative state more often. |
| Extreme conditions: Radiation & Media Incidents | Run a scenario with no incidents, and one with all 3 incidents with severity 6 (Fukushima had severity 3). | For no incidents, public opinion was positive throughout the process for all communities. With the 3 incidents, there was a significant increase in negativity around these times. |
| Results: Community | Final results for each community was assessed with experts (positive, neutral and negative). | The experts agreed that the final results, and trends observed matched their knowledge of the process. |
| Results: Knowledge | Final results for each community's knowledge level was assessed with experts (know at least a little or not). | The experts agreed that the final results, and the slowly increasing trend over time matched their knowledge of the process. |
| Results: Council results | Final results for each council was assessed with experts (positive, neutral and negative). | The experts agreed that the final results, however were uncertain how the council viewed the process before the final vote and so could not validate the trends. The councils had no impact on the results for the public (but vice versa was true) |
| Results: NGO activity | The NGO events and influence over time was presented to experts. | The experts agreed that the events modelled captured the most important parts of the siting process. |
| Results: Government Trust | The government trust evolution over time was presented to experts. | The experts agreed that the trends observed matched their expectations. They were unable to validate the initial value used, however were content when a sensitivity analysis was performed to show it had relatively little impact as long as it was within their expectations. |

| | | |
|---|---|---|
| Sensitivity: Initial values | Similar to the extreme conditions test, with more 'realistic' changes. They were considered on a case-by-case basis. Government trust was between 0.2 and 0.5, community interest, starting opinion and knowledge was plus and minus 0.15, 0.1 and 0.2. These values were selected by the modeller, but validated with the expectations of experts. | Under each case, the model showed a noticeable, but not severe change in the direction expected. Changing the starting knowledge had the least effect, and community interest had the largest. |
| Sensitivity: Deliberation structure | A high intensity and low intensity campaign was considered for the partnership. The high intensity campaign had twice as many events in each PSE equally spaced within the PSE, while the low intensity campaign removed half of the events used in the siting process, again keeping events evenly spaced within the PSE. | For the high intensity campaign, there was a not much change during PSE1, a noticeable improvement during PSE2 ( 5-15%) and an even larger improvement for PSE3 (10-25%). The low intensity campaign saw similar behaviour in the opposite direction. |
| Sensitivity: Feedback | The strength of feedback loops was increased and decreased by a scalar multiplier at the impact on media (2x and 0.5x). | While the results and trends do reflect an increased sensitivity in each community, the change was not too significant. Opinion swings tended to happen a little faster (e.g. at the end of the process) |

| | | |
|---|---|---|
| Sensitivity: Delay | The delay time was changed to 0.25 and 2. | This affected the sensitivity of the public to the trends accordingly. In the case of delay 2, the final result was about 5% more positive due to the increasing resistance not speeding up the opinion change. |
| Sensitivity: Population size | Increasing and decreasing the populations of each community by 0.5 and 2 in turn | The results had a minor change according to the community changed, and in what direction. E.g. Copeland doubling its population increased positive opinion marginally in other communities (by 1%-2%). The rest of Cumbria had the largest effect (as it had the largest population). |
| Sensitivity: Speed of opinion change | Two scenarios were run with slightly faster (2x) and slower opinion (0.5x) change, due to the inclusion of a scalar multiplier to flow rates | The results for the slower opinion change can be seen in Figure 5.9, which demonstrates a reduced sensitivity. Increasing the speed of opinion change saw changes happening faster, with slightly higher negativity ( 5%) due to more people entering the strong negative state. |
| Sensitivity: Time step sensitivity | The time step was reduced to 0.125, and increased to 0.5. | The model's results did not change much when the time step was altered, as long as the consistent reductions and additions that happened every time step were altered accordingly (these were designed to be updated 4 times per month). |

Table D.2: A summary of the formal SD validation tests. All tests were passed in the final SD model.

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