

Visualisng Ant Colony Optimisation

Final Report for CS39440 Major Project

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Abstract

Ant Colony Optimisation and its variations are commonly used swarm intelligence methods, however the underlying concepts can be difficult to comprehend for people who have recently come across the subject area. The majority of existing resources either inadequate visual representations or rely on the user having some prior knowledge about the underlying behaviours. The author of this project aims to create an application for deployment in educational environments allowing for a richer, more interactive experience in regards to the teaching of Ant Colony Optimisation methods. The author has set out to achieve a full visual representation of the algorithm's execution as well as providing an intuitive user interface allowing for user defined algorithm parameters and a choice of algorithm types and modifiers.

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Chapter 1

Background

1.1 Algorithm Overview

Ant Colony Optimisation is a probabilistic technique usually used on problems which can be resolved by resolving an optimal path through a graphical representation of a given problem. Ant Colony Optimisation refers to a collection of methods and techniques which represent a specific family in swarm intelligence. Swarm intelligence “...deals with natural and artificial systems composed of many individuals that coordinate using decentralized control and self-organization. In particular, the discipline focuses on the collective behaviours that result from the local interactions of the individuals with each other and with their environment” [14]. In simpler terms each agent is simple and each agent follows a series of fairly simple rules as it performs its operations. If you increase the population size of these simple agents and allow them to communicate with each other and the world they are in then there will be an emergence of intelligence which would otherwise be unavailable to any individual agent. Ultimately each agent collectively works towards the same goal increasing the quality and appropriateness of the result.

The initial proposal for Ant Colony Optimisation came from Marco Dorigo et al. through the publication of his PhD in 1992 [6]. The Algorithm is based upon the real world behaviour of ant colonies. Ants in the real world will generally always find the most optimal path between two or more points, often described the route between their nest site and the location of the food source(s). As an Ant leaves the colony in search of a food source it begins to deposit a chemical trail (pheromone) which can be analysed by other agents in the population. The pheromone however is non consistently present once deposited, as this is the real world there are several factors which impact the concentration of the pheromone at any location once it has been deposited. Once an agent has deposited the pheromone it starts to decay overtime, and in the real world this could be accelerated by outside factors; such as adverse weather conditions. As the pheromone decays, new pheromone will be deposited at the same location by other agents in the colony also looking for a food source because of this, as more and more agents continue through their tour the locations which have the highest concentration of pheromone are generally the most traversed locations. Ultimately the locations with the highest concentration of pheromone will not only be the most frequently used, but together they will form the optimal route between the start location and the destination. This is due to the fact that the longer the route, the more susceptible pheromone levels are to decay, thus the longer paths will have less pheromone present. The pheromone levels are important because these levels are the main influence in the probabilistic function for any agent

choosing its next location for any given intersection. The higher the concentration of pheromone, the greater the probability that the agent will choose this location as the next stop on its tour, however as this is probabilistic the agent may not always choose the location with the highest concentration allowing for other solutions to be sought after, allowing for a shift in the current best path.

1.2 Double Bridge Experiment

The double bridge experiment is an early experiment devised to help understand the real world behaviour of ants and their path finding capabilities. The double bridge experiment, as the name suggests involves a nest location separated from a single food source by two bridges. This experiment designed and carried out by Deneubourg and colleagues in 1989-1990 performed using real Argentine ants [12].

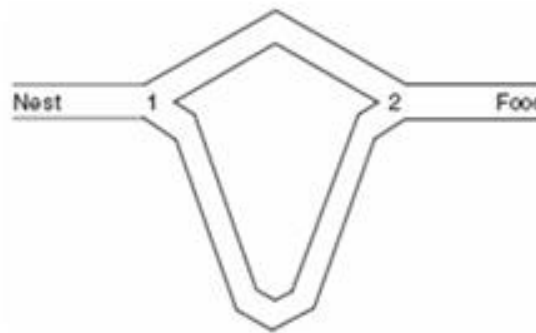


Figure 1.1: Image representing the Double Bridge Experiment. Image source [21]

Figure 1.1 represents the scenario the Argentine ant were faced with for the Double Bridge Experiment. As previously stated in section 1.1 the foraging behaviour of most ant species is dependant of communication using the pheromone deposits by each colony member during its tour. Initially there will be no pheromone trails for the ants to follow, so as the first ant approaches intersection marked “1” in figure 1.1 the probability that they choose the top path, or lower path is therefore 50%. Regardless of which path the ant chose, pheromone will now be deposited on the path it took. Now the next ant will approach the intersection marked “1” however, as there is no an existing pheromone trail this ant now no longer has an equal probability to choose either path but instead is more likely to chose the same path that the previous ant had taken. This process will continue for every ant in the nest. The pheromone will however decay. Generally speaking as the bottom path is significantly longer than the top path, the pheromone deposited on its path will more subject to this decay, and will eventually have a lower pheromone concentration than the shorter top path. Overtime this will cause more and more ants to take the top path over the bottom path due to the higher pheromone level directly impacting the probability of the ant choosing this path. The same applies to intersection marked “2”, the ants will still tend to prefer the path with the greater pheromone concentration, the fact that the ant now has food does not affect the ants choice in anyway, aside from the fact that the ants new target is the nest and no longer the food source.

1.3 Travelling Salesman Problem

One of the most common applications for Ant Colony techniques is the Travelling Salesman Problem (TSP). The TSP consists of a graph of N cities, and you must find the shortest route between each of these N cities, however each city can only be visited exactly once. Generally this N value is often fairly large for example the Berlin52 [16] is a variation of the TSP where this N value is 52. The number of possible routes between these 52 cities is incredibly large. The application of heuristic algorithms such as the Ant Colony methods enables solutions to be found within a reasonable time. One solution for the Berlin52.tsp problem is shown in figure 1.2.

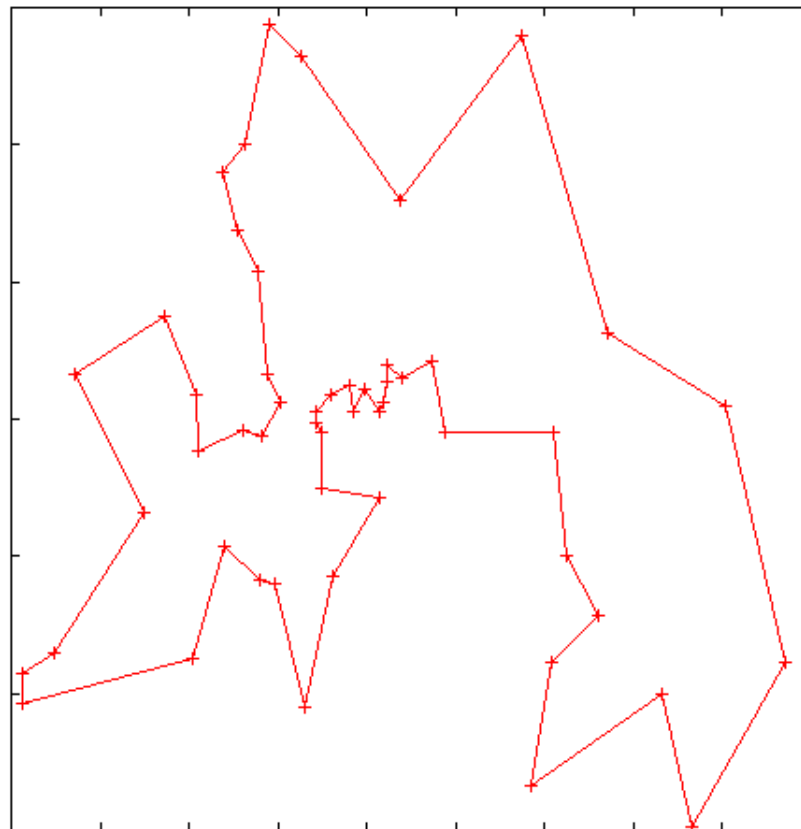


Figure 1.2: One solution to the Berlin52.tsp problem plotted using GNU Plot. Modified version from original image source [5]

The TSP is not the only problem which can be tackled using the Ant Colony family of methods. As these methods have metaheuristic properties the general behaviours and structure can be applied to several other problems such as image segmentation however this application will not cover such problems and will focus on the TSP style problem.

1.4 Ant System

The Ant System is the most basic implementation of an Ant Colony Optimisation method, because of this it provides the basis for other extensions and variations. This does not mean that the Ant System is lacklustre in performance. Due to its basic nature, the Ant System is ideal for

demonstrating and teaching the behaviours of a virtual ant colony to someone, and it can be done regardless of their prior background knowledge. In this implementation there is no recollection of the best path between iterations and every agent is equal in terms of its importance in finding a solution.

1.4.1 Formulae

Sections 1.4.1.1 and 1.4.1.2 refer to the underlying formulae which govern the agents pheromone deposits for a given edge and the probability for an agent to move to a specific location anytime it reaches an intersection.

1.4.1.1 Probability

The probability formula is as described in appendix B section 2.6.2.1. This is the function which drives the agents movements and enabled agents to generally pick the best looking path (path with the strongest pheromone concentration) whilst also allowing for agents to select other paths helping to prevent localised solutions forming.

1.4.1.2 pheromone

The pheromone function for the Ant System algorithm is as described in appendix B section 2.6.2.2. This function is the real difference between the Ant System implementation and the Elitist Ant System.

1.5 Elitist Ant System

The Elitist Ant System is the first adaptation to the initial Ant System algorithm. The Elitist Ant System is again, proposed by Marco Dorigo et al. in his 1992 PhD Thesis [6]. The main difference between the Elitist Ant System and the Ant System is the fact that the best ants for a given iteration have pheromone deposited upon their route. This means that the best x number of ants where x is an integer representing the number of elite ants will have their routes remembered across iterations allowing the fact that they performed well to persist, with the intention to improve the performance of the population as a whole as the extra pheromone on these elite paths will increase the probability that any agent traverses an elite edge (an edge that is part of an elite path).

1.5.1 Formulae

Sections 1.5.1.1 and 1.5.1.2 refer to the underlying formulae which govern the agents pheromone deposits for a given edge and the probability for an agent to move to a specific location anytime it reaches an intersection.

1.5.1.1 Probability

The probability function for the Elitist Ant System remains the same as it is in the Ant System, see section 1.4.1.1 and appendix B section 2.6.2.2

1.5.1.2 pheromone

As stated in section 1.4.1.2 the pheromone function is the main different between the two algorithm variations. This new pheromone function takes into account that there is elite agents and enables pheromone to be deposited along the current X elite paths.

$$p_{xy}^k = (1 - \rho)\tau_{xy}^k + \Delta\tau_{xy}^k + e\Delta\tau_{xy}^{best} \quad (1)$$

Figure 1.3: Algebraic model of the pheromone deposit function for the Elitist Ant System [11]

The majority of the formula remains the same as defined in appendix B section 2.6.2.2 however, there is the addition $e\Delta\tau_{xy}^{best}$. This is the part of the formula which is responsible for the pheromone deposit on the retained best (elite) paths currently found. xy refers to the x and y coordinate for an edge in the best path this is where pheromone will be deposited. *best* simply donates that this edge belongs to one of the currently stored best paths. The e value is a constant, and varies between implementations. Research suggests that a good value for this weighted value, e is $\frac{1}{4} \cdot \# \text{ of nodes}$ [17] however, there is evidence to support using $\# \text{ of nodes}$ as the e value [13].

1.6 Existing Solutions

There are a number of pre-existing solutions which attempt visualise Ant Colony algorithms however, the majority of these based upon the authors experience are in fact subpar in what they visualise. Rather than visualising the algorithms execution in a logical manner, which would enable the user to understand what the algorithm is doing and how the best path converges over time, more often than not the existing solutions simply show the algorithms final state leaving the user confused.

Another problem with some of the existing solutions is that the graphical user interface for the application is far too inconsistent. Inconsistent here refers to the fact that there are a number of interaction method present which can be quite daunting for a user and therefore might cause a less than satisfactory experience for example, some features may require a user to use a scroll bar to set the value, others may require direct textual input and another feature may require the user to check a checkbox. In combination with this, the interfaces themselves are usually far too crowded and often unnecessary features for the current algorithm selection. If the user has selected that they want to use a specific variation of an Ant Colony algorithm then there is no point in allowing them to be able to modify a parameter which will have no impact on the current execution. The irrelevant interface elements can cause confusion amongst the users in terms of what in fact they are modifying and how it impacts the algorithms behaviour.

One of the major problems the author faced when assessing the competition was the fact that there was rarely any visualisation of the agents themselves, this meant that you has to effectively

guess which cities the agents were currently at. In addition to this as there was no visualisation of the agents there is no visualisation of the agents moving between the cities themselves thus, it was difficult to visualise the path the agents took aside from coming to your own conclusion based on the pheromone trails which were also often poorly represented.

1.7 User Interaction Methods

As discussed in section 1.6 the methods of user interaction must be superior to what is provided by the competition. This application will be authored in accordance with several preferred user interaction methods enabling a more user friendly experience for all users and not just those who are experienced with this or similar applications.

1.7.1 Law of Context

The law of context refers to the users expectation that they should only see interface controls relevant to the current object they want to control [1]. This relates to one of the fundamental problems found in competitor applications (see section 1.6). Should the user request a change of algorithm type which requires an extension to default features, these new controls will be self-contained and represented suitably so the user knows that the new dialog or interaction method is a direct result of request a change in algorithm type, allowing for a logical mapping between their selection and the new control interface.

1.7.2 Law of Feedback

The law of feedback related the ideology that every significant action has some form of informative, relative feedback associated with it [1]. This enables the users to quickly develop an understanding of what interaction control which action allowing for a more enjoyable experience. This also covers any incorrect actions performed by the user. The application will be developed in such a way that any incorrect actions will be displayed to the user in a manner that anyone can understand and provide the user with the required knowledge to resolve said issue.

1.7.3 Law of Easing

The law of easing is very important, especially for this application. This law suggests that complex actions should be segmented into simpler steps to allow the user to comprehend what they are actually doing [1]. The way this application will adopt this is that rather than specifying all of the algorithms parameters at once, each parameter will have its own method of interaction and its own series of user feedback prompts enabling any user to simply modify select parameters however they see fit, assuming the value is legal.

Chapter 2

Analysis

2.1 Key Tasks

Based upon the research undergone in chapter 1 the problem can be decomposed into several key tasks. These tasks will directly relate the requirements described in appendix A section 1.3.3.

2.1.1 Problem Representation

The problem representation is key for both creating an application which is best suited to the proposed task whilst also ensuring the underlying algorithm can correctly calculate a solution in a reasonable manner. Chapter 1 explains two stypes of problem which could be represented in this application, the Double Bridge experiment (see section 1.2) and the Travelling Salesman Problem (see section 1.3) each of these problems has its own merits and demerits.

2.1.1.1 Double Bridge Experiment

Opting to represent the problem in a similar format to the Double Bridge Exprimment would enable the visualiation but more user friendly as the actual problem itself is far simplier than the Traveling Salemen Problem. In addition to this users may relate more to this style of problem as they can map the on screen representation of the nest and food to a real world scenario, this is not easily done with the Travelling Salesman Problem. The authors feels that representing the problem in this basic form will negatively impact the applications success as having a nest location, a food source and two bridges for the agents to navigate accross can only be represented so many ways before the user becomes fully aware of the expected outcome.

Instead of maintaining the exact ideas behind the Double Bridge Experiment, the key concepts can be extracted and applied to a more complicated problem representation. The idea that every agent will start and the same nest location, and attempt to navigate to a food source is a fairly simple concept to understand, however as described in Appendix B section 2.7.1 the world can be expanded to no longer only accomodate two paths for the ants to navigate, but instead have a matrix of nodes which vastly increases the problems complexity. As the problem is no longer represented as a simple 2 path paths, it becomes exceptional more difficult to predict the agents movements which could lead to a much richer experience for the users.

2.1.1.2 Travelling Salesman Problem

Representing the problem in the form of a Travelling Salesmen Problem may come across as quite daunting to new users. As discussed with the Double Bridge problem representation the idea of a nest site and a food source is easily relateable to the real world for the majority of people however, the Travelling Salesman problem does not boast any kind of instantly relateable real world mapping to ants and their colonies. One of the main advantages with the use of this representation is that the graph is a fully connected graph. As this is the case the author does not have to worry about complications such as wrapping the edges of the graph to simulate connectedness, this would be the case if the Double Bridge and the suggested modifications were to be used.

This form of representation is far more customisable thus it may be more appropriate an educational application such as this as it enables a greater degree of user customisation allowing for users to experiment with different configurations in order to understand how the algorithm operates in different scenarios.

Initially the author chose to use the suggested adaptation to the Double Bridge Experiment however, the result this produced happened to be very unsatisfactory. As this is the case the application underwent a somewhat agile re design process in order to accommodate the change in problem representation to the Travelling Salesman type of problem (more details found in **REFERENCE PROCESS AND DESIGN CHAPTERS HERE TALKING ABOUT CHANGE OF REPRESENTATION**).

2.1.2 Algorithm implementation

The applications success will be heavily dependent on having a working, customisable implementation of at least the basic Ant System (see section 1.4). If the algorithms implementation is flawed in anyway then it cannot be accurately visualised. As this application has educational objectives incorrect implementation of underlying algorithm(s) would cause improper algorithm behaviours to be both taught and demonstrated thus, the quality of the implementation is paramount to the success of the application. The combination of background research and a suitable test strategy will ensure the application exhibits expected behaviours.

2.1.3 User interaction

The methods of user interaction will be key in ensuring the users actually fully utilise the functionality on offer. Using the key user interaction principles identified in section 1.7 the author will develop a simple yet effective user interface incorporating these key design concepts. The user must also be familiar with the look and feel of the interface, research will be carried out and will consist of looking at successful application of similar design then adapting any suitable design styles they provide to suit this applications needs.

2.1.4 Algorithm Variations

Given the time constraints of the project it is not realistic to attempt to implement support for every variation of Ant Colony algorithms. It is far more realistic for the application to support few algorithm variations which will at a minimum include two different algorithm variations so

users can have some insight into how different algorithms impact the overall result. Although it is unrealistic given the current development timeframe, this does not mean that supporting the majority of algorithm variations cannot be a high level objective for the application.

2.2 Objectives

The objectives listed below are generalised overall system goals. The author fully expects to have objectives which are not yet met, however these will be used as a reference point to further develop the application for future releases. The design decisions will be made with these high level objectives in mind and any design implementation which negatively impacts the applications ability to meet one or more of these objectives needs strong rationale for doing so.

- Create an application which can visualise a basic Ant System algorithm execution including the problem representation, the agents solving the problem and the optimal returned path
- Provide a suitable user interface which enables the user to modify the algorithms key parameters enabling the user to experiment with different parameter combinations
- Provide the visual representation of the algorithms execution in real time
- Allow the user to set the algorithms execution speed, enabling the user to slow the algorithm down if they want to focus on each agents movement or speed the algorithm up if they are more focused on the returned solution
- Support the majority of Ant Colony algorithm variations to enable the user to freely choose any algorithm they wish
- Support multiple problem representations, enabling the user to change the problem representation as they wish
- When using the Travelling Salesman Problem representation allow for the ability for the graph to not be fully connected to see how the algorithm returns different results
- Support the option for some paths between nodes to be weighted, these paths will cost more to travel one way than the other
- Allow configurations to be loaded from and exported to external files, enables the user to consistently apply the algorithm to the same problem

2.3 Requirements

These requirements are seen by the author as essential features that the application must provide. The requirements defined in appendix A section 1.3.3 describe the immediate goals for the application however, there is some overlap between the overall objectives described in section 2.2 and the functional requirements. In addition to this each functional requirement defined does not have equal importance, some of the requirements are indeed critical and must be completed at the earliest convenience. The evaluation of these requirements is described in appendix A table A.2 which shows a summary of all requirements and their dependencies.

2.4 Desireable, non-essential Features

The features mentioned in this section are seen by the author as non-essential, however, if implemented these features would significantly improve the applications performance. The implementation of these features will only be considered, if and only if the requirements mentioned in section appendix A, section 1.3.3 have been met to a significant degree of accuracy. The application will however be designed in a way that will allow modification and maintenance to be less problematic, therefore the author feels there should be no reason why these features could not be implemented if there enough time during the development process to do so.

- Enable the user to switch between automated solving and an iterative step-by-step process, enabling a greater teaching potential.
- Upon completion or stoppage, a summary or report should be displayed to the user, enabling the user to perform analytics based on the contents of these reports.
- Allow the ability for the application to generate graphs which are not fully connected to visualise how the algorithm deals with such complications.

The author realises that these features are outside of the projects general scope. The author also feels that although they maybe outside of the projects scope the implementation of these features is by no means out of the realms of possibility. The intentions and efforts of the author will reflect the functional requirements being a top priority.

Chapter 3

Process

This project is largest project the author has solely been responsible for however, this does not define the project as a large project. The author is working alone and does not have a dedicated team as assistance. This combined with the fact that the time frame which the project has to be completed in has lead the author to come to the conclusion that there is no single Process Model that would be entirely suited for him and this project. The lack of one specific process gives the author the temptation to fall back on process at all however, the lack of any rational structure is vastly inappropriate for this project. Rather than using one single process, the author feels that is can modify existing processes in order to create a process which captures the necessary principles required in order to create a logical structure which can be applied effectively to this project. Agile methodologies are often used in small development teams, specifically eXtreme Programming (XP). XP places heavy importance of quality and responding to customer demands through the use of multiple iterations and a simple design process (compared to planned design). However, small development teams are using XP as a scapegoat for not adhering to a specific process or methodology. XP is still very much focused around a team of people working are there is constant deliberation about XP and its adaptation to single developer project such as this [4]. However, there are XP principles which are well suited to this style of project for example, there is less emphasis on a heavy design process allowing for a more flexible development process which has been vital for this project in particular as the proposed design had to be significantly changed during development (more details can be found in section 4). The author feels that in a solo project, the ability to be flexible and independent of any concrete design is key to a successful project. As the author has created a brief design specification individually without the help of a specialised team (see appendix B) there is the possibility that there are some key elements missing which may not be noticed until the implementation stage. XP flexibility effective makes this a non-issue during development as it accounts for the projects features to change, if the author adopted a strict plan based methodology then this maybe an issue.

As stated the process used is a hybrid process containing relevant ideologies from other software development processes. In conjunction with XP principles discussed above, the author has decided that there has to be some planned process involved in the projects development. The idea behind using a planned approach as the main underlying process is because the author feels that when working on solo projects it is easy to get lost in terms of what goals still need to be achieved. This planned process wont be as strict as it would be if a planned approach was the sole process being used for this project, instead the design and requirements processes will be much shorter than usual and will only cover the main requirements and overall system interactions.

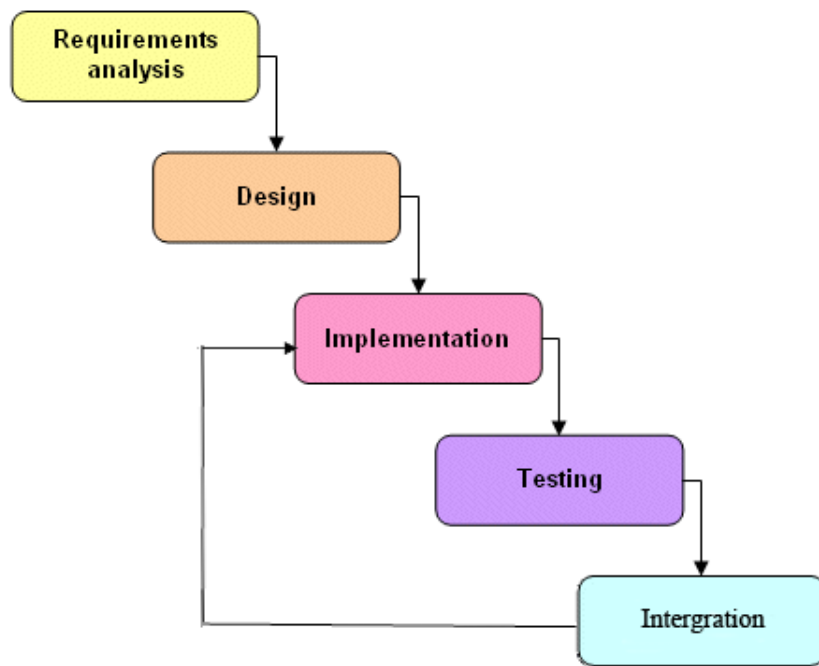


Figure 3.1: The variation of the waterfall model used for solo development in this project.
Modified from source image [19]

Figure 3.1 represents the variation of the waterfall model used as part of the hybrid process in this project. The general waterfall structure has remained the same, the process starts off with a problem analysis stage which is reflected in appendix A and chapter 2. With the introduction of the XP principles, the design stage is reduced in its complexity. This is with the intent to reduce how concrete the design is and also reduce the amount of time spent on the formal design of the application. The main adaptation comes from the approach to implementation and testing. As the introduction of XP has enabled the author to be more flexible in the implementation process if a new feature or refactoring is required, rather than going back to the design stage, this new process allows the author to implement the change or refactored code, test the changes and integrate the changes into the current working application. This saved tremendous amounts of time during the development process. Each change is handled in small sections rather than implementing several changes at once, each change will be broken down into logical sections which will each in turn go through the implementation and testing process. This process continues until the requirements defined in appendix A have been adhered to. This hybrid process is based on the work by Tom Blanchard [3], the process is very effective for use in solo projects.

Chapter 4

Design

Section 3 states how the author has a somewhat flexible approach allowing for adaptations to the initial design stated in appendix B. This section explores how the process has enabled the significant change of design to be implemented easily and without severe complication. The proposed design in appendix B and the final structure of the system are very different however, at an abstract level the key components still exist they are just represented different in each system architecture.

4.1 Language

The author has identified that the choice of language is an essential decision which must be made early in the projects development cycle. Appendix B, section 2.2 denotes the language decision process the author went through and ultimately states the final language choice.

The use of an appropriate language became even more important due to the fact that the design has undergone significant modifications since the initial proposed design. If the author had selected a language which happened to be unfamiliar but seemed good at the time, then the changes made to the initial design may have been much more complicated to implement. The author is very familiar with Java, more specifically Java 7 (Java 1.7) and above thus, implementing new features or refactoring existing systems is fairly familiar territory. The initial language choice rationale (appendix B, section 2.2) did not factor in the potential for radical design change however, if it did the outcome would not change and the existing rationale would still be applicable to the project. In the authors opinion Java is the most appropriate language for this project.

4.2 Development Tools

4.2.1 Development Enviroment

4.2.1.1 Command Line Tools

The author considered using the combination of a simple text editor which in this case would have been Atom [10] to write the code, and compilation of such written code using the command line and the default compiler through the use of the *javac* command. Atom is a free, open source

hackable text editor provided by GitHub and provides syntax highlighting support for numerous language, including Java which is the language of choice for this project. This syntax highlighting is especially useful and makes the writing of the source code slightly easier, as it becomes much simpler to track the start and termination points for specific code blocks. However, as Atom does not have built in Java compilation abilities, the compilation process can become somewhat complicated.

Using this approach, the Java source files composed using Atom must be compiled using the default Java compiler, provided by the language specification. The problem with this method of compilation is that error detection and correction can become a very tedious process. If any compilation errors are present after the *javac* command has been executed, the trace presented in the terminal window can sometimes be quite difficult to parse for the error message, and tracking down the error in the source files could be a difficult task. For smaller projects, this method of compilation is perfectly suitable and can be effectively managed. However, this project as discussed in section 3 this is a rather large project for the author to undertake. As this is the case, the combination of size of the applications source code and manual compilation leads the author to believe this method of writing and compiling code is not only inefficient, but also inappropriate for this project and could potentially hinder development.

4.2.1.2 Integrated Development Environment

The use of an Integrated Development Environment (IDE) can help to alleviate the problems that can come from using a writing and compilation process such as that defined in section 4.2.1.1. There are many IDE's which support Java, however the author has preference is the use of the Eclipse IDE for Java Developers [9]. The Eclipse IDE provides a multitude of useful features as part of their default package.

One of the main features which Eclipse provides is automatic building of the projects source. This is a major benefit when developing as you can simply write your code and run the built project without having the unnecessary complication of switching between several applications to achieve the same task. Also, as there is automatic building, any compilation errors will be clearly highlighted using a system which is familiar to most computer users. If there are any misspellings of method or variables names for example, Eclipse will underline these in red to show there is a clear problem with this exact line of code. This is similar to the default scheme provided by most word processors, enabling a logical mapping between this red underlined line of code and the fact that there is an error present there.

Another useful feature provided by the Eclipse IDE is the auto completion of variables and method names. This has sped up the development process for the author as there was no need to constantly look at the API's or other project source files for method names, the author could simply type the Object of interest's identifier and see a list of all methods and variables associated with such Object. This is not possible to do if the author used an approach similar to that discussed in section 4.2.1.1.

In addition to the built in compilation feature, Eclipse also provides an integrated debugging toolkit. The Eclipse debugger enables easy creation and removal of break points, as well as all the usual features you would expect from a debugger such as, step through and step over, exploring the various contents of different variables and objects. These features are also provided by command line debugging tools, however the author is far more comfortable using a graphical interface

to debug the application as it is much earlier to access the features of the debugger using this approach.

Eclipse also has built in JUnit support. This project will use the JUnit library as part of the testing process (more details see 4.2.3.1). Similar to how the IDE makes the writing of the applications code easier, the support of test suites such as JUnit makes the test process much easier. The code responsible for the tests will also have access to the features provided by the IDE as mentioned above, this includes in place builds and auto completion. In addition to this you can run the tests inside the IDE and get accurate feedback on how many test ran, how many failed and why these tests failed. The author uses this to identify failed tests to be easily identified and repaired. Eclipse also supports a variety of other languages and features but these are not relevant to this project currently.

4.2.2 Support Tools

4.2.2.1 Maven

Maven is tool used for building and managing projects, specifically Java-based projects [2]. The Maven framework provides a lot of useful utilities for developing successful Java-based projects and ensuring that such projects adhere to certain standards. The Maven framework aims to provide convention, over configuration. If there are multiple projects which have many different dependencies, some of which could be external Jar files, then Maven can allow other projects to make use of these dependencies. As a result, if a new project is decided there is less time spent configuring as the dependencies are already presented using this Maven framework. However, the author is working alone, and is not expecting to have any other projects which will share dependencies with this one, thus the author has to weight up if this framework would actually help the development process.

Maven provides some useful testing capabilities. When testing using the Maven framework, tests are still written using the Junit libraries (see 4.2.3.1). However, the Maven framework provides some additional features which the author feels could be of use. Maven, will give the author a Unit test report should one be required which will cover numerous details, most important a coverage report will be produced. This enables the author to assess how well the unit testing has been done. Although this test report is a very useful feature, the Maven is not a necessity nor is it complication free.

The main complication that the author has with use the of Maven for this project is that fact that as this is generally a small project, Maven and its features would not be fully utilised but the hassle of configuring the framework would still be present. The initial project configuration would be time consuming, given that the author is inexperienced with the framework and this time could be spent on the actual project development. There are plugins which enable Maven to be used with an IDE such as Eclipse, the author feels that Maven would not be appropriate for use here, however the test reports would be extremely useful.

4.2.3 GitHub

The author has seen the use of GitHub as an essential part of the development process. GitHub has enabled the author have strict version control throughout the development process. As this is the

case, the author has been able to store a local repository, which will exist as the working directory for the applications development whilst also allowing a working copy, with the current most up-to-date fully working project code to be stored safely online using GitHub. There has been numerous times throughout the development lifecycle where the author has had to revert back to a previous version of the applications code, GitHub has allowed this process to be more hassle free. As it is so simple to manage different versions of the application, each representing a different collection of working or non-working features the author has been able to develop in confidence as he knows that any mistakes or experiments are not very costly as there is always a backup version stored at the GitHub repository location.

Without the use of GitHub (or another version control system) the author would have found it difficult to progress the application as expected. If there was no form of version control, then the mistakes the author made or external factors which then rendered the current development code unusable would be a far more disastrous. There was a time during development where the authors working directory became corrupt. This was easily resolved by simply retrieving the code stored in the projects GitHub repository, however if GitHub was not being used here, then there would have been a high possibility than the author would have lost all progress on the application.

4.2.3.1 JUnit

JUnit is an open source framework for unit testing Java applications. The Junit libraries provide a multitude of features that allow for a more simplistic approach to testing. Numerous other test frameworks are available however, the author is very experience with JUnit and feels that the features provided by this framework are more than suitable for the unit testing of this application.

The author feels that a testing framework is essential for efficient and accurate unit tests for any application. If the author had neglected to use a testing framework such as Junit and manually tested the application using a looking manually for abnormal output (LMFAO) then the quality and coverage of the unit testing would reduce significantly. If the author used a manual approach such as this which relied on outputs then the author could potentially have a situation where the code in outputting the correct result, but the inner workings are expressing incorrect behaviours which cant be manually checked. This means that you could ship a product which is assumed to be functioning as expected then suddenly, the application is significantly misbehaving. In addition to this it is difficult to automate manual testing as the author would need to check the outputs himself. A testing framework such as JUnit not only allows for the tests to be fully automated, the tests also become scalable. Every code change would need to be re-evaluated against the existing unit tests, which is easily done if you have a series of test which can be executed automatically. If a manual approach was used, then it becomes a near impossibility that every change can be tested as it would simply be too much to check as the addition of this new code has scaled the number of application inputs and outputs as well the conditions in the codes logic.

4.3 Overall Architecture

The process used during this applications development has enabled the author to modify the proposed overall architecture significantly. This has enabled the author to add additional features which were not additionally planned, this includes the addition of extra algorithm types and modifiers as well as enabling the potential heavy refactoring of code into more logical methods and

classes. The new application architecture is much more complex than the initial proposed design, as a result each package will be represented as its own set of diagrams, and then an overall representation showing the interactions between these packages will be explained.

4.3.1 Controller

4.3.2 View

4.3.3 Model

4.3.4 System Interactions

4.4 Some detailed design

4.4.1 Even more detail

4.5 User Interface

4.6 Other relevant sections

You should concentrate on the more important aspects of the design. It is essential that an overview is presented before going into detail. As well as describing the design adopted it must also explain what other designs were considered and why they were rejected.

The design should describe what you expected to do, and might also explain areas that you had to revise after some investigation.

Typically, for an object-oriented design, the discussion will focus on the choice of objects and classes and the allocation of methods to classes. The use made of reusable components should be described and their source referenced. Particularly important decisions concerning data structures usually affect the architecture of a system and so should be described here.

How much material you include on detailed design and implementation will depend very much on the nature of the project. It should not be padded out. Think about the significant aspects of your system. For example, describe the design of the user interface if it is a critical aspect of your system, or provide detail about methods and data structures that are not trivial. Do not spend time on long lists of trivial items and repetitive descriptions. If in doubt about what is appropriate, speak to your supervisor.

You should also identify any support tools that you used. You should discuss your choice of implementation tools - programming language, compilers, database management system, program development environment, etc.

Some example sub-sections may be as follows, but the specific sections are for you to define.

Chapter 5

Implementation PUT IN OWN FILE

The implementation should look at any issues you encountered as you tried to implement your design. During the work, you might have found that elements of your design were unnecessary or overly complex; perhaps third party libraries were available that simplified some of the functions that you intended to implement. If things were easier in some areas, then how did you adapt your project to take account of your findings?

It is more likely that things were more complex than you first thought. In particular, were there any problems or difficulties that you found during implementation that you had to address? Did such problems simply delay you or were they more significant?

You can conclude this section by reviewing the end of the implementation stage against the planned requirements.

Chapter 6

Testing PUT THIS IN OWN FILE

Detailed descriptions of every test case are definitely not what is required here. What is important is to show that you adopted a sensible strategy that was, in principle, capable of testing the system adequately even if you did not have the time to test the system fully.

Have you tested your system on real users? For example, if your system is supposed to solve a problem for a business, then it would be appropriate to present your approach to involve the users in the testing process and to record the results that you obtained. Depending on the level of detail, it is likely that you would put any detailed results in an appendix.

The following sections indicate some areas you might include. Other sections may be more appropriate to your project.

6.1 Overall Approach to Testing

6.2 Automated Testing

6.2.1 Unit Tests

6.2.2 User Interface Testing

6.2.3 Stress Testing

6.2.4 Other types of testing

6.3 Integration Testing

6.4 User Testing

Chapter 7

Evaluation

Examiners expect to find in your dissertation a section addressing such questions as:

- Were the requirements correctly identified?
- Were the design decisions correct?
- Could a more suitable set of tools have been chosen?
- How well did the software meet the needs of those who were expecting to use it?
- How well were any other project aims achieved?
- If you were starting again, what would you do differently?

Such material is regarded as an important part of the dissertation; it should demonstrate that you are capable not only of carrying out a piece of work but also of thinking critically about how you did it and how you might have done it better. This is seen as an important part of an honours degree.

There will be good things and room for improvement with any project. As you write this section, identify and discuss the parts of the work that went well and also consider ways in which the work could be improved.

Review the discussion on the Evaluation section from the lectures. A recording is available on Blackboard.

Appendices

Appendix A

Requirements Specification

1.1 Introduction

1.1.1 Purpose

The purpose of this document is to give a detailed description of the ‘Visualising Ant Colony Optimisation’ application. This document will cover the interface interactions and methods as well as providing definitions to important terminology. The document is primarily intended to be used as a reference point for the initial stages of development.

1.1.2 Scope

The ‘Visualising Ant Colony Optimisation’ application is a desktop application which is designed to demonstrate the behaviour of an underlying ACO algorithm given various algorithm parameters. These parameters will be defined by the user and can be modified at their convenience. The algorithms behaviour given these parameters will be visible and the users can make a clear assessment about how each of the parameters impacts the algorithms performance.

During the background research into this subject area there does not seem to be too many applications which offer ACO visualisations and there are even less which provide a ‘friendly’ environment which is simple and intuitive to use regardless of the users background knowledge in regards to the subject area.

The software will be deployed in an educational environment, and aims to provide a means for teaching ACO to students as part of an Artificial Intelligence course or for independent use as a self-learning exercise. As a result the software must cater for the majority of user groups to maximise its effectiveness. This means the software must be accessible on all major platforms and perform equally well on said platforms.

Term	Definition
ACO	Ant Colony Optimisation
user	Anybody who is using or wishes to use the software
user group	A collective group of users representing different user needs.
interface	A graphical user interface
standalone	Operates independently of other hardware or software
agent	The entities which will be traversing the graph

Table A.1: Definitions for the keys terms used throughout this document

1.1.3 Definitions

1.2 Overview

This section will give an overview of the proposed application. This section will also expand on the expected user groups and functionality required by said groups. The constraints

1.2.1 Product Descriptive

The software application will be standalone and does not need to communicate with another system or application, because of this there is no need for any form of network connection to be present in order to use the application to its maximum potential.

The application will communicate with the Operating System on the host machine in order to enable the save and load functionalities through simple file input and output. However the users access to the host machines file system will be restricted by the fact that the saving and loading will be restricted to the users home directory preventing the overwriting of important documents.

The application itself will not take up too many system resources even if a large problem is being handled. This allows the users on a system or network to run the application without it impacting the performance of other services. Given that the target audience is educational establishments this is especially important as many teaching fellows have multiple applications running during a lesson or lecture and a negative impact on their system could reduce the amount of information taught during said session.

1.2.2 Product functionality

The users will be able to view a world which represents the Agents and the nodes in the graph otherwise known as the world. The state of this world will be directly related to the algorithm parameters specified by the users using the interface provided. There are several parameters which can be modified by the user, each of which will have a different impact of the state of the word and the algorithms behaviour.

The parameters which can be modified will be clearly labelled and will be obviously editable. As these parameters will be user defined there will be strict error checking measures in place to catch any illegal values before they can cause problems for the algorithm, and in addition each parameter will have a range of legal limits applied to them. This will prevent the users from

entering values of the incorrect type (String when the systems needs a double) and will also prevent values from outside of the specified range being accepted. When a complication or error arises there will be a simple error message presented to the user informing them of both the error and why it occurred which should enable the user to resolve what they did incorrectly.

1.2.3 User Groups and Characteristics

There will be three main user groups associated with this application. Each of these user groups will interact with the application in a different manner but the main purpose and result will remain the same.

Teachers/Teaching fellows will use the application with the underlying knowledge already in hand. They will be mainly be using the applications to visually portray ideas and will have expectations in regards to what to expect for a solution and will have some idea how the parameters impact the final result.

Students will use the application with some background knowledge of the underlying concepts but will still use the application in an experimental manner and may have little expectations or understanding of how changing certain parameters impacts the final result.

People new to the subject area will use the application with potentially no idea about the underlying concepts. There will be measures in place to explain the underlying metrics and give an insight into what the application is actually doing. Given that they have less knowledge of this subject area that the other two user groups mentioned above, they will still be able to achieve the same results and levels of functionality. The application will cater for all users regardless of prior knowledge.

1.2.4 Constraints

As the application is standalone is reduces the amount of constraints which it becomes subject to. The main constraint which the application is associated with is the dimensions of the users display. The interface has to house a lot of elements in order to produce a simple and effective environment, thus it takes up quite a lot of screen real estate. However in modern times the amount of space required for the application to perform as expected is far from unreasonable and the application will be developed with this in mind.

The algorithms execution time directly proportional to the user defined parameters, more specifically the number of agents and the number of nodes in the graph. The more agents and nodes the larger the execution time and resource requirements will be. The application will be developed with this in mind as there will be a constraint on how much memory and system resources the application should use. There is no expectation on the user to have a superfast high end machine therefore the application will be designed to accommodate a standard machine for these modern times and correct limits will be placed on these user parameters.

The application does write the host systems file store so there must be adequate room to do so, however the files that will be written are simple text files which will not take up a lot of room

on the host machines disk. Depending on the users machine this could still be a constraint. The responsibility and handling for this will belong to the users machine.

1.2.5 Assumptions

It will be assumed that the user will have the correct drivers installed and their machine will be able to handle the algorithms execution. The applications algorithms are not too resource intensive, therefore this is a reasonable assumption given the modern era and the advancement of computer technology.

It will be assumed that users will meet the minimum display requirements thus no dynamic re-sizing of the interface based on the users display dimensions will be performed. This significantly reduces complexity.

Another assumption is that every user will have some experience of using similar software and the interface will be familiar and therefore will be easy to use and navigate. The interface will use traditional methods such as simple buttons, text boxes and drop down menus to provide the user access to certain functionality.

1.3 Specific Requirements

This section contains the function requirements of the software as well as giving details about the different interfaces.

1.3.1 User Interface

There will be one main user interface for this application. This interface will contain a display area which is where the algorithms current state of execution will be represented visually to the user. There will also be an area which will house the text boxes which will be used by the user to interact with the algorithm and modify the parameters.

The display area will be simple and will be clearly identifiable. The text boxes responsible for handling user inputs will be clearly labelled so the user knows exactly what parameter they will be modifying. The text boxes will be obviously editable and the user will associate the look and feel of these text boxes with the fact that their contents can be modified.

The display will represent everything about the algorithms current state. This will display all of the graphs Nodes and all of the Agents at their current Node. The display area will also show the current pheromone levels for each connecting edge for a given node, this will be done in a way that is clear and understandable by all of the user groups mentioned in section 1.2.3.

There will also be a textual representation of the current best agent. This will display the best route and the distance of the best route and will update as the global best is updated. There will also be textual representations of how many agents are currently working in addition to how many agents have finished.

1.3.2 Hardware Interface

The application does not require any specific hardware or host environment as it will be fully cross-platform compliant there are no direct hardware interfaces. There is no network use in this application thus there is no need to communicate with network adapters or anything of similar nature. The system interactions between this application and the host's Operating System file system will be delegated to the Operating System itself.

1.3.3 Functional Requirements

ID: FR1

Title: Launch the Application

Description: Regardless of the users host environment the application should be able to be launched by the user using an executable .jar file.

Dependencies: None

ID: FR2

Title: Generate a World

Description: The user must be able to randomly generate a world for the algorithm to be executed on.

Dependencies: FR1

ID: FR3

Title: Visualise a World

Description: The user must be able to visualise the world and its parameters including the number of agents, the agent locations and the number of Nodes.

Dependencies: FR1, FR2

ID: FR4

Title: Provide a means to modify parameters

Description: The application must provide simple ways to modify the algorithms parameters.

Dependencies: FR1

ID: FR5

Title: Generate a World with specified values

Description: The user must be able to generate a world for the algorithm to be executed on. This World will have user defined properties such as the number of Nodes and Agents.

Dependencies: FR1, FR4, F10

ID: FR6

Title: Visualise the Pheromone

Description: Every edge in the graph will have its own pheromone value. This must be visually displayed to the user and correctly model the pheromone deposit and decay operations.

Dependencies: FR1, FR2, FR3, FR13

ID: FR7

Title: Visualise the Agents movement

Description: As the algorithm is executing the Agents will move through the graph. The movement of these Agents must be displayed to the user in a logical manner.

Dependencies: FR1, FR2, FR3, FR8

ID: FR8

Title: Start the Algorithm's execution

Description: There must be a simple way for the user to start the algorithms execution.

Dependencies: FR1

ID: FR9

Title: Stop the Algorithm's execution

Description: There must be a simple way for the user to stop the algorithms execution anytime the user wishes to.

Dependencies: FR1

ID: FR10

Title: Validate parameters

Description: As the users will be able to define thier own parameter values there must be correct measures in place to ensure the values entered are legal. If they are indeed illegal then suitable error messages will be displayed.

Dependencies: FR1

ID: FR11

Title: Display the best path

Description: As the algorithm is performing its task there must be a way to display the current best result to the user.

Dependencies: FR1, FR2, FR3, FR5, FR7, FR8, FR12

ID: FR12

Title: Agents must be able to move between Nodes

Description: In order for algorithm to perform as expected there must be a way for each Agent to move between Nodes in the graph.

Dependencies: FR1, FR2, FR3

ID: FR13

Title: Model Pheromone operations

Description: There must exist a way for the algorithm to correctly deposit and decay pheromones on graph edges adhering to specific formulae.

Dependencies: FR1, FR2, FR3, FR11

ID: FR14

Title: Load Configuration from a file

Description: There must exist a way for the users to load a pre-existing configuration from a file

of their choosing. This allows the algorithm to be executed on the same problem multiple times.
Dependencies: FR1, FR2, FR3

ID: FR15

Title: Save Configuration to a file

Description: There must exist a way for the users to save the current configuration to a file of their choosing. This allows the algorithm to be executed on the same problem multiple times.

Dependencies: FR1, FR2, FR3

ID: FR16

Title: Exit the application

Description: The user must be able to exit the application completely killing the process and freeing system resources.

Dependencies: FR1

1.3.4 Requirement Evaluation

Each of the functional requirements mentioned in section 1.3.3 differ in their levels of importance. The dependencies field for each requirement donates which requirements must be completed before said requirement itself can be finished. As this is the case the following represents the order of importance for each functional requirement.

Requirement	Dependant Requirements
FR1	FR2, FR3, FR4, FR5, FR6, FR7, FR8, FR9 ' FR10, FR11, FR12, FR13, FR14, FR15, FR16
FR2	FR3, FR6, FR7, FR11, FR12, FR13, FR14, FR15
FR3	FR6, FR7, FR11, FR12, FR13, FR14, FR15.
FR8	FR7, FR11, FR13
FR4	FR5
FR5	FR11
FR10	FR5
FR12	FR11
FR13	FR6
FR7	FR11
FR11	
FR6	
FR9	
FR14	
FR15	
FR16	

Table A.2: Table representing the Functional Requirements and which other requirements are dependent on them.

As described in Table A.2 the number of dependant requirements a requirement has the more important it is to the progress of the application. FR1 is the first task that must be accomplished therefore every other requirement is dependent on this being completed. FR1 is the ability to launch the application, if the application cannot be launched then none of the other requirements can be completed, this is a critical requirement.

FR2 is another critical requirement which must be completed early in development as many other requirements are dependent on its completion. FR2 is the ability to generate a World. A World contains all the data that the algorithm needs in order to both execute and visualise, therefore if there is no way to generate a World there is no way to visualise or model the algorithms execution (FR3).

Apart from FR8 (start the algorithms execution) the remaining functional requirements are somewhat independent of each other and are less critical. However this does not mean that they can be avoided as they will be needed in the final application version.

Appendix B

Initial Design Proposal

2.1 Introduction

2.1.1 Purpose

The purpose of this document is to give a detailed description for the design of the 'Visualising Ant Colony Optimisation' application. This document will cover the proposed interface designs and interaction methods, choice of language and the underlying data structures and logical modules used in the application.

2.2 Language

The choice of implementation language for both the graphical user interface and the Ant Colony Optimisation algorithm is extremely important. The nature of the project suggests that an Object Orientated approach would best suit as the implementation language. One of the main reasons for this is because the manipulation and use of Objects in such languages allows for Object-based decomposition allowing for more logical modules system wide when compared to a non-Object Orientated approach. A non-Object Orientated approach may be more subject to functional decomposition (the application is split into modules grouping similar functions rather than representing separate Objects).

An Object Orientated approach has been identified as most suitable. Therefore there are two main languages which are at the forefront of the selection process. These two languages are C# (*C Sharp*) and Java. Both languages have the potential to achieve a high level of success when applied to the projects problem however; they both have different consequences depending on the environment and application in which they are used. C++ (*C plus plus*) is another popular Object-Orientated language. C++ has been discounted due to lack of language experience therefore using a more familiar language such as the two specified above (Java and C#) is far more appropriate in this instance.

One of the major factors in deciding on the implementation language is the suitability of the languages features when applied to the projects problem including any external resources or compatible libraries. Both Java and C# are very similar at an abstract level in terms of provided

features by default. Both include everything that would be necessary to implement the proposed design for this application. Both languages provide the ability for Objective decomposition and allow for polymorphic behaviours (multiple entities of different types using the same interface) which enables effective use of inheritance to allow multiple Agent variations (Ants in this case) to be supported easily.

C# has been created and is continually being developed by Microsoft and is focused around the .NET framework which is also a product of Microsoft. As C# is heavily Microsoft orientated its cross-platform capabilities are significantly reduced. The .NET framework(s) have only recently been open sourced so they lack full support on all platforms reducing the applications cross-platform reliability. The project is being developed with a focus on educational value; therefore cross-platform reliability is very important as maximisation of potential consumers is important (more people using the application implies more people are learning). A standard build will not be specified or assumed so there must be necessary measures in place to accommodate as many environments as possible. C# is heavily coupled with Windows based systems therefore; If C# were to be used there is a risk of alienating Macintosh and UNIX users. There are attempts to port .NET to other architectures (for example, Mono [15]) but the implementations of such approaches are not exact replicas of Microsoft .NET framework(s), therefore they cannot be relied upon. The use of Java would eliminate the cross-platform support issues as Java applications execute inside the Java Runtime Environment (JRE) which is available across most platforms and behaviours can be accurately modelled and predicted in the vast majority of cases.

Little differs between Java and C# in terms of feature presence (abstractly, how each language achieves each task is very different) thus, Java will be used for this project. The cross-platform constraints that come with the use of C# are not balanced by any necessary exclusive key features. As a result Java is the most appropriate language for the project, this all but ensures cross-platform reliability without sacrificing any important libraries or features.

2.3 Architecture

There have been considerations as to what key elements will be present in the composure of a suitable underlying architecture for the application. The architecture must accommodate both major elements of the application (graphical user interface and the Ant Colony Optimisation algorithm) in a manner that enables the best possible expansion/modification opportunities to accommodate any additional features or unforeseen changes. Selecting relevant Design Patterns will enable the above goals to become reality however; design patterns should be respectfully and must represent a general solution to a problem. The Overuse or misuse of such patterns can cause significant complexity issues through the system, this needs to be avoided.

2.3.1 Design and Architectural Patterns

2.3.1.1 Model-View-Controller

The Model-View-Controller (MVC) Architectural Pattern is designed to reduced coupling between system components, these are represented here as the user interface(s) (View) and the underlying data and its representation(s) (Model). The interaction(s) between the View and the Model “established using a subscribe and notify protocol” [7] (Controller). The Controller updates the View(s)

based on the model(s) current state or vice-versa however; The View(s) cannot directly communicate with the Model, the Controller must govern such interactions.

This project will make effective use of Model-View-Controller in order to produce an environment which is much easier to maintain and has little coupling between the Model and the View(s). This allows the Model(s) and/or View(s) to be substituted or modified in order allowing different representations of the current algorithm, or in fact different algorithms altogether.

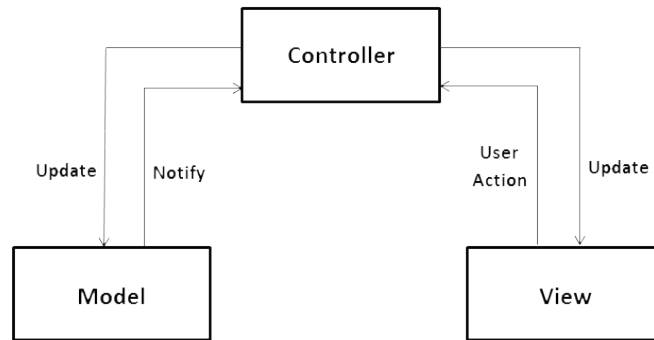


Figure B.1: Basic abstract overview of the Model-View-Controller pattern

- **Model** represents the underlying Ant Colony Optimisation algorithm. The Model also contains the required arithmetic functions and any additional operations required to execute the algorithm correctly.
- **View** represents the graphical user interface which will not only display the algorithms execution, but also enable the user(s) to modify the algorithms parameters.
- **Controller** represents the Observer required to enable interactions between the Model(s) and View(s).

2.3.2 Observer and Observable

The implementation of the Model-View-Controller design pattern is handled using the Observer and Observable interface provided as part of the default Java language specification. The general premise is that the Model will have an Observer which will have an update interface allowing it to receive signals from what it is observing (Model). The Model will implement the Observable interface which will enable it to send update signals to the Observer through the `notifyObservers()` method. This enables the Models dependencies to be updated as the Model itself changes ensuring the correct state of the Model is captured in the Views.

As figure B.2 demonstrates the View will Observe the Model and will wait for an update signal sent by the Model's `notifyObserver()` method. The Model can have multiple Observers using this pattern so there is the potential for future modification or enhancement without having to rework the existing system should the needs for extra views be needed.

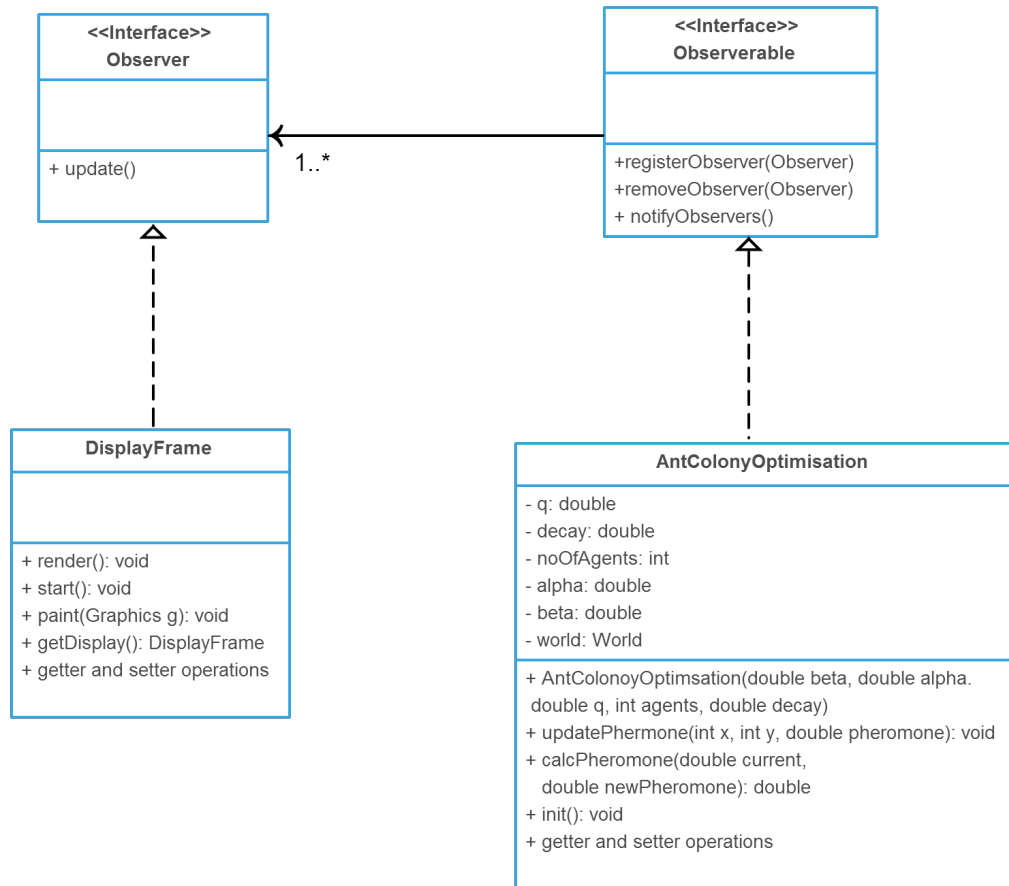


Figure B.2: Proposed implementation of the Observer and Observable Design pattern

2.3.2.1 Singleton

In order to maintain simplicity throughout the application the Singleton design pattern will be implemented for key Objects where one and only one instance of an Object must exist. The Singleton pattern prevents multiple instantiations of specific Object(s) as the Object itself is solely responsible for tracking the currently instantiated instance of itself [8].

The application will consist of a graphical user interface which in turn, will be composed of several different components. Such components must only be instantiated once in order to ensure correct interactions are performed. Without the presence of the Singleton pattern there exists the possibility of multiple instances of such components which could potentially cause unforeseen complications and undefined behaviours.

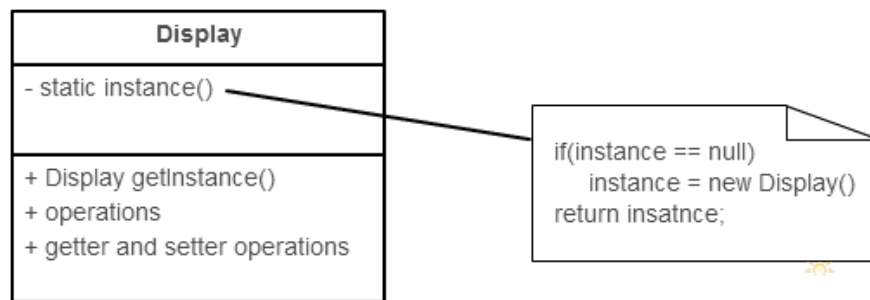


Figure B.3: Proposed high-level implementation of the Singleton pattern demonstrating how the sole instance of the graphical user interface will be tracked.

2.3.3 Structure

?? Adhering to the concepts of the patterns described in sections 2.3.1.1 and 2.3.2.1 the following Class Diagram shows proposed application structure. This is not concrete and could potentially change throughout development, the Class Diagram in question is represented below by figure B.4 and is represented using standard UML notation.

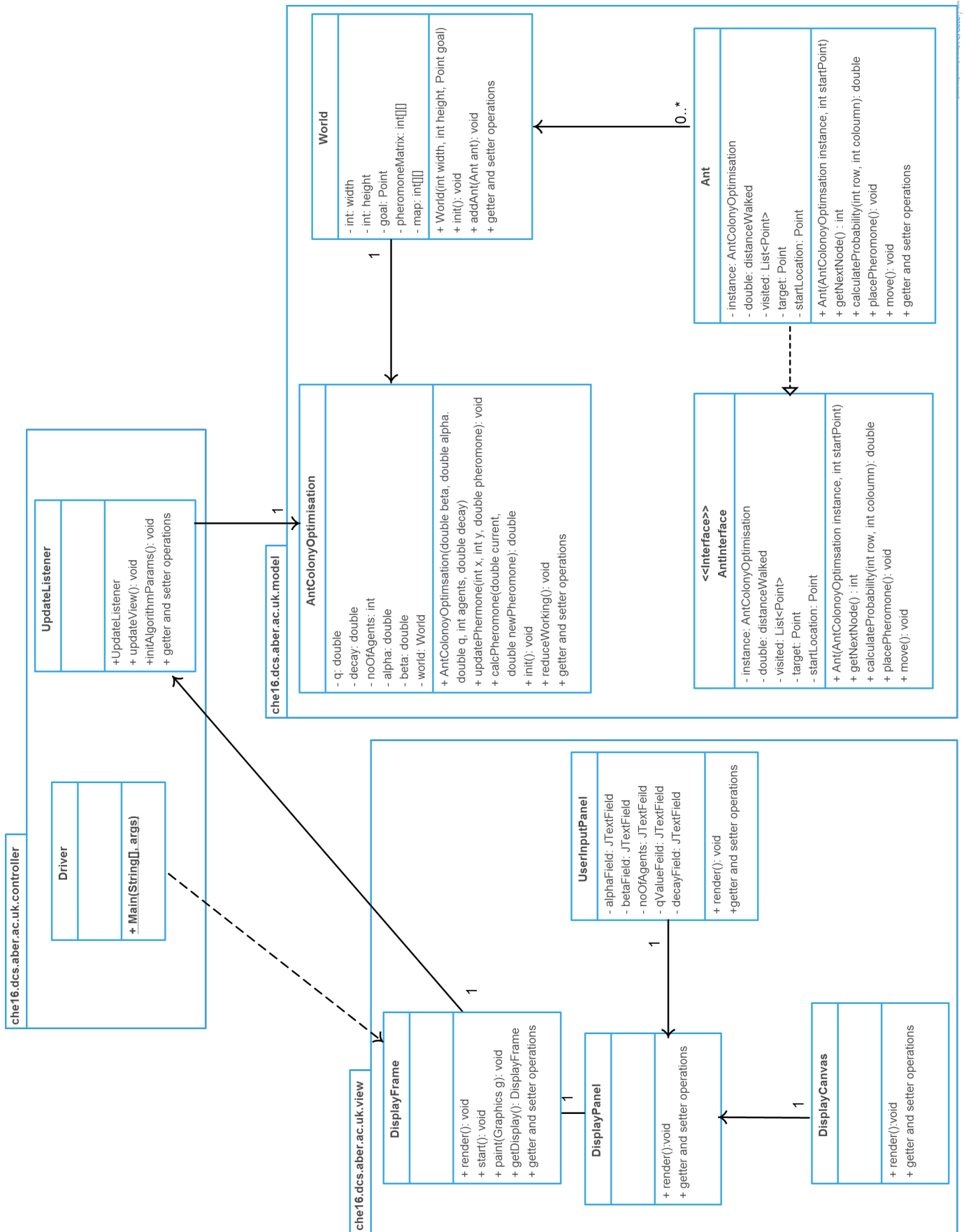


Figure B.4: Initial Class Diagram representing the main modules, packages and system interactions using UML notation.

2.3.3.1 View Package

The *che16.dcs.aber.ac.uk.view* package contains the graphical user interface components. The main concept behind this is the use of nested components such as JPanel, JTextFields and the like. These will be contained inside top level JFrame. This allows modification of each component in isolation without impacting the other components behaviours and/or elements. This is the first module of the application which is initialised, and is done so directly from the *main* method. This package has no direct knowledge of any package members mentioned in 2.3.3.2. Instead the *che16.dcs.aber.ac.uk.controller* package members handle the communication(s) between the model(s) and view(s), adhering to the principles discussed in section 2.3.1.1.

2.3.3.2 Model Package

The *che16.dcs.aber.ac.uk.model* package contains the necessary elements and attributes required in order to accurately represent the algorithms state(s) and ensure correct algorithm execution. This package has no direct knowledge of any package members mentioned in 2.3.3.1. Instead the controller package members handle the communication(s) between these the model(s) and view(s), adhering to the principles discussed in section 2.3.1.1.

2.3.3.3 Controller Package

The initial concept for the controller is basic and will grow in complexity during the development lifecycle as more and more control based mechanisms will become prevalent. This initial concept is a simple Observer which notifies the view(s) should the model change in a significant way; the inverse of this is also true.

2.4 Class Descriptions

The Classes defined in section ??, Figure B.4 are described textually below.

2.4.1 Controller

2.4.1.1 Driver

The Driver Class is fairly simplistic and exists as an entry point to the application. This will Class handles any necessary instantiations and correctly assigns any key associations.

2.4.1.2 UpdateListener

The UpdateListener Class serves as a point of control for the update operations. The main updates will be handled internally by the relevant Classes (as described by Figure B.2) however, this Class will handle the updates caused when a user interacts with the application through the user interface. This includes, but is not limited to the modification of parameters or starting the algorithm's execution.

2.4.2 View

2.4.2.1 DisplayFrame

An instance of the DisplayFrame Class will serve as the highest level container for the applications user interface elements. This Class will be responsible for controlling access to, and the instantiation of the other graphical user interface elements.

2.4.2.2 DisplayPanel

The DisplayPanel instance will be contained inside the DisplayFrame. The purpose of the DisplayPanel is to contain the DisplayCanvas. The reason this Class is used to contain the DisplayCanvas rather than using the top level DisplayFrame is because it gives the author much more control over dimensions and modification of layouts or contents.

2.4.2.3 DisplayCanvas

The DisplayCanvas will be used to display the algorithms execution. This is the user interface element which will be painted and modified during the course of the algorithms execution.

2.4.2.4 UserInputPanel

The UserInputPanel is used to represent the collection of text boxes and buttons which will be used by the user to directly modify the algorithms parameters and state of execution. This will be contained in the top level DisplayFrame.

2.4.3 Model

2.4.3.1 AntColonyOptimisation

The AntColonyOptimisation Class is used to represent the high level behaviours of Ant Colony algorithms. This Class will contain the current instance of the World as well as housing all relevant data such as current parameter values and ways to interact with such parameters.

2.4.3.2 AntInterface

This interface will contain the necessary methods that every type of Ant (agent) has to have. This is by no means concrete, if there is only a need for one type of Ant then an interface is not strictly needed thus, it may be removed to reduce complexity.

2.4.3.3 Ant

An instance of the Ant Class will be used to represent an Ant (agent) in the world. As these are the agents which will be deployed on the world they will need to know about the World, whilst also

knowing information about themselves including where they have visited so far and how far have they travelled. This Class will also contain the operations necessary in order for an Ant to be able to solve the current problem, this is main down the combination of knowing about the World and necessary details inside the move() method which will be used to select the Ants next location.

2.4.3.4 World

The World Class is a representation of the problem representation. This includes all information needed to model the graph as well as containing and manipulating the current pheromone matrix and pheromone concentrations on each edge. The World will be in constant communication with the Ant instances in order to communicate the current state of World to each agent.

2.5 Interface Design

2.5.1 Main User Interface

The interface design must accommodate all the necessary elements required to allow user defined values for each of the algorithm parameters. The interface must also be able to visually represent the current algorithms state including the locations of the agents and nodes without impacting on the usability of the application (the interface must not freeze or be negatively affected by the algorithms execution).

The interface will use a very neutral colour scheme which will maximise the usability and reduce the risk of complications which may arise from users being subject to difficulties understanding or identifying certain colours. Every option for the user will be textually defined and will not rely on any sound or visual prompts in order to user. As a result in addition to the above, users with visual impairments will still be able to use the application as intended.

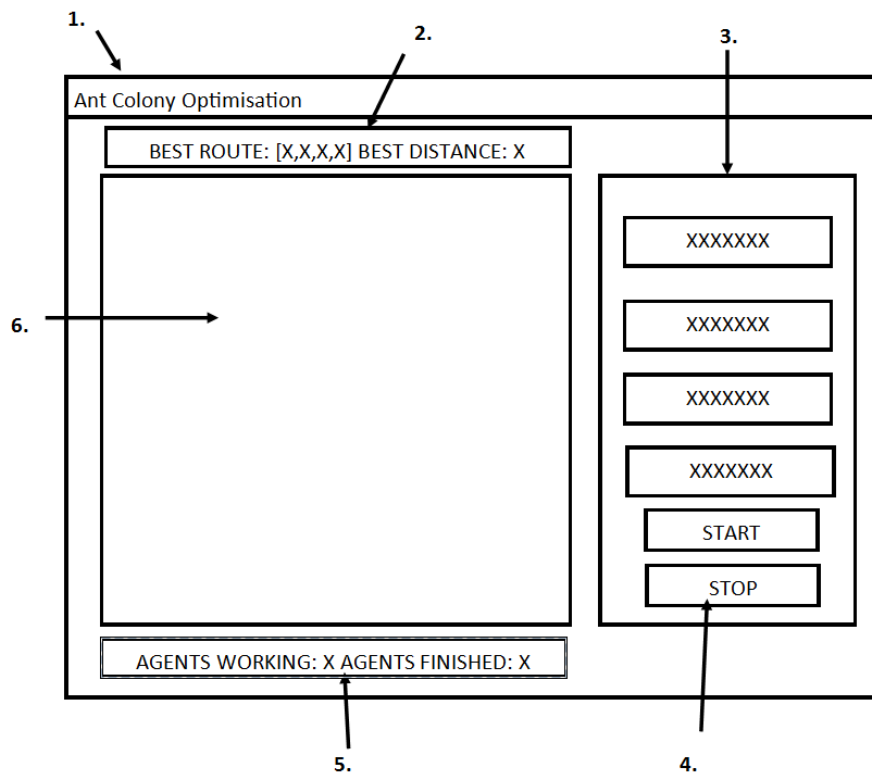


Figure B.5: Proposed design for the graphical user interface, showing the key elements in their planned locations.

1. in figure B.7 refers to the containing frame which will house the reset of the interface elements. This frame will not be resizable preventing complications such as the dynamic resizing of the interface having an impact on the observable range of the world. **2.** in figure B.7 refers to a text view containing information relevant to the algorithms current state of execution. This text view will contain the current best distance as well as the order of nodes visited to traverse the current best path. This will only be populated during the algorithms execution and only if the best path has been initialised. **3.** in figure B.7 refers to container which houses the interactive elements relating to the modification of the algorithms parameters. This will consist of several labels and text fields which can be modified informing the user of what they will be modifying as well as providing suitable error messages if the users enters an incorrect value for any of the parameters. **4.** in figure B.7 refers to the start and stop buttons. These are here to conform to the expectation that a user will expect some clear way to start and stop the application at their free choice, this is the simplest way to do this, and requires no hidden menus or hidden key bindings. **5.** in figure B.7 refers to a text view containing information relevant to the algorithms current state of execution. This text view will contain the number of agents currently working (which means the number of agents who haven't met their own stop conditions) as well as displaying the number of agents which are finished. **6.** in figure B.7 refers to the main canvas area which will display the algorithms current state of execution to the user. The contents of this will reflect the user defined values (elements in: **3.** in figure B.7) as well as representing each agents current location, their movements between nodes and also the modelling of pheromone deposit and decay will be present in this canvas.

2.5.2 Error Message Feedback

As the Algorithm parameters will be user defined using the interface proposed in section 2.5.1, figure B.7 there must be measures in place to catch and inform the user of any illegal values. Not only must the user be told they have inputted illegal values the illegal parameter value will be identified and a range of legal values will be displayed to the user.

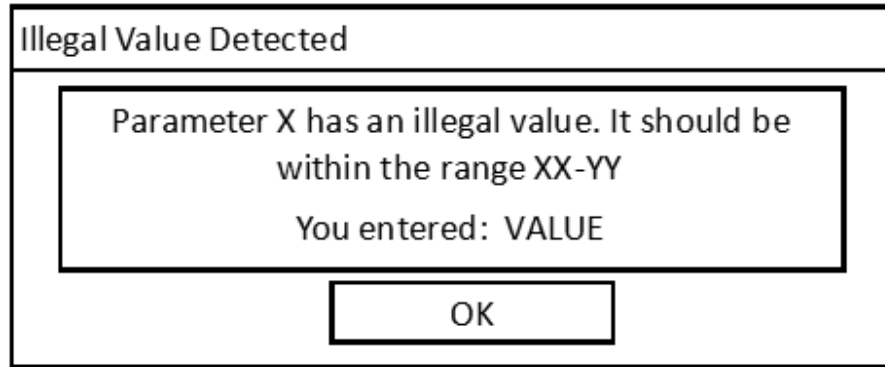


Figure B.6: Proposed design for the illegal parameter error message displayed to the user

As represented in figure B.6 the error message will contain all the information a user needs to identify the problem with their data input. The X value in figure B.6 represents which parameter has the illegal data input (i.e. Alpha, Beta). Range XX-YY represents the legal values for said parameter, and VALUE represents the value the user has specified for this parameter. The combination of these will provide the user with the knowledge of why this error message is being displayed and how they can resolve their issue.

This kind of error message will be composed using the `JOptionPane` and `JDialog` interfaces provided as default by the Java language specification. These views are very customisable and the styling will be handled by the languages underlying protocols which will reduce the codes complexity.

2.6 Algorithm

There are several adaptations of the Ant Colony Optimisation algorithm. Initially the project contain an implementation of Ant Colony Optimisation in its simplest form, without the presence of any enhancements such as using *Elitist Agents* or similar. Once a working implementation is in place the next step will be to adapt the algorithm in various ways to further aid the teaching potential of the project.

The general premise is that each Agent (Ant) embarks and a pseudo random walk through the state space. The Agents movements are influenced by pheromone deposits placed on edges between vertices. This pheromone is deposited by other Agents in accordance with the equations stated in section 2.6.2.2. The Agent's next move is influenced by the result of the equation stated in section 2.6.2.1. However; there is still the probability of the Agent moving to a less attractive point so the Agent does not always travel to the strongest pheromone concentration.

Overtime the pheromone deposit concentration on $edge_{xy}$ is directly proportional to the quality

of the candidate solution, and ultimately the ants will converge to find the shortest route between two or more points.

There are several algorithm requirements;

- **Suitable problem representation** the World and Agents must be represented in a suitable and logical manner allowing the algorithm to execute as expected.
- **Pheromone manipulation metrics** there must exist adequate ways to access the pheromone matrix as well as manipulate (deposit/remove) the concentration of pheromone on a given edge in order to model decay and deposits.
- **Probabilistic movement functions** there must exist functions that calculate the probability of the Agent moving to a specific vertex. This is based on the pheromone concentration and the Agents location (see section 2.6.2.1).

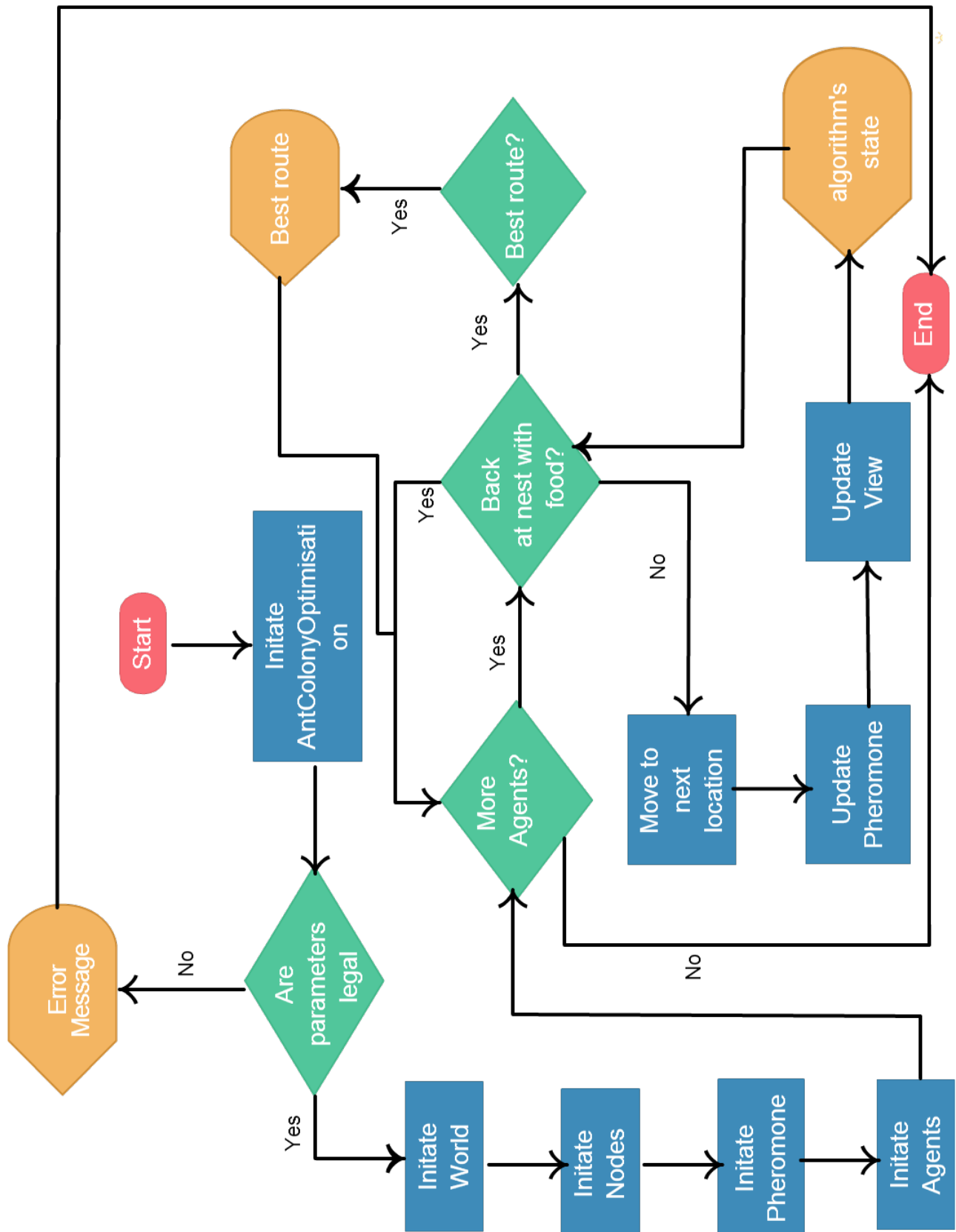


Figure B.7: High level flow diagram representing the psuedo code for Algorithm 1, section 2.6.1

2.6.1 Pseudo-code

Algorithm 1 Pseudo-code for Ant Colony Optimisation

```

1: Initiate AntColonyOptimisation with defined parameters
2: if !parameters are legal then
3:   Display error message to user
4:   return
5: Initiate World with algorithm parameters
6: Initiate Nodes and graph
7: Initiate pheromone values
8: Initiate Agents
9: while !all agents finished do
10:  for all Agents do
11:    while !back at nest with food do
12:      Calculate next move using probabilistic function
13:      Add moved point to Agent's memory
14:      Calculate and deposit pheromone on the path
15:      Update the View
16:    end while
17:  end for
18: if local best solution < global best solution then
19:   globalbest = local best solution
20: end if
21: end while
22: output global best solution

```

Above is a somewhat simplified pseudo-code representation of the proposed Ant Colony Optimisation algorithm. The mathematical formulae required to achieve steps 7 and 10 are shown in section 2.6.2. The final algorithm may differ from the above depending on any additional feature present in the final release.

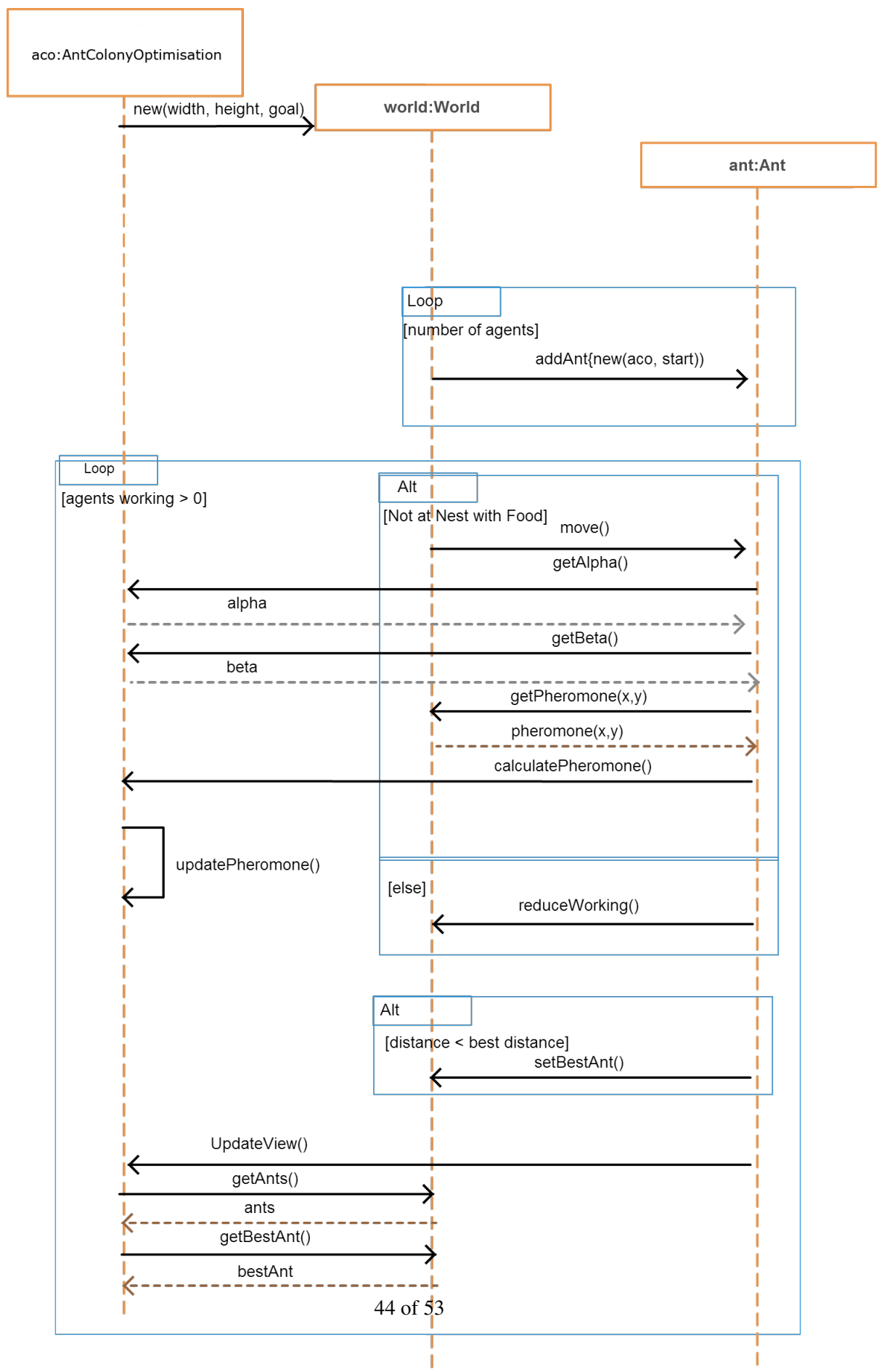


Figure B.8: Sequence diagram representing Algorithm 1, section 2.6.1

The sequence diagram shown in figure B.8 shows the high level interaction between the proposed main Model Classes during the algorithms execution. The Ants are in constant communication with the AntColonyOptimisation and World instances during their movement through the graph to ensure the correct pheromone values are being parsed during the movement process. The View is also updated through the `updateView()` method in the AntColonyOptimisation instance which requires data about the current Ants and the current best Ant. This data is stored in and returned from the World instance.

2.6.2 Metrics

2.6.2.1 Probabilistic function

$$p_{xy}^k = \frac{(\tau_{xy}^\alpha)(\eta_{xy}^\beta)}{\sum (\tau_{xy}^\alpha)(\eta_{xy}^\beta)} \quad (1)$$

Figure B.9: Algebraic model of the probabilistic function used to calculate next move for any Agent [23]

The probability that an Agent moves to vertex xy is described using the above. p is the probability for any Agent k to move through vertex xy . τ is the amount of pheromone deposited on vertex xy , which is raised to the exponent α . α is an heuristic value representing how greedy the algorithm is in its path finding [20]. The result for τ_{xy}^α is then multiplied by the edge xy 's evaluation(η). Generally η will be represented using $\frac{1}{\text{Euclidean distance}_{xy}}$ [20] [18]. This will then be raised to the exponent β which like α is an heuristic parameter however β describes the Agents path finding speed. $\sum (\tau_{xy}^\alpha)(\eta_{xy}^\beta)$ is the sum of all possible solutions.

Algorithm 2 Pseudo-code for Probabilistic function - Each Agent - figure B.9

- 1: read the *pheromone* level for vertex xy
 - 2: raise the value from 1: to the exponent α
 - 3: Multiply the result of 2: by $(\text{inverted distance}_{xy})^\beta$
 - 4: initiate a temporary double *columnTotal*
 - 5: **for all** visted vertex **do**
 - 6: $\text{columnTotal} += (\text{read the pheromone level for vertex } xy)^\alpha \times (\text{inverted distance}_{xy})^\beta$
 - 7: **end for**
 - 8: divide the result of 3 : by the result of 5 : - 7 :
-

2.6.2.2 Pheromone deposit

$$p_{xy}^k = (1 - \rho)\tau_{xy}^k + \Delta\tau_{xy}^k \quad (2)$$

Figure B.10: Algebraic model of the pheromone deposit function used to calculate the correct values for the pheromone matrix [24]

τ represents the pheromone deposit for an edge xy by Agent k [20]. ρ is a value between 0 – 1 which represents the decay rate *decay*. $1 - \rho$ is multiplied by the existing amount of pheromone at $edge_{xy}$ to correctly account for decaying trails. The new amount of pheromone is then added using the equation from figure B.11.

$$\Delta\tau_{xy}^k = \begin{cases} Q/L_k & \text{if Agent } k \text{ uses curve } xy \text{ in its tour} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Figure B.11: Algebraic model of the function used to calculate the how much new pheromone is deposited at xy [22]. Pheromone is only updated if the Agent k has visited point xy .

figure B.11 represents the new amount of pheromone to be added to the existing concentration at $edge_{xy}$. This can be read as change in τ ($\Delta\tau$). Q is simply another heuristic parameter which is divided by the distance *agentk* travelled to get to $edge_{xy}$. If the result of this is ≤ 0 return 0. This ensures that new *pheromone* is only added to the existing concentration at $edge_{xy}$ is used by *agentk* in its tour.

Algorithm 3 Pseudo-code for Pheromone function - figures B.10, B.11

```

1: if pheromoneDeposit = Q value/totalDistanceWalked ; 0 then
2:   pheromoneDeposit = 0
3: pheromonexy = (1 - algorithm decay rate) × currentPheromonexy +
   pheromoneDeposit
4: if pheromonexy ≥ 0 then
5:   pheromoneMatrixxy = pheromonexy
6: else
7:   pheromoneMatrixxy = 0
8: end if

```

2.7 Representation

2.7.1 World

The World Class is used to model the graph that the Ants will traverse during the algorithms execution. The graph will be represented as a two-dimensional Array, with each element in said array representing a Node in the graph itself. The two dimensional array will be composed of integer values with each element containing an integer value representing the terrain type at this index, this will also be used to set the nest and food locations.

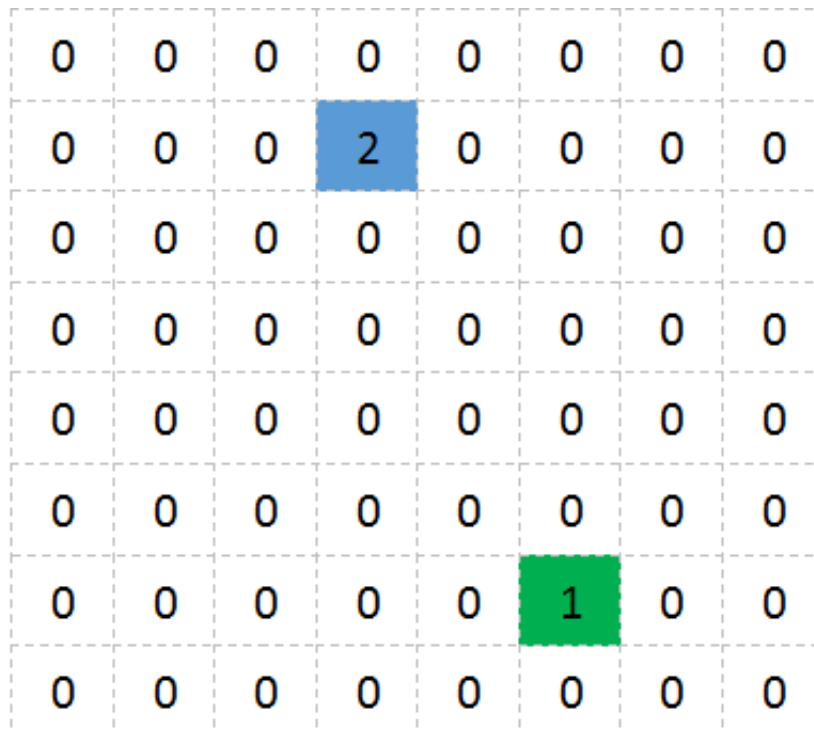


Figure B.12: Example World representation using a two-dimensional Integer Array

Figure B.12 shows how the proposed graph representation would be implemented. A '0' value represents normal terrain where the Ants can move to, '1' represents the nest location where the Ants will start and '2' represents the food location which is the initial target for the Ants. This is a simplistic way to model an environment for the Ants whilst also allowing a multitude of terrain options without having to modify the way the graph is stored.

2.7.2 Pheromone

The pheromone must be modelled in a way which is both easily accessible and modifiable. The data structure used to store the pheromone must also relate to the graph mentioned in 2.7.1 to allow for logical mapping between the representation of the Ants environment and the pheromone associated with each Node in the graph. The pheromone will be stored as a two-dimensional Array of Doubles. Each element in the Array will represent the pheromone concentration for the corresponding Node in the graph for example, the double value at `pheromone[x][y]` will represent the pheromone concentration on edge `[x][y]` in the graph, thus there is a logical link between the two representations.

0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Figure B.13: Example Pheromone representation using a two-dimensional Double Array with default initial values

Figure B.13 demonstrates how a two-dimensional Double array can be effectively used to model the pheromone values for every Node in the graph. The values in this figure are default initial values which will be user defined when the application is executed. As the Ants moves through the graph the pheromone values at each index will correctly model the pheromone operations mentioned in section 2.6.2.2. As the values are stored in an array accessing or modifying the values is extremely simple and involves a simple getter or setter operation.

2.7.3 Visualisation

The data structures described in sections 2.7.1 and 2.7.2 must be visualised to the user in a manner that anybody can understand. Given that the graph will be stored as a two-dimension array it is perfectly logical to display this graph to the user in a grid format similar to that shown in figure B.12. The challenge with the visualisation process is visualising the pheromone deposit and decay operations as well as displaying the Ants moving between Nodes.

Given that the pheromone is stored in a two-dimensional array of doubles and the fact that accessing these values is extremely simple the value at each index can be used to directly influence how the user sees the pheromone. If each cell in the grid is coloured, and this colour's opacity is directly representational of the value at the corresponding index in the pheromone matrix then it becomes an accurate way of displaying the values of the pheromone to the user, which also allows the decay and deposit operations to be shown.

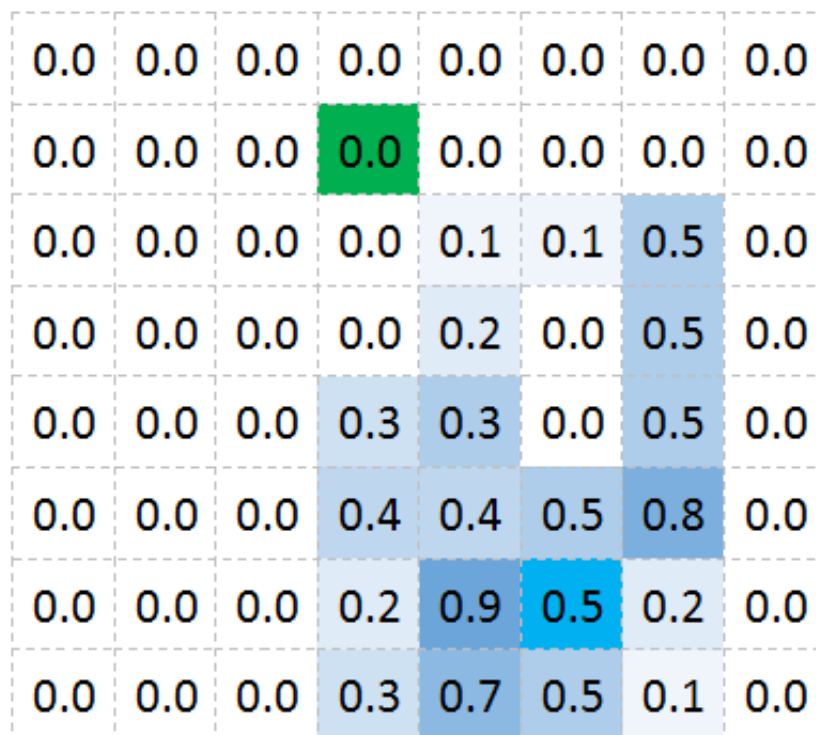


Figure B.14: Example Pheromone visualisation

Figure B.14 shows how the pheromone value for a given [x,y] co-ordinate has a direct influence on the opacity of the cells colour. In said figure the pheromone value at each index is multiplied by 100 to convert it to a percentage, which then becomes the opacity value for the given Node. However, if the pheromone values for each Node become extremely small during execution there must be a measure in place to covert the small values back into percentages using a larger scaling factor than 100.

Annotated Bibliography

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A list of laws and explanations of such laws regarding important user interaction styles and principles

- [2] Apache, “Maven,” Available: <https://maven.apache.org/what-is-maven.html>, accessed: 11th April 2015.

An overview of how the maven framework can be used and an analysis of the features provided.

- [3] T. Blanchard, “Development of an Autonomous, Tethered and Submersible Data Buoy,” Master’s thesis, Aberystwyth University, Wales, Computer Science Department, Penglais Campus, Aberystwyth University, Aberystwyth, Ceredigion, SY23 3DB., May 2011, pp.15-16 [Online]. Available: http://users.aber.ac.uk/ttb7/files/ttb7_diss.pdf.

Tom Blanchard’s dissertation, referenced pages contain relevant information and rationale about a suitable process which suited my development needs. Permission from Tom has been granted to adapt his rationale

- [4] c2.com, “eXtreme Programming for one,” Available: <http://c2.com/cgi/wiki?ExtremeProgrammingForOne>, accessed: 9th April 2015.

An informal insight into eXtreme Programming and how it can be applied to solo development projects.

- [5] cleveralgorithms.com, “Berlin52.tsp solution image,” Available: <http://www.cleveralgorithms.com/images/tsp2.png>, accessed: 7th April 2015.

An image mapping one solution to the Berlin52.tsp problem.

- [6] M. Dorigo, “Optimization, learning and natural algorithms (in Italian),” Ph.D. dissertation, Dipartimento di Elettronica, Politecnico di Milano, Milan, Italy, 1992.

Marco Dorigo PhD thesis containing information about Ant Colony methods. Marco first came up with this concept however this thesis is extremely detailed and too complicated for this project and is used merely as a reference point should a reader want further information.

- [7] E. Gamma, R. Helm, R. Johnson, and J. Vlissides, *Design Patterns: Elements of Reusable Object-Oriented Software*, 1st ed. Addison-Wesley Professional, Nov 1994, pp. 4-6, [Online]. Available: <http://www.worldcat.org/isbn/020163361>.

This book is a very good reference point for design patterns in general, providing concise descriptions, examples and use cases. The book examples are implemented using C++, as this will be a Java based project the main concepts are still relevant as the languages aren't too diss-similar.

- [8] —, *Design Patterns: Elements of Reusable Object-Oriented Software*, 1st ed. Addison-Wesley Professional, Nov 1994, pp. 127-128, [Online]. Available: <http://www.worldcat.org/isbn/020163361>.

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- [9] eclipse, "Eclipse IDE for Java Developers," Available: <https://eclipse.org/downloads/packages/eclipse-ide-java-developers/lunasr1a>, accessed: 13th April 2015.

A free IDE for Java development. This is the IDE selected for this projects development and provided built in support for all the necessary tools.

- [10] GitHub, "Atom," Available: <https://atom.io/>, accessed: 13th April 2015.

A free, Open source text editor provided by GitHub.

- [11] M. Dorigo and T. Stützle, *Ant Colony Optimization*, 1st ed. Bradford Books, Jun. 2004, pp.73[Online]. Available: <http://www.worldcat.org/isbn/0262042193>.

Publication by the creators of the Ant Colony family of methods. This publication contains the majority of information relevant to understanding the interactions and mappings of the real ants against the virtual agents and algorithm interactions. Page 73 contains information about the Elitist Ant System ants its formula.

- [12] —, *Ant Colony Optimization*, 1st ed. Bradford Books, Jun. 2004, pp.2-3[Online]. Available: <http://www.worldcat.org/isbn/0262042193>.

Publication by the creators of the Ant Colony family of methods. This publication contains the majority of information relevant to understanding the interactions and mappings of the real ants against the virtual agents and algorithm interactions. Pages 2-3 contain information about the Double Bridges experiment.

- [13] —, *Ant Colony Optimization*, 1st ed. Bradford Books, Jun. 2004, pp.2-3[Online]. Available: <http://www.worldcat.org/isbn/0262042193>.

Publication by the creators of the Ant Colony family of methods. This publication contains the majority of information relevant to understanding the interactions and mappings of the real ants against the virtual agents and algorithm interactions.

- [14] Marco Dorigo, "Swarm intelligence," Available: http://www.scholarpedia.org/article/Swarm_intelligence, accessed: 7th April 2015.

Online swarm intelligence definition which is somewhat more detailed than usual however, this definition is provided by the Ant Colony Optimisation creator thus it seems very fitting

- [15] Mono, "Getting Started — Mono , [online] Feb 2015," Available: <http://www.mono-project.com/docs/getting-started/>, accessed: 13 Feb 2015.

Mono provide an open source implementation of the Microsoft .NET framework enabling the development of C Sharp across multiple platforms and environments. The Framework is based on ECMA standards for C Sharp so there is some reliability when developing C Sharp in different environments. However, based on research the implementation of certain features, specifically the newer features in the latest releases of the .NET framework do not always behave as expected. This causes development problems which can easily be avoided for this project.

- [16] neos, "Berlin52 source file," Available: http://neos.mcs.anl.gov/neos/solvers/co:concorde/Berlin52_TSP.txt, accessed: 7th April 2015.

Contents of the Berlin52.tsp problem representation.

- [17] V. E. Sjoerd, "Dynamic ant colony optimization for the travelling salesman problem," Master's thesis, Leiden University, The Netherlands, Leiden Institute of Advanced Computer Science (LIACS), Leiden University, Niels Bohrweg 1, 2333 CA Leiden, The Netherlands, Jul 2012, pp.11 [Online]. Available: <http://www.liacs.nl/assets/2012-08SjoerdvanEgmond.pdf>.

A Masters thesis looking into a hybrid Ant and Bee Colony algorithm for dynamic TSP problems. The thesis has some good concepts and background into the algorithm, however a lot of the information is highly theoretical.

- [18] —, "Dynamic ant colony optimization for the travelling salesman problem," Master's thesis, Leiden University, The Netherlands, Leiden Institute of Advanced Computer Science (LIACS), Leiden University, Niels Bohrweg 1, 2333 CA Leiden, The Netherlands, Jul 2012, pp.7 [Online]. Available: <http://www.liacs.nl/assets/2012-08SjoerdvanEgmond.pdf>.

A Masters thesis looking into a hybrid Ant and Bee Colony algorithm for dynamic TSP problems. The thesis has some good concepts and background into the algorithm, however a lot of the information is highly theoretical.

- [19] technologyuk.net, "Waterfall model," Available: http://www.technologyuk.net/computing/sad/waterfall_model, accessed: 9th April 2015.

An image depicting the structure of the waterfall life cycle.

- [20] Thomas Jungblut, "Ant Colony Optimization for TSP Problems , [online] Feb 2015," Available: <http://codingwiththomas.blogspot.co.uk/2011/08/ant-colony-optimization-for-tsp.html>, Aug 2011, accessed: 14 Feb 2015.

Simplistic explanations of each function required. Break down of equations is also included in order to make them more digestible.

- [21] vnschool.net, “Double Bridge Experiment Image,” Available: http://www.vnschool.net/images/082010/Thuattoan/ThuatT_2.jpg, accessed: 7th April 2015.

Simple graphic representing the Double Bridge Experiment.

- [22] Wikipedia, “Ant Colony Optimisation New Pheromone Function , [online] Feb 2015,” Available: <http://upload.wikimedia.org/math/6/d/b/6db065218c956a4a7af6da99aaeca5d1.png>, accessed: 14 Feb 2015.

Simple graphic representing the algebra representation of the pheromone function required to update the pheromone matrix.

- [23] —, “Ant Colony Optimisation New Probability Function , [online] Feb 2015,” Available: <http://upload.wikimedia.org/math/6/d/b/6db065218c956a4a7af6da99aaeca5d1.png>, accessed: 14 Feb 2015.

Simple graphic representing the algebra representation of the pheromone function required to select the Agents next movements.

- [24] —, “Ant Colony Optimisation Pheromone Function , [online] Feb 2015,” Available: <http://upload.wikimedia.org/math/e/1/3/e1320f5f72b21e5766dfa7e29b536883.png>, accessed: 14 Feb 2015.

Simple graphic representing the algebra representation of the pheromone function required to update the pheromone matrix.