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Informations Systems Engineering

Group Project

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"I've got to write a Foreword. Where to begin?"

~J Pitt

Contents

1 Introduction

At the start of the project, we were introduced to a game consisting of four simple rules:

1. Each participant is given a number of resources
2. Each participant may put any number of their resources back into a common pool
3. The resources in the pool are multiplied by a factor N (where $N > 1$)
4. Each participant may appropriate a given amount

This set of rules describes a very basic Common Pool Resource (CPR) problem. We found that if participants did not follow the rules regarding appropriation, the common pool resource was abused. This led to some participants being left with no resources at all. It was therefore decided that more stringent rules were necessary, where participants could be subject to random monitoring. However, a certain number of resources from the common pool would need to be used to fund this process. The resulting rules were now as follows:

1. Each participant is given a number of resources
2. Each participant must put at least half of their resources into a common pool
3. The resources in the pool are multiplied by a factor N (where $N > 1$)
4. Each participant may appropriate a given amount
5. Participants may choose to monitor others, at the cost of 1 resource being taken from the common pool.

The addition of monitoring led to a more effective prevention of 'cheating', and therefore a more efficient distribution of the resource. Indeed, this is a good example of the efficacy of common pool resource utilisation when participants act as individuals, and participants agree on rules and monitoring as a collective.

This report details the research, design, and implementation of a multi-agent simulation of the Kyoto common pool resource system, which is similar to the simple game described above. A multi-agent system is a paradigm for expressing systems composed of intelligent agents acting within a defined environment. This maps well to the Kyoto Protocol, allowing us to simulate individual countries and their governments' attitudes as independent agents. The common pool involved in our model is that of worldwide greenhouse gas (GHG) emissions.

We define our model in greater depth, describing how we build upon the existing architecture of Presage2, a multi-agent simulation engine. After giving an overview of our primary design decisions, we outline the specific implementation of individual components within our simulation. Following this, we present simulation data attained from running our Kyoto Protocol system, and compare how our system performs when compared to reality, as well as what predictions it makes about the long term impacts of the Kyoto Protocol on global emissions.

2 Research

2.1 Climate Change

The consensus among scientists is that the Earth is unequivocally warming, with a high certainty that this is being caused by human activities, specifically due to the last 150 years of industrial development. The International Panel on Climate Change (IPCC) defines climate change as:

> "A change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. [...]any change in climate over time, whether due to natural variability or as a result of human activity" [15]

This differs from the United Nations Framework Convention on Climate Change (UNFCCC) definition, which places the blame more squarely on human cause, where:

> "[...] climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods." [15]

There are many different responses to climate change, most focusing on either mitigation ("implementing policies to reduce GHG emissions and enhance sinks") [16] or adaptation. ("Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned.") [17]

2.1.1 United Nations Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty which covers most of the countries in the world. It was signed in 1992 with the aim to stabilise the concentration of greenhouse gases (GHG) in the atmosphere "at a level that would prevent dangerous anthropogenic (i.e. human) interference with the climate system." [13]

The definition of 'dangerous' is up to interpretation, although the IPCC concluded that the definition would vary between different regions of the world, primarily dependent on the local consequences of global warming, the region's ability to adapt to climate change and the ability to reduce GHG. Figure 1 shows the commonly named 'burning embers' diagram, which represents conceptual impact across five "reasons for concern."

2.2 The Kyoto Protocol

Having recognised that developed countries are primarily responsible for the high levels of GHGs in the atmosphere, the UNFCCC formed the Kyoto Protocol to not only encourage countries to reduce emissions, but to commit to that reduction. [33]To make the Protocol more appealing, carbon taxation was avoided in favour of other carbon reduction mechanisms.

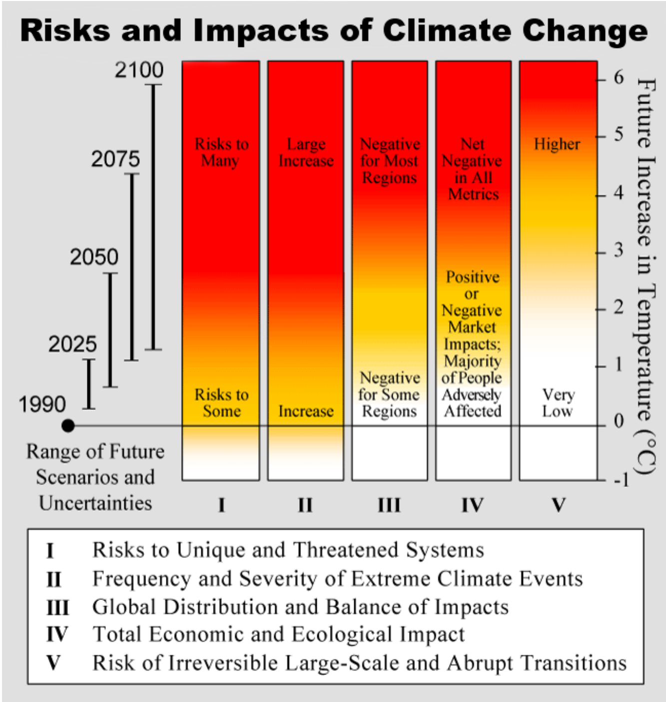


Figure 1: 'Burning embers' diagram [14]

The initial agreement was signed on the 11th December 1997 during the 3rd annual UNFCCC conference and then came into force on the 16th February 2005. The Protocol sets mandatory targets on GHG emissions for the world's leading economies "with a view to reducing their overall emissions of such gases by at least 5 percent below existing 1990 level in the commitment period 2008 to 2012." [27, Article 2, Paragraph 1]. Future targets are expected to be drawn up for "commitment periods" after 2012. [27, Article 2, Paragraph 4]

As of September 2011, 191 countries have ratified the treaty with the United States remaining as the only signatory not to have ratified the protocol. However, some United Nation member states such as Afghanistan, Andorra, and South Sudan never signed the agreement and Canada left in December 2011.

The aim of the Kyoto Protocol is to contain emissions of anthropogenic GHGs in a way that reflects underlying national differences in emissions, wealth, and capacity for reduction; this concept is known as "common but differentiated responsibilities." [19] [26] It was recognised that much of the existing CO_2 emissions were due to developed countries, and that the needs of developing countries would need to be taken into account when calculating emission targets. It was agreed that the per capita emissions of developing countries was still relatively low, and that these participants would be allowed to grow to meet their socio-economic needs.

Participants in the Kyoto Protocol were classified into three groups, according to their responsibilities: [26]

Annex I
Industrialised countries and economies in transition. These countries have committed to

reduce their emissions levels of greenhouse gases to targets that are set according to their 1990 emissions.

Annex II
Developed countries. Annex II countries are a subset of Annex I countries, and are encouraged to invest in developing countries.

Non-Annex
Developing countries which are not required to reduce emission levels unless developed countries have supplied funding and technology through outsourcing. This serves three purposes:

- To avoid restricting a country's development, since burgeoning economies tend to rely on carbon based industry.
- To permit sale of excess emission capacity to those nations having difficulty meeting their targets.
- To encourage investment from Annex I countries in low-carbon technology.

The Protocol structures rolling emission reduction commitment periods, with the first scheduled to end in 2012.

2.2.1 Initial Commitment Period

Parties partaking in the Kyoto Protocol commit themselves to reducing four GHGs (carbon dioxide, methane, nitrous oxide, and sulphur hexafluoride) and two other groups of gases (hydrofluorocarbons and perfluorocarbons). These are considered CO_2 equivalents when calculating emission reduction.

With the understanding that only Annex I countries have targets that they must commit to, the aim is to reduce global CO_2 emissions to at least 5% below the base year by the end of the first commitment period. Through negotiation, the base year decided on was 1990, due to the lack of accurate data for years prior to this. Participants would need to agree to their individual targets in line with the global target, the results of which can be read in Annex B of the Convention [27]. It should be noted that the EU-15 opted for a 'burden sharing agreement' whereby the EU set a target of -8%, and assigned individual targets to its member states.

Countries can meet their targets by reducing their greenhouse gas output or by offsetting their output by using the flexible mechanisms outlined in the Protocol. Even if Annex I countries meet their targets for the first period, future reductions will be required if the overall goal of GHG stabilisation is to become a reality.

2.2.2 Flexible Mechanisms

While participant countries must meet their emission targets primarily through domestic carbon reduction methods, Flexible Mechanisms were also put in place to make targets more attainable and affordable. These market based mechanisms help stimulate sustainable development through technology transfer, help countries with Kyoto commitments to meet their targets in a cost-effective way, and encourage the private sector and developing countries to contribute to emissions reduction. The three mechanisms defined in the Protocol are:

Emissions Trading
: Member states can trade a newly created commodity representing the surplus created if their emissions are below their assigned target.

Clean Development Mechanisms
: Annex I & II countries can invest in sustainable, greenhouse gas reduction projects in Non-Annex countries in exchange for 'Certified Emission Reductions' (CER). [28]

Joint Implementation
: Annex I countries can invest in sustainable greenhouse gas reduction projects in other Annex I countries as an alternative to national reduction.

International Emissions Trading With international markets already trading in commodities, Article 17 of the Protocol allows for countries to sell their excess 'Assigned Amount Units' (AAUs) to countries unable to meet their target. This ability for countries to sell their excess capacity saw the birth of the 'carbon market'.

Some Annex I countries, categorised as Economies In Transition (EIT), have a large surplus of AAUs, which can be sold on the carbon market. One example is Russia: having closed many cold-war-era industries since its 1990 base year, Russia was given more headroom for growth when its carbon target was set. Despite the abundance of AAUs in the market, to stop countries overselling units and becoming unable to meet their own targets, participants must keep a reserve of AAUs (known as a 'commitment period reserve') which cannot fall below 90% of its assigned amount.

European Union Emission Trading System The European Union Emission Trading System (EU ETS) allows for trading between participants in the EU and between industry operators in the EU. Governments of EU states agree on national emissions caps, and then allocate allowances to their industrial operators. Operators may privately move allowances between themselves, privately match buyers and sellers, or trade on the carbon exchange. Trading has proved to be very unpopular outside of the EU. [20]

Clean Development Mechanisms Article 12 of the Protocol allows for Clean Development Mechanisms (CDM), whereby Annex I countries may invest in emission-reducing projects in developing countries. In exchange, projects earn saleable CER credits, which the investor may use to meet their target. Article 12 of the Protocol describes its objectives:

- Assist Annex I parties to develop sustainable emission-reduction projects in Non-Annex countries (in line with the primary UNFCCC goal).
- Assist Annex I parties to meet their emission targets.

Figure 2 shows a map of CDM projects worldwide.

Industrialised countries wishing to take part in CDM need to get assurance from the project host that it will contribute to sustainable development. The applicant must also prove that the project would not have happened regardless of their support, and must project future emissions had the project not gone forward. This ensured there are no 'free riders' and that the applicant is awarded the correct amount of units for their contribution to the project.

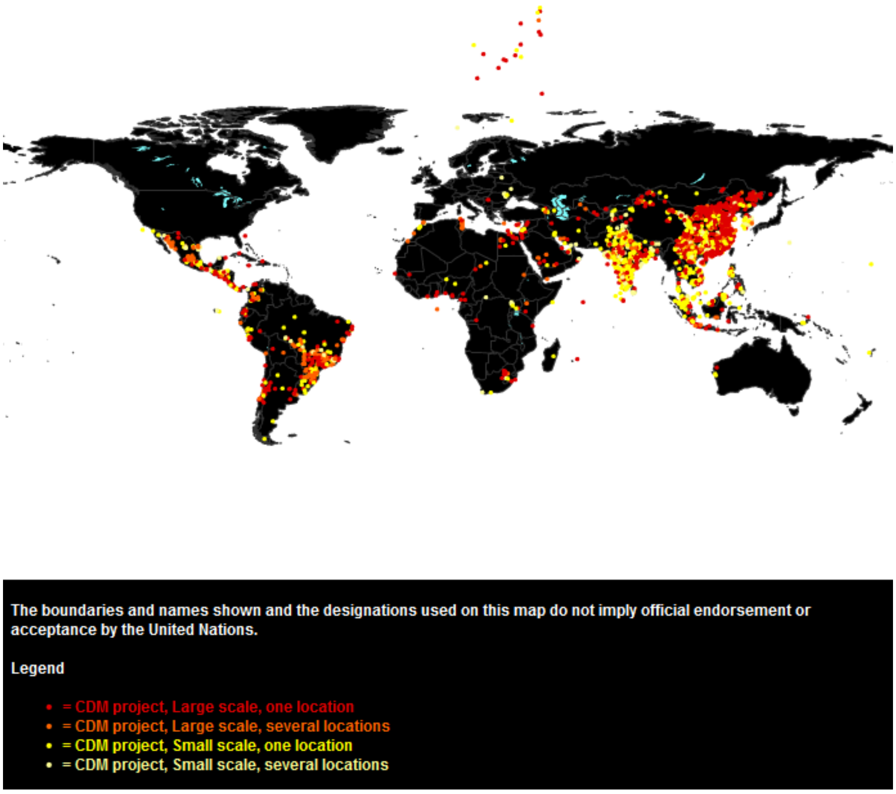


Figure 2: Map of CDM projects worldwide [30]

Joint Implementation Article 6 defines the Joint Implementation (JI) mechanism, which allows countries to invest in carbon-reduction projects in other Annex I countries as an alternative to national emission reduction. In exchange for the investment, the investor will be awarded an Emission Reduction Unit (ERU), which is to be taken from the investee's AAU pool. This requirement ensures that the total amount of units shared between Annex I countries does not change during a commitment period.

JI may be advantageous where carbon reduction is cheaper to implement in another Annex I country rather than nationally (an example might involve replacing dirty power plants with cleaner energy producers). To date, JI has not been very popular, with only 22 projects having been registered prior to 2008.

2.2.3 Reporting, Monitoring, and Sanctioning

Each participant must designate an authority to create and manage its GHG inventory. While not specifically required, many Non-Annex countries have also set up national bodies to manage their Kyoto obligations (primarily CDMs).

Kyoto requires that: [32]

- Annex I countries must have in place a national system to estimate GHG emissions (natural and anthropogenic) and any CO_2 that has been removed through sinks.
- Annex I countries must report their greenhouse inventories annually and provide regular communication detailing supplementary information to demonstrate compliance.
- Expert review teams periodically review greenhouse inventories and any national communications (this must be conducted at least once every 5 years).

The efficacy of the Kyoto Protocol depends on the participants following the Protocol's rules and regulations with respect to their commitments and the accuracy and reliability of their reports. Keeping in line with the core aim of the Kyoto Protocol (that is, an alternative to a carbon tax) financial sanctions were avoided, instead opting for the setting of harsher emissions targets.

Part of monitoring involves an expert review of reports submitted by participants. Reviewers may mark reports as 'question of implementation' where there is an unresolved problem regarding implementation, may suggest 'adjustment' where inventory is incomplete, and may suggest 'correction' where there are clear inconsistencies (suggesting 'cheating'). 'Correction' is analogous to an inventory adjustment. [31]

There are also sanctions for parties not meeting the emissions target they committed to. If the enforcement branch determines that Annex I countries do not comply with their emissions limitations, that country is required to make up the difference in future commitment periods plus an additional 30%. That country will also be suspended from emissions trading. [29]

2.2.4 Criticisms

Opinions on the effectiveness of the Kyoto Protocol vary significantly; while some consider it a move in the right direction for the stabilisation of GHG emissions, others believe the Protocol is inherently unfair and ineffective.

Inception Problems of fairness were raised early in the negotiation stages of the Protocol. During the negotiations for the setting of the base year, 1990 was chosen as reliable data prior to this date was unavailable. This base year was also highly favoured by the UK, Germany, and Russia as their respective CO_2 levels were high in 1990. Following 1990, UK emissions dropped as the energy sector moved away from coal power, toward cleaner gas power stations. Germany's CO_2 emissions also decreased following 1990 when East Germany and West Germany reunited, resulting in a decrease in dirty industry in East German territories. There was much disagreement as Japan wished to use 1995 as the base year, while former Soviet block countries wanted to use emission rates from before their industrial collapse at the end of the cold war.

There were also disagreements over the size of the emission cuts, with the EU supporting cuts in the range of 10-15%, while the US wanted a more conservative cut of between 0-5%. The level of cutbacks wanted varied from country to country, with the only common theme being that the proposals suited the interests of the country making the proposal. [34]

Trading There was also concern regarding the implementation of emissions trading. The EU and Japan wanted to ensure that emission trading was free and transparent, and wanted to prevent the US from using its political pressure to gain preference when trading with Russia. This concern was echoed in developing countries, where they believed the US would use flexibility mechanisms to its own advantage, over the interests of less able countries that needed support.

With Russia having an abundance of AAUs, there was concern that it would have a monopoly on the carbon trading market, and would be able to adversely affect the price of carbon. Russia could withhold AAUs to inflate the price for units, and inflate its profits. While possible, the situation was also difficult for Russia, since it has both an excess of AAUs, and was one of the largest oil producers. Selling AAUs would encourage the purchasing of oil, while withholding AAUs would increase their value, but might adversely affect the price of fossil fuels.

The effect of Non-Annex countries Following successful negotiation and signing of the Protocol, concern was raised regarding the lack of limitations on the GHG emissions of developing countries. Indeed the US did not ratify the Protocol, stating that "it exempts 80% of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the US economy". [24] Statistics from the International Energy Agency (IEA) show by 2011, emissions from Non-Annex countries had exceeded those from Annex I countries. [18] Only 3 countries from the top 10 table of carbon emitters are currently an Annex I participants.

2.3 Common Pool Resources

A Common Pool Resource (CPR) is a natural or man-made resource in which: the resource is deductible; the size and characteristic of the resource make it difficult to exclude other from its use. [4] CPRs are defined by their core resource (*stock variable*) and the limited quantity of extractable units (*flow variable*). The stock variable is to be conserved such that consumers may continue to exploit/consume excess resources (*fringe variable*), which are produced at a rate defined by the flow variable.

Due to a CPR's deductible, non-exclusive characteristics; it may suffer from congestion or overuse. Many CPR systems form positive feedback loops, and so with careful resource management (ensuring the stock variable is not compromised), fringe units will be continually produced, allowing for efficient operation. Excessive consumption (consumption exceeding the flow variable) will reduce the stock variable, which in turn will reduce the flow variable. Unless the stock variable is allowed to regenerate, excessive use will result in resource depletion; even if the stock is allowed to regenerate, the damage may be irreparable. The key to efficient CPR is to ensure the resource is not abused.

An example of CPR is commercial fishing; by overfishing certain species of fish, the stock variable (number of fish) is reduced, which in turn reduces the flow variable (birth rate), which decreases the fringe units which can be sustainably caught by fishers. Unless the stock variable is allowed to regenerate, certain species of fish may be driven to depletion (extinction). This is an example of inefficient use of a CPR, the only viable solution to which is drastically reducing the rate of fishing. This, and further example cases, are discussed in more detail later.

While some CPRs are owned by governments or private parties, making these public or private goods, many have no ownership, and so are an open access resource. We should note the difference between 'Common Pool Resources', as described above, and 'The Commons', which

> "refer to systems, such as knowledge and the digital world, in which it is difficult to limit access, but one person's use does not subtract a finite quantity from another's use." [6]

With the understanding that uncontrolled access to a CPR will lead to inefficiencies and overuse, some resource consumers form an institution, often called a 'Common Property Regime', to reduce the threat to the common resource by independent actions and increase the efficiency of resource harvesting.

2.3.1 Common Property Regime

Common Property Regimes are formed to protect and maintain resource systems by coordinating strategy. These strategies are based on the protection of the core resource, with fringe units being allocated to participants based on an arranged scheme. While regimes can be effective at protecting CPRs, the difficulty is in the devising of rules, limits, sanctions, and other operational variables.

The correct setting of appropriation limits is important, as setting limits too low could lead to overuse and eventual depletion of the resource, conversely setting limits too high reduces the efficiency at which the resources can be harvested. In Common Property Regimes, access to the common property is no longer free; those outside the regime see the resource as a private good, while those part of the regime see it as common good (albeit one in which appropriation is carefully monitored.)

Elinor Ostrom defined eight design principles which are required for an effective Common Property Regime: [4]

- Clearly defined boundaries
- Congruence between appropriation and provision rules and local conditions
- Collective choice arrangements allowing for the participation of most of the appropriators in the decision making process
- Effective monitoring by monitors who are part of or accountable to the appropriators
- Graduated sanctions for appropriators who do not respect community rules
- Conflict-resolution mechanisms which are cheap and easy of access
- Minimal recognition of rights to organize (e.g. by the government)
- In case of larger CPRs: Organisation in the form of multiple layers of nested enterprises, with small, local CPRs at their bases

Indeed Ostrom continues to say:

> "When subjects are placed in settings in which decisions are made in isolation, with minimal institutional structure, their aggregate behaviour is generally consistent with equilibrium predictions of inefficient resource use. On the other hand, when allowed to communicate or use other coordinating mechanisms, subjects often adopt and maintain agreements consistent with efficient and sustainable resource use" [5]

2.3.2 Case Study

These case studies look at examples of CPRs in the real world, the strategy behind these, and whether theses are considered a success.

Commercial fishing In the 70s, the fishing industry was in danger of shrinking due to overfishing. The measures taken to prevent this are analogous to that of a CPR problem. This makes it a good example to demonstrate the theory of CPR.

In 1979 the UN set out new regulations and 'protected zones' for each country with a coastline. [3] CPR models suggest that when individuals are allowed to make decisions in isolation, with minimal institutional structure, the aggregate behaviour will be inefficient. In other words, left to their own devices each countries' fishermen would take as many fish as possible, leading to the eventual depletion of the resource. By putting institutional rules in place, the UN were aiming to control the behaviour of the individuals (fishermen).

> "[...]not only do governments now have the legal power and the self-interest to apply sound principles of resource management within this area, but they have an obligation to do so." [6]

The aim of the new regulations was to get all the countries to cut back their fishing by an equal proportion, which is exactly how a typical CPR problem is solved. However, instead of imposing restrictions on fishing, many countries expanded their fishing fleets to take advantage of their new 'property'. This was due to incorrect data and models used by various countries when calculating what limitations would need to be put in place, which indicated an increase was feasible.

Ozone Layer & CFCs Scientists in the 1970s discovered an area of the Antarctic stratosphere with very low levels of ozone (33% less than ozone level for that area pre-1975), which became known as the ozone hole. The increasing ozone layer depletion would eventually led to significantly more UV radiation reaching the surface of the Earth, with possibly disastrous effects. [22]

Chlorofluorocarbons (CFCs) were to blame for this destruction of the ozone layer, with a single CFC molecule having the power to chemically unbind 4000 molecules of the ozone. The individuals in this case were the manufacturers working with CFCs. Their isolated decisions would be to not regulate their CFC usage at all, in order to maximize the profit made on their products. Consequently, the ozone layer was in danger of being totally depleated.

A regime was put in place, the 'Montreal Protocol on Substances that Deplete the Ozone Layer', which set out plans to cut production of CFCs by 100% over 10 years. The benefit provided by the ozone layer outweighed the increased cost to manufacturers and consumers caused by the removal of CFCs from industrial manufacturing processes. This reflects CPR theory, where by applying institutionalised proportional cutbacks, a shared resource can be used sustainably. [22]

The ozone holes have now ceased growing (and will eventually disappear), and so this example case of CPR can be considered a success.

Analysis The success of schemes to protect CPRs worldwide varies substantially. The key to success is understanding that there is no 'one-size-fits-all' solution to the problem of common resources, and that often quick fixes can cause more harm than good. While Ostrom's design principles are an integral part of Common Property Regimes, studies on the relative successes of CPR implementation has shown that there are a few requirements for a successful regime: [6]

Achieving accurate and relevant information
: Published information must combine accurate scientific data with an understanding of the environmental system. With the continually evolving environment, data must be kept up to date so that it is relevant.

Dealing with conflict
: When resources are allocated, conflict over policy and administration of regime will certainly occur. Conflicts should not be ignored, but dealt with immediately to ensure these do not become a problem further down the line.

Enhancing rule compliance
: Rules are only effective when participants consider these legitimate, fair and enforced. Participants should take some responsibility for monitoring.

Providing infrastructure
: Physical, technological, and institutional infrastructures must be provided such that participants may operate effectively within the regime

Encourage adaptation and change
: It is difficult to 'fix' institutions for the long term, when they are still dealing with past issues. Institutions must embrace changes as part of their developments.

2.3.3 The Kyoto Protocol as a CPR

The problem which the Kyoto Protocol attempts to resolve, the reduction and stabilisation of global carbon emissions, is not dissimilar to other CPR problems already discussed in this report. Both the Kyoto Protocol and CFC reductions are cpr systems which have a global effect on the environment, economies, and development. The difference between these problems however, is one of scale.

In the first instance, Kyoto is an open resource with no real ownership; this makes it difficult to impose regulations and limitations on emissions, even if a Common Property Regime is formed. Unlike the CPR system involving fisheries, dividing up the world's atmosphere by country does not prevent the actions of other adversely affecting the global environment, and unlike the problem of CFCs, the economic consequences are large and affect the development of countries, not just individual industries.

As in the overfishing example, participants will always attempt to play to their advantage. We have seen this to be the case in Kyoto, as described in the Criticisms subsection of the report, and this may lead to inefficiencies within the Kyoto CPR system. While the long term gains from participating in the Protocol are obvious, some have more to gain than others, particularly in the short term. Russia, with its excess of AAUs has the potential to make money on the emissions trading system (or indeed, play with the market to increase profits).

The EU, having seen the efficiency advantages of working as part of a common regime, have further imposed regulations, systems, and sanctions within the member states. The aim of this is to ensure EU members are as efficient as possible within the scope of the CPR. Indeed this appears to be the case, as most EU states are on track to meet their target. [9]

Research has also shown that there may be problems of efficiency when there are significant wealth and technology inequalities. Where there are no regulations for a CPR, technology inequalities can exacerbate inefficient use and those participants with better technologies over-extract from the core resource, while less technologically advanced participants will lag behind. Where CPRs are regulated, efficiency gains from the regime will be lower as inequality amongst participants increases. This has somewhat been avoided in the Kyoto Protocol by the introduction of Clean Development Mechanisms; this allows Annex I countries to invest in clean development in Non-Annex countries, thereby reducing the technology gap between developing and developed countries, which in turn increases the efficiency of participants in this regime. [7] [8]

Summary It appears that Kyoto can be mapped to a Common Pool Resource scheme, and while some of the problems faced by other CPR systems have been carefully thought out (efficiency of regimes, CDM to combat wealth inequality), other problems still remain (no limits for Non-Annex countries, countries playing Kyoto to their advantage), which may cause long term problems to the efficacy of the protocol.

2.4 Multi-Agent Systems

2.4.1 Definition

A multi-agent system (MAS) is a paradigm for conceptualising, designing, and implementing a system composed of multiple intelligent agents within an environment. We can therefore use MAS as a model to portray computing as a process of interaction [10] where agents can autonomously cooperate, reach agreements, or even compete with other agents that have different interests. Thus topics such as portfolio management [11], joint mission planning, [12] and the modelling of social structure [21] are areas where MAS research may be an appropriate approach.

A MAS has the following advantages over a single agent or centralised approach:

- A MAS distributes computational resources and capabilities across a network of interconnected agents. In addition, a MAS should not suffer from resource limitations, performance bottlenecks, and/or critical failures due to its decentralised nature.
- A MAS allows for agent wrappers around one or more existing legacy systems which allows them to be incorporated into an agent society.
- A MAS efficiently retrieves, filters, and globally coordinates information from sources that are spatially distributed.
- A MAS provides solutions in situations where expertise is spatially and temporally distributed.

2.4.2 Structure of an Agent

Agents are very similar to active concurrent objects except for one key difference: agents can decline to perform an action (e.g. refusing a trade proposition in a trading simulation). Often, they also interact using a common high level peer to peer (P2P) communication language, which allows them to coordinate their activities asynchronously. These similarities do mean that concurrent object oriented programming is a suitable base for building multi agents systems.

As mentioned previously, MAS are composed of agents and an environment as seen in Figure 3. Therefore it is essential that agents are able to perceive the environment where they are situated (e.g.: via sensors, message reception, or event detection) giving partial information on its state and that they are also able to act upon it with possible non-deterministic outcomes (e.g.: via effectors).

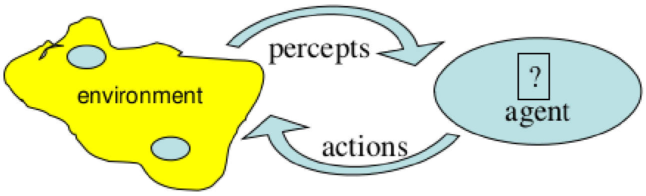


Figure 3: Basic multi agent system structure [10]

This allows the programmer to design proactive agents, which are set out to achieve "well defined goals". Agents' behaviours are thus goal directed. This requires the environment to be maintained in a certain state and the agent to achieve a certain state of its environment. [10]

From a software engineering perspective, the most adapted agent structure for our project is to use agents with states as shown in Figure 4.

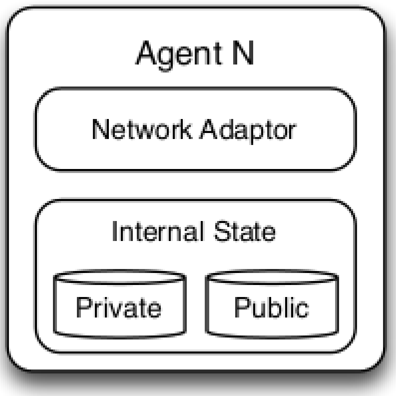


Figure 4: General agent architecture [23]

We can use the agent's internal data to record information about the environment state and its history. Separating the internal state into public and private sectors also allows the agent to keep some information hidden from other querying agents. Finally, all P2P messages are sent via a network adapter which allows us to abstract away communication protocols and methods.

2.4.3 Services and Protocols

In order to simplify the implementation of agents, it was agreed that we would require additional services and protocols on top of the environment and network. Services allow us to retrieve the environment shared state raw data in a more user-friendly way. Similarly, protocols encapsulate inter-agent communication.

By using such components, we can encase the software implementation of our simulation framework. Any changes made to the way the environment stores data or how communications are handled would therefore not affect the behaviour of our agents.

2.4.4 Presage2

There exist several platforms that allow the development of multi agent systems. The two most important ones are Jade and Repast. However, it was decided to use the internally developed Presage2 platform due to the nature of our desired simulation.

Originally written by Brendan Neville and then improved by Sam MacBeth, the platform offers the ability to rapidly prototype complex agent societies. In Presage2, agents are allowed to act during incrementing time steps, which results in discrete time driven simulations. It also offers a rich communication layer as well as the ability to batch multiple simulation runs through a web user interface. Finally, the following requirements are met, which allow for the design of social behaviour and the observation of long term global performance and adaptation [2]:

Abstraction: the agents and network can be as simple or complex as necessary (e.g.: agents can range from being simply reactive to implementing complex belief, desire and intentions (BDI).)

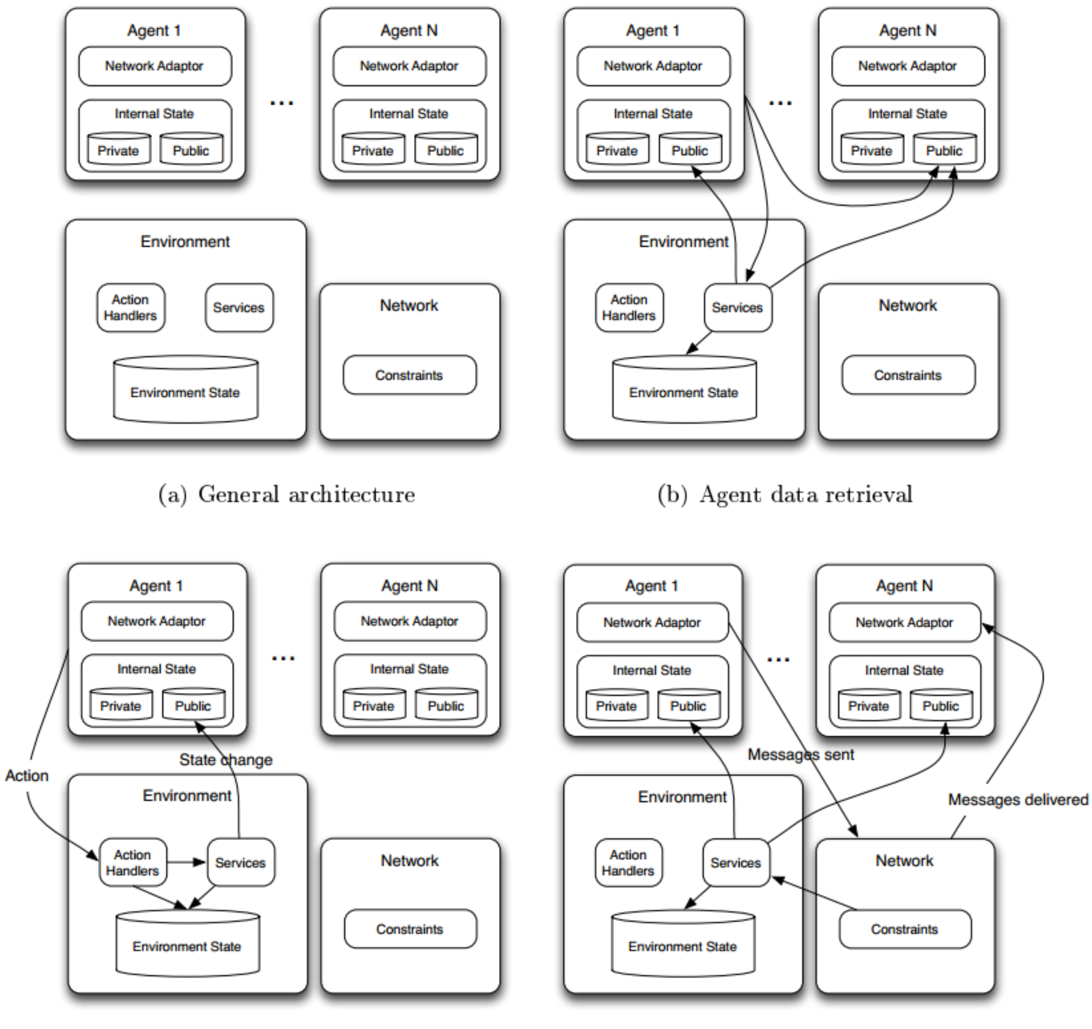
Flexibility: the platform allows the user to easily change the simulation input parameters. In conjunction with the ability to batch run, it is very simple to measure the impact of variable values.

Extensibility: base classes and modules can be extended in order to allow the user to add any desired functionality.

Interaction: Simulation data can be stored in a MongoDB collection which provides easy access and visualisation of the results.

Rule engine: There is support for executable, mutable rule specifications.

Figure 5 and 6 respectively show Presage2's general architecture and the breakdown of a simulation run:



(a) General architecture

(b) Agent data retrieval

(c) Agent acting

(d) Agent messaging

Figure 5: Presage2 architecture [23]

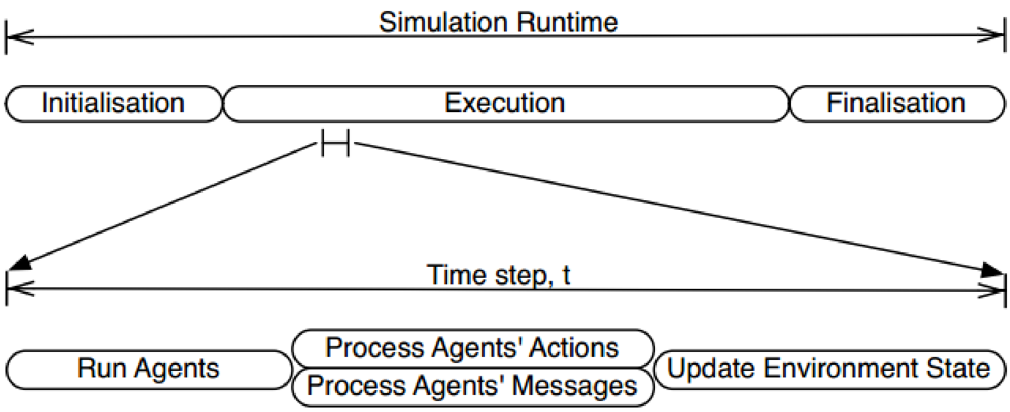


Figure 6: Presage2 simulation architecture [23]

3 Kyoto as a Multi-Agent System

Here we detail the design decisions made regarding the modelling of the Kyoto Protocol CPR and considerations involved in mapping the Kyoto Protocol to a multi-agent system simulation. In order to properly explain the implementation of any one component of our Kyoto Protocol system, we must first elaborate on the larger structure of the project, giving a high level overview of the framework our agents are built upon.

3.1 Time

For the purpose of our simulation we refer to time in terms of sessions, years, and ticks. Presage2 is a discrete time simulation engine and ticks in our simulation map directly to Presage2's discrete units of time. Years last for a number of ticks defined at simulation time. Sessions are composed of multiple years, with a default of 10. In the real world Kyoto Protocol, the length of a session is mutable depending on the global economic and political climate. However, we felt it was a suitable abstraction from reality to use a consistent length for sessions throughout any individual simulation.

3.2 Energy Output

Energy output is an estimator of a participant's productivity. This is calculated in our simulation as the theoretical CO_2 emission were the country's industry entirely carbon based. The calculation of a country's energy output depends on many economic factors, which would be too complex to accurately calculate for our model. We use two factors to calculate this; the country's carbon output and the percentage of its industry dependent on fossil fuels. Hence, energy output is calculated as:

$$energy\ output = carbon\ output\ /\ fossil\ fuel\ percentage$$

3.3 Economy

As with real world governments, our models of agent behaviors are necessarily constrained by the funds available to their respective administrations in their efforts to conserve the environment. GDP is a readily accessible and, for the complexity of our simulation, suitably accurate representation of countries' relative wealth. However, our simulation represents only the Kyoto Protocol in isolation, and an associated model of the global economy would be required to accurately gauge individual spending on the numerous national and international projects flexibly related to the Kyoto Protocol. To abstract away this complexity, each country is allocated a portion of its GDP every year as spendable income on projects relating to the Kyoto Protocol.

Manipulation of a country's GDP growth rate is the primary way we represent economic growth or recession. The formulae involved in modeling GDP growth depend primarily on a country's energy output, as defined above. This encourages investment in industry to promote economic growth, making maximisation of GDP growth a contrary but still achievable objective when adhering to Kyoto Protocol targets. These formulae also discourage drastic cutbacks in industry, which is intended to be an emergency measure for countries that are unable to meet their targets. This penalisation encourages long term thinking in the agent's behaviour, and rewards careful investment and management of targets alongside economic priorities.

3.4 Monitoring and Sanctioning

At the end of every year in our simulation, monitoring and sanctioning are performed to manage the emissions targets and detect fraudulent emissions reports. Each country is queried for its emissions reports by the monitoring service. The service then monitors a selection of countries, extracting their true carbon emissions, representing an investigation by the UNFCCC. The monitoring service carries out sanctioning, imposing financial penalties on cheaters and harsher targets on countries who report emissions above their targets. Once sanctioning has been completed, the targetting service assigns new emissions targets to each country and the simulation proceeds as normal.

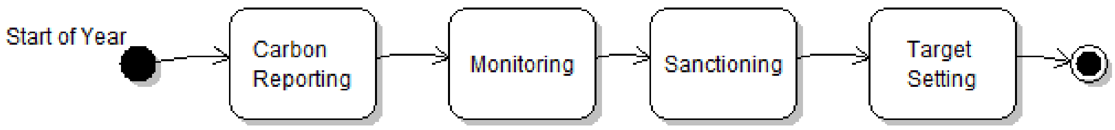


Figure 7

While we were eager to try and have our simulation model the Kyoto Protocol accurately, some changes needed to be made to discourage agents from abusing the game mechanics. For example, in a 10 year session, a participant could maximise their industry and GDP for the first 9 years and hence generate a large amount of funds. This could then be followed by a drastic reduction in industry to meet its target in the last year. This would create an excess of funds while the agent disregarded its emissions targets, giving it and unfair and unrealistic advantage.

Target Setting
In the real world, targets are calculated per session for each participant. However, our model calculates the session target for each participant and then sets incremental, yearly targets which, if an individual country meets these targets, will ensure it meets its session target as well. This removes the potential abuse of the GDP functionality, since our simulated GDP is not externally sensitive to non-Kyoto Protocol events, unlike the real world.

Reporting
Our model follows the Kyoto Protocol and reporting is done annually. Our reporting system is intentionally designed to allow countries to falsify their emissions reports, in the event that they, for any reason, wish to present incorrect emission data. One of the primary reasons for this would be not meeting emissions targets. At the risk of incurring financial penalties, it is possible for a country to avoid target sanctioning, which would have required an even more drastic reduction in the following year.

Monitoring
As per the CPR model, monitoring of participants should incur a cost. Every year all participants are 'taxed' a certain percentage of their GDP, which is used to cover the cost

of monitoring participants. The Kyoto Protocol does not specifically call for a tax to cover its monitoring, although the UNFCCC is funded by its members, so our model represents a suitable simplification.

In the real world, monitoring is done every 5 years by a team of experts. We decided to monitor more frequently in order to discourage unrealistic participant behaviour. A number of random participants are checked yearly using the funds gained from the 'monitor tax'. Repeat offenders, who have been found cheating before, have an increased probability of being monitored in the future.

Sanctioning

Sanctions are applied immediately when participants are found to have missed targets or have reported fraudulent emissions. The sanction for missing a target is a proportional increase in that participant's target in the following year, which is in line with the Kyoto Protocol regulations.

The sanctions for fraudulent reporting in real life appear lenient, only suggesting a recalculation of the reported figures. This kind of activity would also result in political pressure from other Kyoto participants, but this would be difficult to model in our simulation. We wanted to look at the effect of a more stringent form of sanctioning, and thus we decided to impose financial sanctions for fraudulent reporting. This makes cheating, from an artificial intelligence perspective, a decision rather than a default. If the real world approach of simple target correction were employed then correctly reporting a failure to meet an emissions target is, from the isolated perspective represented in our simulation, never a sensible course of action. We wanted to avoid eliminating potential actions countries could take.

3.5 Participants & Actions

The countries which form the Kyoto Protocol membership have been split into 4 groups:

- Annex I (Must reduce emissions – e.g. EU)
- Annex I (Must sustain emissions – e.g. Russia)
- Non-Annex (Developing countries)
- Rogue States (Not part of Kyoto)

While Annex I and Non-Annex countries have been implemented as per the Protocol specification, it was decided that we would remove the Annex II class (which is just a subset of Annex I), and allow all Annex I classes to invest in CDM.

Table 1 defined the actions which participants can use:

3.5.1 Domestic Carbon Reduction Measures

Carbon Absorption

Carbon absorption is the process of building carbon sinks, projects which offset carbon emissions, for example planting large sections of forest. Our carbon absorption model follows a law of diminishing returns, so as more carbon absorption actions are taken, the return received for a given investment decreases. This models the increasing value of land

Class	Target	Report Monitoring	Sanctions	Reduce Absorb	Energy Handler	Trading	CDM
Annex I (Reduce)	Y	Y	Y	Y	Y	Y	Y
Annex I (Sustain)	Y	Y	Y	Y	Y	Y	Y
Non-Annex I	N	Y	N	Y	Y	N	Y
Non-Kyoto	N	Y	N	Y	Y	N	Y

Table 1

as it becomes more scarce and the increasing difficulty of building further carbon sinks as more are constructed. In theory, the cheaper, more efficient projects are prioritized, so once they have been completed, greater investment is required for further improvement.

Our model only allows for forestation of arable land; this differs from real life where trees can be planted on various types of land. This simplification allows us to use freely accessible country data. Another simplification is the immediate building/growing of trees; in real life, a participant would only get gradual carbon reduction gains from planting trees. However, there are mechanisms in place within the Kyoto Protocol to immediately reward member states for sustainable development projects which reduce long term emissions. Our carbon absorption handler models an simplication of these two factors.

Carbon Reduction

Carbon reduction is the process of reducing carbon output of dirty industry. As in real life, our carbon reduction model follows a law of diminishing returns. Hence as more industry is cleaned, the cost of further reductions increases. This maps to the ease of upgrading from coal power to existing, but cleaner natural gas technology, when compared to the investment required to pioneer nuclear fusion research.

Our model is only affected by the percentage of total dirty industry. In real life, there are various ways in which carbon reduction can be implemented, although the simplification used is suitable for the complexity of our model.

Energy Usage

As previously described, participants need to be able to have some influence over their GDP rate. In our model, energy output is a driving factor behind the GDP rate calculations, and so participants have the option of either growing or constricting their industry. This has the effect of changing the energy output and carbon output accordingly.

Investments in carbon industry will result in GDP growth, capped at sensible levels, but increases in carbon emissions. Countries who must reduce their overall emissions but wish to still maximize their economic growth must first invest in carbon industry and then in carbon reduction or absorption.

3.5.2 Flexibility Mechanisms

Emissions Trading

In the real world, while being a viable carbon offsetting measure, carbon emission trading has proved less popular than domestic carbon reduction. Our model places more emphasis on emissions trading than in the real world, as we were interested in the simulation of an active commodities market.

It is understood that the world has several emission trading schemes and markets, the EU ETS being one of the largest. While we did plan to incorporate the EU ETS into our game, this was eventually scrapped as the time available did not warrant the extra complexity this would add to the simulation.

Clean Development Mechanisms
CDM is a significant action available to participants of the Kyoto Protocol, and similar to our interest in an active carbon market, we were keen to see the effects of an active market for clean investment. This mechanism is broadly unchanged from the real world specification, with the exception that we are not differentiating between AAUs and CARs.

Joint Implementation
The JI flexibility mechanism did not prove to be very popular in the real world, and with so few examples of this mechanism being carried out, it was left out of our simulation, and its inclusion would add unnecessary complexity.

3.6 Flowcharts

Before moving to the coding phase of the project, some initial flow charts were drafted to help us visualise the different states and actions that would have to be implemented. The high level architecture of the simulation can be seen in Figure 8 with a more detailed composition of the country behaviour sub-process in Figure 9:

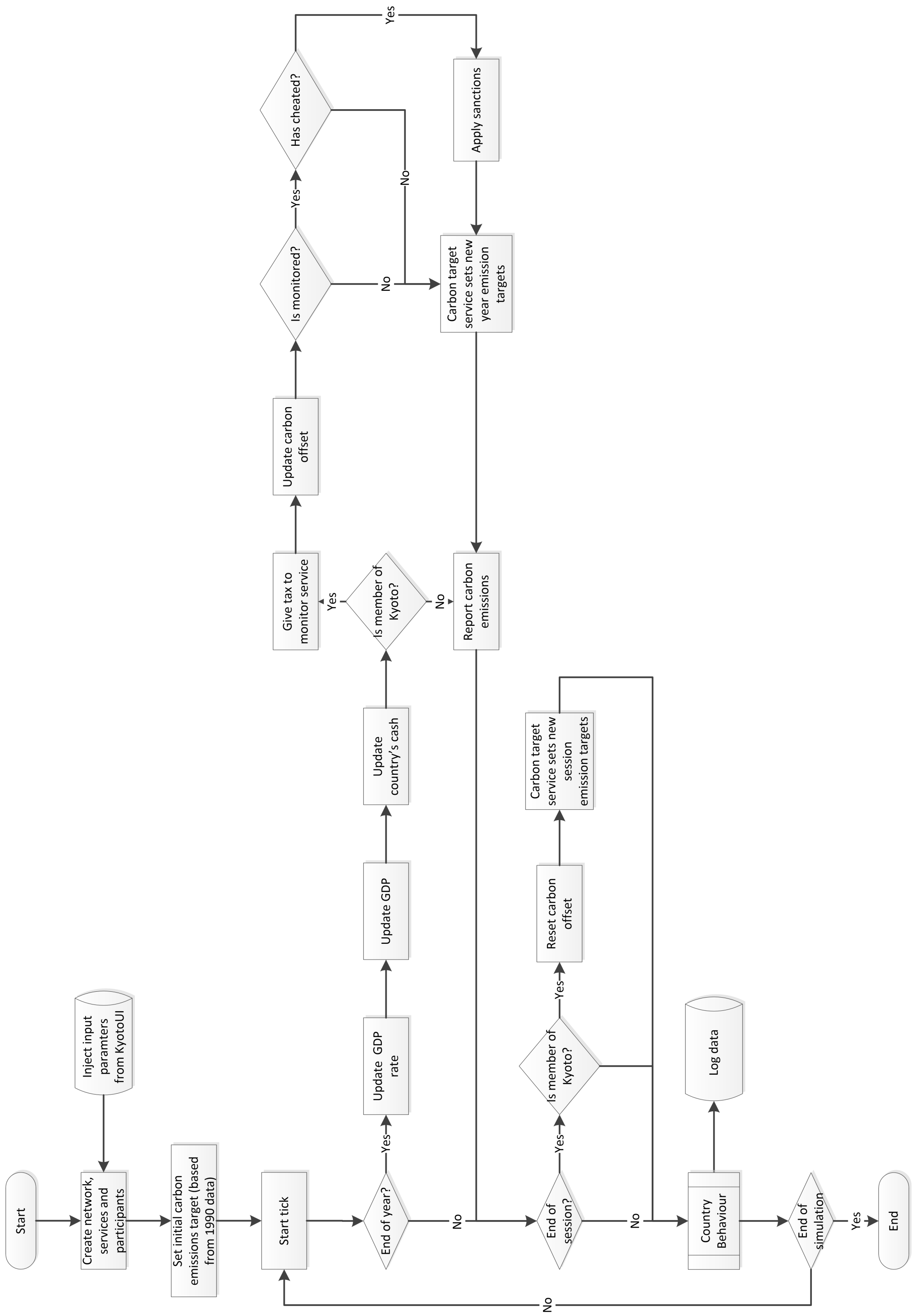


Figure 8: Kyoto Simulation Flowchart

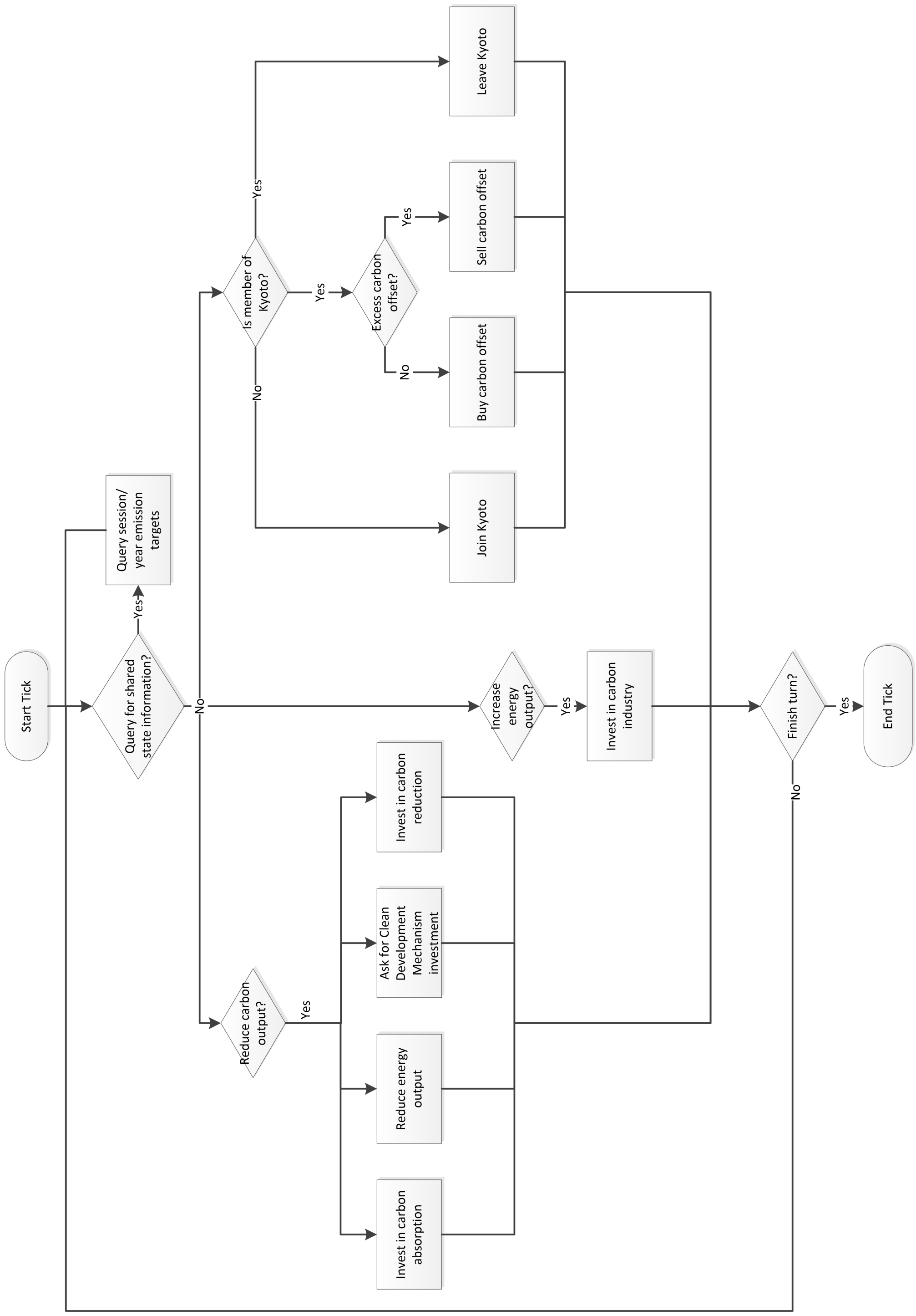


Figure 9: Country Behaviour Flowchart

4 Implementation

Having broadly introduced the framework within which our multi-agent simulation of the Kyoto Protocol operates, we can now elaborate on the specific implementation of individual components of our system. Implementation, in this sense, does not refer to Java constructs or actual code, but rather the design decisions that team members made during the project's development.

4.1 Agents

Agents are the intelligent actors within an environment that represent countries interacting with the Kyoto Protocol. The initial structure of our project groups allocated the distinct country behaviours discussed earlier in the report to groups of four people. Though this group structure became less rigid as the project progressed, each type of agent as originally outlined still approaches the Kyoto Protocol with markedly different strategies.

4.1.1 Participants

Annex I (Sustain) Agents implementing this type of strategy are meant to represent countries which are part of Kyoto and belong to Annex I group, but their emission targets are equal or higher than their emissions for the first Kyoto session.

The usual reason for this is that normally, while the first session started in 1990, the data used for setting the targets comes from 1990. During this period of history, many Eastern Bloc countries moved from heavily carbon-based economies to more environmentally conscious economies. Hence, even though Kyoto takes their former high carbon emissions into account, they have reduced their carbon output quite significantly since then, reaching or even exceeding the targets before the first session started. That, in turn, means that they do not have to reduce their emissions further during the first session.

Strategy In order to make strategies distinct between Annex I sustain and Annex I reduce, Annex I sustain countries will only remain a part of the Kyoto Protocol as long as they meet their targets. In the event that emission targets are lower than the acceptable output level for that participant, the country will attempt to reduce their emissions by investing in carbon reduction or absorption. Where funds, area or carbon output to reduce are unavailable, participants will leave the Protocol and become a rogue state. A small subset of participants are able to cheat (When their emissions exceed their targets, they report false values). If these cheating participants are caught multiple times, they may leave the Kyoto Protocol.

However, it is important to recognise that Annex I sustain countries did ratify the Kyoto Protocol when it was originally proposed and finalised. These countries' governments have expressed a desire to minimise their impact on the environment to some extent. It is with this in mind, that annex I sustain countries make sure that their overall emissions never rise above their starting levels. Any investment in industry to promote economic growth is offset by corresponding investments in cleaning industry or constructing carbon sinks.

On the other hand, Annex I sustain countries are reluctant to reduce their carbon emissions if it adversely affects their economic growth. Any reductions in emissions are because the country has judged that investment will be profitable when the resulting offset is sold on the carbon commodity market. This may seem like a bleak attitude for a set of countries to adopt, painting them as opportunistic and self-interested. However, this diversified the strategies our countries employ over the course of an entire varied simulation and more properly models Common Pool Resources, where individual interests are weighed against that of the collective.

The strategy contains three steps, taken every year in order:

1. **Invest in industry**

   Part of a year's budget is reserved for increasing the economy. Since this group represents mostly newly-developed countries, this is prioritised to promote long term growth.

   As outlined earlier, the investment must be accompanied with carbon reduction or absorption, so that overall carbon emissions do not increase. To achieve that, a specific point is found for which total price of investments in industry and matching emission decrease is equal to the reserved budget.

2. **Sell carbon credits**

   If the emissions of the country are lower than the target for a given year, the country will accumulate carbon offset, representing the 'unused' emissions. The agents will attempt to sell all of these credits. Since carbon trading is essentially an open market, setting an average price can be challenging. To maximise profits from sales, the agents will start with a high asking price, reducing it gradually as the year progresses if no one is interested in buying, and increasing it when the sales go well.

3. **Invest in emissions reduction**

   When a country has no credits to sell anymore, but there is still demand for carbon offset on the market, it may decide to invest in carbon reduction or absorption to generate additional carbon offset. First, it estimates how many of the generated units can possibly be sold during the current session, assuming the market price persists. If the estimated profit is higher than cost of the investment, the country will proceed with it. Should this occur, the country will reduce its emissions by the end of the session (reducing global output as an incidental benefit), and hence will end up with a target higher than actual emissions in the next session, just as in the previous one. If this is the case, it will stay in Kyoto for the next session.

Annex I (Reduce) In our project, we define Annex I reduce countries as participants whose current emissions are higher than their 1990 base targets, requiring them to prioritise the reduction of their carbon emissions. Good examples of such countries are the fifteen European countries.

For their behaviour, it was decided that the best approach was to design a mini simulation that would, once per simulation year, perform exhaustive testing on every possible country action, extrapolating emissions and industry growth for a number of years into the future. It then decides which sequence of actions results in the best outcome, with regard to maximizing economic growth while still meeting Kyoto Protocol targets, and then performs the action in the mini simulation that corresponds to the current year in the full simulation.

While simple in theory, in practice there is a very major hurdle; there are an enormous number of possible actions a given Annex I reduce country can take, all of which operate on a continuous scale. Every action has an almost infinite number of options that can be taken. For example, a country could choose to reduce their carbon emissions through absorption by spending 1% of their available cash, or by spending 100% of their available cash, or any number in between. They could then decide to buy vast amounts of carbon offset from the market, at any price, or put up sell offers. All of these actions can be performed in a single tick.

Strategy In order to simulate the behaviour as efficiently as possible, some heuristics had to be implemented that would decrease the number of actions that could be taken to a manageable number. The first technique used was to take the previously continuous scale of actions and cut it into a variable number of discrete chunks. The number of chunks is variable upon how many years into the mini simulation have been calculated; the later into the simulation, the fewer chunks. This decreases the total number of branches produced while keeping as much accuracy as possible at the beginning of the simulation.

The next was to split the previously potentially infinite sequence of actions into a finite number of actions. To do this, it was decided to split each turn into three phases: the 'reduce' phase, the 'maintain' phase and the 'sell' phase.

The reduce phase happens first. It checks whether our current carbon output is below our carbon target. If we are at or below our target, then nothing is done. However, if we are above our current target, the testing will branch off into combinations of three distinct actions. The carbon target will be met by either buying carbon offset from the market, by reducing the carbon output through investing in absorption and reduction or, if in particularly dire financial situation, by reducing the economic output of the country. Every time a branch occurs, a new 'state' is created.

Before the maintain phase occurs, we compare every branched state with one another and check whether one state is objectively superior for every possible pair of states. For example, let a state have two attributes 'Money' and 'Carbon', where a higher 'Money' and a lower 'Carbon' is better. If state 1 has a 'Money' value of 100 and a 'Carbon' value of 50, and state 2 has a 'Money' value of 90 and a 'Carbon' value of 60, then state 1 is objectively better than state 2. Therefore we can immediately eliminate state 2 as a possible action. Alternatively, if a state 3 has a 'Money' value of 110 and a 'Carbon' value of 60, we cannot objectively say that it is any better than state 1 and thus cannot remove this from the simulation. By performing this culling, we can prevent our search space from getting too large and avoid going down paths where we can already tell there will be better alternatives.

Next is the maintain phase. As we are now guaranteed to be at least at or below our carbon target, the country can focus on improving its industry, which will eventually result in an increase in the available cash to spend. The simulation will branch off from each unculled state created in the reduce phase by first investing in industry (i.e. increasing our energy output, which in turn increases our GDP) by some amount and then by offsetting the extra carbon created by investing in absorption and reduction, or by buying the offset from the market. Once again, a cull is performed after all branches have been taken.

Finally there is the sell stage. Here, we reduce our carbon output (by investing in carbon absorption and reduction, or by shutting down factories) by a certain amount and then sell our newly created carbon offset at the highest possible price. Once again, all unrealistic states are culled.

The combination of these three phases makes up a list of possible actions for one year of the game. However, since a session lasts a number of years (at which point any accumulated carbon offsets are abandoned when new emissions targets are calculated), simulating the possible behaviour for a single year simply does not provide us with enough information to choose an ideal action path. The simulation needs to continue the internal projections up until either the end of the current session or until we reach a maximum number of branches.

Once this is over and we have a large number of end states, we can analyse our them to find the ones which can be objectively considered the best. This will be the one with the best economy and the lowest carbon output. When identified, we simply traverse our path back to the initial state and perform the action for the current year in the actual game.

As the Annex I reduce countries were deemed to be paragons of justice, some actions such as cheating and ignoring carbon targets weren't coded in. Overall, though, this method takes as much advantage as it can of the possible options available to a country, including utilising the market as much as possible. Unfortunately, due to computational constraints and the aggressive heuristics that were used, the absolute best possible action a country can perform in a given year doesn't tend to be taken although something very close will be performed.

This behaviour approach is an example of an uniformed breadth first general graph search where the ideal end state has no constraint other than to be superior to any other possible end state. This method means that the underlying algorithms can change in any way (e.g. the calculation of GDP) with only minimal changes to the behaviour code, while still being able to maximise economic growth and manage carbon output correctly.

Non-Annex The Non-Annex group is mainly composed of developing countries whose primary aim is economic growth. Since GDP growth is directly proportional to energy output in this project, the aim of Non-Annex countries is to increase its industry as much as possible.

Investing in industry, and therefore growing a country's economy increases its carbon output at the same time. However, the Kyoto Protocol dictates that sanctions are not enforced on Non-Annex countries since they are not set targets to fulfill. They are therefore free to emit as much CO_2 as their industry requires.

Nevertheless, the Non-Annex behaviour was implemented such that they do care about the environment as well as their growth when cash is available in abundance.

The following keywords will be used to describe the general behaviour of Non-Annex countries:

1. **energy_aim:** the energy output the country wants to reach by the end of the year.
2. **times_aim_met:** how many consecutive times the energy output aim was met.
3. **aim_success:** variable that represents whether the country met its energy target or not.
4. **green_care:** variable that controls if the country cares or not about the environment.
5. **green_lands:** variable that controls whether the country has actually met its environmental commitments.
6. **environment_friendly_target:** if it exists, variable that stores the country's carbon emission target.

The country starts by having a policy of increasing its energy output, whilst trying to meet an internally set carbon emission target.

Each year, the country calculates the difference between its achieved energy output and the target aim that was set the previous year. The difference is then used to estimate the amount of money to invest in carbon industry each tick in order to reach the required energy output. Before the country proceeds with the investment, certain conditions have to be met:

- It has the available cash to spend.
- If the country has decided to care about the environment, the increase in carbon output due to the investment should not lead to its emission exceeding the set target.

If the latter condition is not met, then the country tries to invest in carbon absorption or carbon reduction in order to decrease its carbon emissions. However, the country will switch to non environmental friendly policies if it does not have enough money.

Non-Annex countries take part in Clean Development Mechanisms. This allows Annex I and Non Participant countries to invest in Non-Annex countries in exchange for carbon offset.

In other words, Annex I countries use Non-Annex land area and carbon output to reduce their own emissions in order to meet their targets in the Kyoto Protocol. There are two ways in which countries can invest:

Carbon Absorption Decrease available land area, increase carbon absorption

Carbon Reduction Carbon output decreases

The amount of carbon output to be changed/given to the Annex I country depends on whether the Non-Annex countries meets its energy output aim.

Carbon absorption offers are all accepted if the country is in an environmentally friendly phase (unless the available land area is at a minimum).

4.1.2 Non-Participants

For the purposes of our simulation the rogue states are comprised of the US, who operate independently of one another, yet necessarily share certain actions and behaviours.

United States The United States agent uses a metric of "greenhouse gas intensity", defined as the ratio of emissions to economic output, measured in units of tonnes of CO_2 per million dollars of GDP to monitor its emissions. For example, using the 1990 data values, the intensity evaluates to 4,879,376/5,722,300 = 0.853 (3dp). To put in historical perspective, the Bush administration committed to reduce the intensity of greenhouse gas emissions by 18% over the period 2002-2012.

In the real world it is the governing political party that makes any decisions regarding climate change mitigation, whose actions are in theory in response to the prevailing attitudes of the electorate, and so it is the case for the agent in our simulation. Every four years an election is held, with the initial party in power chosen at random. For simplicity's sake only the two major parties of the republicans and the democrats are represented. Broadly speaking, the democrats seek to increase the intensity value being targeted (which will have a greater impact on carbon reduction), whilst the republicans will target higher growth rates. The ultimate goal of the governing party is to gain re-election, which, as will be detailed below, is determined by the reductions implemented and economic growth over the period. The degree to which each of these effects the re-election chances of the incumbent party varies according to the prevailing attitude of the electorate, and the party in question. The republicans are more strongly punished and rewarded for economic growth, whereas the democrats are more strongly influenced by their carbon reduction efforts (reflecting the concerns of their core supporters).

The agent has three overarching behaviour patterns controlling its attitude toward carbon reduction, represented by a integer variable between 1 and 10, where 10 is highly positive, and 1 is ambivalent. The real world representation of this being the prevailing attitude of the electorate, to which, in theory, the governing party responds and chooses actions in accordance with. This attitude variable is specifiable at the beginning of the simulation, and can change year by year. A more positive attitude results in more ambitious targets for the desired intensity level improvement chosen for the election cycle. Additionally, the more positive the attitude, the more influenced by success or failure in reaching or exceeding reduction targets the populace are, and the less they are influenced by lower economic growth. The opposite is true for more ambivalent attitudes.

The agent, as in reality, is not a member of the Kyoto Protocol at the start of the simulation, and thus is not subject to either monitoring or sanctioning. Despite its non-member status however, it is not entirely ambivalent toward carbon reduction. The agent has been designed so that through the natural oscillation of the party in power intensity levels will steadily decrease, and ultimately result in a decrease in absolute levels, which will result in the agent eventually joining the Kyoto protocol. Each year the agent checks to see if, were it part of Kyoto, would it have met its emission target. If for three years in a row the target is met then the agent joins Kyoto, conversely, if targets are not met for three years in a row after joining Kyoto, the agent will once again leave.

The winner of an election is decided by a function of the economic performance over the election cycle and the election year (the justification for the latter being the relatively short term memory of the typical voter), the carbon reduction measures undertaken, and the attitudes of the electorate and the party's core supporters toward these. After these factors have been taken into account, some level of randomness is introduced (perhaps one party has a particularly compelling candidate).

As the political party's re-election chances are determined by the levels of carbon reduction and economic growth achieved during the election cycle, it chooses targets for these (in the case of economic growth, assuming stable market conditions) in order to maximise this chance. The targets are initially based on the long term percentages reductions/growth rates achieved before being adjusted up or down. In order for an absolute decrease in emissions it is necessary for the emissions intensity to improve faster than economic growth. So, for an absolute decrease the targeted improvement in intensity must be higher than this. The desired improvement in the intensity level is thus taken at base to be the long term economic growth rate over the four year election period plus a value determined by the overall attitude of the electorate. E.g. If the year on year growth rate was 5%, this would result in a 21.5% compounded rate from the start to the end of the period. Targets are valid and acted upon over the four year election period in order to allow behaviors to adapt to the prevailing global economic conditions, in times where growth is strong, giving rise to more available cash, more investments toward carbon reduction are made, contrarily, during periods of poor economic growth more investments into the economy are made.

Once the target is set, the agent sets about choosing actions. The agent aims to implement any actions over three years within the four year election cycle, allowing no action to be taken in one of the years if conditions are not favourable. If conditions are amenable, all available cash will be used. At the beginning of the election cycle the absolute carbon reduction required over the four year period (taking into account the expected GDP growth) is calculated. The goal in absolute terms for each of the three years is then set. The agent will attempt to fulfil its commitments during the first 99 ticks of the year (assuming a year is 100) through the clean development mechanism (CDM), or subsequent to Kyoto membership, through trading carbon offset with other agents. Before implementing any action, the agent evaluates whether the benefit to their election chances will be increased more by taking the action in question or an alternative. On the last tick of the year, if the targets for carbon reduction or GDP growth have not been met, then the agent will take appropriate action through the carbon reduction and absorption mechanisms, or through investing in industry. The party will take measures to meet either its reduction or growth targets first depending on, once again, the projected effect the meeting/not meeting one will have on their reelection chances. Then use any remaining cash available to meet (if possible) the remaining target. If both targets have been met, they will spend the remainder on their preferred action.

4.2 Participant Actions

4.2.1 Carbon Reduction Handler

The cost of carbon reduction for a country depends on its ratio of carbon output to energy output, which can be described as a dirty industry percentage:

$$\textit{Dirty Industry} = \textit{Carbon Output} \;/\; \textit{Energy Output}$$

The less dirty our industry is, the more expensive it gets to clean it further. Therefore, it is reasonable to use a measure of clean industry:

$$\textit{Clean Industry} = 1 - (\textit{Carbon Output} \;/\; \textit{Energy Output})$$

The relationship between the cost of reducing carbon output by one unit and the percentage of clean industry at a given moment is given in Figure 10:

Where:

- a: cost of reducing carbon output by 1 with 0% clean industry (min cost, constant)
- b: cost of reducing carbon output by 1 with 100% clean industry (max cost, constant)
- x0: clean industry percentage before investment
- x1: clean industry percentage after investment

Hence, we can calculate cost of single unit investment at specific clean industry percentage using the following formula:

$$\textit{Unit Cost} = a + ((b - a) \times x)$$

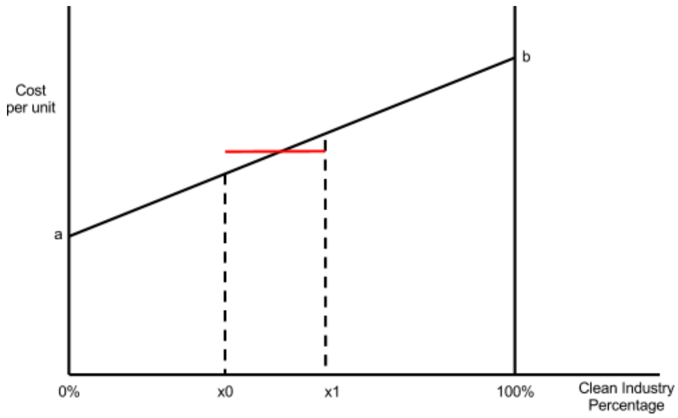


Figure 10: Price of carbon reduction

Since the cost will increase linearly with every unit invested, we can find the average cost for the whole investment as the average of the initial and final cost (based on the x0 and x1 values). This is represented by the red line on Figure 10.

$$\begin{aligned} Average\ Cost &= ((a + ((b - a) \times x1) - (a + ((b - a) \times x0)))/2 \\ \Leftrightarrow Average\ Cost &= (a + ((b - a) \times (x1 - x0)))/2 \end{aligned}$$

We can now calculate the total cost of a carbon reduction action by multiplying the average unit cost by the amount required by the country.

Reduction Cost Estimation This 'inverse' operation is mathematically solved with a quadratic equation. However, this is difficult to implement and is error-prone due to double arithmetic in Java. Instead, a binary search bounded between 0 and the current carbon output was used. In each iteration, the function calls the `getInvestmentRequired()` function with a hypothetical carbon reduction as parameter. It then adjusts the amount of reduction the country will receive depending on whether the returned value is higher or lower than the actual investment. Since there are 30 iterations, it will produce a an accurate result providing the current carbon output is less than 2^{30}.

This function allows participants to estimate and compare the profitability of a carbon reduction investment. As it is not used by the investment function itself, the lack of absolute accuracy is not crucial.

4.2.2 Carbon Absorption Handler

The implementation of carbon absorption is very similar to that of carbon reduction investment. Here, the cost of forestation is inversely proportional to the percentage of area that is unoccupied with respect to entire land area of a country:

$$Occupied\ Area = 1 - Arable\ Land\ Area/Land\ Area$$

The cost of this action is calculated in the same way as for carbon reduction, with the only difference being the constant values for a and b. Additionally we also now need to calculate the area occupied by newly planted trees. This is done by using a constant specifying how much forest area is needed to absorb single unit of carbon, which is then multiplied by the amount of carbon absorption done.

Absorption Cost Estimation Again, the implementation is the same as in the case of carbon reduction. There is only one difference, which causes a slight problem. Binary search requires lower and upper bound, and, potentially, carbon absorption can be as high as possible (providing a country has sufficient land and funds). Hence, we needed to use some upper bound to allow using binary search algorithm.

Even though a country can invest in carbon absorption as much as it wants, it does not make much sense for it to exceed carbon output, and shouldn't be realistically possible providing reasonable constants for prices. Hence, the upper bound which is used here is a difference between carbon output and carbon absorption of a country, so that, for maximum investment, the function will return absorption change which forces actual emissions to atmosphere to 0.

Still, this will produce false results where investment is high enough to potentially increase carbon absorption beyond carbon output. Again, this is just an additional function for countries to make writing strategies easier and make them more interesting. Since there is no way around it, it was decided to allow this potential inaccuracy.

4.2.3 Energy Handlers

Each country in our simulation has the ability to influence its economy by investing or reducing its carbon industry. This functionality is provided to each participant through an instance of the energy handler. Unlike the carbon handlers, the price of a unit of investment in your carbon industry is a constant defined at the start of the simulation. In addition, there is no cap on the amount a country is allowed to develop its industry.

The cost of an investment for a given desired growth can be modelled by the following linear function:

$$Cost = Growth \times Price\ of\ Carbon\ Investment$$

Similarly, each participant can also use the handler to query how much economic growth can be achieved for a given cost:

$$Growth = Cost/Price\ of\ Carbon\ Investment$$

Using these two functions, participants can make an informed decision on whether to invest in their industries or decide to reduce it. A country can increase its GDP by building factories which in turn will give them more money to spend in the following year. However, its carbon emissions will also increase as a result.

On the other hand, a country can decide to close down factories. This is a cost free method of reducing carbon emissions, though it also leads to a contraction of its economy and GDP.

4.2.4 Carbon Reporting

Each country is required to submit yearly reports of their GHG emissions. The timing of reports is coordinated by the monitoring service to ensure synchronicity with the targetting service and consistency between separate agents. Each agent submits its report by acting on the environment, altering the shared state. They also update an internal record of their emissions reports, to make sure that agents can properly query their own history.

Countries are given an opportunity, at this juncture, to cheat and falsify their emissions reports by reporting incorrect carbon output data. If a country has exceeded its emissions target, correctly reporting their carbon emissions will guarantee that they receive a missed target sanction, which is a more severe target in the following year. Countries can attempt to avoid this sanction by reporting lower than their actual emissions. However, there is a chance that their emissions report will be monitored. If it is, they will be subjected to financial sanctions, arguably more damaging than severe emissions targets. This tradeoff must be evaluated by each country's behaviour.

4.2.5 Joining & Leaving Kyoto

In our simulation platform, we allow countries to leave and join the Protocol. In order to replicate the Kyoto country categories, it was decided to offer participants three distinct levels of subscription to the simulation using Java enumerated states. Each of these give access to a different set of possible actions as described previously. Using this functionality, we can emulate real world scenarios such as Canada leaving the Protocol.

4.3 Services

4.3.1 Trade Protocol

The Trade Protocol allows participants to engage in trading of carbon offset or Clean Development Mechanism (CDM) investments in other participants/countries. The Trade Protocol class inherits from the `FSMProtocol` class provided in the Presage2 API, which is an implementation of agent protocols, used by agents to communicate with one another.

The trade protocol can be used for both carbon trading and Clean Development Mechanisms. The type of message that the trade protocol deals with is an object of type `OfferMessage`. The `OfferMessage` object has information of who initiated the conversation and who broadcast the offer in the first place and all the information about the quantity and unit cost of the offer. The quantity refers to the total, in tonnes of carbon offset, that are being offered. The unit cost refers to the price per ton. The total cost of the offer is the product of these two values.

When a participant broadcasts a carbon trading offer then the type of the `Offer` (also another object that `OfferMessage` encapsulates) is set to either:

- `BUY`: If participant wants to buy carbon offset.
- `SELL`: If participant wants to sell carbon offset.

For Clean Development Mechanisms, the trade protocol allows the participant to advertise whether they want other countries to invest in their industry to reduce carbon emissions.

When a participant wants to advertise about CDM then the following types need to be assigned to the `OfferMessage` Offer type:

- `INVEST`: participant wants to invest in another country.
- `RECEIVE`: participant is asking for other countries to invest in their industry/country.

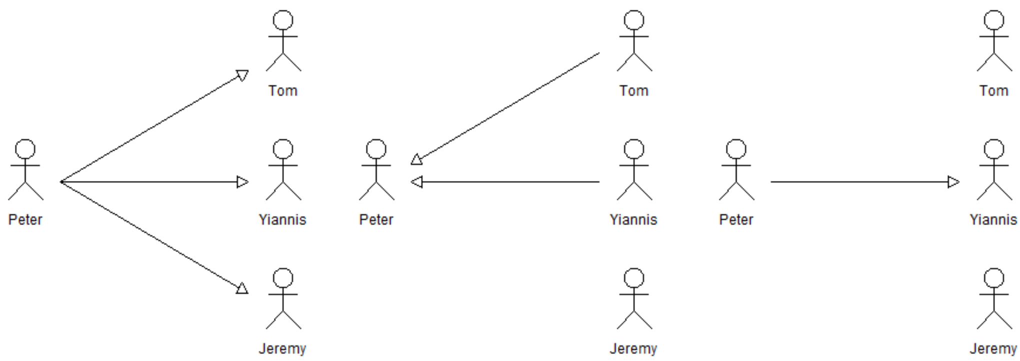
It is also further specified whether the form of CDM is for carbon reduction or carbon absorption, which restricts the participant to choose the following investment types:

- `ABSORB`: Whether the investment will be used to reduce carbon emissions by investing in absorption techniques.
- `REDUCE`: Whether the investment will be used to reducing carbon emissions via investing in carbon reduction techniques.
- `INVALID`: If investment type does not exists as it is a buy or sell carbon offer.

Trade Protocol works in the following ways:

1. A participant who is willing to engage in a trade sends a broadcast message using the `network` object provided to every agent. This message contains information about the trade as they wish it be carried out.
2. Another participant who is interested in the offer broadcasted can start a protocol conversation with the broadcaster. They can reply with slightly altered offers, to simulate a minor form of negotiation.
3. The broadcaster can then accept or reject the offer that is proposed by the initiator.

The process is illustrated in Figure 11: a shows agent Peter mulicasting a sell offer to all agents; in b, agents Tom and Yiannis are interested in the offer, and so initiate the `TradeProtocol` with peter; finally, in c, agent peter decides to accept the offer initiated by Yiannis.



(a) (b) (c)

Figure 11: `TradeProtocol` action diagram

In the event that a trade is unable to be carried through to the end, possibly caused by one of the countries not having enough available funds to complete the transaction, the trade can be reverted, and the involved parties are refunded.

Trade Protocol State Machine The protocol has two different state machines that are used by the initiator and the broadcaster. The state machines are as follows:

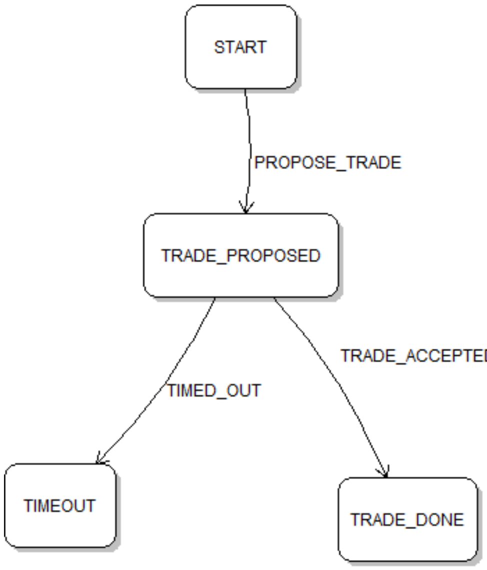


Figure 12: Initiator FSM

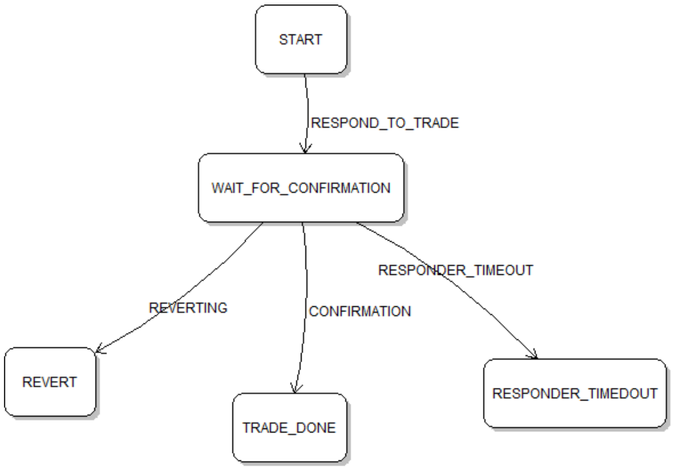


Figure 13: Responder FSM

Figure 12 and 13 shows the state machines used by the Initiator and Responder respectively along with the transitions labelled on the arrows. The transitions in an `FSMProtocol` happen when a participant receives a message.

Initiator FSM Both the initiator and the responder have a single `START` state as required by the `FSMProtocol`. The initiator has two end states, which are `TIMEOUT` and `TRADE_DONE`. Each transition results in the participant performing a particular action of sending back a message to the responder, which makes the responder transit to the next state.

1. `PROPOSE_TRADE`**:** When the participant responds to the offer, it transitions to the `TRADE_PROPOSED` state and sends a Unicast message to the broadcaster waiting for its response.
2. `TIMED_OUT`**:** From the `TRADE_PROPOSED` state a timeout of 3 ticks is set so that the initiator times out into an error state.
3. `TRADE_ACCEPTED`**:** If the responder accepts the trade proposal, the Trade Protocol handles the trade completion through a function called `handleTradeCompletion()`. If anything goes wrong while handling the trade completion then the participant (initiator) transits to the `TRADE_DONE` state by sending a Unicast message to the responder to revert the changes. If the handling of trade completion works well then the participant transitions to the end state `TRADE_DONE` by sending a confirmation message to the responder.
4. `TRADE_REJECTED`**:** If the trade was rejected by the responder then the participant (initiator) transits to the `TRADE_DONE` state by sending a confirmation unicast message to the responder that it has received the message.

Responder FSM Figure 13 shows the FSM that is used by the responder. Upon receiving a message form the initiator. There is only one `START` state and the three end states are `REVERT`, `TRADE_DONE` and `RESPONDER_TIMEOUT`. Similar to the initiator, the transitions happen with the participant sending a unicast message to the initiator agent.

1. `RESPOND_TO_TRADE`**:** This transition occurs when the initiator spawns a message, which makes the responder transition to the `WAIT_FOR_CONFIRMATION` state. If the responder accepts the exchange then it transitions to the next state by sending a unicast message to the initiator that it accepted the trade, otherwise it transitions to the next state by sending a unicast message to the initiator that it has rejected the offer. Once the participant makes the decision to accept the offer then the `handleTradeCompletion()` function is called to adjust the carbon offset and cash of the responder. If things fail for reasons such as not enough cash exception from the responder then the changes made to the responder's carbon offset and available to spend will be reverted. Nevertheless, a reject message is sent to the initiator to inform him that the trade was unsuccessful.
2. `REVERTING`**:** If the initiator fails in completing the trade for reasons such as not enough cash exceptions, then the initiator reverts itself and sends a message to the responder. Once the responder receives this message then it goes to the `REVERT` state via the `REVERTING` transition. There, it reverts all of the changes since the start of the conversation.
3. `CONFIRMATION`**:** This is a transition to from `WAIT_FOR_CONFIRMATION` to the end state `TRADE_DONE` state. This transition happens when either trade was successful or was unsuccessful (i.e. the responder rejected the trade in the first place).
4. `RESPONDER_TIMEOUT`**:** Timeout condition of 3 ticks from `WAIT_FOR_CONFIRMATION` state to the `RESPONDER_TIMEDOUT` state, which is the end and error state of the responder.

4.3.2 Time Service

The time service is an environment service, extending Presage2's existing environment interaction classes and development framework. It allows for coordination of time-based events and synchronises various features within our Kyoto Protocol simulation. Although Presage2 does have existing objects (`SimTime`) which can be used to attain simulation time, this is an absolute value in discrete logical time since the beginning of the simulation. It therefore does not take into consideration the variety of chronological distinctions the Kyoto Protocol requires, such as subdivisions into years and sessions.

It was initially decided to use a global service. It would perform most of the logic integral to coordinating time-driven activities, and would be layered on top of Presage2's integrated `SimTime` object. However, it is necessary for agents to be able to query for information regarding the current year and session in order to make important strategic and behavioural decisions. Presage2 enforces that agents (participants) are unable to communicate directly with global services. While agents can act on the environment and affect services, performing the reverse is somewhat more complex.

At this stage, it would seem a participant time service would be more appropriate, since participant services can communicate directly with agents. However, another key functionality of the time service is the publishing of new events, both for the end of years and sessions, which trigger key monitoring, sanctioning, reporting, and architectural actions essential to the managed nature of the Kyoto Protocol. Unfortunately, implementation is not in place within Presage2 for participant services to generate (or interact with) the `EventBus` class, the object essential to publishing or receiving events.

With these restrictions in mind, the time service was subdivided into two separate services. The participant service communicates with agents and relays information regarding the current year and session, among other minor time-related information gathering tasks. The global service is the backbone of the time service, generating new year and session events for the monitoring and targeting services to hook onto. It also carries out calculations to derive the current year and session from the discrete simulation time and communicates this information to the participant service.

Both classes extend from Presage2's predefined `EnvironmentService` class, and use Google's Guice injection systems for initialisation and, in the global service's case, to register with the `EventBus`.

4.3.3 Monitor

The monitor's purpose is to regularly check whether countries are meeting their targets and randomly check for false carbon emission reports. If either case is true, a scaling sanction is applied to the country.

We were initially unsure whether the monitor should be an independent agent or an environment service. We settled on making it a service, so that it could listen to an event that would trigger the monitoring as agent are unable to do so.

When countries are initialised they subscribe to the monitor either as Annex I or Non-Annex. Although only Annex I countries are monitored, the Non-Annex countries list was required to fix an issue with events at the end of a year happening in the right order. Indeed, countries were calling for their targets for the next year to be updated before the monitor could compare the results for the previous year against its previous targets. This was fixed by updating targets after the monitoring function in the Monitor service.

Every year the monitor charges the Annex I countries a tax, which is used to perform the monitoring action on randomly selected countries. If the monitor runs out of money, it cannot monitor and countries are free to behave without fear of sanction (although this information is hidden).

4.3.4 Carbon Target

The carbon target service is responsible for reducing the world carbon emissions through the calculation of targets for all Annex I Kyoto members. Within the Presage2 simulation it is set up as a global service, this enables it to listen on an event bus and run independently from the country agents.

All target calculations are triggered by the end of year event generated by the time service via a method call from monitor.

How the worldwide targets are calculated:

$$\begin{aligned} \textit{Reduction Coefficient} &= 0.95 \ (5\% \ \textit{reduction}) \\ s &= \textit{current session number} \end{aligned}$$

$$\begin{aligned} \textit{World session target}[s] &= \textit{world session target}[s-1] \times \textit{Reduction Coefficient} \\ \textit{Kyoto target}[s] &= \textit{world session target}[s] - \textit{total non annex I output}[s-1] \end{aligned}$$

Annex I target calculations, in each session:

$$y = \textit{current year number}$$

$$\begin{aligned} \textit{Country Proportion}[s] &= \textit{country output}[y-1] \\ &\quad / \ (\textit{world output}[y-1] - \textit{non annex I output}[y-1]) \\ \textit{Country Session Target}[s] &= \textit{Kyoto target}[s] \times \textit{country proportion}[s] \end{aligned}$$

In each Year:

$$\begin{aligned} \textit{Session Progress} &= \textit{current year in session} \ / \ \textit{number of years in session} \\ \textit{Session Target Difference} &= \textit{session target}[s-1] - \textit{session target}[s] \\ \textit{Year Target} &= \textit{session target}[s-1] - \textit{session target difference} \\ &\quad \times \textit{session progress} - \textit{penalty} \end{aligned}$$

In the event that a session target is needed from before session 0, world data from 1990 is used in its place. This models the Kyoto Protocol's basis of its initial targets.

To avoid unfairness and promote economically feasible targets, as is negotiated in the real Kyoto Protocol, we restricted the maximum reduction across a single session to be 10% of total emissions. Without this limitation, large emissions from rogue states can cause targets for Annex I targets to reduce unreasonably quickly. To handle unusual corner cases that may cause a country's session target to be higher than its previous session target (possibly due to drastic reductions by other member states, or large emissions from rogue states) we have restricted session targets so they cannot have a higher value than the previous session target.

Only Annex I countries are calculated a target. However, both Non-Annex countries and rogue states have an impact of target assignment. As can be seen in the above formulas and in keeping with the objects of the Kyoto Protocol in reality, the aim for a single session is to reduce global CO_2 emissions by 5%. After calculating the desired output for this session, the targeting service calculates the required reduction from member states, assuming Non-Annex countries and rogue states continue producing the same amounts of CO_2 .

Implementation The carbon target service retains all the necessary data required for the above calculations in a private `ArrayList`. Year targets are also set using a package protected method in the `AbstractCountry` superclass.

Within our simulation it is possible for countries to report false carbon emissions. Each year monitor service decides to monitor a subset of the countries. If a country is found to have reported a false value, its `UUID` is added to a list of cheaters. This list is then passed to `CarbonTarget` each year by `Monitor`, and is referenced when querying carbon output values for the target calculation.

Some countries (for example the US) may wish to join Kyoto at some point during the simulation. Since individual year targets are interpolated values dependent on session targets, and session targets are dependent on global emissions and each country's status as a rogue or member state, having a country join the Kyoto Protocol mid session is, in our simulation, extremely difficult. Each country's target would need to be recalculated and this introduces potential conflicts with existing strategies that the member state AIs have chosen. As a solution to this, we decided that rogue states could only join Kyoto at the beginning of a new session. Any rogue state that attempts to join the Kyoto Protocol in the middle of a session will be put on a waiting queue and will automatically be registered and become an Annex I country at the beginning of the next session.

We decided that any rogue state joining the Kyoto Protocol would automatically become an Annex I country for two reasons. One was the simplification of the rejoining process, which had already become extremely complex. Also, when compared to reality, it seemed reasonable that any country which left the Kyoto Protocol and then rejoined at a later date would then be assigned targets and monitored, to ensure that the system was not abused for financial gain. The US, the only major nation that did not ratify the Kyoto Protocol at its inception, would be an Annex I country regardless, were it to participate.

Leaving Kyoto is another potential action taken by member states, as seen in reality when Canada departed the Kyoto Protocol in 2011. When a member state leaves, its output is immediately recognised as that of a rogue state, and its departure has an effect on the setting of new session targets after the current session ends.

Joining and leaving the Kyoto Protocol, as well as other actions such as reporting CO_2 emissions to the monitoring service, are implemented via action handlers, integrating with Presage2's defined structure for agents communicating with non-participant services and the multi-agent systems design paradigms regarding agent interaction with the environment.

4.3.5 Market

Our Kyoto simulation integrates a very basic emulation of the state of the financial markets. Each year, the market state will be determined randomly and affects by how much a country's GDP will change. By default, there is a 10% probability that the economy is stable, 10% that it is in recession and a 80% probability that it is in a period of growth, but these can be changed by the user when running a new simulation.

4.4 Game Balancing

As we have seen, the game is made up of a series of mathematical functions, many of which rely on a set of constants (eg. `GROWTH_SCALAR`, `MAX_GDP_GROWTH`). Varying and balancing these constants allows us to create varied and accurate simulations. These can be either initialised at compile time, or injected by the Kyoto UI at runtime, in order to run a wide range of different scenarios.

The balancing of these constants was not a simple task, since changing one may have an impact on others. The following three facts were used as a starting point for calculating suitable values for some of the constants:

1. Each country has an emission target of -5% from their base year.
2. Countries typically invest 0.5% of their GDP in developing clean industry every year. [25, Figure 12]
3. It takes 0.0156 km^2 of trees per tonne of carbon absorbed. [1, Accessed Jun 2012]

From 1, we can derive:

4. The likely energy change per year (0.05%)
5. GDP rate, since we can work out the energy difference

From 2, we can derive:

6. The amount of cash each country gets each year
7. Sanction rate and tax rate as proportion of cash

From 4 and 6, we can derive:

8. The cost of carbon reduction and absorption.

4.5 Kyoto UI

The Kyoto UI is a web interface designed for instantiating and editing Presage2 simulations. Web technologies used include an Apache web server, PHP, HTML and Javascript. Combined with a few additional libraries, these technologies provide the functionality required to display rich pages which allow for good visual representation and easy editing of data.

4.5.1 Inception

Initially, investigations into a UI began to solve the problem of a large amount of incoming data. This data can be used to initialise the agents and simulation in order to more effectively model the Kyoto Protocol in different global environments.

Each agent requires ten fields of initialisation data, and data was collected for 179 countries, so a Comma Separated Value (CSV) file could be used to export data for analysis.

A CSV file including simulation parameters is used alongside the country data, to initialise the simulation. This data sets up the document in mongodb that Presage2 is expecting.

It quickly became clear that the KyotoUI could be more than a database initialisation program and with some improvements it could become a dashboard for politicians and economists and have commercial value. The further development to KyotoUI is inspired by the idea that we are applying an accessible front to a specialised Presage2 simulator (Kyoto) in order to setup and report on simulations. Making simulations easier to initialise and interpret, means users can more efficiently analyse large numbers of simulations, and draw better conclusions on whether the Kyoto Protocol could work such as these will last in the long run.

Some additions made to the Presage2 simulation collection were to add a description and author field, to better represent the multi-user approach and have better record keeping. Also in the simulations collection is a list of all the starting data kyoto to load the necessary, under a branch named “countries”.

4.5.2 Database Implementation

The mongo database is interfaced using an Object Document Mapper (ODM) library called mongorecord. This wraps interfaces for querying and writing the collections in the database with PHP classes which can be instantiated and used throughout the project.

4.5.3 Simulation Initialisation Data Import and Export

In order for any simulation to have a starting point, data files must be imported containing information such as how long the simulation should run for and the data is required to set up each of the agents. Presage2 has a command line interface which can be used to create simulations in the database and add parameters to them. The structure of these simulations in the database was used as a framework to import CSV files of data to create simulations in the same format as generated by the Presage2 CLI.

4.5.4 CSV Import and Export Functionality

To get data in and out of the system CSV files are used. This is a convenient method of transferring data as the CSV file can be opened and edited in spreadsheet software such as Microsoft Excel. Country data is inserted into the simulations, as are parameters from ‘default’ CSV files. Once these are in the database, the UI can copy and edit them. Simulations can then be exported as a backup or to transfer them to another database. This functionality underpins the whole simulation by providing an easy way to get a huge amount of data in and out of the system quickly, easily, and reliably.

4.5.5 Simulation Editor UI

Once data has been imported from the CSV file it may be necessary to make new simulations by changing parameters etc. This is one of the main tasks of the web UI, to make this editing visually comprehensive and easier than manually editing the CSV file or the database entry.

4.5.6 Agent (Country) Data

Agents in the simulation represent countries, and in order for the simulation to be as realistic as possible, these are modelled on real countries with parameters describing land mass etc. stored in the database. It is useful to edit some of these parameters, such as the percentage of land mass available for green development, to investigate what happens in a simulation given agents with different parameters. The UI features a page specifically for editing countries which displays a clickable map of the world with a dropdown menu for country selection. This way all countries within a single simulation can be edited dynamically.

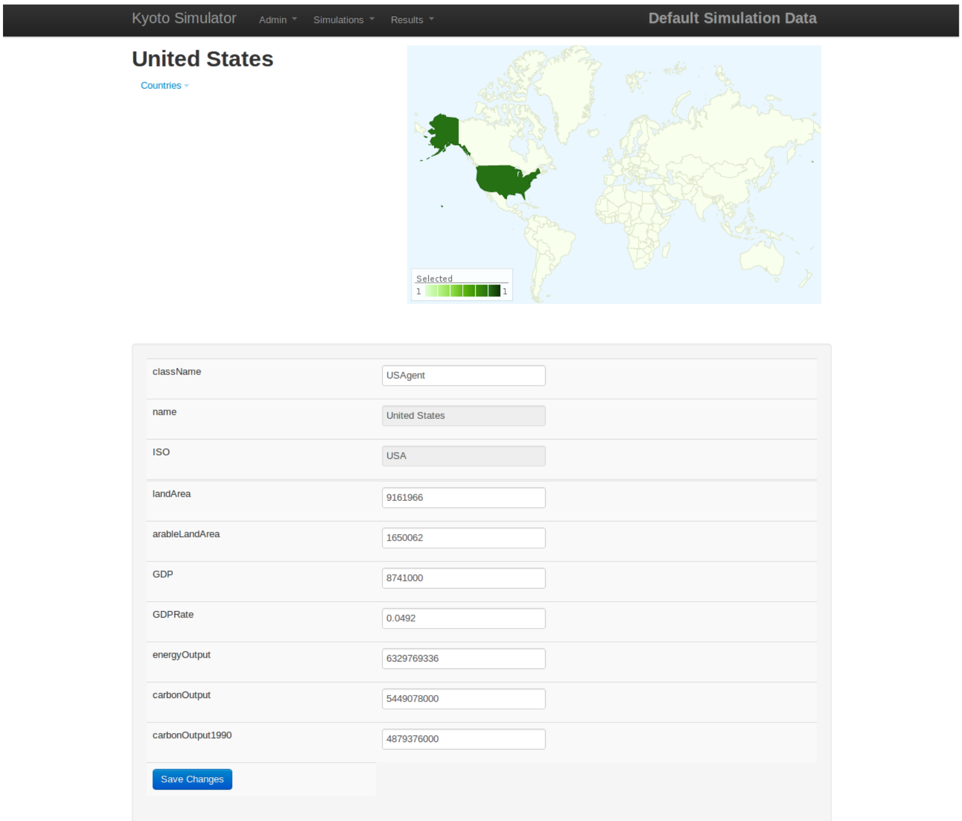


Figure 14

4.5.7 Simulation Data

Once imported, simulation data resides in a collection within the database. The UI provides a list of all simulations stored in the database with some basic information about the simulation displayed in the list. Next to each simulation is a menu which allows you to do several things with the simulation: view (detailed view of the simulation in the database), export the simulation as a CSV file, edit the simulation, copy it, or delete it.

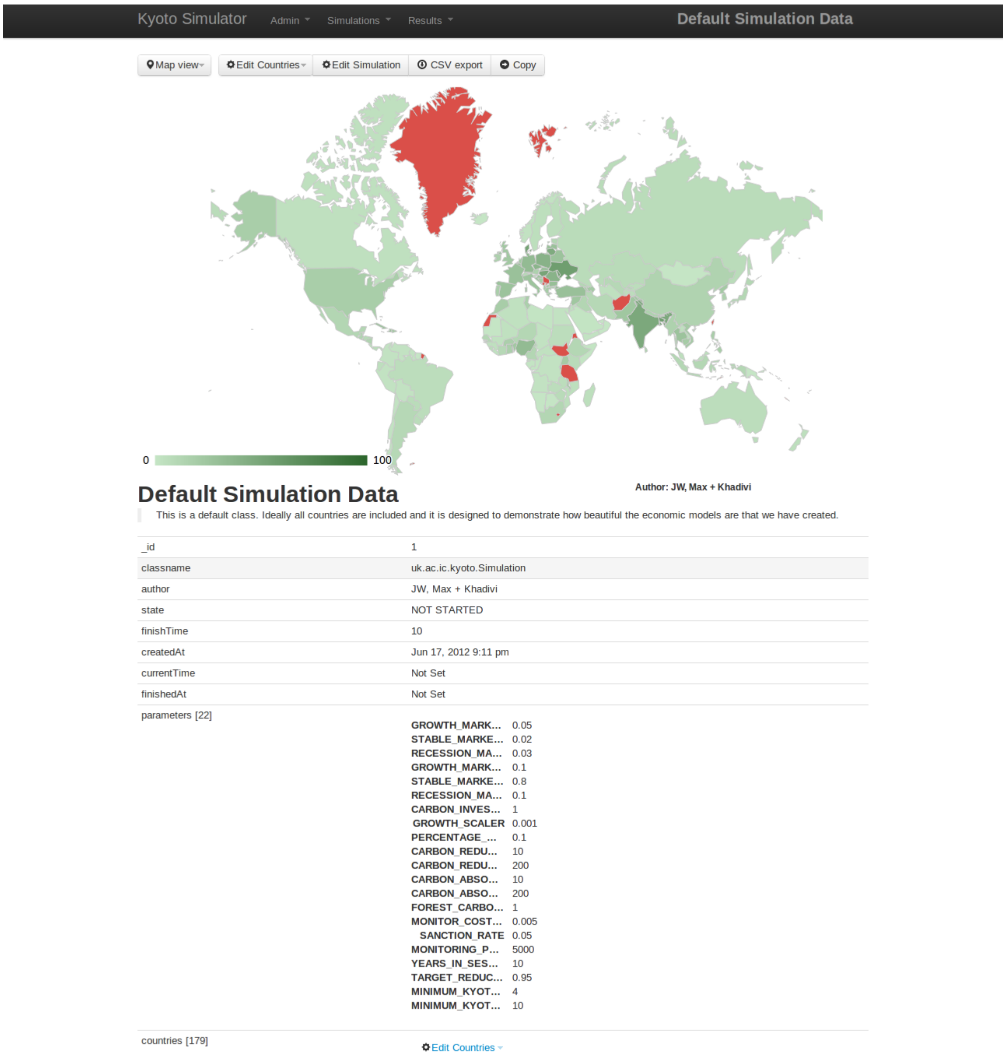


Figure 15

Simulation Overview Page The simulation overview page displays a world map using colour to indicate the values of a selected parameter for each country (default is arable land area percentage). There is a drop down menu (Map View) which allows changing of the parameters displayed on the map. Below this is a table displaying a detailed output of all the simulation data from the database. This page also links to the CSV export feature, copy feature, edit simulation page and a dropdown is present to allow editing of all the countries within the simulation.

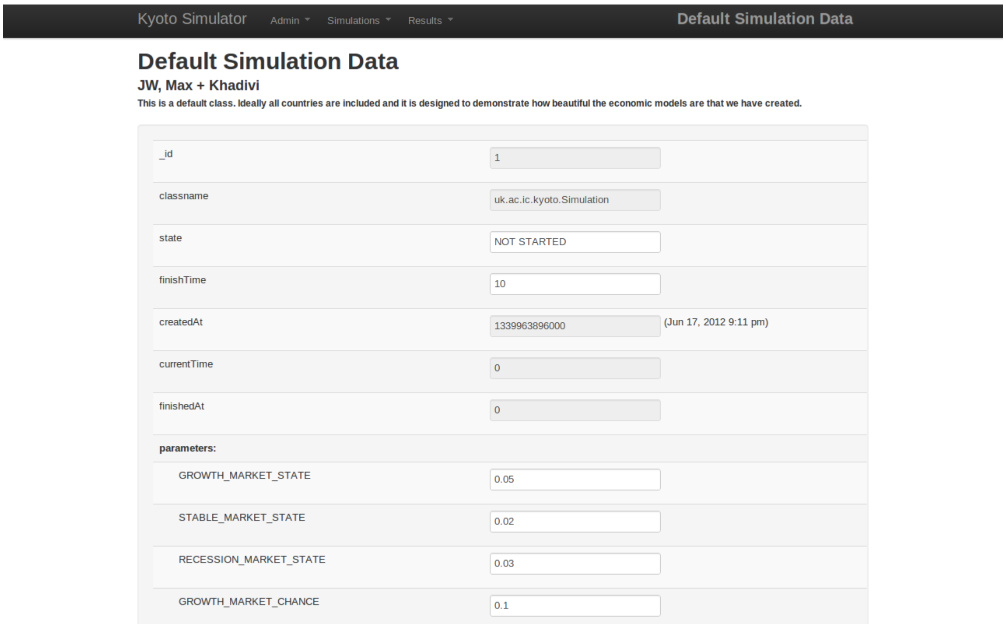


Figure 16

Simulation Edit Page The simulation edit page is a low level editor for the simulation. Functionality is provided to rename the simulation, the simulation authors and all other simulation attributes which it makes sense to edit. It also provides a link to the country editor page (the simulation ID is passed in the URL to ensure editing takes place on the countries of the correct simulation).

Simulation Results Data from the mongo database is extracted and processed into a compressed, standardised output form that is simpler to manipulate. Some of the data is collated to provide overall simulation statistics to be displayed on a results page. Yearly data is used in conjunction with the Google Graph API to provide year by year moving analysis. Trade data is extracted to form an overview of trading relations between countries.

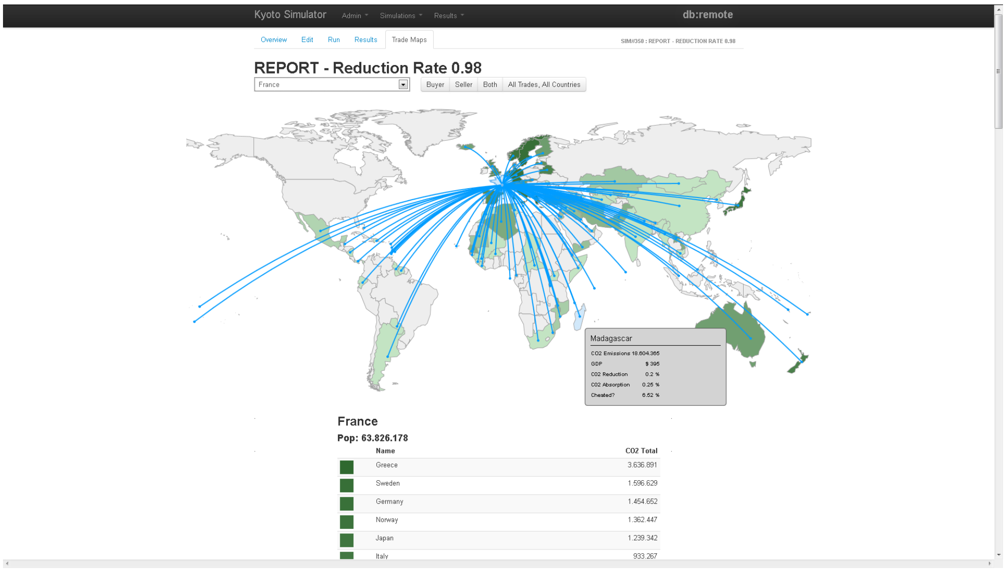


Figure 17: KyotoUI illustating all trades which France has completed.

5 Issues

During the implementation of the Kyoto protocol, we encountered various issues, particularly with regards to running simulations.

5.1 MongoDB

Initially, testing and simulations were performed on local machines which connected Presage2 to a MongoDB server hosted on the Imperial College Network. The web UI was based on a remote server hosted by one of our group members. We encountered difficulties as simulations began to increase in size. When executing country behaviours on a scale required for simulating the real world (approximately 180 countries), the volume of output became problematic.

On Monday (18th June), the MongoDB server hosted on the Imperial College network crashed. Following the database crash, we altered Presage2's runtime settings so it used local databases installed on individual user machines. However, this became untenable for the collation of results for analysis and data representation. This was one of the reasons we elected to the the Amazon Web Service (AWS).

5.2 Deployable JAR

To be able to use multiple college computers easily, we needed to turn the project into a portable JAR file. Time restrictions and the complexity of Maven's dynamic dependency systems made this more complex than we anticipated. We attempted to use a college cluster (Crayfish), but it did not have Maven installed and so required a JAR file.

5.3 Simulation Execution Time

Individual simulations can take up to four hours to run, depending on the complexity. We initially believed that the bottleneck was a lack of processing power for simulations (hence the attempts to utilise the college cluster). Simulations were set up on multiple college machines all pointing to one of two AWS based databases. However, the load proved too much and the database servers failed.

Our compromise was to use two AWS machines with each hosting a their own instance of the UI, database, and simulation files. This meant we could only run two simulations in parallel but it was a reliable way of producing results.

5.4 Behaviour Bugs

Bugs in individual country behaviours proved difficult to debug before integrating the countries into larger simulations. While any large architectural bugs were diagnosed through local bug testing simulations, some unexpected issues arose when all of the countries attempted to run concurrently.

Throughout the testing phase in development of our Kyoto Protocol simulator, our design became progressively more threadsafe.

Maps One of the simpler issues which was did solve in most instances was that of concurrent access to java `HashMap` objects. This was remedied by introducing concurrent hash maps in their place. Due to an executive decision to code freeze in the final few days of testing, not all `HashMap` have been replaced with concurrent maps.

Semaphores In order to manage access to the large quantity of shared code accessed by countries as they act during a simulation, we introduced semaphores to manage shared resources.

Shared State At the beginning of the project, our understanding of the shared state, as it was implemented in Presage2 and even the concept of its existence in the context of multi-agent systems, was severely limited. When our code interacted with the shared state, since we structured our queries incorrectly, we encountered `NullPointerException` that were difficult to track down through debug step throughs since Maven's dependency system meant many components were compiled binaries only.

5.5 Carbon Reporting Synchronisation

This was an issue that has since been resolved but severely delayed our development process in the final week. When reporting carbon emissions, countries updated the shared state by acting on the environment. However, we were unaware that there was a secondary, internal recording system was embedded within each agent via inheriting some shared code. By not updating the internal records, `NullPointerException` were generated at the end of every year and targets were not set properly. This is clearly a communication issue between project members and was resolved when the appropriate team members approached the code at the same time.

5.6 Trade Protocol Timing

The trading protocol which allows countries to buy and sell carbon offset and participate in CDM was a class that extended an existing Presage2 agent communication protocol architecture. The single transaction involves multiple messages sent back and forth between the two participant parties, to ensure that negotiation can be properly handled and that any errors are reverted as intended. However, these messages happen in separate discrete time units and are driven by Presage2's underlying architecture, rather than any code that we have implemented ourselves. As such, controlling how long a transaction takes proved difficult.

In our final implementation, trades can take varying, unpredictable amounts of time. This presents problems when the trades overlap the ends of years and particularly the ends of sessions, because carbon offset is updated or reset at those times. Countries' behaviours are dependent on the values currently stored in the class's fields and their attitude toward a given trade has a tendency to fluctuate should these adverse conditions arise. However, these are corner cases that do not affect the general trends of the simulations.

6 Results

We carried out a variety of simulations which involved different countries and available behaviours, as well as different restrictions and valuations applied by our Kyoto Protocol's backbone systems. An individual simulation, with specific configurations regarding which countries are present, what behaviours are being used, and how services act is referred to as a scenario.

6.1 Possible Scenarios

During the design and implementation of our Kyoto Protocol simulator, we made any individual simulation configurable in the following ways. This allows us to make sweeping changes to outcomes and agent activities without altering implementation of components of our system. Theoretical alternative scenarios can be contructed in order to test aspects of the real world Kyoto Protocol.

Session Length
: Session length refers to the number of years in a given commitment period. The longer the sessions, the longer countries will have to meet their target. If this is set too short, countries will be more likely to miss their targets or cheat. This will have repercussions on their ability to spend and invest. They may also choose to just leave the protocol altogether. The first session of the actual Kyoto Protocol has been extended.

Monitor Price
: The action of monitoing each country has an associated cost. This has been chosen to allow fewer countries than there are in the simulation to be monitored. We were aiming for approximately 10% of cheating countries to be caught. This was to emulate a more realistic situation where monitoring everyone is not possible, and to allow for countries to cheat and not be caught. However, setting the price to high would reduce the number of countries monitored and lead to cheating becoming an optimal behaviour.

Disabling Monitoring
: The monitor provides a form of insurance against countries cheating. Giving countries free reign over meeting their carbon targets would be a test of the morality in their behaviour. The likely result would be no targets being met and global carbon emissions increasing.

Participants
: Removing the so called 'rogue' countries (US) from our simulation would have a large beneficial effect on global emission targets for the remaining participants. This scenario could be compared to a real-world situation where these countries' outputs don't contribute to the way Kyoto set its targets. Although this probably wouldn't help the global carbon emission problem, countries would be more likely to stay if their targets were easier.

  On the other hand, we could simulate only having rogue states who behave only according to their own internally-set targets. The resulting behaviour would probably be chaotic and not beneficial to the global emission problem. This would be similar to the possible real-world situation where all countries withdraw their support for Kyoto, but commit to their own reduction targets.

The last hypothetical situation we thought would be of interest was if all countries ratified and were classified as Annex I. Emission targets would be simpler to understand (and fairer compared to the US's current unrattified status). Also no CDM would take place. This would take away one of the easiest ways for a country to meet their targets while keeping their heavy carbon industry. There is much concern in the real world over the effectiveness and morality of using CDM to reduce carbon emissions. Taking away arable land from third world countries that could be used to grow crops, just to plant trees which will take several decades to become effective carbon sinks sounds very dubious.

CO_2 Reduction Rate
Kyoto aims to reduce the global CO_2 output by a set amount per session. The faster countries have to reduce their carbon, the more likely they are to miss their target, cheat and/or leave the protocol. We predict a lower reduction rate would be the most beneficial in the long term.

GDP Investment
Realistically, countries will invest a different proportion of GDP into clean initiatives. Due to countries not needing to worry about spending money on anything non-Kyoto related in our system, we set a fixed percentage to be invested in clean initiatives and industry expansion. The amount of money a country can spend significantly affects their behaviour. A lower percentage can cause countries to leave Kyoto as their financial postiion becomes untenable. Greater percentages may lead to price inflation, or a possiblity of increasing the reduction per year.

GDP Growth
We have enforced an upper and lower limit on GDP growth of $\pm 7\%$. This reflects the typical real world values for the majority of stable countries. Increasing this range would make the market more volatile. During growth, investment in industry will have an exaggerated effect, whereas global recession could make it difficult for anyone to meet their targets.

Market State Factors
These effect the chances of the global economy being in recession or growth, with a weighting towards remaining stable. The state of the market makes industry investment more effective by scaling it. These could be varied to emulate the protocol during an extended period of either negative or positive growth. The effects would be very similar to changing the GDP growth range as above.

6.2 Tested Scenarios

We have a variety of scenarios which have been simulated and run through to completion, with the results then collated and analysed for graphical representation. We attempted to cover a wide variety of Kyoto Protocol environments across our scenarios, while also maintaining baselines for comparison between them. However, we were also limited by the net processing time of running so many scenarios. Running multiple scenarios concurrently, as addressed in the Issues section, presents problems with the MongoDB server, so they must be run relatively sequentially. A single scenario can take up to four hours to run, depending on complexity and number of agents. After execution, the raw data dumped to the database must be processed for representation, which can take up to an additional two hours.

6.2.1 Real World Scenario

The real world scenario runs with the default parameters and the full complement of countries. It aims to mirror the real world and the majority of the Kyoto Protocol as accurately as possible, although some variables are approximated, since some values cannot be found, or are not uniform across all countries. Each country has accurate data from 1998 and the simulation runs 40 years from that date.

From our simulation, the data would suggest that the Kyoto Protocol has been a success. Globally, the world has reduced its carbon output by 5081 million tonnes of CO_2 equivalents, whilst also increasing its overall GDP. The US becomes an Annex I country due to it bringing its emission targets down to a manageable level. The US manages to increase both its GDP and decrease its carbon output at a steady rate, and is perhaps most responsible for the large global decrease in CO_2 .

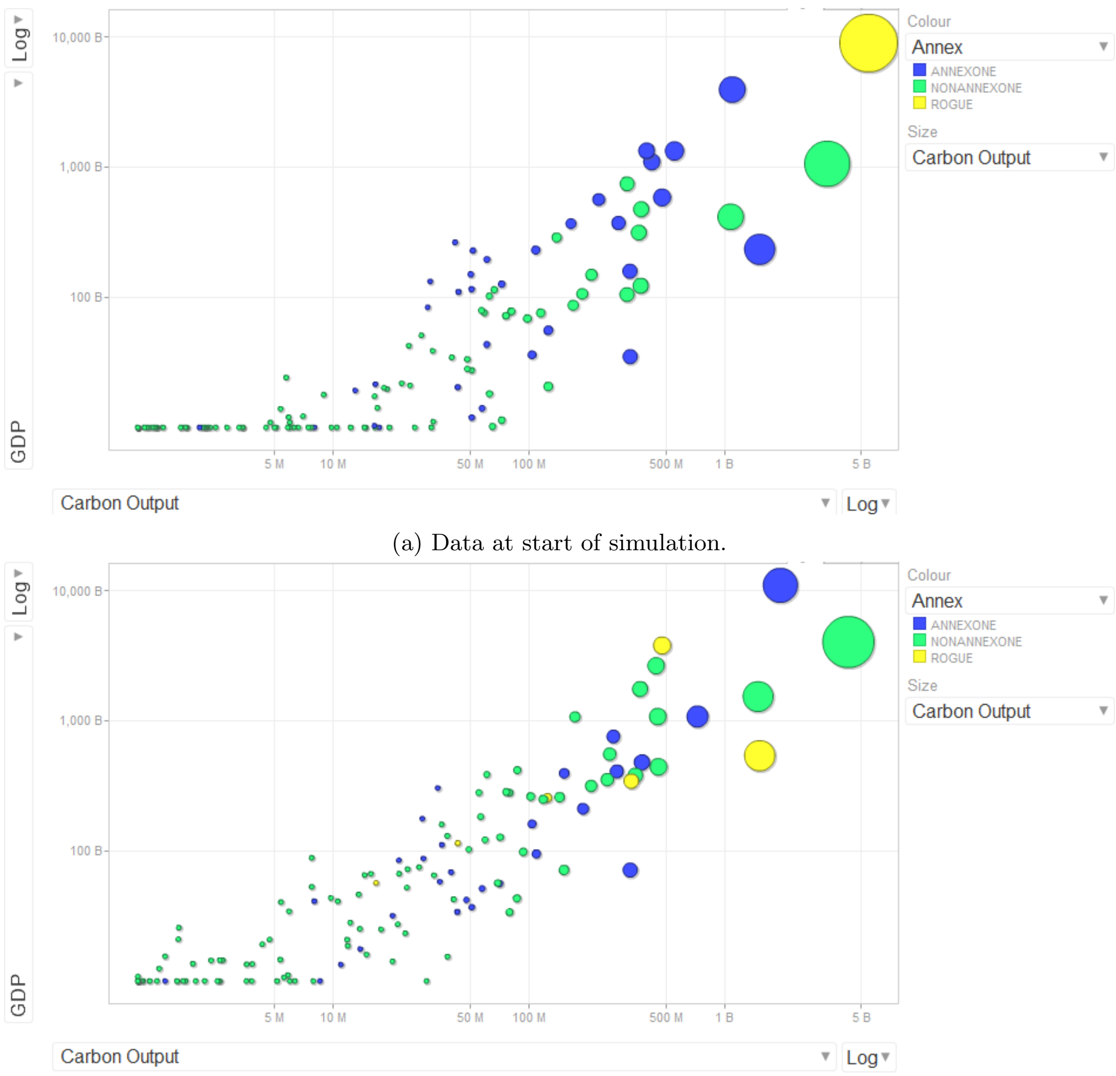
However, on closer inspection, the Protocol can be be seen to have harmed the countries who are most responsible for the global decrease in CO_2 levels. The motion chart shows Annex I countries generally decreasing in GDP as they aim to decrease their carbon output to match their emission targets. The western nations who are the main exponents of Kyoto will refuse to leave the Protocol, and will instead aim to cut down on their industry. This has a detrimental effect on their growth, and pushes many countries into recession.

In contrast, many of the ex-Soviet Bloc countries initially have emission targets well above their current carbon outputs and so can make a significant profit by selling excess credits and reinvesting in their economy. This benefits them throughout the 40 year period, and they correspondingly have a noticeably increase in GDP, and also increase their carbon output. Further to this, these countries are ambivalent towards Kyoto's aims and so leave when their emissions targets force them to reduce their growth.

Canada is the first Annex I country to leave Kyoto. It has a large emissions target and an economy highly dependant on fossil fuels. Interestingly, in this simulation Canada is implemented using the same behaviour code as the countries who are ambivalent towards Kyoto (it is an Annex I sustain agent), but is still the first to leave. This demonstrates that our agent code acts dependent upon its parameterisation and is flexible enough to make intelligent, branching decisions based on its current status in any given scenario. This closely mirrors real world behaviour, as Canada actually left the Kyoto Protocol around 10 years in.

$785.8b worth of trades were performed in the 40 year period. Trade values vary hugely with a maximum value of $193421 but an average of $2611. Trade prices can be falsely inflated by countries hoarding credits until near sanction deadlines and temporarily increasing the price when certain countries are forced to buy.

CDM acts as a stabilising force within the market. Prices for CDM are not set by countries, but are based on the actual cost of their investment. Cost of CDM will increase throughout the game, due to carbon absorption and reduction costs increasing relatively. High demand for CDM will increase the cost faster.



(a) Data at start of simulation.

(b) Data at end of simulation.

Figure 18: Results from real world senario

6.2.2 Annex I Only

This simulation only takes countries that are part of Annex I into account, but is otherwise identical to the Real World Simulation.

Non-Annex countries put additional burden on Annex I countries due to their emissions forming part of the global output. Since the former are not set emission targets, they will generally increase their energy and carbon output to help their developing economies. This means stricter emission goals for developed countries, so that the global emissions can still be decreased by 5% every session. If we remove Non-Annex countries from the simulation, achieving that target becomes significantly easier and cheaper for Annex I countries, as their individual targets are lower.

This behaviour has been evident from the simulation data. With agents being able to meet their targets early on, energy output and GDP would not need to be cut. With countries now able to afford to lower their emissions by means of carbon reduction and absorption, they have enough funds left to invest in industry and increasing their GDP. It is noted that after 35 years, carbon reduction and absorption becomes prohibitively expensive, and some participants need to scale back their economies to reach their emission targets. Likewise, countries start leaving Kyoto much later than Canada does in the main simulation, with Estonia, Slovakia and Poland being the first to do so in the 38th year.

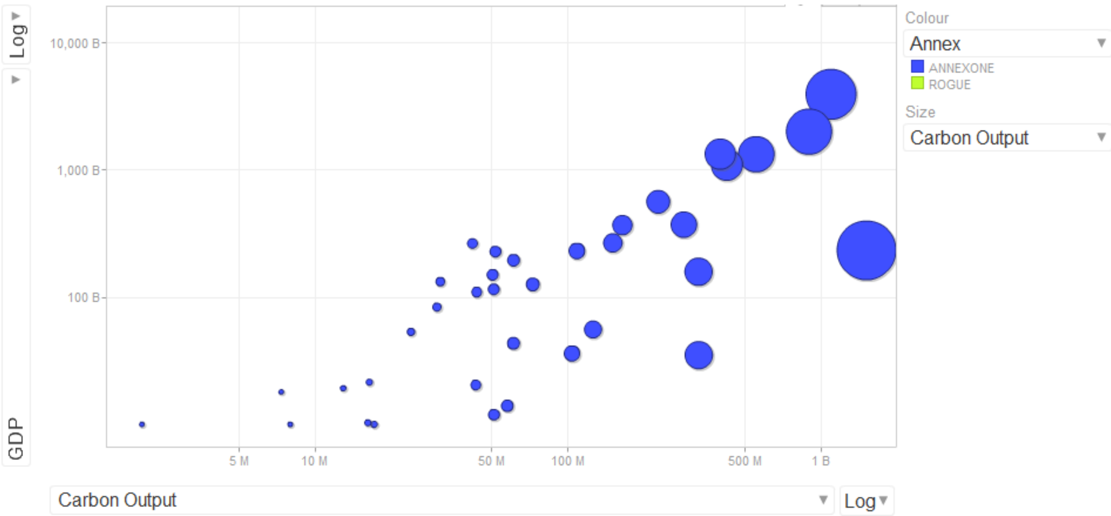
As a consequence, the global increase of GDP almost doubles compared to the original simulation. There may be two reasons for that:

- Allowing developed countries to keep investing in and increasing their economies produces much higher gains than what developing countries can generate, even when they do not need to keep to any targets, or
- The economy state - which is random for every scenario - was significantly more favourable for the Annex I only scenario than for the real world scenario.

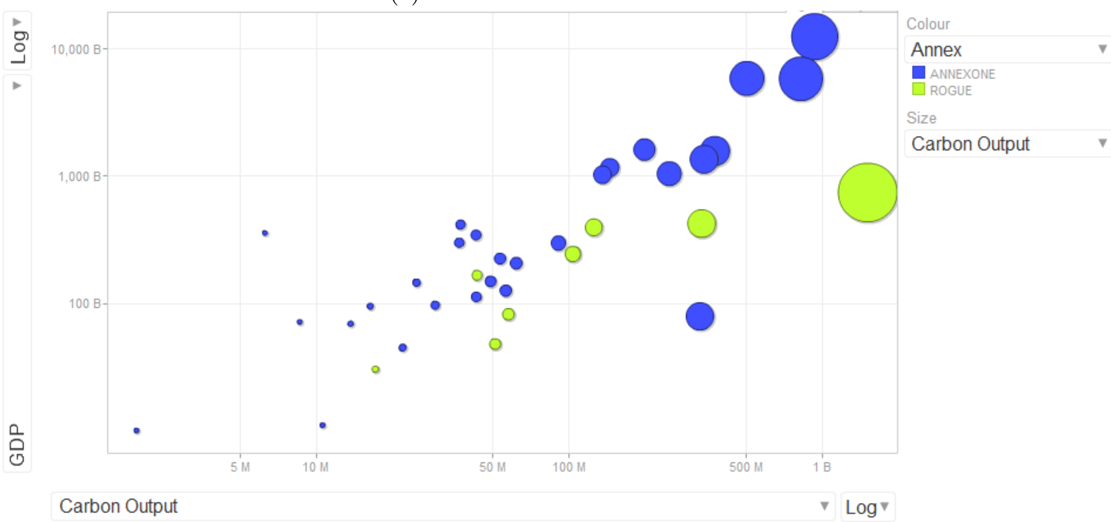
Another significant difference is the price of obtaining carbon credits. Following the free market rules, removing the option to invest in developing countries in exchange for the credits should decrease their supply on the market, and hence increase their price. However, the existence of United States disrupts that theoretical model completely. They cannot participate in trading, but still have significant funds to spend and a will to contribute to lowering global carbon emissions. Hence, they invest heavily in Non-Annex countries, regardless of the price. This explains why the average price of obtaining carbon credits is almost 4 times lower if US is removed from the simulation.

CDM also acts as a form of price stabiliser since the value of a credit is derived and not determined by the AI. This can account for the greater deviation in price from the main simulation.

All of the other figures scale linearly with the number of countries being simulated. Global emission target and reduced carbon emissions, as well as the total number of credit trades and their combined value are decreased by a factor of 6-8 comparing to the original simulation, which matches the decrease in number of participating countries.



(a) Data at start of simulation.



(b) Data at end of simulation.

Figure 19: Simulation running only Annex I participants

6.2.3 Comparing Reduction Rates

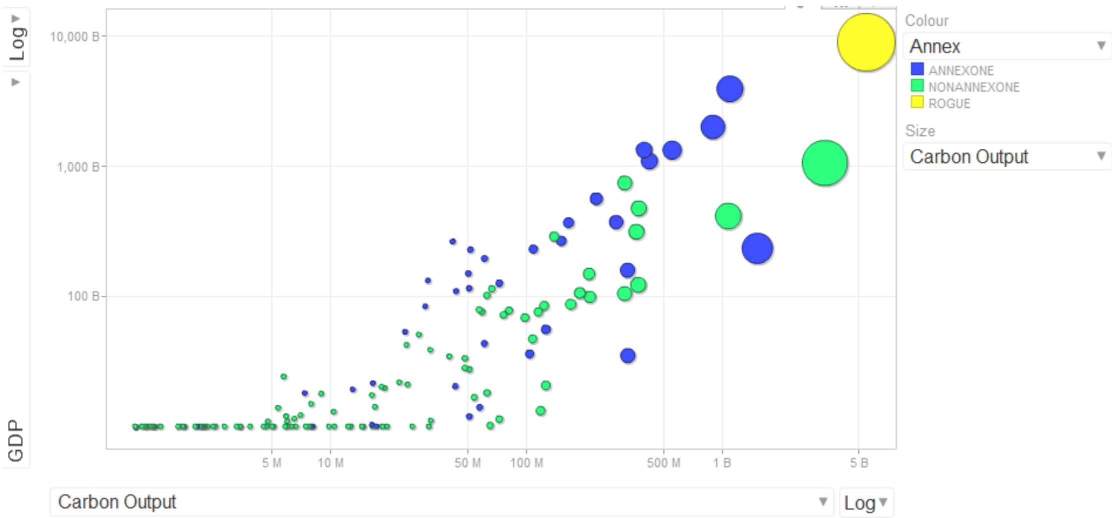
We ran a set of three scenarios which used reduction rates of 0.98, 0.95, and 0.92. These scenarios were otherwise identical, so that we could analyse the effect reduction rates have on the efficacy of the Kyoto Protocol.

The two extreme values, 0.98 to 0.92 (hereby known as high and low respectively), differ from the actual Kyoto Protocol. Both of these scenarios present similar global reductions in CO_2 , which is a lower global reduction than the 0.95 (hereby known as middle) scenario. The high scenario has a lower global reduction for obvious reasons, emissions targets are set higher so countries do not make concerted efforts to reduce their CO_2 emissions. The reasons for low global emissions reductions in the low scenario, however, are not as immediately obvious. After carefully assessing the scenario, we realized that the harsher target in the low scenario led to larger numbers of countries becoming rogue states more quickly, with their excess emissions offsetting the increased reductions by other Annex I countries.

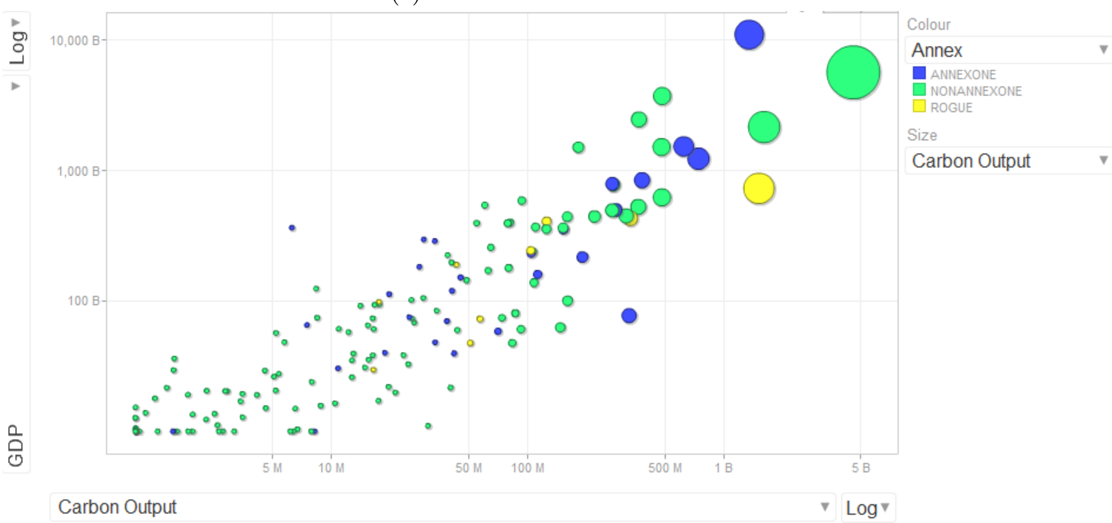
Global reductions in the high and low scenarios are in the range of 2000 megatonnes. The middle scenario has a global carbon reduction of approximately 5000 megatonnes. From this result we can conclude that the real world reduction targets set out by the Kyoto Protocol lie in an ideal maximum range which will lead to effective global reduction in carbon emissions.

In the low simulation, the first country to go from being an Annex I country to a rogue state does so 12 years after the start of the simulation. In the high scenario, the first country does so after 17 years. This difference demonstrates the variation introduced by the reduction rates.

As can be seen by comparing Figure 20 and Figure 21, the Annex I countries are most drastically affected by more or less severe emissions targets.

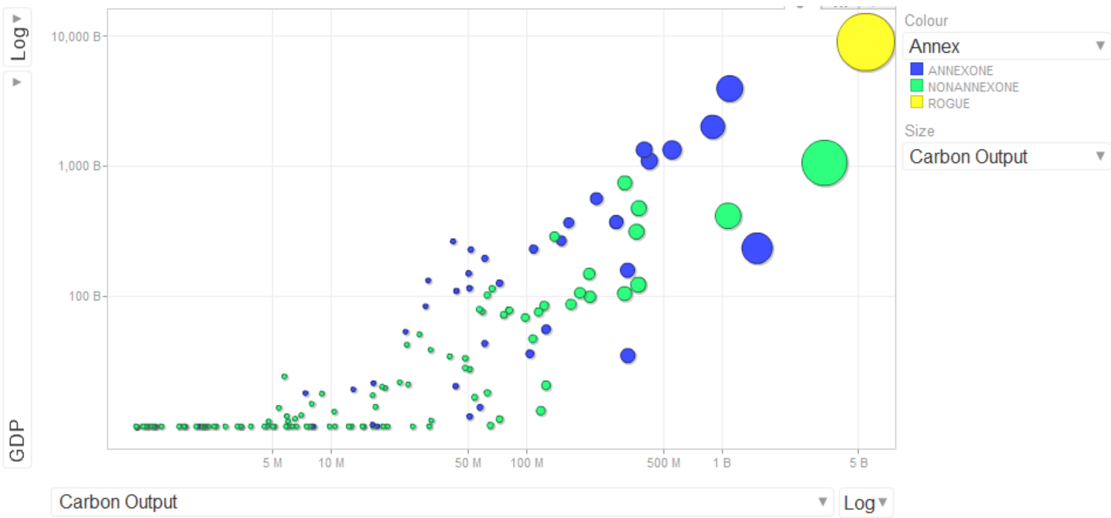


(a) Data at start of simulation.

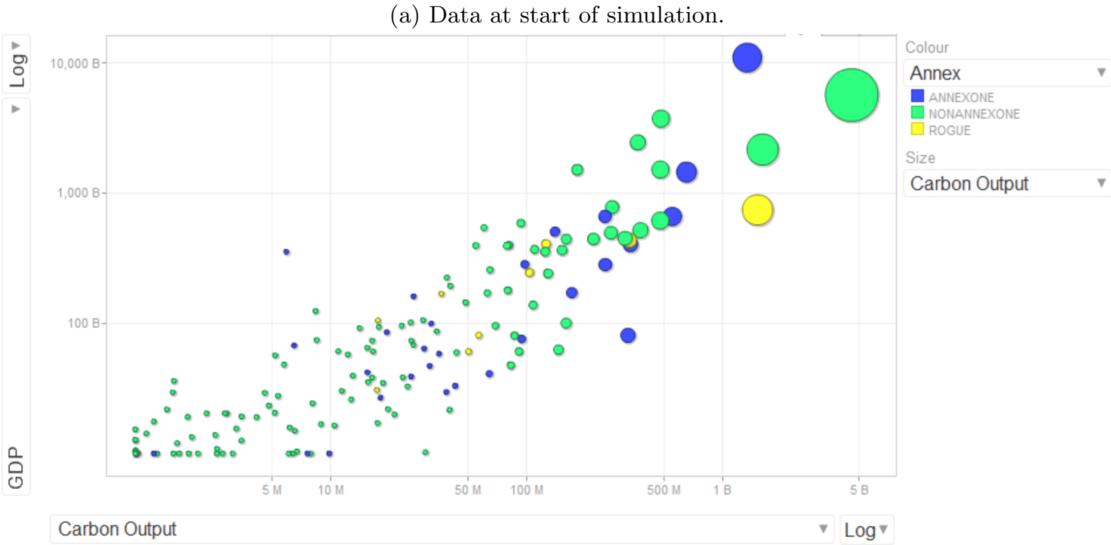


(b) Data at end of simulation.

Figure 20: Results for simulation ($reduction\ rate = 0.98$)



(a) Data at start of simulation.



(b) Data at end of simulation.

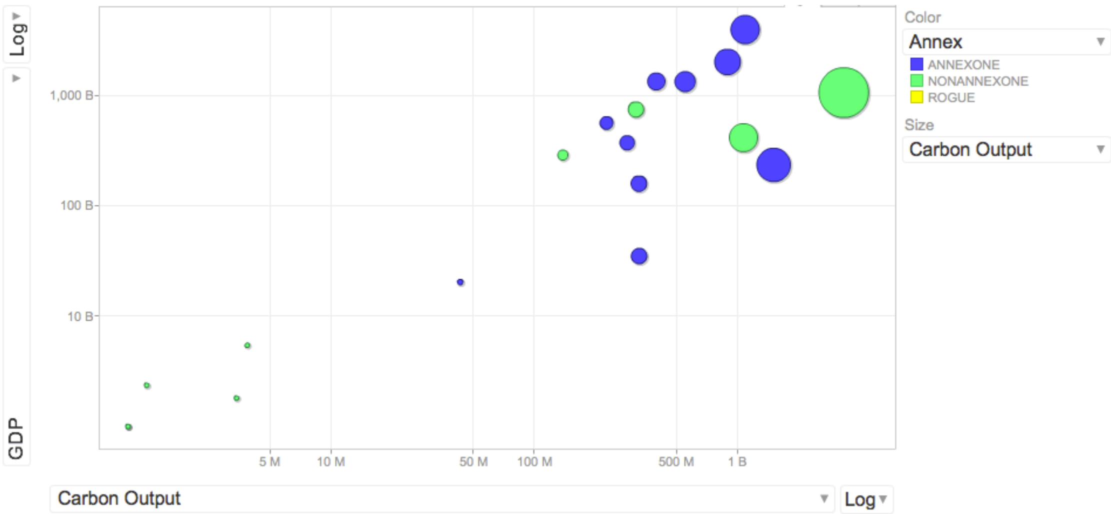
Figure 21: Results for simulation (*reduction rate* $= 0.92$)

6.2.4 Recession

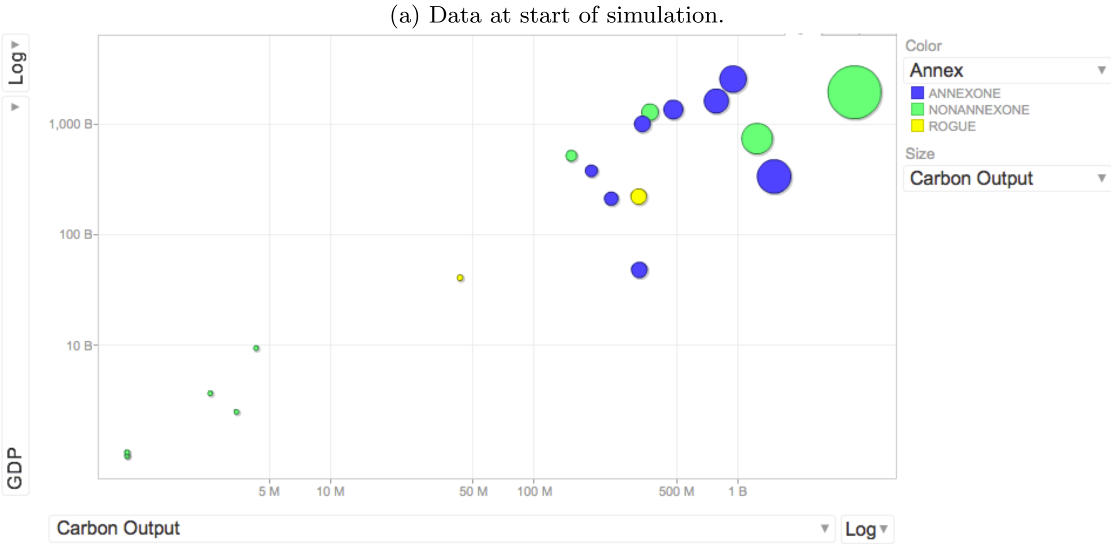
The scenario modelling recession was run with a subset of the total number of countries available. The parameters were chosen such that it would be more likely, at any given time, to have a global recession rather than stability or growth.

Realistically in a recession, countries will increase government spending to get positive economic growth. This particular simulation models the phenomenon quite well. In the subset simulation, countries which were part of the kyoto protocol as Annex I nations faced strict targets, which made it more difficult for them to maintain a stable economic growth in the recession. Figure 22a illustrated the initial GDP vs the carbon output figures for participants in this simulation.

As the simulation progresses the GDPs of the Annex I countries decrease and a general trend of increasing GDP can be noted in the Non-Annex countries. Non-Annex countries do not get carbon emission targets nor do they get monitored so there are more opportunities for spending in economic expansion with little concern to the carbon output. On the other hand, Annex I countries find it more difficult to meet their targets especially in a difficult global economic condition. An interesting point in the simulation is when Slovakia, an Annex I countries leaves kyoto because of difficulties in meeting the carbon emission targets. At the end of the simulation two countries leave the Kyoto Protocol (Slovakia and Poland). Figure 22b shows the state of the simulation when the two countries left Kyoto.



(a) Data at start of simulation.



(b) Data at point where participants leave Kyoto.

Figure 22: Results for simulation (recession)

The total carbon emission reduction totalled to -411 tonnes, which is an expected result when countries spend more in the economic growth with little concern to the carbon output.

CDM is a cheaper alternative for countries to increase their carbon offsets. In the simulation there was a total of 449 CDM investments. This is expected as it is a viable route for countries which are concerned about keeping their carbon emissions below the emission target.

In more complex simulations it can be seen that the total carbon emission reduction is quite large, if this simulation was run with more countries then the collaborative contribution from other countries would perhaps give a positive reduction as opposed to the one originally obtained for the simulation.

7 Future Developments

If given more time, there are a number of additional layers of complexity we would like to add to our simulation.

7.1 Political Pressure

A political pressure system would represent the international relations and varying attitudes of countries toward one another considering their performance regarding the Kyoto Protocol. Initially this was a system that we felt should be achievable within the scope of our design. However, as time progressed and the difficulty of other systems within the Kyoto Protocol and country implementations became apparent, we decided that this system, while desirable, was non-essential. Adding a facility for countries to affect others' decisions through a simplified influence modifier would make our simulations more complex and representative of reality.

Political pressure would also allow Non-Annex and rogue states to participate more fully in the Kyoto Protocol even without becoming Annex I members. This would allow the US to exert political pressure on Kyoto member states and encourage them to become rogue states.

7.2 Global Economy

As outlined previously in our report, our simulation of the global economy is a vast simplification of reality. We maintained only the level of complexity absolutely necessary for the Kyoto Protocol to be cohesive and for any sanctions and spending patterns to be suitably realistic. If we were to expand the scope of our project, we would aim to implement a more accurate model of the economy. Early on in our project design phase we discussed using real world GDP models to represent the growth of each country over the course of a simulation. However, we decided that countries required feedback in their GDP to affect their behaviour, otherwise it was difficult to model the inverse association between spending on Kyoto Protocol related sustainable projects and promoting economic growth elsewhere in the country.

7.3 Impoverished Countries

The behaviour of Non-Annex countries appears to be too successful in simulations. Although it takes several years, the motion graph shows many Sub-Saharan countries, who are mired poverty, to be extremely successful in improving their GDP. Many external factors affect the wealth of country, none of which are modelled within our simulation. A simple addition such as factoring a countries Human Development Index when calculating growth may help rebalance a countries propects.

7.4 Industry Modelling

Our carbon trading model and offset assignment concepts are entirely simplifications of how the Kyoto Protocol responsibilities are distributed in reality. While countries are given specific targets as a part of the Kyoto Protocol, most governments then pass on those mandates to industries operating under their jurisdiction. In reality, the majority of emissions trading is between private companies, rather than governments. If we were to expand the complexity of this component of the Kyoto Protocol, we would create industry agents which operate within countries and alter countries so that they, while still being agents, acted more like monitoring agencies that dictated the activities of their associated industries.

7.5 Available Country Actions

Some country behaviours are limited in the way that they can interact with the Kyoto Protocol. Non-Annex countries have a limited set of actions available to them within the scope of the Protocol itself, and Rogue states are even further restricted. The global economy and political pressure systems, as described above, would provide a number of different agents with additional avenues of interaction with the global stage. This could potentially have a large effect of scenario outcomes as agents make differing decisions when confronted with new influencing factors.

8 Conclusion

Our Kyoto Protocol simulation engine represents the culmination of weeks of work by a diverse team of software engineers. We have created a modelling system which is vastly interdependent yet highly mutable. Given accurate data there are interesting parallels between our results scenarios and the reality of the last fifteen years of the Kyoto Protocol's existence. The representation of any single value or functionality has been scrutinised by a core team of group coordinators who have overseen the vast majority of the code base throughout the project's implementation.

We have had standout performances in design from some of our individual group members, the wrapping of Presage2 and its associated pieces, the MongoDB, and our own implementation code in an impressive UI which can be accessed remotely from any internet-enabled PC. Intelligent agent implementations have discovered routes to favorable positions in ways that were unforeseen by other group members and even their original designer.

We are aware of limitations to our Kyoto Protocol simulation. Some of our group design decisions led to complicated workaround changes later on in the development cycle and if asked to work on a similar project again, understanding of the underlying framework system, in this case Presage2, and design paradigms, in this case multi-agent systems, would be seen as paramount during the project's inception and planning.

Our models of pricing and other non-core concepts to the Kyoto Protocol are purposeful but still largely arbitrary simplifications of real world factors such as the economy and political influence. These have been explored in more detail in the Future Development section. We also fail to simulate more human factors, such as public opinion and general society's influence on policy.

It is important to note that our Kyoto Protocol system does simulate instances of the Kyoto Protocol that extend further into the future than the real Kyoto Protocol has progressed thus far. Any results beyond this point are conjecture on the part of our artificial intelligence agents, and make the assumptions that world activities can continually be modelled in a way that maps to a current day political climate.

There is a potential for emergent technologies to invalidate any predictions our model makes with regards to future emissions and Kyoto Protocol participation, or even the continued existence of the Protocol itself. Our model does, for the simulated future, demonstrate a generally decreasing global emissions output, even accounting for nations that elect to depart from the Protocol.

The parallels with reality that our realistic scenarios have demonstrated range from general trends to almost eerily specific details of some countries, despite shared artificial intelligence code between the analagous agents. For example, the United States' emissions stabilise a few years after Kyoto is put in place, while China's emissions, unrestricted by the targets and sanctions applied to Annex I countries, continues to grow rapidly in the future, until its carbon emissions eclipsed that of all other Annex I states.

We believe that we have designed and implemented a solid framework that if built upon could provide powerful modelling tools for estimating worldwide GHG emissions. Our systems are suitably interrelated to model the meshed nature of the Kyoto Protocol and its cascading effects on global economies and governmental decisions, while still maintaining a suitably implementable level of complexity.

We also believe that, from a purely multi-agent systems perspective, the Kyoto Protocol is in reality an extremely well tuned CPR implementation which avoids the pitfalls of the most obvious avenues of attacking CO_2 emissions (e.g. carbon taxation). However, it does have limitations. The lack of penalisation for fraudulent reporting relies heavily upon morality and the incidental difficulty of believably falsifying carbon emissions reports that have been collated from a variety of public and private sources.

Our Kyoto Protocol simulation engine, through countless revisions and cooperative decision making, has become a worthy simulation of GHG emissions and speculative modelling of carbon based economy.

9 Learning Outcomes

Many of the learning outcomes of this project related to working in a group. In particular the challenge coordinating member's work in way that is productive. As a group we took an informal approach to leadership, with a number of individuals taking lead at different points depending on what most needed to be done. This felt most natural as a group, however, in retrospect, we feel that a more formal leadership may have had its benefits. One being better use of individuals who fell behind with the project.

Similarly, the relatively short time frame of the project meant that working concurrently was extremely important. However, the dependent nature of components within the project inevitably made this difficult. This became more prominent as the deadline approached when we brought previously separate components together. The necessity for concurrency ran contrary to the requirement for holistic scenarios that involved code from all contributors.

Early in the project we decided that, for ease of management and to divide the tasks, we would split into smaller groups. We originally arranged so there were four people focused on each behaviour type and the remaining five would focus on the common framework. This structure was soon abandoned (although we still loosely retained our groupings) as we discovered that the common framework required a greater portion of development. In the end we had roughly one or two people working on each behaviour type with the remaining members working on the common framework. (services, protocols, and UI etc.)

Many of our group members were unfamiliar with one or both of Java and Eclipse. The added complexity of Maven's dependency system on top of Eclipse raised the barrier to entry further. However, adaptation from CPP to Java proved an amenable transition. The facilities provided by a more automatic memory management based language were appreciated and the similar syntax to familiar languages was a great boon.

Other learning outcomes related to the tools we were using for the project. We had particular success with the source code management software Git - a tool that is engineered toward snapshot based parallel development. We also relied heavily on Github - a web frontend and Git repository host that also provides some incredibly useful functionality such as issue tracking. Github's issue tracking was particularly helpful for bug fixing, as testers could open issues easily when they found unexpected behaviour. These could then be assigned to individuals who had experience dealing with the effected sections of code. Over the course of our project we opened and submitted around 2500 commits (Git's term for code snapshots) and closed over 130 issues.

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