A MULTI-AGENT SYSTEM FOR A BUS CREW RESCHEDULING SYSTEM

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by

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Abstract

Unpredictable events (UE) are major factors that cause disruption to everyday bus operation. In the occurrence of UE, the main resources - crews and vehicles - are affected, and this leads to crew schedule disruption. One way to deal with the problem is crew rescheduling. Most of the current approaches are based on static schedules do not support rescheduling in a real-time scenario. They have the ability to reschedule but a new complete schedule is produced without concerning the real time situation. The mathematical approaches which are used by most scheduling packages have the ability to search for optimum or near optimum schedules but they are usually slow to produce results in real-time because they are computationally intensive when faced with complex situations. In practice, crew or bus rescheduling is managed manually, based on the supervisor's capabilities and experience in managing UE. However, manual rescheduling is complex, prone to error and not optimum, especially when dealing with many UE at the same time.

This research proposes the CRSMAS (Crew Rescheduling System with Multi Agent System) approach as an alternative that may help supervisors to make quick rescheduling decisions by automating the crew rescheduling process. A Multi Agent System (MAS) is considered suitable to support this rescheduling because agents can dynamically adapt their behaviour to changing environments and they can find solutions quickly via negotiations and cooperation between them. To evaluate the CRSMAS, two types of experiment are carried out: Single Event and Multiple Events. The Single Event experiment is used to find characteristics of crew schedules that influence the crew rescheduling process while the Multiple Events experiment is used to test the capability of CRSMAS in dealing with numerous events that occur randomly. A wide range of simulation results, based on real-world data, are reported and analysed. Based on the experiment it is concluded that CRSMAS is suitable for automating the crew rescheduling process and capable of quick rescheduling whether facing single events or multiple events at the same time, the success of rescheduling is not only dependant on the tool but also to other factors such as the characteristics of crew schedules and the period of the UE, and one limitation of CRSMAS that was discovered is it cannot simulate different type of events at the same time. This limitation is because in different events there are different rules but, in Virtual World, agents can only negotiate with one set of rules at a time.

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In the name of Allāh, Most Gracious, Most Merciful. All praises belong to Allah, the Rabb (Only God, Cherisher and Sustainer) of the Worlds: Most Gracious, Most Merciful; Master of the Day of Judgment. You alone we worship and You alone we seek for help. Guide us to the straight way, the way of those on whom You have bestowed Your Grace, not (the way) of those who earned Your anger and who went astray. I bear witness that there is nothing worthy of worship but Allah, He is One and has no partners; and I bear witness that Muhammad (peace be upon him) is His servant and the last Messenger. May Allah send His blessing and peace to Muhammad, his companions, family and all those who call to his way till the Day of Judgement.

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Abbreviations and Symbols

MAS- Multi Agent System

EU- European Unions

EC- European Councils

TU- Trade Unions

BSC- Bus Crew Scheduling

UE – Unpredictable events

AI- Artificial Intelligences

LS – Literature Survey

CRSMAS – Crew Rescheduling System with Multi Agent System

CA- Crew Agent

DA- Duty Agent

LFSO – Late for Sign-On

LFR – Late for Relief

LFSW – Late for Second Work

DFSO – Delay for Sign-On

DFSW – Delay for Second Work

UNV - Unavailability

DMM- Decision Making Machine

Chapter 1: Introduction

1.1 Introduction

Bus services play a pivotal role in a city and represent the largest component of the public transport network, and more so than trains, have the greatest reach potential. Cities such as London, New York, and Paris have 700, 298, and 246 routes served by 6500, 4860 and 3860 buses respectively (Desaulniers, 2002; Transport for London, 2004). A good mass public transport network is not only an essential part of the social infrastructure but also a solution to road congestion.

There are four main important processes in the operational planning of buses. These are timetabling, vehicle scheduling, crew scheduling, and crew rostering. Currently, most researchers and schedulers treat these processes independently due to the complexity of each process (Wren *et al.*, 2003). This thesis is particularly concerned with crew scheduling.

There are three major aspects associated with crew scheduling, their *complexity*, *cost* and *unpredictability*. The *complexity* aspect can be attributed to the fact that crew scheduling is a well-known *NP-Hard* problem (Non-deterministic Polynomial-time

Hard) because there are certain rules that need to be adhered to, that is labour agreement rules and EC drivers' hours rules (Wren and Rousseau, 1995; Fores *et al.*, 2002; Kwan *et al.*, 2000; Wren, 2004). Moreover, the time taken to find an optimum crew schedule rises exponentially with the size of the problem (Wren, 2004).

The *cost* aspect is attributed to the fact that crew expenses involve a large portion of a bus's operational costs (Yunes *et al.*, 2000). According to Meilton (2001), the cost of crews is at least 45% of total operational costs. This proportion is likely to rise as the shortage of bus drivers, a common phenomenon in London and the whole of the United Kingdom (UK), is considered to be increasing (Kwan *et al.*, 2004). Thus, it is of paramount importance for bus operators to manage crews efficiently.

Bus services usually operate in *unpredictable* environments, where unpredictable events (UE) such as crew absenteeism, vehicle breakdown, demand variation, and temporary traffic congestion take place any time (Cheng and Chang, 1999). In the occurrence of UE, crew schedules will be affected. Usually, bus operators are not penalised if the delay is due to traffic related problems, such as congestions, but they are penalised if it is related to mechanical or crew problems (London Transport Users Committee, 2001). Therefore, the smooth management of vehicles and crews is usually the responsibility of bus operators and they should manage their vehicles and crews properly so that no service disruption will occur, otherwise they will be penalised.

This research focuses on UE that disrupt crew schedules and proposes an *Automated Crew Rescheduling System* to minimise the effect of UE to crew schedules. A Multi-Agents System (MAS) is used to implement the proposed system. To the best of our knowledge, the use of a MAS in bus crew rescheduling is a novel idea, however a MAS has been used in scheduling for other problem domains such as manufacturing scheduling (Jia *et al.*, 2004), logistic management and scheduling (Karageorgos *et al.*, 2003), and meeting scheduling (Lee and Pan, 2004).

The following section presents the background of the research problem and describes the limitations of current approaches in dealing with UE and the limitations with manual crew rescheduling. Section 1.3 presents the aim and objectives of this research, followed by a brief overview of the research methodology. The chapter then outlines the whole chapters in this thesis and finally Section 1.6 summarises the chapter.

1.2 Background of the Research Problem

Crew schedules show crew activities (in this research crew refers to bus drivers) in detail, from sign-on until sign-off. In the occurrence of UE, the timing of activities in crew schedules will be affected. For example, if a crew comes late, it will cause delay not only at sign-on time but also possibly to driving time, relief time and sign-off time depending on the level of lateness.

Thus, how can the effect of UE to crew schedules be overcome or minimised? One method is by "crew schedule rescheduling" and another is "crew rescheduling" (Kwan, 2004). The term "crew schedule rescheduling" means that whenever UE occurs, current crew schedules will be rescheduled. However, "crew rescheduling" means if UE take place crew schedules will remain the same, however, the assignment will be changed. The missing or unavailable crew's duty (because of UE) will be assigned to another available member. In this research, we propose to use crew rescheduling because of the complexity associated with crew schedule rescheduling. Chapter Three will explain this further.

Most of the current approaches, which are based on static schedules, do not provide the capability of rescheduling in a real time scenario. They have the ability to reschedule but a new complete schedule is produced without concerning the real time situation. Although there are efforts in managing UE, attention is paid only to vehicle schedules (Giannopoulos, 1989; Cheng and Chang, 1999; Huisman *et al.*, 2004; Li *et al.*, 2007). Huisman and Wagelmans (2006) proposed rescheduling when a crew or a bus is late but there are a few assumptions in their research that are not feasible in a real world situation. For example, passengers have a higher priority than crews so there is a possibility of crews violating EC driving hour rules, and the assumption that bus operators have unlimited crew resources is not possible in the real world.

In practice, crew or bus rescheduling is manually managed based on supervisors' capabilities and experiences in managing UE. They often employ commonsense and past experiences that are blended in a messy, sometimes inconsistent, and not well-understood way (Li *et al.*, 2007). For example, the current practice in Taiwan as mentioned by Cheng and Chang (1999), is that experienced dispatchers (supervisors) use their intuition and knowledge to manage abnormal conditions in an ad hoc manner. This is more or less common practice in the rest of the world. We argue that manual crew rescheduling has many deficiencies that are hard to reschedule and result in slow decisions when many UE happen at the same time, possibly breaking the EC driving hour rules, and that the decisions are not optimum in the use of crew resources. Thus in this research we propose automated crew rescheduling to overcome these deficiencies.

The following subsections discuss the limitations of current research approaches in dealing with UE, then the limitations of manual crew rescheduling, and finally suggests our approach that may help to overcome those limitations.

1.2.1 Limitations of Current Research Approaches

Research into automated crew scheduling has attracted a large number of researchers since the 1960s (Wren, 2004). Most the research was presented in a series of international conference on Computer-Aided Scheduling of Public Transport since 1975 (Preprints proceeding, 1975; Wren, 1981; Rousseau, 1985; Daduna and Wren, 1988; Desrochers and Rousseau, 1992; Daduna *et al.*, 1995; Wilson, 1999; Voss and Daduna, 2001; Hickman *et al.*, 2004; Preprints proceeding, 2006).

The common objective of automated crew scheduling is to find the optimum schedule with the minimum number of duties/shifts and minimum total duty costs. In fact, minimisation of the total number of duties is regarded as more important since there are many costs that depend directly on the number of crews regardless of their wages (Wren and Rousseau, 1995). Crew expenses involve a large proportion of a bus's operational costs and form at least 45% of total operational costs (Yunes *et al.*, 2000; Meilton, 2001). Duty costs depend on the combination of work that they contain, incorporating the hourly wage and penalty costs for undesirable features such as long or unsociable hours.

Current approaches used in bus crew scheduling can be grouped into three main groups: heuristics, mathematical programming, and others (Li and Kwan, 2003; Fores *et al.*, 2002). These groups are not mutually exclusive as some mathematical programming approaches may involve heuristic techniques to some extent; other approaches such as genetic algorithm or tabu search may involve mathematical programming, etc (Fores *et al.*, 2002; Li and Kwan, 2003; Wren, 2004; Li and Kwan, 2005). However, the most common crew-scheduling package uses mathematical programming combined with heuristic approaches (Wren, 2004).

Before the 1980s, heuristics were mainly used to solve crew scheduling problems because computers were not powerful enough to run mathematical programming models, and the techniques in mathematical programming were also not advanced (Wren and Rousseau, 1995; Li and Kwan, 2003). Heuristic approaches rely on the knowledge of expert schedulers to build schedules or restrict the duty formation to those duties that are likely to appear in good schedules. Many of the approaches are first to construct an initial schedule, and then improve the schedule by making limited alterations (Wren and Rousseau, 1995; Wren, 1998).

In mathematical programming approaches, crew-scheduling problems are usually formulated as set covering problems. A set-covering model is established to find a set of feasible duties that covers all pieces of work and minimises the total costs of the operation (Smith and Wren, 1988; Fores *et al.*, 2002; Wren *et al.*, 2003). If the objective is to cover each piece of work with exactly one duty then it is called a set-partitioning model (Banihashemi and Haghani, 2001). According to Banihashemi and Haghani (2001), there are three different approaches for solving this problem. These are first, formulating the problem as an integer linear programming model then finding the best combination of the feasible duties. Second, a column generation approach is used to find the best combination of the feasible duties. The third starts from a set of feasible pre-constructed duties but continues to produce other feasible duties if they could improve the solution.

Other approaches exist such as genetic algorithm (Clement and Wren, 1995; Kwan *et al.*, 1999), tabu search (Cavique *et al.*, 1999; Shen and Kwan, 2001), ant system

(Forsyth and Wren, 1997), and constraint programming (Layfield *et al.*, 1999). In the genetic algorithm approach, the pieces of bus work are represented as chromosomes and the value of each gene identifies the duties that cover it. It then discards or chooses duties from the complete set until the bus work is covered and no duty is redundant (Li and Kwan, 2001; Li and Kwan, 2003). Tabu search is a searching approach that searches from a large set of feasible duties by iteratively removing some inefficient duties and then repairing the broken schedule (Shen and Kwan, 2001). In the ant system, the virtual ants trace paths through a bus schedule (with the paths representing crew duties) to create crew schedules. Good duties will be used more often by the ants and are more likely to be chosen for a crew schedule (Forsyth and Wren, 1997). Constraint programming provides a powerful and easy system for modelling restrictions and uses these restrictions to search for a solution. In bus crew scheduling, problem variables represent pieces of work and the domain of each variable is the set of indices of the duties that covered the piece of work. The algorithm performs iterative process to construct a feasible crew schedule that satisfies all the constraints (Layfield *et al.*, 1999).

Most of the current approaches described above are primarily focused on finding optimum or near-optimum crew schedules. These approaches assume a static deterministic environment where complete knowledge of the problem is available without consideration of any kind of UE. This is rarely the case in the real world. Most real-world scheduling systems operate in dynamic environments subject to various UE that can happen at any time. The probability of occurrence of such events is usually higher when buses operate in high-frequency routes and in busy cities. UE usually disrupt bus operation and they are difficult or impossible to foresee. Consequently, the resulting schedule may be neither feasible nor nearly optimum any more.

To the best of our knowledge, there are two pieces of research (Wren *et al.*, 2003 and Huisman and Wagelmans, 2006) that look at how to deal with UE that relate to crew. However, TRACS II (Techniques for Running Automatic Crew Scheduling, Mark II - by Wren *et al.*, 2003) only deals with planned changes, that is those that can be predicted several days or weeks in advance, and not unpredictable events. Wren *et al.* (2003) argue that any automatic approach that deals with UE has to rely on the drivers' acceptance of new workings which may extend the working day and interfere with leisure activities.

Huisman and Wagelmans (2006) have proposed a dynamic integrated bus and crew scheduling system that will reschedule the crew and bus simultaneously whenever an UE occurs. However, in our opinion, and in realistic situations, it is not practical to reschedule the whole crew schedule whenever a crew becomes unavailable. This is because the complexity associated with rescheduling can be understood from the constraints (i.e. driving hour rules) of the crew itself. When trying to conduct any rescheduling activities, schedulers need to consider cost and time factors, such as the number of available members, driving hours left for each one, and their location of every crew. With such added constraints it becomes very difficult for the system to find an optimum schedule.

There are a few assumptions in the research by Huisman and Wagelmans (2006) that are not feasible in a real world. First, the passengers have a higher priority than crews. Thus, there is a possibility of violation of the crew rules whenever a bus late occurs before the break time. The crew has to shorten the break or not take a break just to make sure the bus operate on time. Although this is appropriate to guarantee that the bus services run smoothly, the EC driving rules should not be broken. Furthermore, this is not acceptable to crews. Second, a trip can only start late due to a delay of the vehicle and thus not due to the crew. This assumption is not real due to the fact that crews are one of the causes of UE. Third, availability of unlimited crew members, however, this is hardly realistic.

1.2.2 Limitations of Manual Way of Crew Rescheduling

When many UE happen at the same time, especially different types of events, making decisions will be difficult and slow for supervisors. Consider, for example, a time that a bus is involved in an accident, two crews are late, four buses are stuck in a traffic jam, and a crew is unavailable because of the emergency. In this situation, if a supervisor wants to reschedule crews it is quite difficult and decisions are made without the help of an automated system.

In the real world situation, when UE takes place, supervisors have to make quick decisions within a short time. The pressure might cause them to make mistakes in crew rescheduling. The decisions could possibly break the EC driving hour rules. For example, because of an accident a crew is not available to continue his/her duty. A supervisor may request other crew to replace the unavailable crew without realising that the crew has to drive more than maximum hours allowed in a day.

The decisions that supervisors make when UE occurs may not be optimum. Optimum in this context means minimising the use of crews or spare crews. Without the help of an automated system, it is hard to make decisions that achieve an optimum solution because the time is limited. For an example, a crew member is not available for two hours of his/her duty. Instead of using a spare crew as a replacement, an optimum way is by using an available crew who has finished his/her duty but not yet signed off to replace the unavailable crew provided they do not exceed the maximum driving hours.

We argue that the limitations mentioned above (hard and slow to make decisions, prone to error and not optimum) make it difficult for supervisors to manage UE. The limitations above were elicited from interviews with three bus companies in London which will be presented in detail in Chapter Two.

1.2.3 What May Help

The overview of the current approaches so far has shown that while these approaches may be adequate for deterministic environments, they do not provide solutions that could help supervisors in reschedules crews in real world situations. Now the question becomes: what fast and accurate appropriate approach can be used to automate the crew rescheduling process that can help supervisors in dealing with UE that disrupt crew schedules?

Mathematical approaches are able to search optimum or near optimum schedules (Wren, 2004), but they also have some limitations, for example, they are usually slow to produce results in real-time because they are computationally intensive when it comes to complex situations (Kwan *et al.*, 1999). Conventional programs allocate resources to demands following pre-programmed algorithms in a sequential manner and therefore, when dealing with a large number of resources and demands, they require a long time to find optimum allocation (Rzevski, 2002). Whenever resources or demands change, these programs start the allocation process from the beginning and if changes are frequent, they oscillate and cannot reach the optimum solution.

The main characteristic for a tool that we are looking for is the ability to find quick solutions in real-time whenever UE take place and in an uncertain environment. The capabilities of a MAS, especially when dealing with changes in real-time and in uncertain environment, matched our requirements (Weiss, 1999; Shen *et al.*, 2001; Wooldridge, 2002). To the best of our knowledge, the application of a MAS to bus crew scheduling problem is a novel idea. Thus, in this research we propose using a MAS as a tool to automate the crew rescheduling process. Details of a MAS are discussed in Chapter Two.

1.3 Research Aim and Objectives

The research carried out in this dissertation is based on the stance that current approaches do not provide solutions to automate the crew rescheduling process and help supervisors in dealing with UE so that the effects can be minimised. *The aim of this research therefore is to develop an automated crew rescheduling system using a MAS to assist supervisors in managing UE. By doing so, it should minimise the effect of UE on crew schedules and hence reduce the amount of disruption to bus operation.* To achieve the research aim some suggested objectives are summarised as follows:

1. The first objective is to review and critically examine the existing approaches in producing crew schedules and whether they have any mechanisms for tackling UE. The reason for this is to learn from current approaches if they have a mechanism for dealing with UE problems and to know its efficiency.

2. The second objective is to understand the nature of UE, the causes of UE, and how bus operator/companies deal with UE. This is in order to understand UE in detail and the manual way of managing UE to model them before automating the process, especially crew rescheduling.

3. The third objective is to assess whether a MAS can be used to develop the proposed system.

4. The fourth objective is to design/develop an automated crew rescheduling system. The aim of the automated system is to help supervisors in managing UE in everyday operation.

5. The fifth objective is to evaluate the proposed system as to whether it achieves the aim of minimising the problems of manual crew rescheduling and what could be learned from the findings that may improve the proposed system.

1.4 Research Methodology

This section presents the research methodology that used in this research as ways of achieving research objectives. In this research several methods are employed based on different objectives as outlined below:

1. The literature survey (LS) is used to obtain information on UE, the sources of UE, how to deal with UE, current approaches in developing crew schedules and whether the approaches have the ability to deal with UE. Through the LS we also justify the use of a MAS to implement the proposed system. The LS reviews and analyses the relevant literature in books; theses; working papers; journal papers; conference proceedings; websites and other academic sources, which are searched by using electronic databases and academic search engines.

2. Interviews are used to gain knowledge of practical experiences of bus companies in managing their daily operation and dealing with UE and how crews are rescheduled manually. This information helped in modelling the manual way of crews rescheduling.

3. A conceptual model of the proposed automated crew rescheduling system is designed using the MAS concept. AgentPower, a MAS based software package, is used to develop and simulate the conceptual model.

4. To evaluate the proposed system, the research carried out two sets of experiments based on a single event and multiple events. The single event experiment involved testing one event at a time but with different types of events, different types of schedules, different duties distribution and different event timings. The purpose is of this to test the capability of the proposed system in all types of events and schedules and also to identify the characteristics of crew schedules that influence the possibility of successful rescheduling. Multiple events test several events that take place concurrently and randomly. The purpose is to test the robustness of the proposed system in handling many random events at one time. In both experiments, the proposed system is examined with regard to the research questions, which are elicited in Chapter Two.

5. The experiments' results are analysed to measure whether the proposed system achieves its aim by looking into its capability of performing quick rescheduling in real time. The experiments and analysis section will be used to refine the initial hypothesis and revise the initial conceptual approach where appropriate.

1.5 Dissertation Outline

This dissertation is structured in seven chapters, each addressing a distinct point related to carrying out this research project. A brief outline of chapters is as follows:

Chapter One: Introduction. This chapter gives an introduction to the problem area of this thesis, which is managing UE in everyday operations that disrupt crew schedules. Some of the problems associated with current approaches in crew scheduling, the limitations in manual crew rescheduling, and possible techniques to overcome these problems are briefly discussed. Thereafter, the aim and objectives of the research are stated. The research methodologies are then presented. The chapter ends with the dissertation outline.

Chapter Two: Literature Review and Interview. Chapter Two expands the problems addressed in Chapter One starting by reviewing the UE problem, the sources of UE, and how to deal with UE. The chapter then reviews the different approaches used in crew scheduling in terms of dealing with UE. Some technical aspects related to the different types of approaches used in crew scheduling are presented. Thereafter, the chapter presents critiques to the current approaches in relation to their ability to deal with the UE problem. The chapter then presents the interviews with three bus companies in London and their subsequent analysis pertaining to their practical experiences in dealing with UE. Based on the critiques of current approaches, and the interview analysis, the chapter proposes an automated crew rescheduling system and chooses a MAS as a tool to implement the proposed system. It also presents the theoretical descriptions of agent and the MAS, and the use of the MAS in other scheduling fields. Finally, the chapter draws a hypothesis and a research question. The research question is "*Is a MAS a suitable approach for automating the crew rescheduling process in real-time so it will help supervisors in dealing with the UE problem in relation to crew schedules?*"

Chapter Three: The Proposed Approach. Chapter Three proposes the automated crew rescheduling system in detail, which is developed as an attempt to answer the research question, discuss issues that are related to the proposed system, and models the system with the concept of a MAS. Two issues are discussed. First, whether to reschedule crew or reschedule crew schedules. Second, whether to propose a complete crew scheduling system or just an addition to the current system. The chapter then discusses the manual way of rescheduling that is currently practiced by bus companies in London and proposes the automated crew rescheduling system in detail. Thereafter the proposed system is modelled with the concept of a MAS. The MAS models are the system architecture, agent's type and interaction between agents.

Chapter Four: Single Event Experiments. This chapter presents the results and analysis of the single event experiments to the proposed system. The purpose of single event experiments is to test the capability of the proposed approach in coping with different types of events in different types of schedules, duty distributions, and timings, and also to identify the characteristics of crew schedules that influence the possibility of rescheduling. Events types, schedule types, duty distributions, and timing are the factors that we expect to have influenced rescheduling results. The chapter then presents the analysis of the results. The analyses will evaluate the results based on the proposed system rescheduling capability and the time taken to perform it. The outcomes of the analysis will be used to assess the research question mentioned in Chapter Two, and also to modify the proposed system if necessary.

Chapter Five: Multiple Events Experiments. Chapter Five presents the results and analysis of the multiple events experiments to the proposed system. The purpose of multiple events experiments is to evaluate the capability of the proposed system in facing different numbers of events that take place with different event timings in different types of schedules at any time. The results will be analysed based on the successful matched and the time taken to execute it. The outcomes of the analysis will be used to assess the proposed system and propose modifications wherever appropriate in Chapter Six.

Chapter Six: Approach Analysis and Modifications to the Proposed System. This chapter presents an analysis of the proposed system and then proposes modifications to it. The purposes of this analysis is to discover whether the proposed system will achieve its aim or not, to identify its strengths and weaknesses, and to indirectly answer the research question. Based on the evaluation, the modification process takes place to improve the proposed system so that any weaknesses or limitations can be eliminated, or at least minimised, and ensure the system achieves its aim.

Chapter Seven: Summary and Conclusions. This chapter provides detailed summaries of the chapters in this dissertation. The chapter also presents the final conclusions for this research and lessons learned. Chapter Seven ends by identifying some areas for continuation of research in the future.

1.6 Summary

The research described in this chapter (see the summary as shown in Figure 1.1) is concerned with UE that cause disruption to bus crew schedules and subsequently bus operation. One way to manage UE is by crew rescheduling. Most of the current approaches, which are based on static schedules, do not providing the capability of crew rescheduling in a real time scenario. In practice, crew rescheduling is manually managed based on supervisors' capabilities and experiences in managing UE. There are many limitations to manual crew rescheduling such as it being hard to make decisions and decision making being slow when many UE happen at the same time, the possibility of breaking the EC driving hour rules, and the decisions not being optimum in the use of crew resources. To overcome these limitations, this research proposes an automated crew rescheduling system. The aim of the system is to help supervisors in making decisions of crew rescheduling while managing UE. This chapter is an introduction to the research described in this dissertation. It sets the background; defines the problem; outlines the research aim and objectives; describes methods used for this research and provides a basis for discussing the research work and drawing conclusions from it in subsequent chapters.

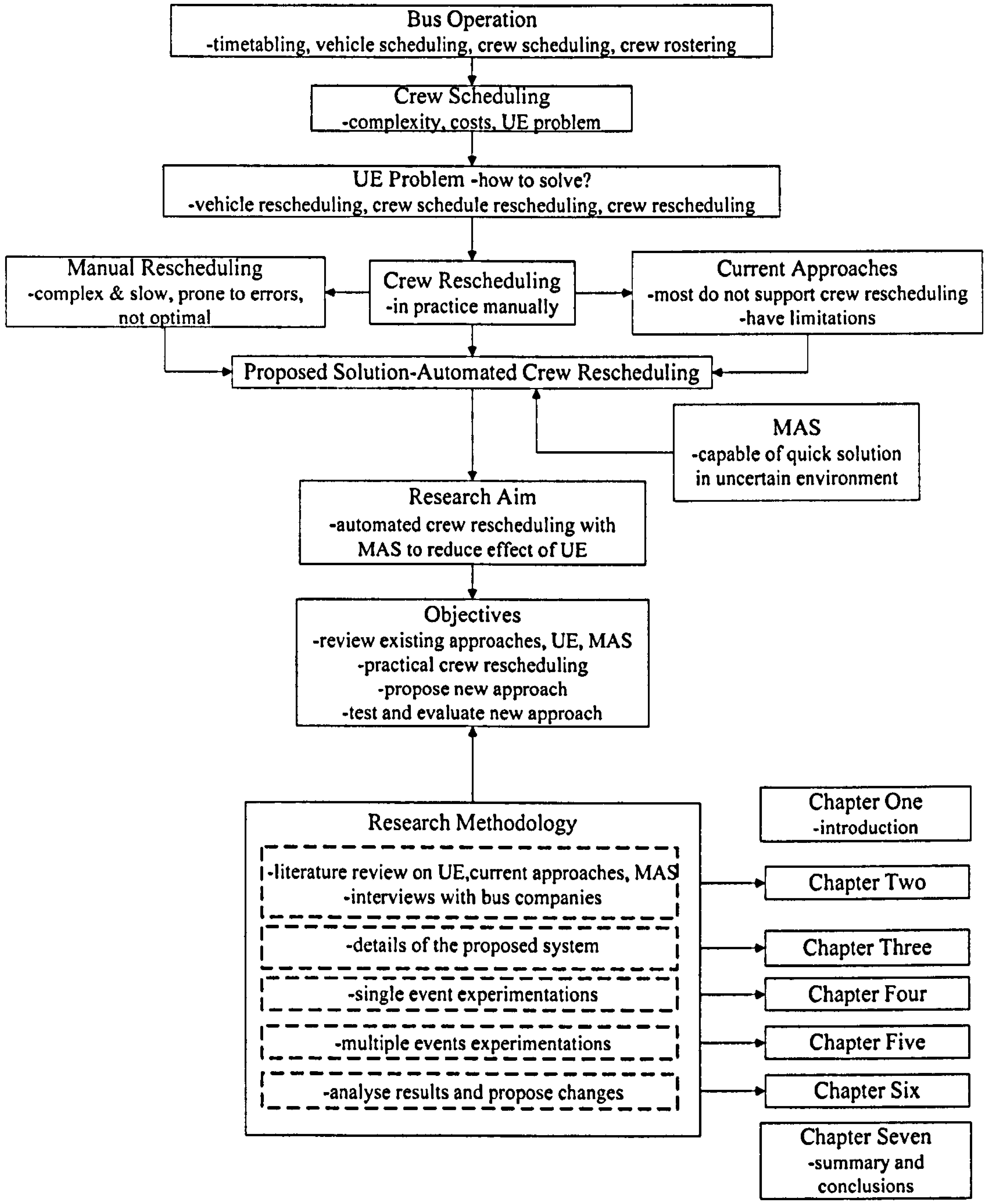

Figure 1.1: Summary of Chapter One

Chapter Two: Literature Reviews and Interviews

2.1 Introduction

The research at this point tries to understand the UE problem, how to deal with it in detail, and tries to see current crew scheduling approaches and whether they have mechanisms for dealing with UE. The information will help to identify limitations in dealing with UE and will be used as a foundation to propose a suitable approach to deal with such problems. Then the research also justifies the choice of a MAS as a suitable tool to implement the approach. To achieve the above aim, we do a literature survey to find information on UE, to evaluate current crew scheduling approaches, and to justify the use of a MAS. Also, we perform interviews with three bus companies to obtain empirical information about the UE problem, the current scheduling system in use, and how to deal with UE. Findings from literature and interviews will identify the research gap and then the proposed approach (in Chapter Three) is our attempt to fill the gap.

2.1.1 Chapter Objective

The objectives of Chapter Two are to present information gathered from the literature survey and interviews, to identify a theoretical gap based on critiques of current approaches and proposes a MAS as a suitable approach to tackle this gap. This proposal is then put as the research question to be tackled throughout the rest of the dissertation. Three types of information are gathered from the literature survey: the UE problem and ways of tackling it, current approaches in regard to dealing with UE, and a MAS as a suitable implementation tool. The interviews give information on practical experiences of bus companies in managing their daily operations and dealing with UE, how crews are rescheduled manually, and the current system that they use.

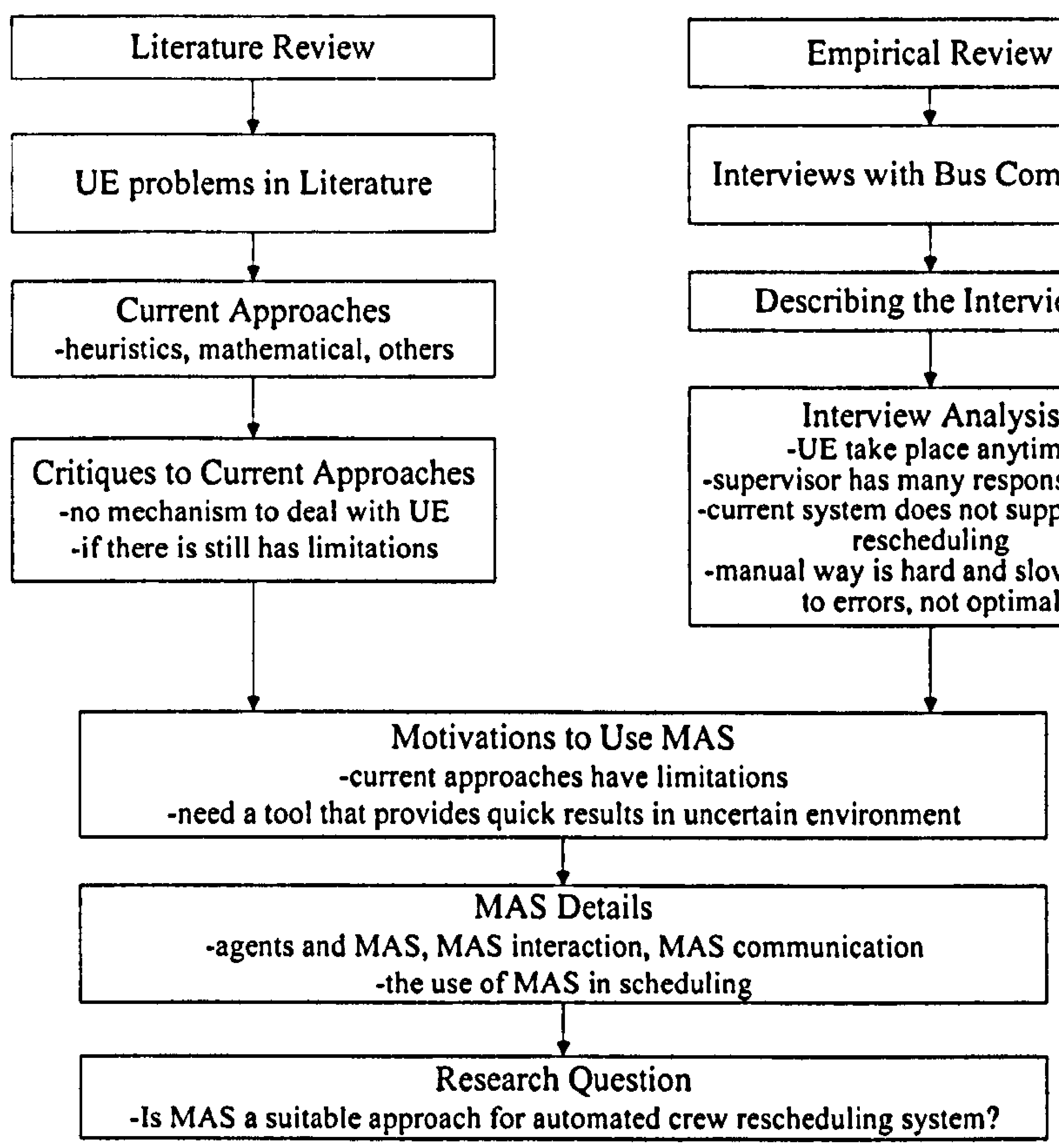

Figure 2.1: The Structure of Chapter Two

2.1.2 Chapter Outline

Section 2.1 started with an introduction to Chapter Two, its objectives, and outline (see Figure 2.1). Section 2.2 presents an overview of the UE problem, its sources and how to deal with them in the literature. Thereafter, Section 2.3 presents the definition of crew scheduling problems and then examines the three groups of most commonly used approaches in crew scheduling problems: heuristics, mathematical programming, and other approaches. These approaches are evaluated with respect to their abilities to deal with the UE problem. Section 2.4 presents the interviews with bus companies, and the analysis. Section 2.5 justifies the selection of a MAS as a suitable tool, introduces basic concepts and properties of a MAS and its advantages that may help in managing UE problems, and also presents the use of a MAS in scheduling problems. Section 2.6 discusses the findings and then presents the main research hypotheses and research question. Section 2.7 then presents a summary of the chapter.

2.2 The UE Problem

UE usually disrupt bus operation and they are difficult or impossible to foresee. The probability of occurrence of such events is usually higher when buses operate in high-frequency routes and in busy cities. There are many reasons that lead to UE as discussed by Cheng and Chang (1999), Huisman *et al.* (2004), and Li *et al.* (2007). Bus operation reports in the UK categorise these events into traffic, staff, mechanical and others (Commission for Integrated Transport, 2002). These categories are discussed in detail below.

Traffic

Traffic congestion is a normal occurrence that usually takes place during peak hours either in the morning or in the evening. Normally, this event is allowed for when constructing bus timetables and times schedules (Commission for Integrated Transport, 2002). However, UE such as, accidents; special events; heavy rain; snow; signal failure or terrorist alerts are usually the main causes of unpredicted traffic congestion. This causes delay to bus trips. Such delays will subsequently lead to delays in the next few trips (Huisman and Wagelmans, 2006). This is particularly the case when resources (bus and crew) that are supposed to be used for the next trip are stranded in traffic.

Staff

UE that are related to staff include absenteeism, being late for duty, and being unavailable for part of the duty because of an emergency like an accident. Studies by

Winkleby *et al.* (1988), Kompier *et al.* (1990), and Berlinguer (1962) as cited in Tse *et al.* (2006) found that absenteeism is higher in the bus industry than average work absence in other fields. This is mainly caused by uncomfortable and fatigue-inducing working conditions, extended hours of work and a situation that is aggravated by resorting to 'call in sick' when denied leave.

Mechanical

Although bus companies normally have preventive maintenance in place, sometimes UE happen that make the vehicle unfit for operation. Some of the events can be related to mechanical reasons including breakdown of vehicle, vehicle-door not working, vandalism, ticket machine on the bus is not working and vehicle being involved in an accident (Li *et al.*, 2007; Commission for Integrated Transport, 2002). These events will cause the vehicle to be unfit for service.

Others

There are some others events that are not included in the above categories but that cause disruption to bus operation such as; road closure due to safety reasons, assault on driver, and marching (Commission for Integrated Transport, 2002). Although these are unlikely, they do contribute to the uncertainty factor in bus operation.

2.2.1 How to Deal with UE

There are a number of strategies in the literature when it comes to dealing with UE. Giannopoulos (1989), as cited in Cheng and Chang (1999), suggested extra trips to deal with UE. Huisman *et al.* (2004) and Li *et al.* (2007) proposed vehicle rescheduling when dealing with UE that are related to vehicles. Huisman and Wagelmans (2006) also proposed crew schedule rescheduling when crew or the bus is late. In the UK, bus operators are not penalised if the bus operation is disrupted due to traffic events but they are penalised if they are related to mechanical or staff problems (London Transport Users Committee, 2001).

In practice, rescheduling of crews and buses is manually managed at depot or garage based on the capability of supervisors as reported by Cheng and Chang (1999) and Li *et al.* (2007). There is no structured way of making decisions; therefore they use their own common sense and past experiences. The decisions are sometimes inconsistent and not well understood (Li *et al.*, 2007). There are not many articles in the literature on how bus operators manage UE in a real world scenario. In order to obtain more information we conducted interviews with three bus companies in London and the outcomes are presented in Section 2.5.

2.3 The Current Bus Crew Scheduling Approaches

In this section, we discuss the current approaches and their ability in tackling the UE problem. The current approaches used in bus crew scheduling can be grouped into three main groups: heuristics, mathematical programming, and others (Wren and Rousseau, 1995; Fores *et al.*, 2002; Li and Kwan, 2003). The reviews are based on previous research published in books; journals; conferences proceedings; theses; reports and websites. Before presenting the findings, Subsection 2.3.1 gives an overview of the crew scheduling process, its definition, constraints and shift types. Thereafter, the following subsections present the three groups of current approaches. Subsection 2.3.5 presents evaluations and critiques to the current approaches in regard to tackling the UE problem.

2.3.1 Crew Scheduling Problem

This subsection explains the crew scheduling process, terminology used in this thesis, constraints and types of shifts that are referred to from Wren and Rousseau, 1995; Fores *et al.*, 1998; Fores *et al.*, 2002; Li and Kwan, 2003; Li and Kwan, 2005. Crew scheduling is a process to find an optimum schedule with a minimum number of duties and minimum total duty costs. From the vehicle schedules, we can get a list of a bus's itinerary in a day. Figure 2.1 shows an itinerary for Bus 1. It shows the journey of Bus 1 in a day from depot A back to the same depot. A *depot* is a place where buses that are not in use park for some time. The bus starts from *depot* A at 7:15 and finishes at 19:45 in the same *depot*. Between these, the bus passes the *relief points* B and C. A *relief point* is a location and time where and when a change of crew may occur. Between a *relief point* or a *depot* is a *piece of work*. The work of a single crew in a day is called *a duty/shift*, which consists of several *spells* of work. A *spell* contains a number of consecutive pieces of work on the same vehicle, and a *crew schedule* is a set of duties that covers all the required driving tasks.

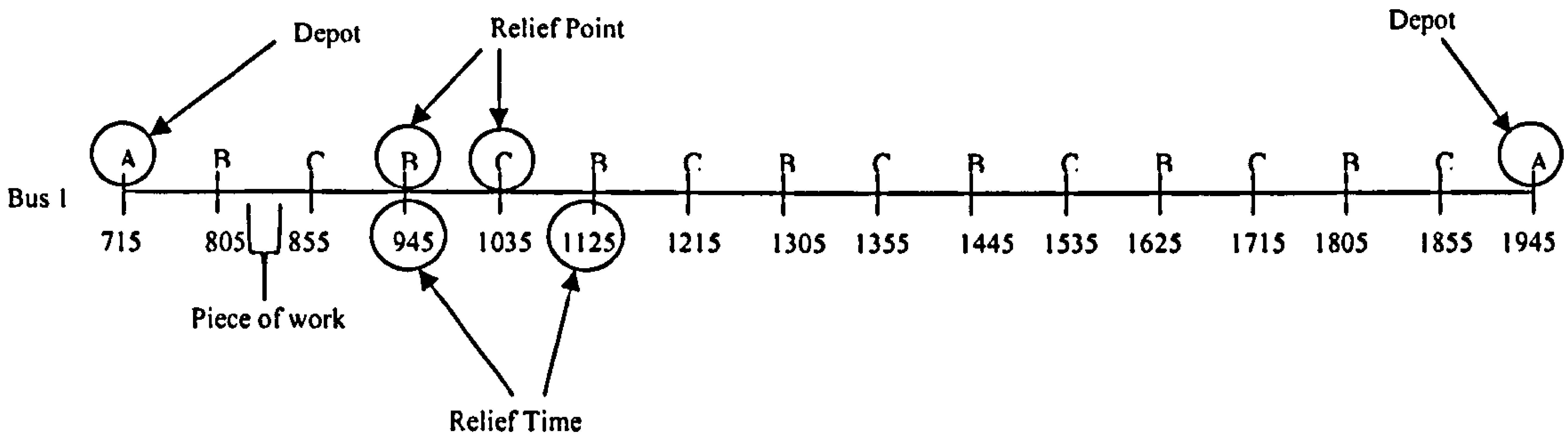

Figure 2.2: Representation of a Bus Journey in a Day (adapted from Li and Kwan, 2005)

The main constraints that affects the bus crew scheduling problem is the labour agreement rules that exist between (1) the Transport and Workers' Union and bus operators and (2) European driving hours rules and the UK directive governing the working condition. The main purpose of these rules is to ensure that crews do not work unacceptable duty; hence the rules provide rigid guidelines relating to the construction of duties. The following is a list of some global rules typically used by bus operators: maximum total working time; minimum time allowance for signing on and off at the depot; paid allowance for signing on and off at the depot; minimum length of a meal break and the shift pattern. Having these rules makes it is a challenge to find optimum schedules especially when involving large resources of crews and buses to serve the high frequency route in an urban area.

There are three types of shift: straight shift, split shift and overtime shift. The straight shift is a shift consisting of two stretches separated by a meal break of thirty to sixty minutes. A split shift is spread over maybe about twelve hours containing two stretches separated by a long break of several hours. A straight shift can be further divided into the following three types: an early shift that takes an early bus out of depot and covers part of the morning peak, a late shift that takes a late bus into the depot and covers part of the afternoon peak, and middle shift. The main purpose of the split shift is to provide drivers to cover the peak periods when more buses are in operation. They also assist in maintaining the service whilst drivers from other duties take their meal breaks.

Overtime shifts consist of one-part shift of around two to four hours. These are in addition to normal shifts for relatively high payment and may be useful in covering peaks in demand.

2.3.2 Heuristics

Before the 1980s, heuristics were mainly used to solve crew scheduling problem because computers ware not powerful enough to run mathematical programming approaches, and the mathematical programming techniques were also not advanced (Wren and Rousseau, 1995). A complete review of heuristics can be found in Wren and Rousseau (1995) and Wren (1998). Heuristic approaches rely on the knowledge of expert schedulers to build schedules, and many approaches start by constructing an initial schedule and then improving the schedule by making limited alterations.

Examples of heuristic based approaches are TRACS (Techniques for Running Automatic Crew Scheduling), which was developed at the University of Leeds (Parker and Smith, 1981); RUCUS (Run Cutting and Scheduling) in America by The Mitre Corporation (Bennington and Rebibio, 1975;Bodin *et al.*, 1985); HOT (Hamburger Optimierungs Technik) in Germany (Hoffstadt 1981; Daduna and Mojsilovic, 1988) and COMPACS (COMPuter Assisted Crew Scheduling) at the University of Leeds (Wren *et al.*, 1985)

According to Wren (1998), the approach taken by TRACS is first to create an initial schedule that satisfies all the labour agreement constraints, then a set of refining heuristics is applied to the schedule generated in order to try to improve its quality (both in terms of number of duties and costs). An initial schedule is constructed in the following steps: form early duties from the beginning of the bus schedule; construct late and middle duties at the end of the bus schedule; put together split duties by matching early duties with late or middle duties; attach remaining work to existing duties if possible.

This initial schedule contains two-spell and three-spell duties. A concept of marked time is used to guide the formation of duties. For early duties, a marked time is the latest time by which the first crew of each bus must be relieved. For late duties, a marked time is the earliest time at which the last crew can start work on each bus. To minimise the number of crews during peaks hours, meal break chains are designed so crews can take meal breaks in turn (Fores *et al.*, 1998; Wren *et al.*, 2003).

The initial schedule is improved by two sets of procedures (Fores *et al.*, 1998). The first set attempts to reduce the number of duties by considering every duty and whether it can be fitted in with other duties. This procedure redistributes work between duties so that duties with long spreadovers are assigned with more work. This makes short duties become shorter and they subsequently can be removed. The second set is intended to reduce costs by implementing several procedures including swapping or moving parts of duties, re-matching first and second parts of stretches of duties, switching the relief point of a duty to another relief time, and relocating short pieces of work around the middle of the day.

Parker and Smith (1981) reported that TRACS was implemented in the 1970s for several UK bus companies with some success. These include Bristol Omnibus Company, Midland Red, Cleveland Transit, West Yorkshire Passenger Transport Executive, Greater Glasgow Passenger Transport Executive and Great Manchester Passenger Transport Executive. However, Parker and Smith (1981) observed that modifying the programme to work with different labour agreement rules could be difficult.

RUCUS was developed in the late 1960s. According to Bodin *et al.* (1985) RUCUS first generates an initial solution and then refines it using heuristics. First, one spell duties are formed then two spell duties, finally, any unallocated pieces of work are considered as overtime duties. After the initial schedules are ready, the system begins to use local search to improve the schedules. It either exchanges parts of work with other duties, or moves selected relief points forward or backward. A repair procedure is then used to fix any unfeasible duties due to the changes. In case there are still unfeasible duties left in the final schedules, manual interventions are used.

HOT was developed and has been used by schedulers at Hamburger Hochbahn AG since the 1970s (Daduna and Mojsilovic, 1988). It starts by trying to form good duties, one at a time, for early buses, and then for late buses. Any pieces of works that cannot fit into the initial schedules are formed into partial duties, which are then combined into full duties by a variant of the Hungarian Algorithm (Taha, 1997). Little improvement can be achieved to the schedule once it is constructed, and sometimes it may even leave unassigned pieces of work (Wren and Rousseau, 1995).

COMPACS (COMPuter Assisted Crew Scheduling) is an interactive system developed in the early 1980s (Wren *et al.*, 1985), and later incorporated into the BUSMAN scheduling package (Chamberlain and Wren, 1992). According to Wren *et al.* (1985) COMPACS is designed to operate in two different ways. One way is to produce an entire duty schedule automatically using heuristics similar to those used in TRACS. The schedule is then created quickly with no interaction from the user. The second produces a duty schedule in an interactive fashion. Users can create their own duties to add to the schedule or ask COMPACS to form duties, which can then be accepted or rejected as seen by the scheduler. At any point the scheduler can have COMPACS finish the partially created schedule automatically. The scheduler also has complete control over the schedule through facilities to edit or delete duties, which are already present in the schedule.

2.3.3 Mathematical Programming

Mathematical programming approaches usually formulate a crew-scheduling problem as a set-covering problem. A set-covering model is established to find a set of feasible duties covering all pieces of work and minimising the total costs of the operation (Smith and Wren, 1988; Wren and Rousseau, 1995; Fores *et al.*, 2002). If the objective is to cover each piece of work with exactly one duty, then it is called a set-partitioning model. Mitra and Darby-Dowman (1985) proposed a "generalized set partitioning" formulation that allows the algorithm to choose a solution that does not cover all of the work pieces if there is no solution covering all the work pieces.

There are three different approaches for solving the problem (Banihashemi and Haghani, 2001). First, formulating the problem as an integer linear programming model then finding the best combination of the feasible duties. Smith and Wren (1988); Paixão (1990); and Paias and Paixão (1993) followed this approach. Second, a column generation approach is used but within a limited number of feasible duties. Carraresi *et al.* (1995) and Fores *et al.* (1999) adopted this approach. Third, the solution procedure starts from a set of feasible pre-constructed duties but it continues to produce other feasible duties if they could improve the solution. Desrochers and Soumis (1989) have implemented this approach.

IMPACS (Integer Mathematical Programming for Automatic Crew Scheduling) is a crew scheduling software package developed by the Operational Research Unit at the University of Leeds in the late 1970s (Parker and Smith, 1981; Smith, 1988; Smith and Wren, 1988). This system was installed in London Transport in 1984 and in Greater Manchester Buses in 1985. A large number of possible duties with associated costs are first generated; a subset is then selected to cover all the pieces of work at minimum cost. As the number of variables and constraints could be too enormous to be handled for the computer power at that time, IMPACS employed a number of heuristics to reduce the number of variables and constraints. IMPACS also used the branch-and-bound algorithm to obtain the integer solution for the constructed set covering problem.

TRACS II (Techniques for Running Automatic Crew Scheduling, Mark II) was developed in 1994 also by the Operational Research Unit at the University of Leeds and is being used by many bus and train companies in UK (Willers *et al.*, 1995; Fores *et al.*, 1999; Fores *et al.*, 2001). TRACS II has shown significant savings when compared with standard methods for scheduling drivers of railways and buses, and has helped to negotiate more flexible working rules with the trade unions. TRACS II follows almost the same approach as IMPACS, but the components have been considerably redesigned to cope with the complexity of rail operations and to incorporate new algorithmic advances. Generally, it consists of seven modules (i.e., VALIDATE, TRAVEL, BUILD, SIEVE, SCHEDULE, REDUCE, and DISPLAY). Fores *et al.* (1999; 2001) explain details of all these modules.

HASTUS (Lessard *et al.*, 1981; Rousseau and Blais, 1985; Blais and Rousseau, 1988) is a widely used commercial package with a graphical user interface that deals with crew scheduling, vehicle scheduling, and rostering. The HASTUS crew scheduling component is divided into two parts, HASTUS-micro and HASTUS-macro. HASTUS-macro constructs an initial schedule and HASTUS-micro produces the final schedule. HASTUS-macro uses linear programming to generate a pseudo-schedule that provides an estimate of the number of crews needed. The pseudo-schedule is built by pseudo-shifts, which are generated using simplified relief points by simply cutting the day into user-defined time slots. Then HASTUS-micro uses the pseudo-schedule to create a final schedule by producing real duties that relate to those in the HASTUS-macro solution as closely as possible.

EXPRESS (Falkner and Ryan, 1992) is a bus crew scheduling system based on a set partition model specially developed for Christchurch Transport, New Zealand. Its earlier version and a study of the use of set partition are presented in (Falkner and Ryan, 1988). During the search process, the strictness of the model is diminished by the addition of slack variables. It then uses a ZIP package (Zero One Integer Programming Package for Scheduling by Ryan, 1980) similar to those being used in IMPACS and TRACS II. However, its branching model is slightly different. In this system, the branch and bound algorithm branches on the pieces of work (constraint branching) rather than the relief points.

Freling *et al.* (2001, 2003) use Lagrangean relaxation with column generation to find solutions for a set partitioning based model and solve integrated vehicle and crew scheduling problems. Huisman *et al.* (2003) extend the work of Freling *et al.* (2003) to the multiple depot case. They present two similar formulations for the multiple depot vehicles and crew scheduling problem, incorporating variables for both crew schedules and vehicle arcs. The problems were solved using Lagrangean relaxation with column generation with the extra restrictions that: drivers are only allowed to operate vehicles stationed at their home depot; a maximum of only one vehicle change is permitted in a crew schedule, significantly simplifying the column generation sub algorithm; and not all trips can be driven by a vehicle operated out of any depot. Huisman and Wagelmans (2006) extended their works on a dynamic integrated vehicle and crew-scheduling problem that will reschedule the crew and bus simultaneously, whenever lateness occurs. Several reschedulings could occur in a single day. The method produced good results but they have still not been tested in a real life setting.

2.3.4 Other Approaches

In this subsection we discuss approaches that do not belong to heuristics and mathematical programming. These approaches include genetic algorithms (Wren and Wren, 1994; Clement and Wren, 1995; Kwan *et al.*, 1999), tabu search (Cavique *et al.*, 1999; Shen and Kwan, 2001), ant system (Forsyth and Wren, 1997), and constraint programming (Layfield *et al.*, 1999).

Wren and Wren (1994) carried out a feasibility study to test whether or not genetic algorithms could be used to solve larger crew scheduling problems more robustly, more quickly, and more cost-effectively than other methods. The bus schedules are represented as chromosomes and the values of each gene identifies the duties that cover it. Then duties are discarded or chosen from the complete set until the bus work is covered and no duty is redundant (Wren and Wren, 1994). Processes based upon genetic algorithm techniques of crossover (forming a schedule from a combination of two or more others) and mutation (slightly altering a schedule in some small way) can be applied to the schedule in the hope of producing better solutions and allowing a limited number of schedules to evolve. Results obtained using genetic algorithm approaches without the option of mutation, and with limited constraints on small test problems, produced very good solutions quickly, encouraging further investigation.

Further work was carried out by Clement and Wren (1995), which depicted chromosomes as an unordered set of duties, each with a binary value dependent on whether or not the duty is present in schedule. Different methods of crossover and mutation techniques were experimented with and tested on three real world problems. Although the genetic algorithm was successfully applied to real world scheduling problems with relatively limited research, the results produced were generally poorer than those of more established techniques (Clement and Wren, 1995).

The method by Clement and Wren (1995) was subsequently modified by Li and Kwan (2003) by incorporating fuzzy set theory. Li and Kwan (2003) used a greedy heuristic method to collect sets of duties. These sets are then evaluated using fuzzy set theory. A genetic algorithm with fuzzy evaluation is processed repeatedly in a number of steps. The objective is to find a schedule cover with minimum cost using the minimum number of duties. The genetic algorithms are used to fine-tune the objective by evaluating the structure using multi-starting points. This is done repeatedly in five steps. The main finding is that the approach produces a near-optimum weight distribution for large size real life problems.

Tabu search is an iterative technique that moves step by step from an initial solution towards a solution close to the global optimum. Cavique *et al.* (1999) used tabu search to reduce the number of pre-generated shifts. The algorithm iteratively removes some inefficient shifts, and sometimes their adjacent shifts from the current solutions, and then applies the re-cutting algorithm to construct shifts to repair the broken schedule. The result was found very efficient at improving the initial solution after the first few iterations, but it was then found it difficult to make further improvements.

Shen and Kwan (2001) developed HACS (Heuristics for Automatic Crew Scheduling), which also used a tabu search to get rid of infeasibility shifts and fulfill the objectives. Four neighborhood structures were applied, namely: swapping two links, swapping two spells, inserting one spell, and recutting blocks. The first three concentrate on refinement of links with fixed relief opportunities, while the last one considers variable active relief opportunities while links are reconstructed. HACS starts from a rough initial solution, and can deal with complex problems by simply adjusting the cost function and the penalty function to the rules stipulated in specific problems.

Ant colony optimization was developed by Dorigo *et al.* (1995) based on the behaviour of ants searching for food, which can be modelled into a search algorithm. The fundamental idea is that when ants move they leave pheromone trails that can be detected by other ants and which slowly evaporate over time. Forsyth and Wren (1997) used virtual ants to trace paths through a bus schedule (with the paths representing crew duties) to create crew schedules from pre-generated duties. Each ant will create a solution at each iteration. A heuristic approach is used to select relief points, and then the ant chooses a duty from the set that starts at that relief point. The process repeats until the entire bus works are covered. Good duties will be used more often by the ants and be more likely to be chosen for a crew schedule.

Constraint programming provides a powerful and easy system for modelling restrictions and using these restrictions to search for a solution (Tsang, 1993). Layfield *et al.* (1999) used constraint programming to remove relief points that are unlikely to be used in good schedules, thus reducing the problem size. The program first produces the morning part of the schedule simulating the manual scheduling process. It puts a limit on the number of spells to prevent too short duties being produced. A morning schedule is constructed by using randomised heuristics to build the partial schedule one duty at a time. Several morning schedules are constructed, and the relief points not used in these schedules are removed. Then the algorithm performs iterative process to construct a feasible crew schedule that satisfies all the constraints. This program can also be used to produce the evening part of a schedule. The process has speeded up TRACS II in several cases, but its solution cost is mostly slightly higher (Layfield *et al.*, 1999).

2.3.4 Critiques of the Current Approaches

In this section we will provide a brief critique of the approaches described in the previous subsections. The aim is to assess whether or not they are able to deal with the UE problem. If there is any approach which can, then we will investigate details of that approach and identify its advantages and disadvantages.

Heuristic approaches rely upon the knowledge of expert schedulers and they are useful in some applications, since they were customised for individual companies and thus could be fully tailored to meet the specific requirements for individual companies. However, these approaches were not easily adaptable to other companies and had to be substantially modified to fit new conditions. Furthermore they were not suitable for general optimisation (Wren and Rouseau, 1995; Wren, 1998). Regarding the ability to deal with UE in real time, we find that heuristic approaches do not have a feature to deal with them. To the best of our knowledge, none of the heuristic approaches touch the issues of UE. We believed that as most of the approaches were employed in the early stage of automated-scheduling (before the 1980s), the prime goal is to automate the scheduling process and obtain an optimum schedule or at least the same results as produced through the manual way of scheduling. This is due to the fact that automating and finding an optimum schedule is really hard task and proven to be NP-Hard (Wren and Rousseau, 1995; Fores *et al.*, 1998; Kwan *et al.*, 2000; Wren, 2004).

Mathematical approaches were the most appealing in terms of commercial prevalence. According to Wren (2004), integer programming combined with heuristics is the best near-optimum solution currently available. This is supported by the fact that most of the prominent scheduling packages use this approach such as IMPACS (Parker and Smith, 1981; Smith and Wren, 1988), HASTUS (Lessard *et al.*, 1981; Rousseau and Blais, 1985), EXPRESS (Falkner and Ryan, 1992), and TRACS II (Willers *et al.*, 1995; Fores *et al.*, 1999, 2001, Wren *et al.*, 2003). However, to the best of our knowledge, most of the mathematical approaches do not have mechanisms for dealing with the UE problem, except in TRACS II and the research by Huisman and Wagelmans (2006). In our opinion, the reason why most of them do not have mechanisms for dealing with UE is because obtaining optimum schedules is the main issue. The issue of UE has become important only recently because of privatisation and the subsequent demand for quality service (Huisman and Wagelman, 2006). That is supported by the fact that research looking at UE only started to emerge in 2003. Although TRACS II was developed in 1994, its flexibility utilities were only reported in 2003 (Wren *et al.*, 2003; Kwan *et al.*, 2004).

There is a limitation in TRACS II when it comes to dealing with UE. According to Wren *et al.* (2003), TRACS II only deals with planned changes, that is, those which can be predicted several days or weeks in advance, and with not day-to-day unpredictable events. Wren *et al.* (2003) argue that any automatic approach that changes crew schedules in real-time has to rely on the crews' acceptance of new workings, which may extend the working day and interfere with leisure activities. However, Wren *et al.* (2003) suggest that it is possible any real-time system can rely on the data produced by TRACS II, and when UE take place the real-time system will generate a number of possible quick responses, which may be discussed with the crews involved. This suggestion by Wren *et al.* (2003) supported the fact that UE are an important issue and TRACS II is still not fully capable in dealing with UE and the urgent need for automatic real-time systems.

Huisman and Wagelmans (2006) have proposed a dynamic integrated bus and crew scheduling system that will reschedule the crew and bus simultaneously whenever lateness takes place. Several reschedulings may be required in a single day. The method produced good results but there are a few assumptions in the research that are not feasible in the real world. First, "passengers have a higher priority than crews". Thus, there is a possibility of violation of crew rules whenever a bus is late. That means crews may have to shorten their break or not take a break just to make sure the bus is running on time. Although this is appropriate to guarantee that bus service run smoothly, EU driving rules should not be broken which is the case here. Furthermore, this is not acceptable to the crew. Second, "a trip can only start late due to a delay of the vehicle and not due to the crew". This assumption is not realistic due to the fact that the crew is one of the causes of UE. Third, "the number of vehicles and crews is unlimited". This is not possible as bus companies usually have a limited number of buses and crews.

Mathematical programming approaches have had more success in obtaining optimum schedules. However the nature of the mathematical approach is such that each computer run may take a long time and larger problems have to be sub-divided, and there is no guarantee that an integer solution can be found within practical computational limits (Kwan *et al.*, 1999). Other approaches (genetic algorithm, tabu search, ant system, and constraint programming) aim to tackle these shortcomings. Some of the approaches were reported producing good results when compared to heuristics such as genetic algorithm (Li and Kwan, 2001; 2003). However, the capability of these approaches for dealing with UE there is still not present. In our opinion, the reason for is because this is not part of their aim, thus their attention and direction is only directed towards obtaining optimum schedules.

In summary, although the current approaches have been successful in finding optimum or near-optimum schedules, more research is needed to develop approaches that would effectively cope with the UE problem. When considering scheduling of public transport, the management of UE, such as lateness, delay and crew unavailability, are of paramount importance. To cope with these conditions the scheduling system needs to have some mechanism for dynamically rescheduling previously agreed schedules in real-time. To tackle this issue this research proposes a MAS approach to bus crew rescheduling that is able to reschedule in real-time without disrupting the whole schedule. The definition and descriptions of MAS is provided in the Section 2.5. Prior to that, the following section presents interviews with bus companies that tell us practical experiences of bus companies in day-to-day operation especially in dealing with the UE problem.

2.4 Interviews with Bus Companies

There is much evidence related to the UE problem provided in the literature as discussed in Section 2.2. However, there is very little literature that discusses how a typical bus company manages the resource (crew) whenever an UE occurs that may disrupt the schedule, particularly the crew schedule. Therefore, the aim of these interviews is to acquire knowledge about the practical experiences of bus companies in managing unpredictable events. Below are the objectives of the interviews in detail:

1. To identify and confirm the main types of UE that are likely to occur and what effect they have on everyday operation.
2. To understand how a typical bus company manages UE problems that lead to schedule disruption.
3. To gain awareness of tools or software that assists them in managing and controlling the UE.
4. To investigate the possibility of using technology to help in managing the UE concerning crew schedules disruption.

We used interviews as a tool to achieve the aim and objectives stated above. There are two types of interviews: structured and unstructured in-depth interviews (Denzin and Lincoln, 1994). A structured interview is suitable for a topic that has already been researched in detail, the interviewer knows enough about the background of the situation to ask exactly the right questions, and obtain appropriate answers. However, in this interview the topic is the practical experiences of bus companies, which is new to the interviewer and no research discusses this in detail, thus an unstructured interview, which is flexible and informal, is more appropriate. Furthermore, unstructured interviews make the respondent feel natural and also encourage them to talk more about issues of interest to the research.

We contacted the main bus companies in London through email and telephone, and told them our objectives of research and asked their cooperation in providing the information that we were looking for. Five of the companies replied but only three were ready for interview. The interview was conducted with the person in charge of operations who had substantial knowledge of scheduling and everyday operations. The interview for each was informal and unstructured. However, there was a set of questions (Appendix A), which were set as a guideline to the interviewer. The set of questions was divided into four sections. Section A was about planning and scheduling, Section B about crew scheduling, Section C about operational problems and Section D about the improvement of the scheduling package. The next sub-sections will describe in detail the background of the companies and the interview's outcome.

2.4.1 Background of the Companies

Three London bus companies were chosen for the interviews. For reasons of confidentiality, they are referred to as Company A, Company B and Company C. These companies operate in a regulated environment under contract with Transport for London (TFL). These contracts are awarded for five or seven years via a rolling tendering programme.

Company A consists of two subsidiary companies in London. They operate over 1300 buses, employ over 3900 staff, and operate from 9 garages. Company A provides nearly 15% of the London market, and account for approximately 260 million bus journeys annually on about 100 day and night routes. One of the subsidiaries runs 600 buses in southeast and central London from 4 garages. Another operates a fleet of 700 vehicles in southwest and central London from 5 garages.

Company B operates a fleet of over 650 buses on 60 routes within central and southwest London and a neighbouring county. The company employs over 2,000 people of whom 1,600 are drivers. The company also operates from 6 garages.

Company C employs about 4200 staff and operates around 1300 buses. Company C operates bus services on behalf of London Buses from 10 garages. Company C also operates a London airport shuttle bus service and has a small coach subsidiary, which operates a series of day trips within the UK and on the continent as well as providing vehicles for private hire.

2.4.2 Describing the interviews

The full descriptions of the responses from the interviews are shown in Appendix B. This section describes the outcomes based on the objectives as presented in Section 2.4. According to the first objective – concerning the types of disruptive events likely to occur and what effect they have on everyday operation – there are a number of problems caused by crew, traffic and vehicle, traffic being the most problematic, which no one can predict and control. According to Company C, Friday is usually the most unpredictable day because Friday is the last working day and people might want to enjoy or organise a gathering or march. In addition, sometimes roads may be closed due to security alerts, demonstrations, or accidents. Also, motorists sometimes use bus lanes, which are special lanes allocated for buses, or park near bus stops also adding to traffic problems. On the other hand, there are some crew related problems such as crew not coming without prior notice, sick while on duty or coming late. The vehicle itself is usually the least cause of problems. Vehicle breakdown either on the road or in the garage is another cause of delay.

The second objective – how a typical bus company manages unpredictable events that are related to everyday schedules – is managed by supervisors at garages. The supervisor's main job is to make sure that the services operate smoothly. The supervisor will make any appropriate adjustments or changes to the schedule. There is no standard procedure for dealing with the problems and it is solely based on the supervisor's experience.

Everyone agrees that there is no absolute solution for traffic problems. When the problem occurs, the bus will be late and will not run according to the schedule. That is why times (vehicle) schedules take into account recovery time concerning traffic problems. However, when they occur they will be resolved on a case-by-case basis. For example, if there is a route closed due to accident or security alert, then the driver has to re-route the service. This, however, may cause the service to skip a few stops from the bus route.

A crew related problem is if a crew comes late for a duty, then the duty will be reassigned to another crew that is available at that time. When the original crew comes they will be assigned to a different duty. However, if a crew member does not come at all then the duty will be assigned to a standby crew at the garage. Company A has a policy that the number of spare drivers should be at least 20% of the total number. Other companies did not provide any specific figures for this. If a crew is sick on duty, which happens quite often (according to company A), then he/she has to change at a depot or a relief point or nearest stop whatever possible. The spare crew will then take over the remaining duty. If a bus has a problem then it will be substituted with any available bus at that moment or spare bus. If a bus breaks down during the journey, then the bus has to stop at the nearest stop and the supervisor will be contacted. A replacement bus will be sent from the nearest depot. Company A has a policy that spare buses should be at least 20% of total buses. Other companies did not provide a specific figure for this.

According to objective three – regarding tools or software that assist in managing and controlling the UE problem – there are tools such as radio, AVL (Automatic Vehicle Locator) and GPS (Global Positioning System). These tools only help in locating buses and communicating with crews. However, there is no software or tool that assists the supervisor to adjust the affected schedule. Any adjustment or reassignment is done manually. Available scheduling packages do not offer this feature as they can only perform total rescheduling.

According to objective four – concerning using technology to help in managing unpredictable events – all of the respondents agree that it is a good idea to have a dynamic schedule that is able to perform rescheduling for only the particular time or disrupted day. However, one of the interviewees indicated the difficulty of achieving this, especially when using traditional algorithms, due to the complexity of the problem.

2.4.3 Interview Analysis

There are a number of lessons that could be learned from these interviews. For example, most bus companies have more or less similar codes of operation. The crew schedules produced by schedulers are mostly based on scheduling packages such as Trapeze

(Company B), IMPACS (Company A) and CAP GEMINI (Company C), each with the sole objective of achieving an optimum schedule. Once such a schedule is produced then it is up to the supervisors to manage the schedule manually. The supervisor has various responsibilities. The main responsibility is to make sure that all buses run on time based on the predetermined schedule. The bus company has to comply with the schedule that has been agreed upon with the TFL. If the company does not perform well, the contract will be suspended. Other than that, the supervisor has to manage the schedules (concerning times, crew, and rota (crew rosters)), manage the crews themselves, and the buses in everyday operation. These responsibilities are immensely hard especially when dealing with UE.

All companies agree that UE are likely to take place every day and every time. As mentioned in the previous section, the event can be caused by problems related to traffic, crew or vehicle. As Company C claimed, no two days are the same and Friday is probably the most likely day for such unforeseen events such as marching, accidents or bad traffic congestion to occur. There is no absolute solution, which means they have to manage the problem case-by-case.

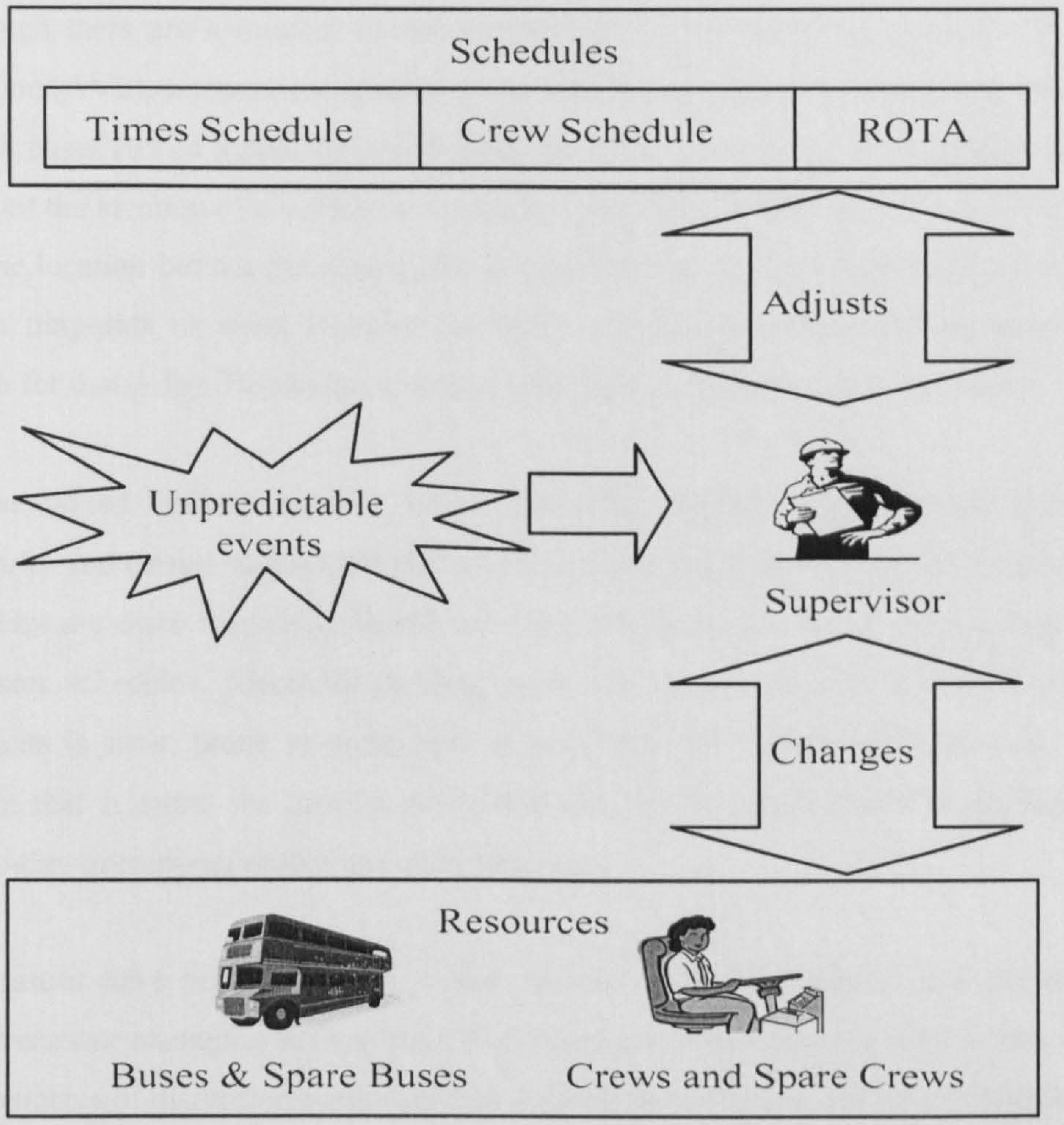

Figure 2.3: Supervisor Manages the Unpredictable Events in Everyday Operation

Based on the interviews, the role of a supervisor in dealing with UE is illustrated in Figure 2.2. The supervisor has time schedules, crew schedules, and ROTA schedules. Time schedules show the movement of each bus, time against location, while crew schedules show the activity for every duty from sign-in to sign-off. ROTA schedules show which person is assigned to what duty. Then the supervisor has to manage resources i.e. crews and buses. When a certain UE problem occurs, the supervisor must perform appropriate adjustments to the schedule or change resource allocation. Time and crew schedules will remain the same. Only re-allocation or reassignment is done to cover the schedule. For instance, if a bus is broken down then a spare bus will be allocated to cover the remaining schedule. Similarly, if a crew is not coming, then his duty will be assigned to a spare crew.

Although there are a number of management tools, for example, Automatic Vehicle Location (AVL), a supervisor still has to manage buses and crews properly to make sure that all buses run on a predetermined schedule. AVL is an automatic tool that is able to pinpoint the location of a vehicle in operation. According to Company C, AVL can give you the location but not the reason. For example, if Bus A is 15 minutes late, the AVL screen pinpoints its exact location, however, it does not provide the supervisor the reason for that delay. He/she has to contact the crew by radio to know the reason.

As mentioned earlier, existing crew scheduling systems only provide optimum schedules and do not support the process of real-time rescheduling, whilst rescheduling activities are done manually. However, when UE problems occur, they disrupt such optimum schedules. Manually tackling such problems is usually hard and making decisions is slow, prone to error and not optimum. This necessitates the need for a system that supports the process of rescheduling to help supervisors in dealing with day-to-day operational problems concerning crew.

Two issues have been discussed in this section - the UE problem and the role of supervisors in managing such events. The first issue shows that the crew is one of the main sources of disruptive events and has a substantial effect on the crew schedule, thus everyday operations. The second issue is that the supervisor plays a major role in managing UE and crew rescheduling is a way of dealing with such events, which currently is done manually. To tackle the above issues, this research proposes an automated crew rescheduling using a MAS that is able to reschedule crew in real-time. The definition and descriptions of a MAS is provided in Section 2.5. Chapter Three will discuss details of the proposed system.

2.5 MAS Approach

The aim of this section is to point out the basic concepts and issues associated with the MAS approach. Before that, we draw out some reasons why we want to use a MAS for the automated crew rescheduling system. The following subsections present the motivations for using a MAS for automated bus crew rescheduling system, provides an introduction to agent and a MAS, and discusses MAS interaction and communication, and the application of a MAS in scheduling.

2.5.1 Motivations to Use MAS

The critique of current approaches (Section 2.3.4) explains that most of the current approaches in bus crew scheduling are concentrated on achieving optimum schedules, and they succeed in finding an optimum or near-optimum schedule (Wren, 2004). However, very little research considers minimising the effect of UE problems on crew schedules (such as Huisman and Wagelman, 2006; Wren *et al.*, 2003). Based on the practical experiences of bus companies (as discussed in Section 2.4.3: Interview Analysis), UE problems caused by traffics, crews or vehicles are likely to take place every day and every time. There is no absolute solution, and the supervisor has to manage the problem case-by-case.

A supervisor has great responsibilities to make sure buses operate on schedules, to manage resources and to deal with UE problems. In the occurrence of UE, a supervisor must perform appropriate adjustments to the schedule or change resource allocation. Crew rescheduling is a way of dealing with such events, which is currently done manually. As mentioned in the critique of current approaches and confirmed by the findings from the interviews, existing crew scheduling systems only provide optimum schedules and do not support the process of real-time crew rescheduling. Manually tackling such problems is usually hard and making decisions is slow, prone to error and not optimum. These limitations necessitate the need for an automated system that supports the process of crew rescheduling to assist supervisors in dealing with UE problems that affect crew schedules.

There are two important characteristics in crew rescheduling that should be borne in mind before selecting a tool to implement the proposed solution. The characteristics are the nature of the UE problem and the desired solution. The nature of UE problems are uncertain and not uniform (no one knows what/when will happen and how it will happen). The solution desired is as quick as possible (within seconds or minutes). The capability to react in an uncertain environment whilst at the same time providing quick solutions in real time are essential for automated crew rescheduling systems. The selected tool should be able to fulfil these requirements in order to achieve the aim of the proposed system.

Current approaches such as heuristics, mathematical and others have some limitations as discussed in the critiques of current approaches. Heuristics approaches are not easily adaptable, and they were not suitable for general optimisation (Wren and Rouseau, 1995; Wren, 1998). Mathematical approaches are usually slow to produce results because they are computationally intensive when it comes to complex situations (Kwan *et al.*, 1999). Other approaches (genetic algorithm, tabu search, ant system, and constraint programming) were not reported to have capabilities in operating in uncertain environments. These limitations as mentioned above prevented us from adopting such approaches for the proposed system.

Alternatively, a MAS can fulfil the requirements mentioned above and be capable of reacting in uncertain environments and providing quick solutions in real time (Jennings *et al.*, 1998; Ferber, 1999; Wooldridge, 2002). A MAS has been used for other scheduling fields (meeting scheduling, manufacturing scheduling, events scheduling and etc.) where similar problem are faced i.e. uncertain environment. The following subsections explain details of a MAS theoretical description and the use of a MAS in scheduling.

2.5.2 Introduction to Agent and MAS

MAS is a relatively new field of research. These systems have only been studied since about 1980, and the field has only gained widespread recognition since about the 1990s (Oliveira *et al.*, 1998; Wooldridge, 2002). MAS have become more important in many aspects of computer science by introducing the issues of distributed intelligence and interaction. MAS seem to be a natural metaphor for understanding and building a range of what were called artificial social systems. They represent a new way of analysing, designing, and implementing complex software systems (Jennings *et al.*, 1998).

What is an agent? Ranges of definitions from different disciplines have been proposed for the term agent. There is no commonly accepted definition of the term, and there is much continuing debate on this matter (Jennings *et al.*, 1998; Wooldridge, 2002).

According to Maes (1995), agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realise a set of goals or tasks for which they are designed. Wooldridge and Jennings (1995) define an agent as a computer system that is situated in some environment and that is capable of flexible and autonomous action in this environment in order to meet its design objectives. By flexible, it means that the system must be responsive, proactive, and social. Ferber (1999) describes an agent as a physical or virtual entity which is capable of acting and perceiving in an environment, can communicate directly with other agents, possesses resources, skills and can offer services. Its behaviour tends towards satisfying its objectives, taking account of the resources and depending on its perception, and the communication its receives.

What is MAS? Ferber (1999) defined MAS as a system composed of a population of autonomous agents, which interact with each other to reach common objectives, while simultaneously each agent pursues individual objectives. Oliveira *et al.* (1998) defined MAS as a collection of possibly heterogeneous, computational entities, having their own problem-solving capabilities able to interact in order to reach an overall goal. According to Jennings *et al.* (1998) a MAS's main characteristics are that each agent has incomplete information, or capabilities for solving the problem, each agent has a limited viewpoint, there is no global system control, data is decentralised, and computation is asynchronous.

Two main MAS architectures have been addressed in the literature: blackboard and autonomous architectures (Jennings *et al.*, 1998; Ferber, 1999). Early MAS were based on the blackboard model proposed by Hayes-Roth (1985). The blackboard architecture is based on the idea that problem solving could result from the opportunistic activation of specialists, the "knowledge sources". The activity of the "knowledge sources" consists of putting down, modifying, and withdrawing solution elements within a common working area, called a blackboard. A centralised control mechanism is used to activate the "knowledge sources". According to Ferber (1999), blackboard architectures cannot be considered as MAS as they do not respond to the characteristics of MAS. In autonomous architectures, the agents are not controlled or managed by any other agents, rather they communicate and interact directly with any other agent in the system to achieve the global objective (Jennings *et al.*, 1998; Ferber, 1999). Knowledge and control are distributed, in the sense that each agent embodies its own knowledge and control.

2.5.3 MAS interactions

MAS achieve its objectives through interactions between agents. The interactions can be categorised as cooperation, coordination, and negotiation (Jennings *et al.*, 2001). According to Doran *et al.* (1997), cooperation occurs when the actions of each agent satisfy either or both of the following conditions: agents have a possible goal in common, which no agent could achieve in isolation; agents perform actions, which enable or achieve not only their own goals, but also the goals of agents other than themselves.

Jennings (1996) defines coordination as the process by which an agent reasons about its local actions and the anticipated actions of others to try and ensure the community acts in a coherent manner. According to Nwana *et al.* (1996), coordination is a process in which agents engage in order to insure their community acts in a coherent manner. Coherent means that the agents' actions work well, and that they do not conflict with one another. The main approaches that have been developed for coordinating activities are centralised planning, multi-agent planning, game theory, and negotiation (Nwana *et al.*, 1996; Jennings, 1996; Ferber, 1999; Wooldridge, 2002).

Negotiation is a widely used technique for conflict resolution in MAS. It is the most fundamental and powerful mechanism for managing inter-agent dependencies. Negotiation is the communication process of a group of agents in order to reach a mutual accepted agreement on some matter (Bussman and Muller, 1992). For Wooldridge (2002), negotiation proceeds in a series of rounds with every agent making proposals, trading options and offering concessions at every round. The proposals that agents make are defined by their strategy, must be drawn from the negotiation set, and must be legal, as defined by the protocol. If agreement is reached, as defined by the agreement rule, then negotiation terminates with the agreement deal. Jennings *et al.* (2001) defined a generic framework of negotiation. In this framework, negotiation can be viewed as a distributed search through a space of potential agreements. For a given negotiation, the participants are the active components that determine the direction of the search. The minimum requirement of a negotiating agent is the ability to make and respond to proposals. To improve the efficiency of the negotiation process, the recipient needs to be able to provide more useful feedback on the proposals it receives. Various negotiation methods have been defined in literature, and most of them are inspired by human negotiations that are market-based, plan-based, game theory-based, and artificial intelligence based. (Kraus, 1997; Faratin *et al.*, 1998; Jennings *et al.*, 2001).

Market-based negotiation is the simplest and the most renowned negotiation protocol, and the most widely used in agent-based systems is the contract net protocol involving offers, bids, and contracts (Nwana *et al.*, 1996; Beer *et al.*, 1999; Shen and Norrie, 1999; Jennings *et al.*, 2001; Shen *et al.*, 2001). It is a high-level negotiation protocol that provides many advantages and most important is its flexibility and dynamic nature, which suits industrial agent-based applications.

Plan-based negotiation is based on cooperation strategies for resolving conflicts among plans of a group of agents. Laasri and Lesser (1990) described a three-phase cycle negotiation plan. This model of negotiation could be centralised or distributed.

Game theory-based negotiation employs techniques based on game theory to structure and organise negotiation between the agents (Nwana *et al.*, 1996; Jennings *et al.*, 2001). The key concepts in the game theory approaches are utility functions, a space of deals, strategies, and negotiation protocols.

Artificial Intelligence based negotiation considers negotiation as an iterative activity and Sycara (1991) exploited case-based reasoning in this iterative process. Sycara (1991) argued that human negotiators draw from past negotiation experiences to guide present and future decisions.

2.5.4 MAS Communication

In MAS, communication is the basis for interactions and social organisations. Communication enables the agents to cooperate, coordinate their actions, and carry out tasks jointly resulting in systems that are more coherent. A number of communication languages have been developed for inter-agent communication, and the most widely used ones are KIF (Knowledge Interchange Format) (Genesereth and Fikes, 1992), KQML (Knowledge Query and Manipulation Language) (Finin *et al.*, 1994), and ACL (Agent Communication Language)(Labrou *et al.*, 1999). Currently, XML (Extensible Markup Language) has started to show its performance as a language to encode messages exchanged between agents, in particular in agent-based e-commerce to support the next generation of Internet commerce (Glushko *et al.*, 1999; Korzyk, 2000; Turowski, 2002).

Several modes of communication have been defined that are shared data and message passing (Ferber, 1999; Shen *et al.*, 2001; Weiss, 1999; Wooldridge, 2002). Repository is a common shared data repository, i.e. a blackboard. A blackboard is used by agents to write messages, post partial results, and obtain information. This mode of communication is used in blackboard architectures.

Message-passing communication is a widely used approach. In the message-passing approach, agents communicate with each other by sending asynchronous messages. Asynchronous communication is the primary mode of interaction in most agent-based applications. There are two basic message types: assertions and queries (Weiss, 1999). Every agent, whether active or passive, must have the ability to accept information. In its simplest form, this information is communicated to the agent by means of an assertion. In order to assume a passive role in a dialogue, an agent must additionally be able to answer questions, i.e. it must be able to accept a query from another agent and send a reply to the agent by making an assertion. In order to assume an active role in a dialogue, an agent must be able to issue queries and make assertions. With these capabilities, the agent then can potentially control another agent by causing it to respond to the query or to accept the information asserted.

There are several methods of communication in message-passing mode. There are point-to-point, broadcast, and multi-cast (Weiss, 1999; Wooldridge, 2002). In point to point communication an agent sends a message to another specific agent. In broadcast, an agent sends out a message to all other agents in the system, and in multi-cast, an agent sends out a message to a selected group of agents.

Formalisms for representing communication in agent theory tend to be based on speech act theory (Wooldridge and Jennings, 1995; Ferber, 1999; Weiss; 1999; Wooldridge, 2002), as originated by Austin in 1962, and further developed by Searle in 1969 (Wooldridge and Jennings, 1995). The key principle of speech act theory is that communicative utterances are actions, in the same sense that physical actions are. They noticed that a certain class of natural language utterances or speech acts had the characteristics of actions, in the sense that they change the state of the world in a way analogous to physical actions. They observed that most things people say are not simply propositions that are true or false, but are performatives that succeed or fail. Since the early 1990s, speech act theories have directly informed and influenced a number of languages that have been developed for agent communication, such as KQML and ACL. In KQML and ACL, each message has a performative (a class of the message) and a number of parameters to describe the format of the message (sender, receiver, content, etc.). The most important differences between these two languages are in the collection of performatives they provide.

2.5.5 Application of MAS in Scheduling

The advantages of MAS have led to increasing interest in the application of MAS in different fields of research, including scheduling. The advantages can be explained by the following points (Wooldridge and Jennings, 1995; Nwana, 1996; Ferber, 1999; Oliveira *et al.*, 1998; Weiss, 1999; Shen *et al.*, 2001; Wooldridge, 2002):

- Robustness and reliability against failures. MAS architecture is distributed where it allows fast detection and recovery from failures, and the failure of one or several agents does not necessarily make the overall system ineffective.
- Scalability and flexibility. Because MAS is an open and dynamic structure, the system can be adapted to an increased problem size by adding new agents, and without affecting the functionality of the other agents.
- Computational efficiency. Agents can operate asynchronously and in parallel, which can result in increased overall speed.
- Clarity of design and reusability. Individual agents can be developed separately and it may be possible to reuse agents in different application scenarios.

Moreover, the overall system can be tested and maintained, and reconfigured more easily.

- Costs. It may be much more cost-effective than a centralised system, since it could be composed of simple subsystems of low unit cost.

In scheduling problems there have been many efforts to apply MAS, such as supply chain scheduling management (Julka *et al.*, 2002), (Wagner *et al.*, 2003); logistics management and scheduling (Karageorgos *et al.*, 2003); airline scheduling (Langerman and Ehlers, 1997); meeting scheduling (Lee and Pan, 2004); processor scheduling (Lopez-Ortiz and Schuierer, 2004); scheduling for patient tests in hospital laboratories (Marinagi *et al.*, 2000); scheduling of robotic explorers in space technology (Muscettola *et al.*, 1998); event scheduling (Riekki *et al.*, 2003); parallel computing (Seredynski, 1997) and manufacturing scheduling (Parunak, 1998, 2000; Maturana and Norrie, 1997; Tharumarajah and Bemelman, 1997; Brennan and Norrie, 1998; Gou *et al.*, 1998; Maturana *et al.*, 1999; Rabelo *et al.*, 1998; Shen and Norrie, 1999; Sousa and Ramos, 1999; Jia *et al.*, 2004).

However, to the best of our knowledge, there is no literature about the application of MAS to bus crew scheduling. In bus crew scheduling, when UE happen, one way to deal with them is quick rescheduling, which is necessary to prevent cancelled journey or bus delay. A MAS is considered suitable to support this rescheduling because agents can dynamically adapt their behaviour to changing requirements and they can find quick solutions via negotiations and cooperation between them. Speed is an important issue when it comes to day-to-day operation management. In MAS, the computational effort is dramatically reduced because each agent knows its attributes and tries to solve the problem through negotiation with relevant agents (not with every agent), and each agent can also capture requirements and preferences of its owner. For example, a crew agent is able to accommodate crew preferences – such as preferred driving time of the day.

2.6 Research Questions

From literature reviews of current research approaches in crew scheduling and practical experiences of bus companies, we can learn that there are many things are still missing. For example, currently supervisors still have to do rescheduling manually because current systems are not able to support real time rescheduling. Although there is research (Wren *et al.*, 2003; Huisman and Wagelman, 2006) that looks into this problem there is still not enough providing support to real time rescheduling. That is why we propose to automate the crew rescheduling process and we want to use a MAS as the tool to implement the solution. Current approaches such as heuristics, mathematical and others have some limitations as discussed in the critique of current approaches. For example, mathematical approaches have the ability to search optimum or near optimum schedule but they also have some limitations, such as being usually slow to produce results in real-time because they are computationally intensive when it comes to complex situations (Kwan *et al.*, 1999). What we consider important when dealing with UE problems is the ability to provide quick results in an uncertain environment. MAS can offer this solution as discussed in Section 2.5. Since there is not much research looking into solving or minimising UE problems, this research will pave the way towards achieving that objective.

The main hypothesis of this research, which can be extracted from the discussions so far is that MAS could be used effectively to automate crew rescheduling process in real-time to handle the UE problems that affect crew schedules. Based on this hypothesis, the underlying question for this research is: *Is MAS a suitable approach for automating crew rescheduling process in real-time so that it will help supervisors in dealing with UE problems in relation to crew schedules*?

This question is actually the underlying question behind this research. However, it could be convenient to put it into perspective by deriving more direct questions that could be tackled from the studies within research.

- What is the MAS approach that should be followed to automate the crew rescheduling process?

This question is related to the possibility of developing a new approach using MAS to automate the crew rescheduling process.

- Is the proposed approach able to reschedule in all types of events or does it depend on certain characteristics of the schedules or the events?

The question is related to the capability of the proposed approach to deal with UE in all conditions whether different types of events or different types of crew schedules. This question however could be answered by testing the proposed approach in different types of UE and different types of crew schedules.

The first question is initially tackled in Chapter Three by proposing an automated crew rescheduling approach and its details, and the development process of the proposed approach using MAS. The proposed approach will be tested in Chapters Four and Five. Chapter Four presents the test where different types of events and crew schedules are used to test the approach. Chapter Five tests numerous events that take place simultaneously and randomly. This will mainly address the second question regarding the robustness of the proposed approach in handling UE problems. Chapter Six looks back at these questions and re-examines the initial hypothesis used to drive them.

2.7 Summary

The chapter has provided a review on UE problems; the current approaches to bus crew scheduling problems; practical experiences of bus companies in dealing with UE problems; motivations to use MAS; theoretical description of MAS and the current use of MAS in scheduling. From the analysis of the current approaches, we have learned about the limitation of current approaches. The limitation is that most of the current approaches in bus crew scheduling are concentrated on achieving optimum schedules. The definition of optimum schedules is limited to minimum duty and minimum cost. Crew schedule should be flexible enough to accommodate real-time changes in everyday operation. The UE problem is one of the challenges in bus operation that need to be tackled. UE will always happen and nothing could stop them because we are living in an imperfect world. The only way is to minimize the effect of the UE problem. When an UE problem takes place it will cause many effects, and one of them is on crew schedules. One way to handle it is with real-time crew rescheduling that currently is done manually at garages by supervisors. MAS is a promising approach that might be useful to automate the crew rescheduling process. MAS has been known to provide quick solutions in real-time and in uncertain environments. However, we do not know whether MAS is a suitable approach for this purpose or not. The next few chapters will answer this question.

Chapter 3: The Proposed Approach

3.1 Introduction

The previous chapter raised the main research issue, that is most of the current crew scheduling approaches, which are generally based on heuristics, mathematical programming, and other approaches are not able to tackle UE problems. This is due to the fact that most approaches concentrate on achieving optimum crew schedules with less consideration for the dynamic aspects of everyday operations. One way to deal with UE problems is crew rescheduling which is currently done manually. To deal with the issues, Chapter Two proposed automated crew rescheduling systems using MAS as an alternative approach to deal with crew related UE problems. MAS is considered suitable to support this rescheduling because agents can dynamically adapt their behaviour to changing environments and they can find quick solutions via negotiations and cooperation between them. The proposed system is constructed so that it is able to help supervisors in managing UE and minimising effect of UE to crew schedules and consequently reduce the amount of disruptions to bus operation. This chapter presents some issues concerning the proposed approach, modelled on the manual way of crew rescheduling, and thereafter proposes the automated crew rescheduling system, and modelling the proposed system with the concept of a MAS.

3.1.1 Chapter Objective

The objectives of Chapter Three are to develop/design an automated crew rescheduling system, discuss issues that concerning the proposed system, and model the system with the concept of MAS. Two issues are discussed here. First, whether to reschedule crew or reschedule crew schedules. Second, whether to develop a complete crew scheduling system or just make an addition to the current system. Before proposing the new approach the chapter also discusses the manual way of rescheduling that is currently practiced by bus companies in London. The MAS models are the system architecture, agent's type and interaction between agents.

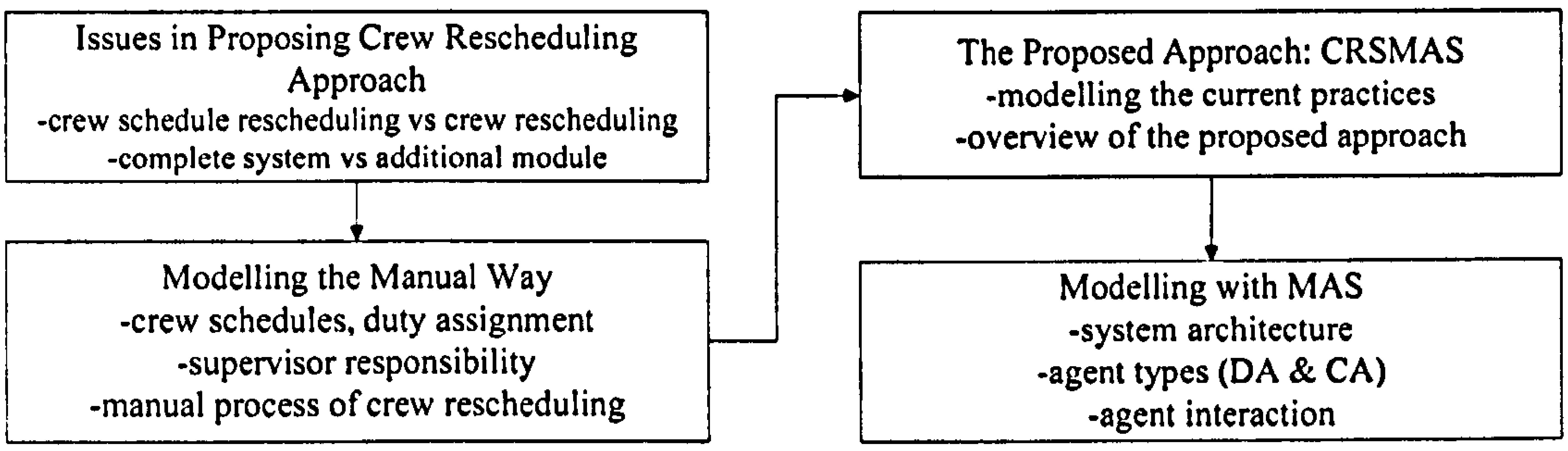

Figure 3.1: The Structure of Chapter Three

3.1.2 Chapter Outline

Section 3.1 starts with an introduction to Chapter Three, its objectives, and outline (see Figure 3.1). Section 3.2 discusses issues in proposing the new approach. Section 3.3 models the manual way of crew rescheduling and then proposes the automated crew rescheduling system approach. Section 3.4 presents the MAS models that include system architecture, agent type, and agent interaction. Section 3.5 then presents a summary of the chapter.

3.2 Issues in the Proposed Crew Rescheduling Approach

This section presents issues related to the proposed crew rescheduling approach and discusses its details. The first issue concerns the crew schedule rescheduling approach or crew rescheduling approach. Both approaches have different concepts and complexities. The second issue pertains to whether to propose a complete crew scheduling system or make an addition to the current system. The complete system comprises finding optimum crew schedules plus an automated crew-rescheduling module while an additional system consists only of a crew-rescheduling module.

3.2.1 Crew Schedule Rescheduling versus Crew Rescheduling

In bus crew scheduling problem there are two ways of rescheduling: one is to reschedule the schedule itself and the second is to reschedule the people/crew/driver (Kwan, 2004). *Crew schedule rescheduling* is whenever disruption or UE occurs, the affected crew schedule will be rescheduled. However, *crew rescheduling* means if any disruption takes place, the crew schedule will remain the same but affected crews/drivers will be rescheduled or reassigned. For example, Crew A is late for morning shift. If we use the *crew schedule rescheduling* approach, then the crew schedules will be changed accordingly. In the *crew rescheduling* approach, the crew schedule is still the same, but other available crew or spare crew has to take over A's duty. Huisman and Wagelmans (2006) have proposed the *crew schedule rescheduling* approach for whenever a bus is late. Yet, in this research, we propose using the *crew rescheduling* approach because of the complexity associated with crew schedule rescheduling. This could be understood from the constraints (i.e. driving hour rules) of the crew itself. When trying to conduct any rescheduling activities, schedulers need to consider cost and time factors, such as number of available members, driving hours left for each one, and the location of every crew. With such added constraints, it becomes very difficult for the system to find an optimum schedule. One of the assumptions of Huisman and Wagelmans (2006) is the availability of unlimited crew members. However, this is not realistic. In realistic situations, it is not practical to reschedule the crew schedules whenever a crew becomes unavailable because this may change driving hours or break timings and assigned routes, in addition to the time it takes to do that. In this research, the *crew rescheduling* approach will be explored in an attempt to tackle the problems of UE related to crew members based on realistic situations.

3.2.2 Complete System versus Additional System

A choice has to be made to either to propose a complete system that can build schedules from scratch or make an addition to the system that can connect to the existing scheduling system. The complete system means the system capable of finding optimum schedules and maintaining the schedules in everyday operation. However, an additional system will only maintain the existing schedules produced by the existing system. For this research, we will concentrate on the additional system because of the reasons discussed below.

This research focuses on solving problems arising with UE that happen in everyday operation on crew schedules, and not on finding optimum schedules. Thus, it is better to concentrate on solving this particular problem rather than widening the scope. From the interviews, it can be seen that the management is satisfied with the scheduling system, but not when it comes to managing it. Wren *et al.* (2003) also suggest the same, that any automated rescheduling system can rely on the data produced by TRACS II. In addition, research into finding optimum schedules began in the 1960s and has reached maturity. So the best approach is to use the current method and concentrate on solving the unpredictable events problem.

3.3 The Proposed Automated Crew Rescheduling System

Before we describe the proposed approach, we model the process to understand the current practices at bus companies in London. The models are presented based on the understanding from interviews as discussed in Chapter Two, and also informal discussions with crews and a supervisor.

3.3.1 Modelling the Current Practices

A scheduler is a person who is responsible for producing schedules for a garage/depot. One of the schedules is the crew schedule. The purpose of crew schedules is to show all the duties on a route(s) and its activities with time and location. After crew schedules are ready, a scheduler will assign all duties to crews according to the agreement with trade unions. This process is called crew assignment. Then crews will work according to their assignment duties. Figure 3.2 shows the ideal situation when no UE takes place. There is no need of supervisors to manage daily operation.

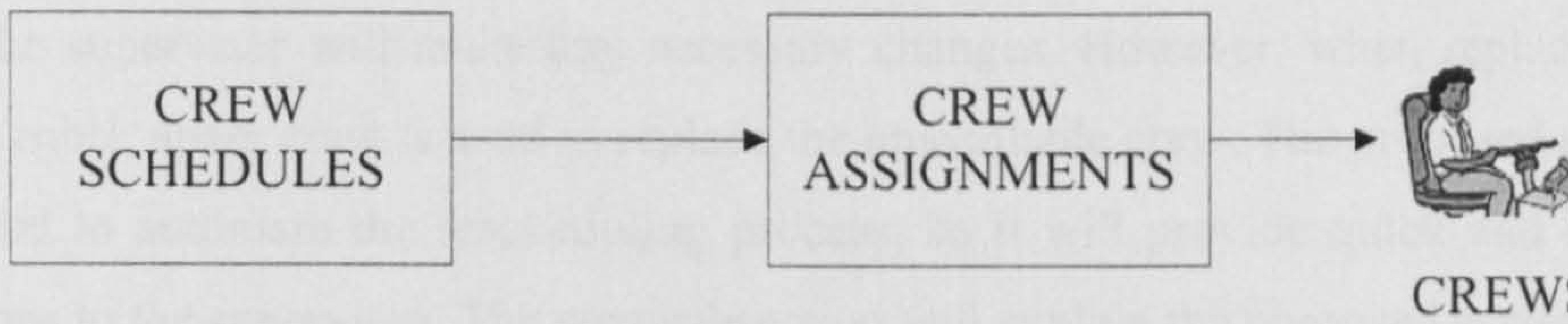

Figure 3.2: The Process in Ideal Situation

However, in reality UE take place almost every day, that is why supervisors are needed to manage them (as discussed in Chapter Two). Supervisors are responsible for making any necessary adjustment or changes to crew schedules and crew assignments when UE take place. Currently, it is done manually at garages. Figure 3.3 shows the function of supervisors in managing daily operation.

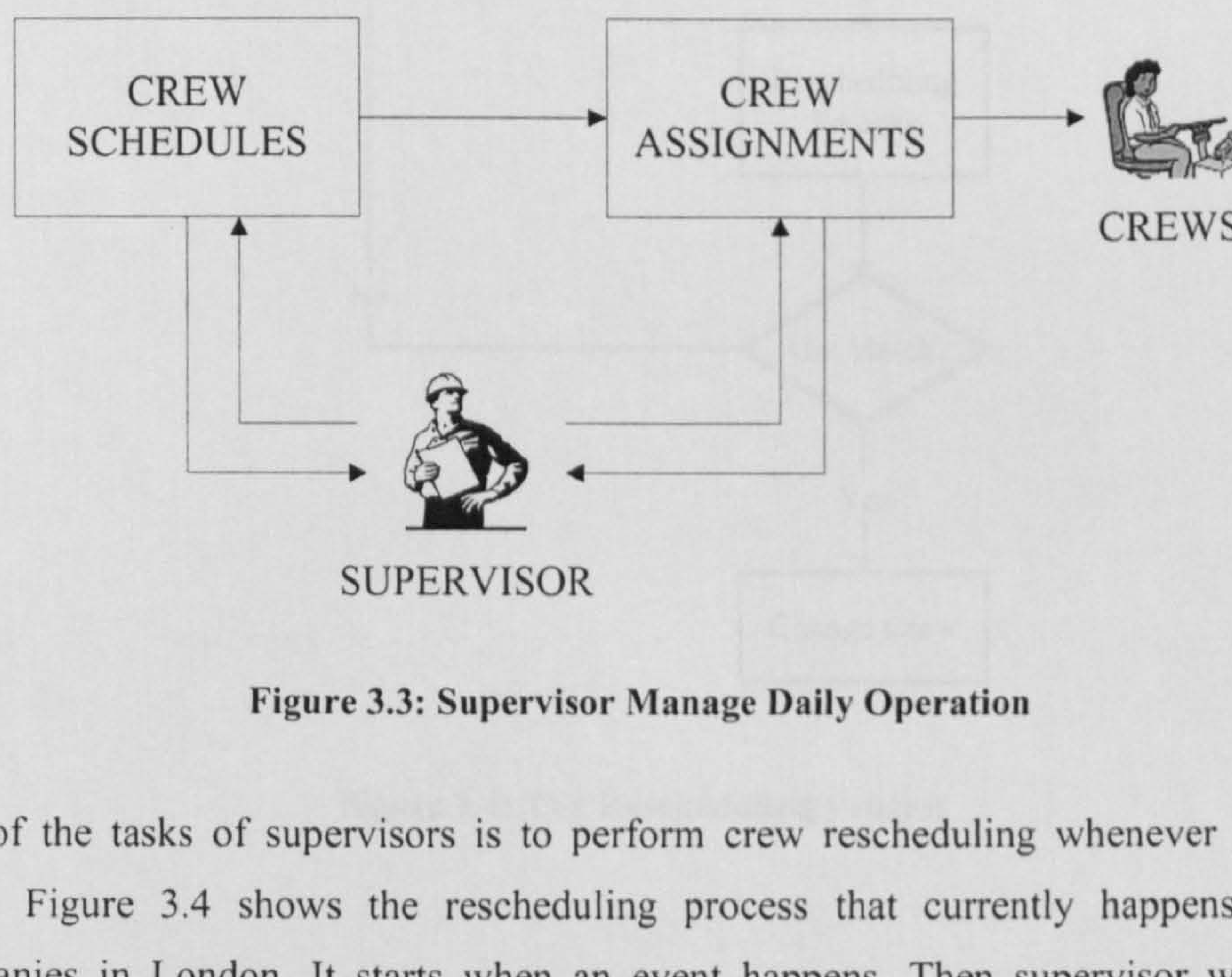

Figure 3.3: Supervisor Manage Daily Operation

One of the tasks of supervisors is to perform crew rescheduling whenever UE take place. Figure 3.4 shows the rescheduling process that currently happens in bus companies in London. It starts when an event happens. Then supervisor who is in charge of the bus operation obtains details of the event and classifies it as to whether it is possible or not to reschedule the crew. There are some events such as absent or unavailable due to accidents that do not allow for rescheduling. Then the supervisor's decision is to straight away use a spare crew. However, in the case of events such as, late, delay or unavailable for a short time, then it is possible to continue the rescheduling process. The supervisor will try to reschedule the crew and find a suitable crew that could replace him/her. If the supervisor can find a match to replace him/her then the supervisor will make any necessary changes. However, when replacement is not possible, spare crew is used to replace the unavailable crew. The proposed system is intended to automate the rescheduling process, so it will provide quick and optimum solutions to the supervisor. The next subsection will explain the proposed system.

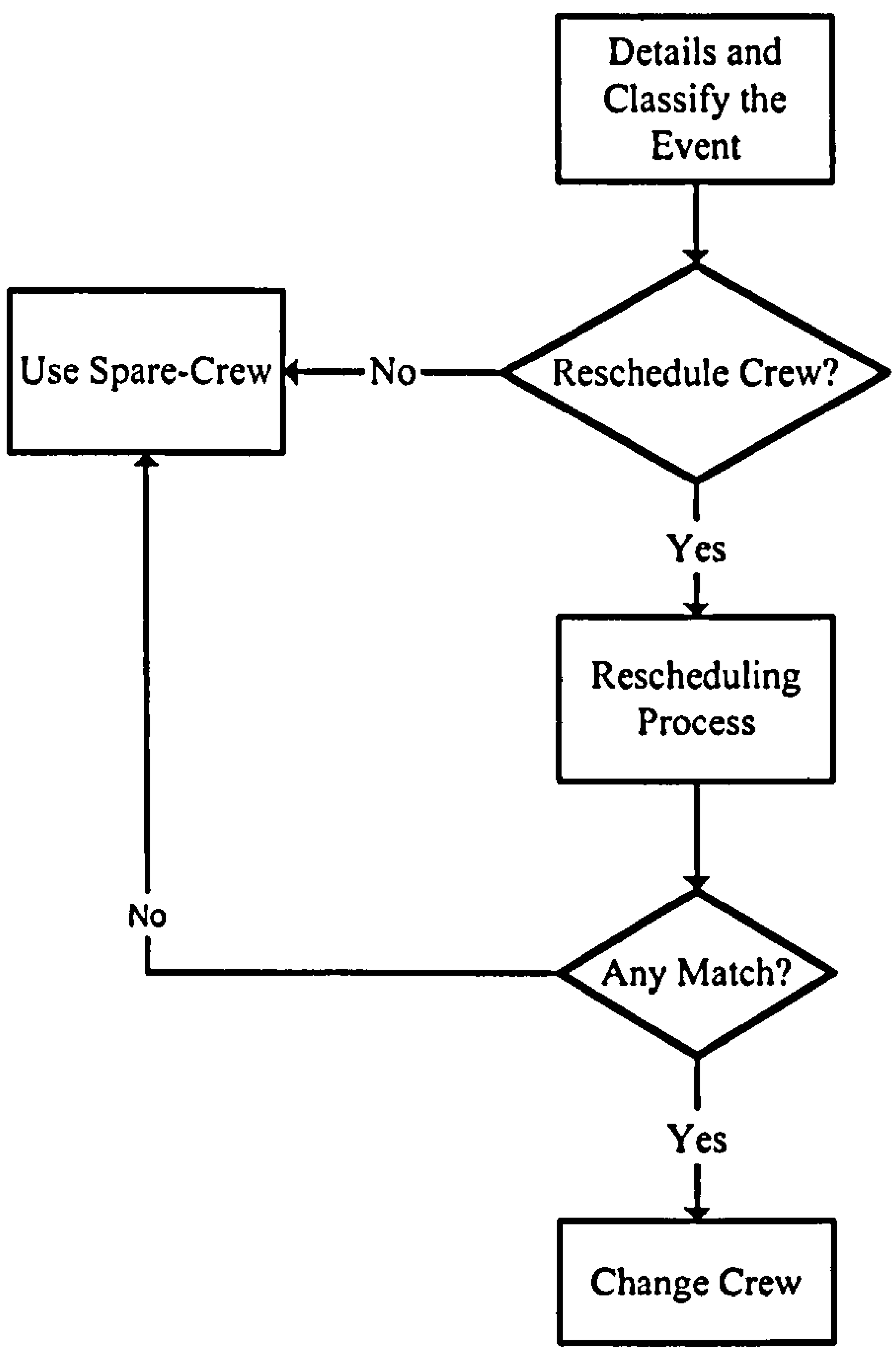

Figure 3.4: The Rescheduling Process

3.3.2 Overview of the Proposed Crew Rescheduling System

In this research, we propose a crew rescheduling system to help supervisors in making decisions relating to crew rescheduling (see Figure 3.4). The intention is not to replace the function of supervisors but to help them. Supervisors are still the people who will have the final say. The objective of the proposed system is to assist supervisors in rescheduling crew for everyday operation in order to cope with UE such as crew arrival late for duty, sickness, or absenteeism without prior notice. The proposed system aims to keep crew schedules optimum in the sense of minimising the use of spare crew and being quick in providing solutions to supervisors dealing with such events.

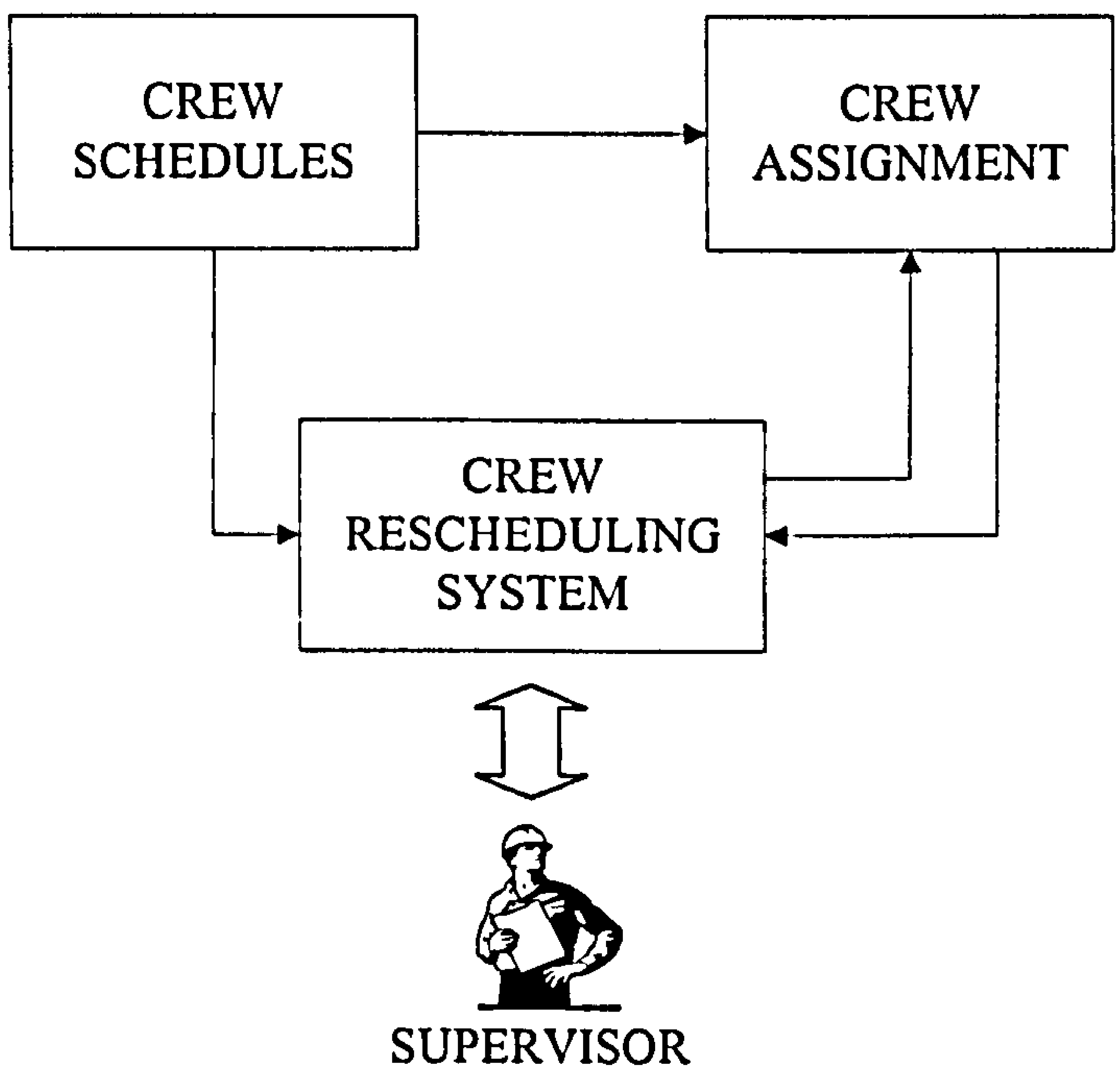

Figure 3.5: The Proposed Crew Rescheduling System

Figure 3.5 demonstrates the position of the new system. A supervisor represents the user of the proposed system. The box identified as "Crew Rescheduling System" is the proposed system. For simplicity, this approach will be referred to as Crew Rescheduling System with Multi-Agent System (CRSMAS). CRSMAS will obtain data from crew schedules and crew assignment. CRSMAS is able to reschedule crews in real time without violating the EC Driving Hour Rules. The most important considerations are the rules concerning relief and daily driving hours. Continuous driving hours should not exceed four and half hours, and total daily driving time should not exceed ten. The relief time should be at least forty-five minutes. Crew rescheduling is based on the manual rescheduling that is currently practised by bus companies in London. In the next sections, we will explain the details of CRSMAS based on the MAS concept.

3.4 Modelling with MAS

This section presents the detailed model of CRSMAS. It presents the CRSMAS architecture, agent types and MAS interactions.

3.4.1 CRSMAS Architecture

Figure 3.6 illustrates the MAS architecture for the CRSMAS. The architecture is based on the autonomous agent architecture where an agent is not controlled or managed by any other agent or human being (Jennings *et al.*, 1998; Ferber,1999; Shen *et al.*, 2001). In the CRSMAS we identify two agents that are Crew Agent (CA) and Duty Agent (DA). We define our agents as cognitive agents. Cognitive agents possess an internal representation model of the world and expertise, have goals and plans, are capable of reasoning, and can cooperate, coordinate, negotiate, and communicate with other agents (Nwana, 1996; Jennings *et al.*, 1998; Wooldridge, 2002). CA represents a crew, and DA corresponds to a duty that needs to find a crew because the original crew is late, or unavailable.

There is a virtual world where agents interact, communicate and negotiate. In this virtual world, there are resource and demand agents. A demand agent represents a task or work to be done. A resource agent represents someone or something that can fulfil the task. In this system, DA is the demand agent whilst CA is resource agent. This is due to the fact that the duty is a task that needs to be done while the crew is the resource able to fulfil the task.

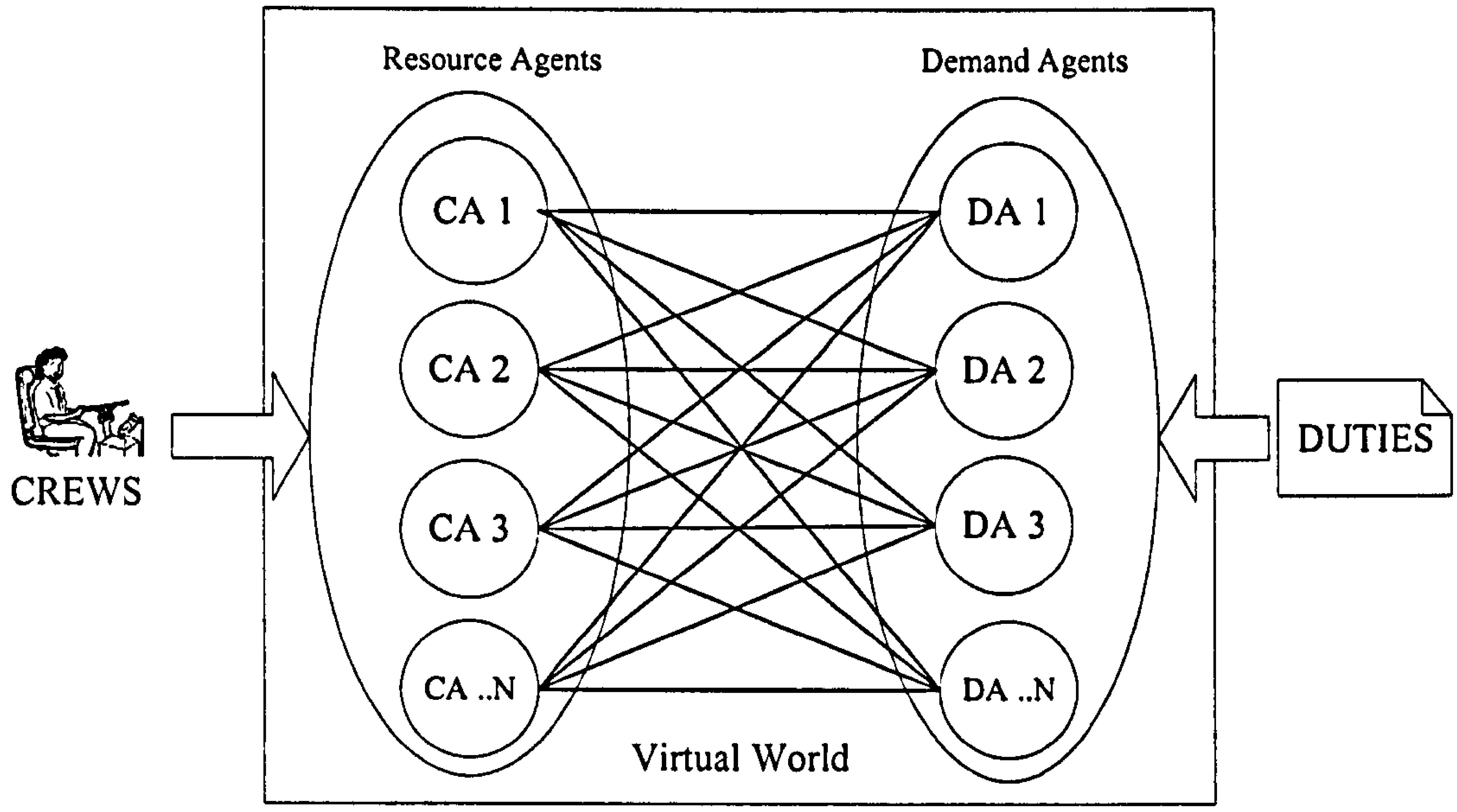

Figure 3.6: Architecture for CRSMAS

3.4.2 Agents Type

There are two types of agent presented in the system architecture: crew agent and duty agent. Every agent has their own objective, responsibility and attributes as presented below:

a) Crew Agent (CA)

CA represents a crew that works for a bus company. Their objectives are to get a salary and to work in a safe and healthy environment. Their main responsibility is to drive a bus according to a prescribed schedule. A crew has five activities SignOn, Drive, Relief, SignOff, and StandBy. SignOn is the time for a crew to start a duty, Drive is when a crew drives a bus, Relief is when a crew takes a break, SignOff is when a crew finishes his/her duty on a day, and StandBy is when the state of a crew is in stand by mode. A crew has permission to read crew schedules, duty assignment, and their crew details. A crew is not allowed to drive continuously for more than 4.5 hours, must at least take a relief equal or more than 45 minutes, and total driving hours in a day should be equal to or less than 10 hours in a day. Table 3.1 shows the attributes for CA.

b) Duty Agent (DA)

A DA corresponds to a duty that results in the loss of its driver because of UE such as lateness, delay, or unavailable. A DA's objective is to find a driver that will drive the duty. A DA's responsibility is to make sure that a crew takes the duty. Table 3.2 illustrates the attributes for a DA.

Table 3.1: The Attributes for CA

Name	Description
Crew ID	Identification number for a crew
Route Number	The route number that was assigned to the crew
Duty Number	The duty number that was assigned to the crew
Sign-On Time	The time the crew should sign-on at garage.
Start Work 1 Time	The starting time for the crew first piece of work.
Finish Work 1 Time	The finishing time for the crew first piece of work.
Start Break Time	The starting time for the break.
Finish Break Time	The finishing time for the break.
Start Work 2 Time	The starting time for the crew second piece of work.
Finish Work 2 Time	The finishing time for the crew second piece of work.
Sign-Off Time	The sign-off time for the crew at garage.
Status	To indicate the status of a crew for the purpose of rescheduling, 0 if not available and 1 if available.

Table 3.2: The Attributes for DA

Name	Description
Route No	Number for the route
Duty No	Number of the duty
Start Time	The start time for the duty to be covered.
End Time	The end time for the duty to be covered
Total Time	Total time that need to be covered
Minimum Required Time	A minimum required time to cover the duty.
Late Crew Ready Time	The time when the late-crew is ready.

3.4.2 Agents Interaction

A MAS achieves its objectives through interactions between agents. In the proposed architecture, agents interact in a virtual world in which agents representing available resources negotiate with agents representing demands for resources until a satisfactory matching is achieved. Agents interact by exchanging messages of various types (Odell *et al.*, 2000). Each message type conveys certain semantics associated to a particular task. Each time an agent receives a message, it immediately knows what reasoning procedure it must activate in order to set up the most appropriate answer or action, or what kind of update it has to perform in its domain specific knowledge. Table 3.3 provides a list of these messages, together with a short description of them.

Table 3.3: Message Passed in Agents Interaction

Message Type	Sender	Receiver	Description
reqDriver	DA	CA	Sent whenever a duty needs a driver.
respond	CA	DA	Sent as soon as a crew received a request from a duty.
detailsSpecs	DA	CA	It conveys information about the details specification of a duty.
beginMatching	CA	DA	Sent to initiate a negotiation
noMatch	DA	CA	Sent to inform that there is no match because the crew does not fulfill the duty's requirement.
reserved	DA	CA	Sent to inform that the crew is reserved to take the duty.
acceptMatch	DA	CA	Sent to inform that the crew is accepted to take the duty.
declineReservation	DA	CA	Sent to inform that the crew reservation is rejected because there is other crew that is more suitable to take the duty.

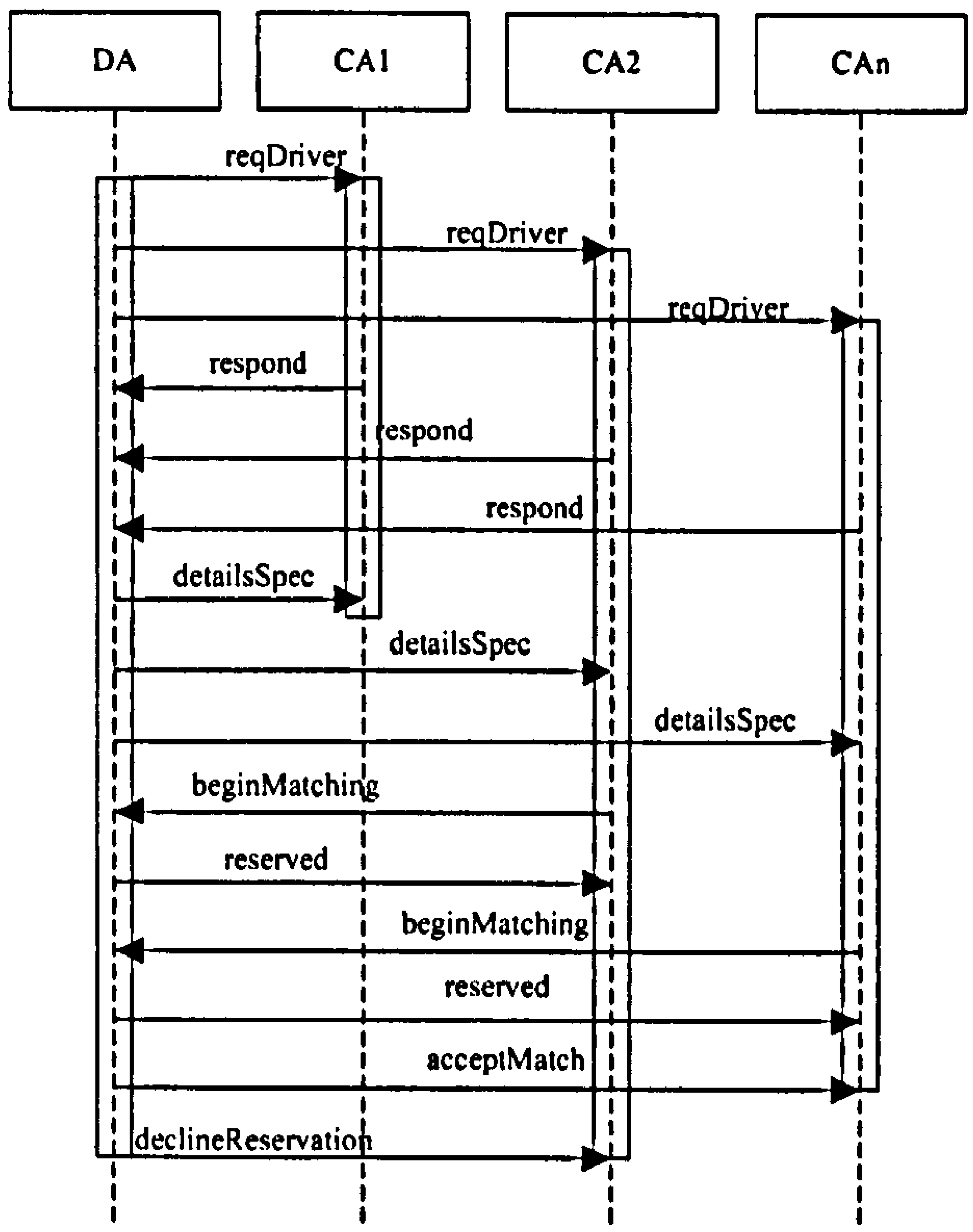

Figure 3.7: Sequence of Messages when Match Is Found

The matching process is initiated by a demand agent, which in this case is a duty agent (DA). Figure 3.7, 3.8 and 3.9 show the sequence of messages in different scenarios of matching process between DA and CA. Figure 3.7 shows the sequence of messages between a DA and CAs in the scenario when there is a match. It starts when a DA needs a driver (crew) to take his/her duty because the original driver is late or not available. The DA sends messages to all the CAs requesting a driver (*reqDriver* message). In return, CAs will respond to the DA (*respond* message). Then the DA sends detailed specifications of the duty (*detailsSpec* message). CAs that are available (in this case CA2 and CAn) for the duty will respond and matching will start (*beginMatching* message). If the CA matches the requirement, then DA will put CA into reserved (*reserved* message). DA will continue the matching process with the next CA and put CA into reserved if it fulfils the requirement. After all negotiation, DA will make the decision to choose the best option. The one that is chosen (in this case CAn) will receive an acceptance message from DA (*acceptMatch* message). In regards to the rest of the CAs in reservation, the DA will send a rejection message (*declineReservation* message). Figure 3.8 shows the same scenario with the only difference that there is no match because all CAs which are available (in this case CA2 and CAn) do not satisfy requirements. When CA details do not match a DA's requirements, the DA will send *noMatch* message to the CA.

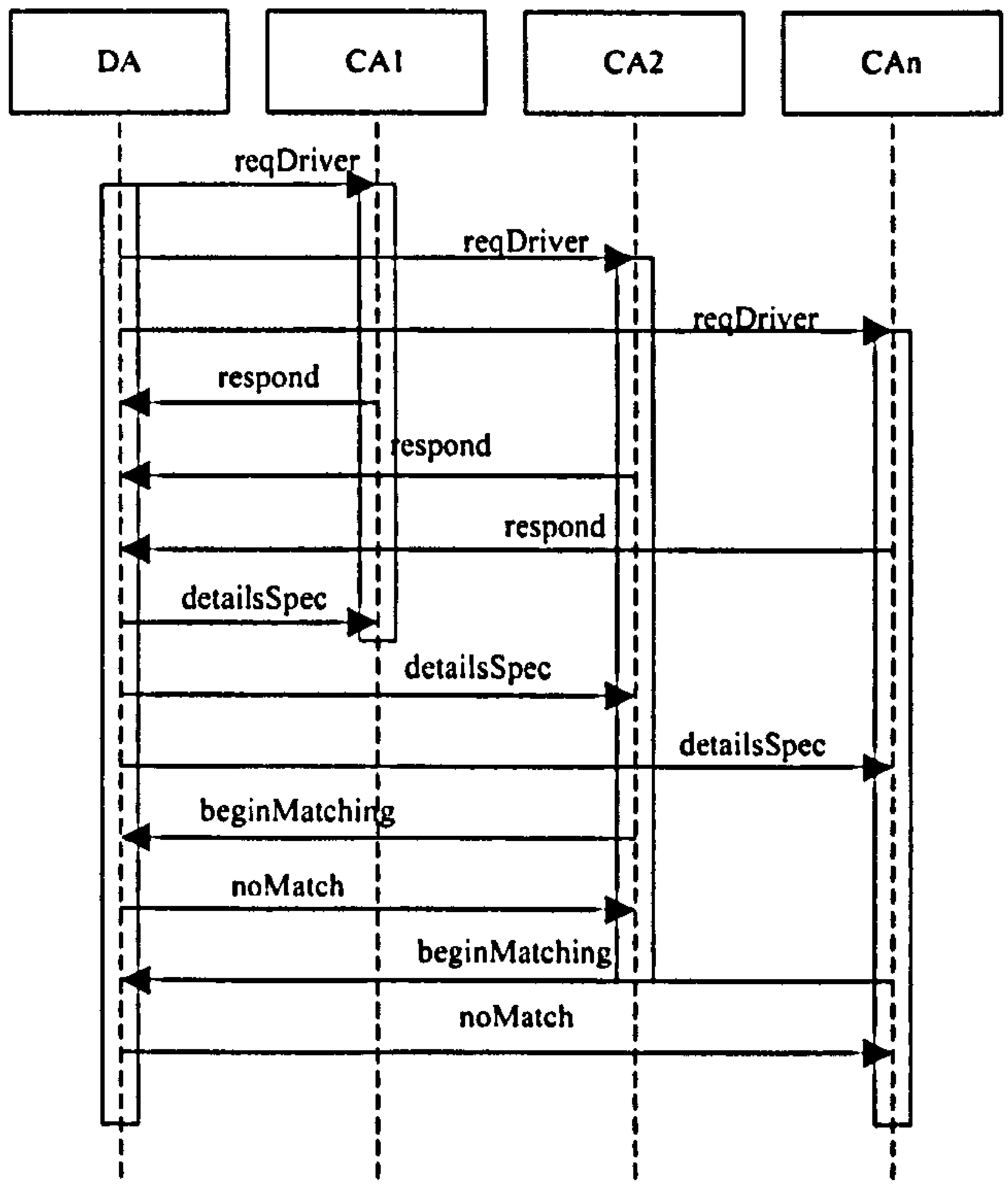

Figure 3.8: Sequence of Messages when No Match is Found

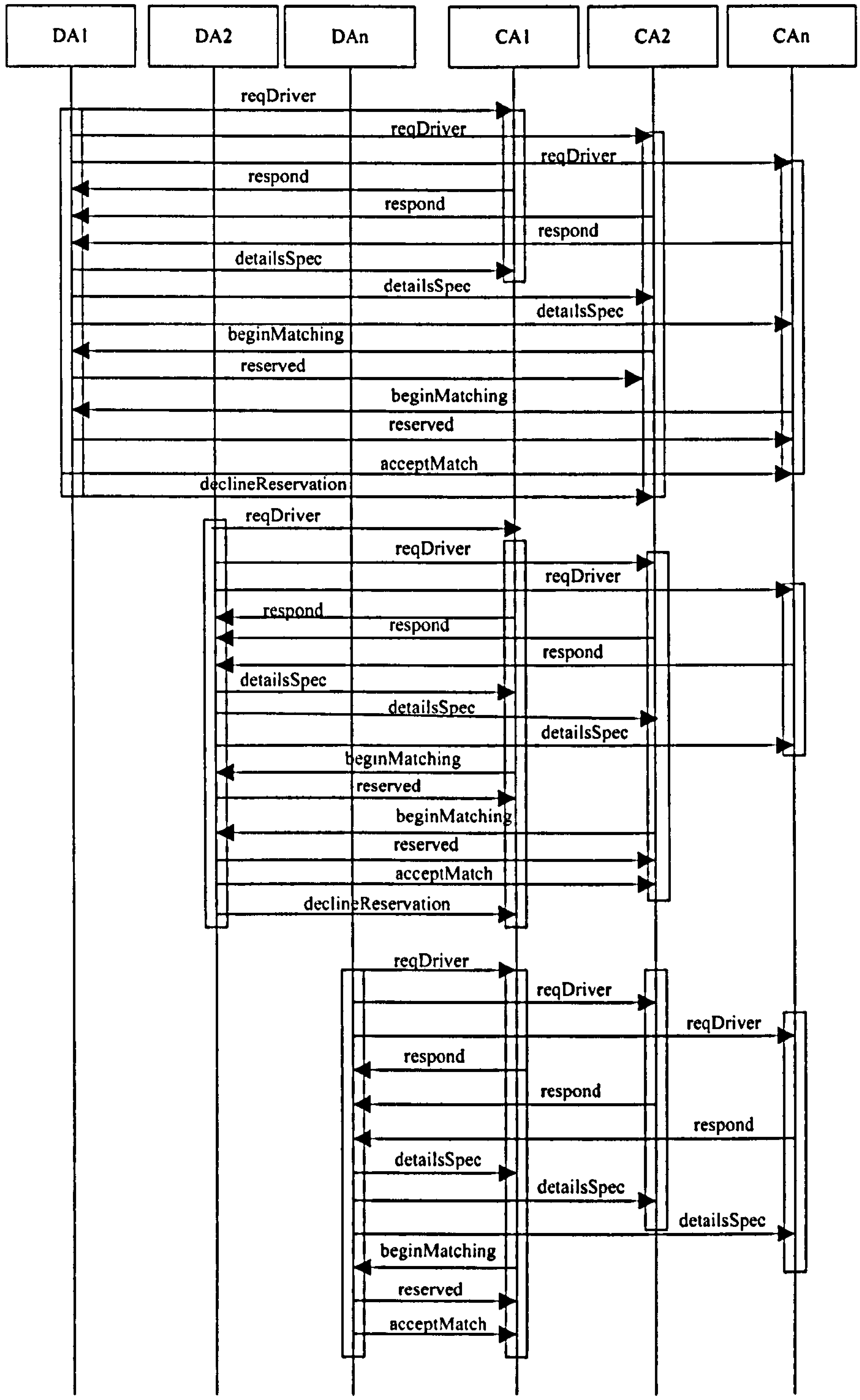

Figure 3.9: Sequence of Messages for Multiple Matches

The two examples in Figure 3.7 and Figure 3.8 show only one DA is involved. However, Figure 3.9 shows the sequence of messages when more than one DA needs drivers. In this scenario, three DAs (DA1, DA2 and DAn) need to find CAs that could take their duties. The matching process takes place in turn between all the DAs. It starts with DA1, then DA2, and finally DAn. The matching process and message passing is the same as described before. The only difference is that the process takes longer. In this example, CAn, CA2, and CA1 match DA1, DA2 and DAn respectively.

3.5 Summary

The main objective of this chapter is to present the proposed approach, which is an automated crew rescheduling system. Prior to that, the chapter presents some of the issues relating to the proposed approach. Two issues are discussed first, whether to reschedule crew or reschedule crew schedules and second, whether to propose a complete crew scheduling system or just make an addition to the current system. The research found that crew schedule rescheduling is not suitable for real time because of the level of complexity associated with it. For example, when trying to conduct any rescheduling to crew schedules, schedulers need to consider the cost and time factors, such as number of available crews, driving hours left for each one, and their location of every crew. These factors make it very difficult and not practical in the real world. Thus, in this research we prefer crew rescheduling, which means that the schedules are still the same but changes are made in the duty assignment. The research also concludes that an additional module is suitable for this research since the focus is on solving problems arising with UE that happen in everyday operation on crew schedules, and not on finding optimum schedules. The chapter thereafter models the manual way of crew rescheduling, and, based on the models, it proposes the Crew Rescheduling System with a MAS (CRSMAS). Then CRSMAS is modelled with the concept of MAS. In CRSMAS architecture there are two types of agents: duty agent (DA) and crew agent (CA). CA represents a crew, and DA corresponds to a duty that needs to find a crew because the original crew is late or unavailable. The agent's interactions are modelled with sequence diagrams that show the types of messages passing between agents in different scenarios. For example, when a match is found, no match is found and multiple matches take place. CRSMAS can be used to help supervisors in making quick decision relating to crew rescheduling whenever a crew is late or unavailable. The decision will not allow the violation of EC driving hour rules and will suggest the best optimum solution within a short period of time (within seconds or minutes). The next two chapters will test CRSMAS whether it achieves the research aim or not.

Chapter Four: Single Event Experiments

4.1 Introduction

The research proposed CRSMAS (as presented in Chapter Three) as an alternative approach for dealing with crew related UE problems. In order to evaluate CRSMAS, two series of experiments were carried out - single event and multiple events. The single event experiments tested one event at a time but with different types of events (lateness, delay, and unavailability), schedules (large, medium, and small), duty distribution (maximum, median, and minimum) and event timings. The purpose was to test the capability of CRSMAS for all types of events and schedules and also to identify the characteristics of crew schedules that influence the possibility of successful rescheduling. Multiple event testing was applied to a numbers of events that took place concurrently and randomly. The purpose was to test the robustness of CRSMAS in handling many random events at one time. This chapter presents the results and analysis of single event experiments, and multiple events experiments, and an analysis is presented in Chapter Five. The experiments were conducted using real-world data taken from bus companies in London.

4.1.1 Chapter Objective

The objective of Chapter Four is to present the results and analysis of the single event experiments to the proposed approach (CRSMAS). The purpose of the single event experiments is to test the capability of CRSMAS in dealing with different types of events in different types of schedules, duty distributions, and timings, and also to identify the characteristics in crew schedules that influence the possibility of rescheduling. Event types, schedule types, duty distributions, and timing were the factors we expected to influence the rescheduling results. The analysis will evaluate the results based on the CRSMAS rescheduling capability and the time taken to perform it. The outcomes of the analysis will be used to assess the research question mentioned in Chapter Two, and also to modify CRSMAS if necessary.

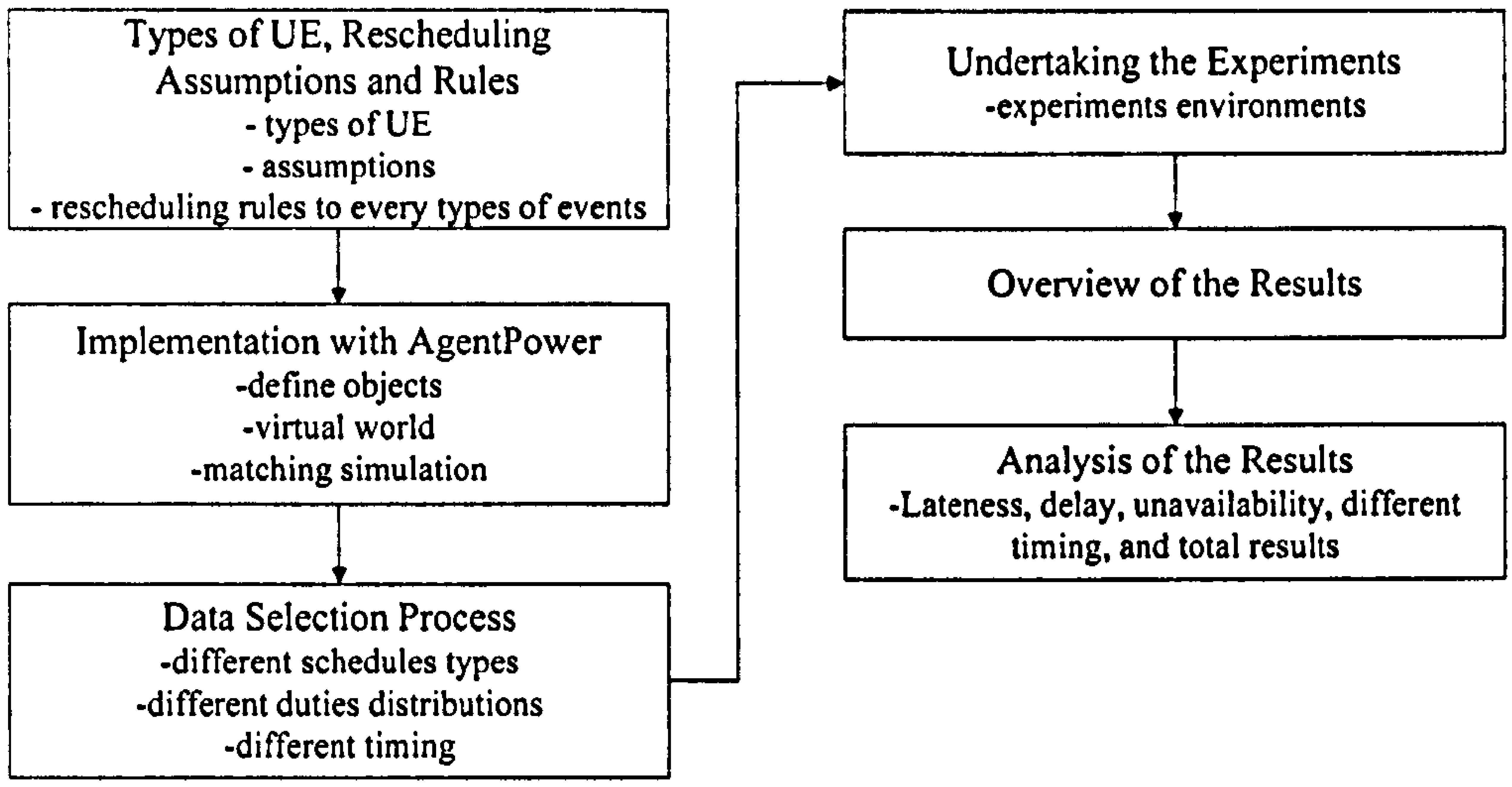

Figure 4.1: The Structure of Chapter Four

4.1.2 Chapter Outline

The chapter starts with an introduction in Section 4.1 describing the objective of the chapter and its relationship to the rest of the chapters (see Figure 4.1). Section 4.2 presents types of events, assumptions, and the rescheduling rules that we used in the experiments. There are three types of events: lateness, delay and unavailability. Section 4.3 explains the implementation of CRMAS in MAS based software (AgentPower). Section 4.4 describes the data selection processes for the experiments based on schedule type, duty distributions, and event timing. Section 4.5 presents the process of undertaking the experiments and Section 4.6 depicts an overview of the results. Section 4.7 provides an analysis of the results and, finally, Section 4.8 concludes and summarises the chapter.

4.2 Types of Events, Assumptions and Rescheduling Rules

The objective of this experiment is to test whether CRSMAS is able to fulfil its purposes in all conditions. For this reason we chose different types of events. This section discusses three types of events that we used in this experiment: lateness, delay, and unavailability. After this, the section discusses the assumptions and rules for crew rescheduling. Based on the rules, the section provides examples for every event.

4.2.1 Types of Events

For this experiment we tested the system with three types of events: lateness, delay, and unavailable part of duty. In this research, lateness refers to the late coming of a crew for a period of duty or for a break/relief. We defined three types of lateness: late for sign-on (LFSO), late for relief (LFR), and late for second work (LFSW). LFSO refers to a crew arriving late to start his/her duty. LFR means that a crew is late for his/her relief because he/she is trapped in traffic or by other emergencies. LFSW denotes a crew is late for his/her second work piece, which is after relief because of an emergency or something else that hinders the crew from arriving on time. The differences between LFR and LFSW are that the event happens at a different time and the effect on crew schedules is not the same. In this research, we consider a period of lateness to be between 15 and 60 minutes.

Delay is similar to lateness although the time frame is different. We define delay as a crew being unable to arrive on time because of emergency or other reasons. Two types of delay are defined in this research: delay for sign-on (DFSO) and delay for second work (DFSW). In this research we defined delay as between 80 to 180 minutes.

Unavailability (UNV) refers to a crew being unable to continue his/her duty due to an emergency reason such as sick while driving or accident. Someone else has to continue his/her duty. The result of UNV is the affected part of the duty not covered. In this research, we investigated UNV times of between 30 to 120 minutes.

4.2.2 Crew Rescheduling Assumptions and Rules

For the experiments purpose, two assumptions were made. These assumptions were made based on informal discussions with crews and according to EC driving hour rules. First, that there was no violation of crew rules regarding relief time (45 minutes), and maximum driving hours (9 hours maximum), in a day as ruled by EC driving hour rules. Second, in case of lateness and delay at least 5 minutes is needed for crews to be ready for work after sign-on, 5 minutes to start relief and to start second work after relief, and 5 minutes for sign-off after finishing work.

The rescheduling rules show how the proposed system does the rescheduling whenever an event takes place. The rules are drawn up based on the manual rescheduling as discussed in Chapter Three and also according to the assumptions above. Below are the details of the rules:

a) **Lateness and delay**. In this event, the system should be able to reschedule their duty to available crews at the garage. The available crews could be crews that have signed-on but have not started driving, crews on relief, or crews that have finished their duty but not signed-off yet. The system should choose a crew that has the starting time nearest to the ready time (arrival time plus 5 minutes) of the late-crew. The ready time of the late-crew is the arrival time plus 5 minutes to get ready for driving. This will ensure that the late-crew does not need to wait long. The chosen crew's original duty may be given to the late-crew. Several rescheduling processes might occur until the match is found. In the case of more than one rescheduling being needed, the principle was to minimise the effect of rescheduling by trying to find the best solution where crew involvement is the least.

b) **Unavailable part of duty**. In this type of event, the system should be able to reschedule the part of the duty to available crews at garage. The available crews could be crews that have finished their duty but not signed-off yet. The system should choose a crew from the available crews that have the lowest driving hours and, after adding the new duty, the total driving hours should not exceed maximum daily driving hours.

The next subsections discuss examples of the crew rescheduling rules applied to every type of event in detail.

4.2.3 LFSO and DFSO

The rules regarding LFSO and DFSO are the same because they are the same except for the difference in timing as explained in the previous section. In the event of LFSO or DFSO, the available crews are those that have sign-on at least 5 minutes before the work start time of the late-crew's duty and those whose work start is later than the work start time of the late-crew's duty. The chosen crew is the one that has the same or later starting time of duty as the ready time of the late-crew. If there are more than one crews available, then the latest starting time will be chosen. To aid understanding of these rules, this section will explain some of the examples of the rescheduling process.

Table 4.1 shows a summary of a crew schedule, which was taken from a bus company in London. This schedule will be used to show some examples. It has 45 duties. *Crew ID* shows the identification of a crew. *Duty no.* indicates the number of a duty, *sign-on* indicates the time for a crew to report for duty, *start work 1* refers to the starting time of the first *work piece*. Normally, a duty has two *work pieces*. *End work 1* shows the end time for the first *work piece*. *Start relief* and *end relief* show the start and finish timed for relief/break. *Start work 2* refers to the starting time of the second work piece. *End work 2* indicates the end time of second work piece. *Sign-off* indicates the time of a crew signing off from work.

Table 4.1: Example of a Crew Schedule

Crew ID	Duty No	Sign-On	Start Work 1	End Work 1	Start Relief	End Relief	Start Work 2	End Work 2	Sign-Off
A	1	03:34:00	03:49:00	08:10:00	08:15:00	09:00:00	09:05:00	11:02:00	11:07:00
B	2	03:43:00	03:58:00	08:16:00	08:21:00	09:30:00	09:35:00	11:34:00	11:53:00
C	3	03:53:00	04:08:00	08:52:00	08:57:00	09:51:00	09:56:00	11:58:00	12:17:00
D	4	04:03:00	04:18:00	08:52:00	08:57:00	10:03:00	10:08:00	12:10:00	12:41:00
E	5	04:13:00	04:28:00	09:09:00	09:14:00	10:15:00	10:20:00	12:22:00	12:41:00
F	6	04:23:00	04:38:00	09:22:00	09:27:00	10:27:00	10:32:00	12:34:00	12:53:00
G	7	04:33:00	04:48:00	09:58:00	10:03:00	11:03:00	11:08:00	13:10:00	13:35:00
H	8	04:41:00	04:56:00	10:10:00	10:15:00	11:09:00	11:14:00	13:16:00	13:35:00
I	9	04:48:00	05:03:00	08:26:00	08:31:00	09:24:00	09:29:00	13:02:00	13:21:00
J	10	04:56:00	05:11:00	10:40:00	10:45:00	11:35:00	11:40:00	13:14:00	13:35:00
K	11	05:03:00	05:18:00	10:46:00	10:51:00	11:53:00	11:58:00	13:32:00	13:53:00
L	12	05:11:00	05:26:00	08:53:00	08:58:00	09:53:00	09:58:00	13:34:00	13:53:00
M	13	05:18:00	05:33:00	09:05:00	09:10:00	10:05:00	10:10:00	13:46:00	14:05:00
N	14	05:30:00	05:45:00	09:29:00	09:34:00	10:35:00	10:40:00	14:16:00	14:35:00
O	15	05:47:00	06:02:00	09:56:00	10:01:00	10:57:00	11:02:00	14:38:00	15:05:00
P	16	05:55:00	06:10:00	11:10:00	11:15:00	12:05:00	12:10:00	13:44:00	14:05:00
Q	17	05:56:00	06:11:00	10:08:00	10:13:00	11:05:00	11:10:00	14:46:00	15:05:00
R	18	05:59:00	06:14:00	10:20:00	10:25:00	11:17:00	11:22:00	14:58:00	15:17:00
S	19	06:00:00	06:15:00	11:22:00	11:27:00	12:17:00	12:22:00	13:56:00	14:23:00
T	20	06:05:00	06:20:00	10:32:00	10:37:00	11:27:00	11:32:00	14:56:00	15:17:00
U	21	06:09:00	06:24:00	10:38:00	10:43:00	11:33:00	11:38:00	13:40:00	14:05:00
V	22	06:10:00	06:25:00	09:35:00	09:40:00	10:33:00	10:38:00	14:14:00	14:35:00
W	23	06:13:00	06:28:00	10:50:00	10:55:00	11:47:00	11:52:00	13:26:00	13:53:00
X	24	06:15:00	06:30:00	11:02:00	11:07:00	11:57:00	12:02:00	14:04:00	14:23:00
Y	25	06:17:00	06:32:00	11:08:00	11:13:00	12:03:00	12:08:00	14:10:00	14:35:00
Z	26	06:20:00	06:35:00	11:14:00	11:19:00	12:11:00	12:16:00	13:50:00	14:23:00
AA	27	06:25:00	06:40:00	11:52:00	11:57:00	12:47:00	12:52:00	14:26:00	14:45:00
AB	28	06:26:00	06:41:00	11:26:00	11:31:00	12:33:00	12:38:00	14:40:00	15:05:00
AC	29	06:35:00	06:50:00	11:38:00	11:43:00	12:41:00	12:46:00	14:20:00	14:45:00
AD	30	06:42:00	06:57:00	11:50:00	11:55:00	13:03:00	13:08:00	15:10:00	15:45:00
AE	31	06:46:00	07:01:00	11:56:00	12:01:00	13:15:00	13:20:00	15:21:00	15:45:00
AF	32	06:57:00	07:12:00	12:08:00	12:13:00	13:47:00	13:52:00	15:26:00	15:45:00
AG	33	07:14:00	07:29:00	12:26:00	12:31:00	13:27:00	13:32:00	15:32:00	16:09:00
AH	34	07:20:00	07:35:00	12:38:00	12:43:00	13:45:00	13:50:00	15:50:00	16:09:00
AI	35	08:36:00	08:51:00	12:16:00	12:21:00	15:16:00	15:21:00	19:56:00	20:01:00
AJ	36	10:26:00	10:50:00	12:52:00	12:57:00	14:05:00	14:10:00	19:01:00	19:06:00
AK	37	10:56:00	11:20:00	13:22:00	13:27:00	14:35:00	14:40:00	19:28:00	19:33:00
AL	38	10:56:00	11:26:00	15:02:00	15:07:00	16:09:00	16:14:00	19:39:00	19:44:00
AM	39	11:26:00	11:56:00	13:58:00	14:03:00	15:05:00	15:10:00	19:53:00	19:58:00
AN	40	11:26:00	11:50:00	13:52:00	13:57:00	14:57:00	15:02:00	20:28:00	20:33:00
AO	41	11:56:00	12:26:00	14:28:00	14:33:00	15:27:00	15:32:00	20:05:00	20:10:00
AP	42	11:56:00	12:20:00	14:22:00	14:27:00	15:21:00	15:26:00	20:43:00	20:48:00

For example, crew P is assigned duty No.16. The crew is supposed to sign-on at 5:55 but for some reason the crew is 15 minutes late. The crew then informs the supervisor at the garage that he/she will arrive at 6:10. The ready time for crew P is 6:15 (arrival time plus 5 minutes). According to the rules, the available crews are those who have sign-on before or at 6:05 (5 minutes before the start work 1 of duty No.16). Based on the crew schedule presented in Table 4.1, we do the rescheduling process according to the rules stated above. The results show that crews Q, R, S and T are available to take duty No.16 as shown in Table 4.2.

Table 4.2: The Rescheduling of 15 Minutes LFSO of Duty 16

Crew ID	Duty No	Sign-On	Start Work 1	New Start Time	Need More Rescheduling	Waiting Time for Late-Crew
Q	17	05:56:00	06:11:00	06:10:00	Y	N/A
R	18	05:59:00	06:14:00	06:10:00	Y	N/A
S	19	06:00:00	06:15:00	06:10:00	N	00:00:00
T	20	06:05:00	06:20:00	06:10:00	N	00:05:00

Table 4.2 shows *crew ID*, *duty no.*, *sign-on*, *start work 1*, *new start time*, *need more rescheduling* and *waiting time for late-crew*. *New start time* is a start working time for duty No.16. *Need more rescheduling* shows that if a crew takes the duty, his/her original duty will need to be rescheduled to other or it will be taken by the late-crew, and *waiting time for late-crew* shows the time for the late-crew to wait before he/she can start their new duty if that duty is assigned to the late-crew. In this example, crew S is the best option to take duty 16. The new start time for crew S is 6:10, no further rescheduling is needed and the late-crew does not need to wait when he arrives. The late-crew will take crew S's duty, which is duty no.19.

If more rescheduling is needed to find matches then in the first round the late-crew's duty will be assigned to the available crew that has the latest start time of his/her original duty. This is because the later the starting time (of the original duty) is; the closer it is to the arrival time of the late-crew. This will result less in rounds of rescheduling and fewer crews will be affected by the changes. After that, rescheduling will continue until the system finds a new duty for the late-crew. For example, crew P is 30 minutes late. He/She arrives at 6:25 and he/she is ready to work at 6:30. The rescheduling process (in Table 4.3(a)) shows that show that all the available crews need more rescheduling because crew P is only available at 6:30, which does not match any of the available duty. In this case, we need to find the crew that has the latest start work 1, which in this example is crew T (6:20). Therefore, crew T is chosen to take over duty 16. The second round reassignment is needed to reassign duty no. 20, which was originally assigned to crew T. Duty no. 20's start work time is 06:20. Whoever has a sign-on before or at 06:15 is eligible to take over duty 20. Table 4.3(b) shows the results of second round rescheduling. The results show that crew X is the most suitable to take duty no. 20 because no more rescheduling is needed and there is zero waiting time for late-crew. The overall results from this example show that crew P takes duty no. 24, crew T takes duty no. 16 and crew X takes duty no. 20.

Table 4.3(a): First Round Rescheduling: 30 Minutes LFSO

Crew ID	Duty No	Sign-On	Start Work 1	New Start Time	Need More Rescheduling	Waiting Time for Late-Crew
Q	17	05:56:00	06:11:00	06:10:00	Y	N/A
R	18	05:59:00	06:14:00	06:10:00	Y	N/A
S	19	06:00:00	06:15:00	06:10:00	Y	N/A
T	20	06:05:00	06:20:00	06:10:00	Y	N/A

Table 4.3(b): Second Round Rescheduling: Reassign Duty No. 20

Crew ID	Duty No	Sign-On	Start Work 1	New Start Time	Need More Rescheduling	Waiting Time for Late-Crew
U	21	06:09:00	06:24:00	06:20:00	Y	N/A
V	22	06:10:00	06:25:00	06:20:00	Y	N/A
W	23	06:13:00	06:28:00	06:20:00	Y	N/A
X	24	06:15:00	06:30:00	06:20:00	N	00:00:00

4.2.4 LFR, LFSW and DFSW

The events of LFR, LFSW and DFSW are different in terms of the effect to crew schedules, and the time frame. However, from a rescheduling point of view the concern is same, which is to reschedule the second work. When any of these events happen, the late-crew may or may not have enough time for relief. If the relief time is more than 45 minutes, and it can absorb the lateness, there is no need for rescheduling. However, if the relief time (after taking consideration of the lateness time) is not enough to absorb the lateness, then rescheduling is needed. This is to ensure that the late-crew has enough relief time (at least 45 minutes). The available crews for rescheduling are those that have spent 45 minutes of their relief time and their end relief time should be later than that of the late-crew. If more than one crew is available, then the crew that has end relief time that is the same or close to the actual end relief time of the late-crew will be chosen. In the case of more rescheduling being needed to find matches, then in the first round the late-crew's duty will be assigned to an available crew that has the latest end relief time of his/her original duty. This is because the later the finishing relief time is (of the original duty), the closer it is to the actual finishing relief time of the late-crew. This will result in less rescheduling and fewer crews will be affected by the changes. Thereafter, rescheduling will continue until the system finds a new duty for the late-crew. These rules can be understood through the examples below.

For example, crew P is assigned duty No.16. Crew P is supposed to finish work 1 at 11:10 but for some reason the crew is 15 minutes late. The late-crew informs the supervisor at the garage that he/she will finish at 11:25. The effects to the schedule after taking account of 5 minutes to start relief, and relief time, should be at least 45 minutes. Crew P is due to finish his relief at 12:15 and is only available for his/her second work at 12:20 as shown in Table 4.4.

Table 4.4: Effect of 15 Minutes LFR to Crew P

	Finish Work 1	Start Relief	Finish Relief	Start Work 2
Real Time	11:25:00	11:30:00	12:15:00	12:20:00
Scheduled Time	11:10:00	11:15:00	12:05:00	12:10:00
Difference	00:15:00	00:15:00	00:10:00	00:10:00

Table 4.5(a): First Round Rescheduling of 15 Minutes LFR of Duty 16

Crew ID	Duty No	Start Relief	Ready Time	Finish Relief	New Finish Relief	Need More Reassignment	Waiting Time for Late-Crew
Z	26	11:19:00	12:04:00	12:11:00	12:05:00	Y	N/A

Table 4.5(b): Second Round Rescheduling of 15 Minutes LFR of Duty 16

Crew ID	Duty No	Start Relief	Ready Time	Finish Relief	New Finish Relief	Need More Reassignment	Waiting Time for Late-Crew
S	19	11:27:00	12:12:00	12:17:00	12:11:00	N	00:02:00

In this situation, we must find another crew to take his/her second work. Based on the rules mentioned above, Table 4.5(a) and 4.5(b) show the outcome of the rescheduling. The results show that two rounds of rescheduling are needed. In the first round, only crew Z is available to take the second work of crew P. In the second round, one crew is available - crew S. The overall results from this example shows that crew P will take duty no.19, crew S will take duty no. 26 and crew Z will take duty no.16.

4.2.5 UNV

The objective of rescheduling in the event of UNV is to use available crews to replace the current crew, who is not available due to an emergency event, without using the standby crew. The part of the duty (later called uncovered duty) without a driver has to be found crew to replace the missing crew. In this event, the available crews are those who have finished his/her second work before 5 minutes of the starting time of the uncovered duty, are not yet at sign-off, and whose total driving hours after adding the uncovered duty will not exceed 9 hours. The reason for the 5 minutes is to give the chosen crew 5 minutes break before starting the uncovered duty. If there is more than one crew available, then the crew with the lowest driving hours will be selected. In this experiment we only do one round of rescheduling.

For example, crew P is assigned duty no. 16. Crew P is supposed to work for his/her second work from 12:10 to 13:44. However, because of emergency reasons, crew P is unavailable from 12:44 to 13:44, which is one hour in total. Table 4.6 shows the information about the uncovered duty of crew P. According to the rules, we want to reschedule crew P's duty to any crew that finishes their second work 5 minutes before the starting time of uncovered duty, which is 12:39 (after subtracting 5 minutes from the starting time of uncovered duty), and is not yet at sign-off. Table 4.7 shows the results of the rescheduling. *Time on duty* shows the total driving hours for that day, *additional time* refers to the period of uncovered duty to be covered, and *total time* is the total of driving hours after adding the uncovered duty time. The results show that three crews are available to cover the period. Based on the rescheduling rules, crew D is the best option because it has the minimum time on duty. Therefore, crew D will cover the uncovered duty of crew P from 12:44 to 13:44.

Table 4.6: Uncovered Duty of Crew P

Crew	Duty No	Unavailable		
		Start Time	End Time	Total Time Uncover
P	16	12:44:00	13:44	01:00:00

Table 4.7: Rescheduling of One Hour Uncovered Duty

Crew	Duty No	Finish Work 2	Sign-Off	Time On Duty	Additional Time	Total Time
D	4	12:10:00	12:41:00	6:36:00	1:00:00	07:36:00
E	5	12:22:00	12:41:00	6:43:00	1:00:00	07:43:00
F	6	12:34:00	12:53:00	6:46:00	1:00:00	07:46:00

4.3 Implementation with AgentPower

The CRSMAS is implemented using AgentPower software that supports MAS. The software is developed by Magenta Corporation Ltd., a company dedicated to building commercially viable technology based on the concept of Multi-Agent Systems (www.magenta-technology.co.uk). The software is provided by Professor George Rzevski (previously visiting professor at Brunel University) who was one of the founders of Magenta Corporation Ltd. AgentPower is a user friendly package with a drag-and-drop user interface, which allows user to develop a MAS system without the need for programming. AgentPower's architecture (as depicted in Figure 4.1) consists of few components: Ontology, Virtual World, Multi-Agent Engine, Human Computer Interface and Software Interface (Rzevski, 2002).

Ontology contains extensive knowledge of the domain in which the system operates, structured in terms of objects, properties, attributes, relationships and scripts. The performance of agents depends on the quality of the domain knowledge stored in ontology. The virtual world is where agents are created when needed and where they solve given tasks by means of sending messages to each other. The Multi-Agent Engine includes runtime algorithms with extensions and associated tools, that is, all the algorithms and protocols required for proper functioning of agents as well as tools for constructing ontology. The engine supports parallel running of a very large number of agents and enables their interaction at great speed. Interfaces link the MAS with users and with other software. The interface with other software is based on international standards, including XML.

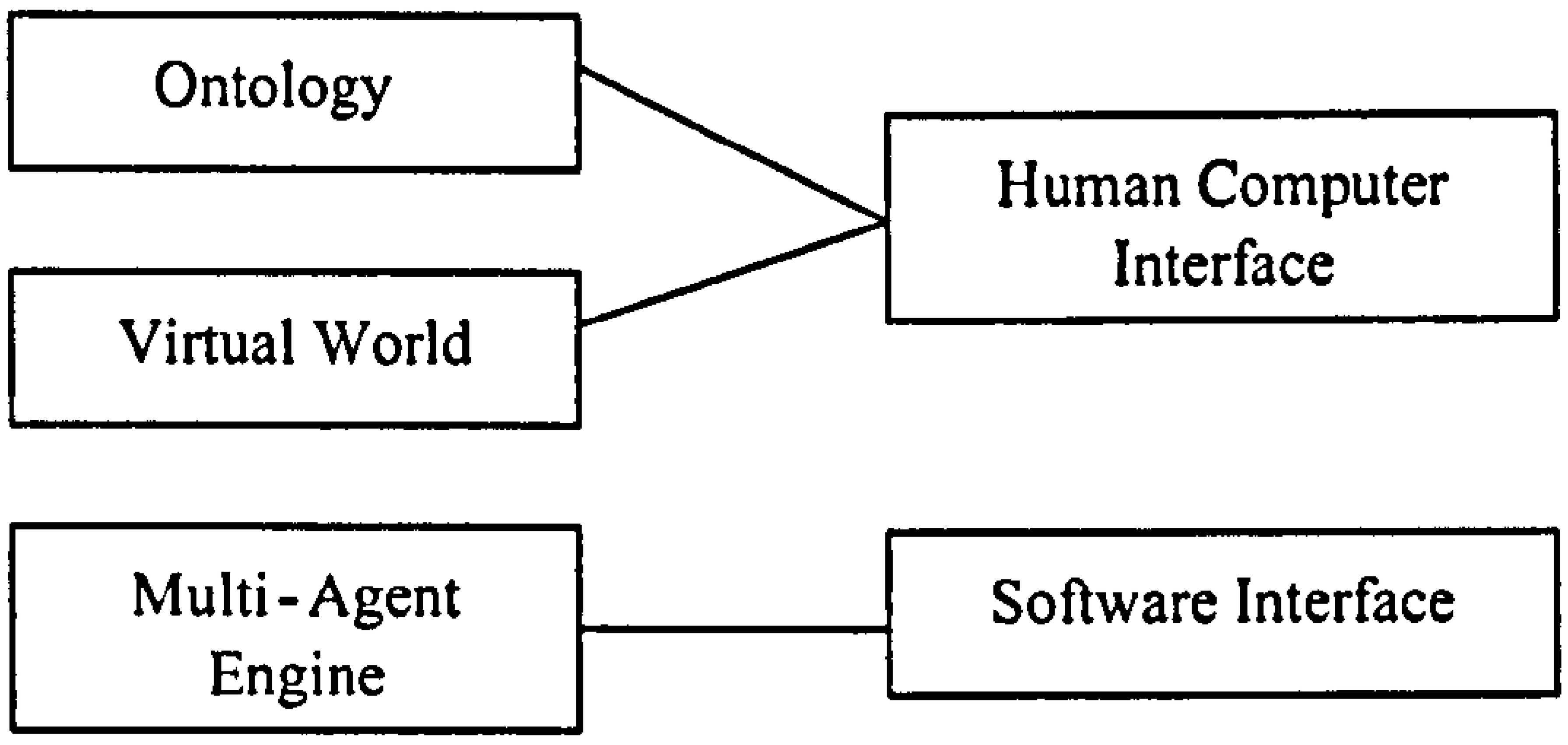

Figure 4.2: AgentPower Architecture (Source: Rzevski, 2002)

There are several steps in developing a MAS in AgentPower. First, objects and their attributes (in AgentPower an agent is called object) are defined, then the supply and demand agents and virtual relations between them in the virtual world are identified. Finally, the demands agents and resources agents are created, the attributes are filled in and the simulation is run to experiment with the agents' negotiations to find a match between them. The next subsections discuss the steps in detail.

4.3.1 Define Objects

In AgentPower, an agent is called an object in the ontology library but in the virtual world it is called an agent. Although the name is different, its purpose and function are the same. Based on the proposed approach in Chapter Three (Section 3.4.2), two types of agents are defined - crew agent and duty agent. In AgentPower, we implement crew agent as crew object, and duty agent as duty object. Details of its attributes, description and data type are shown in Tables 4.8 (crew) and 4.9 (duty). Almost all the attributes are the same as presented in Section 3.4.2 but with a few additions. In object crew there a few attributes added: *route no. 2*, *ready time*, *X*, *Y* and *self nexus*. In object duty, the additions are *X*, *Y* and *self nexus*. The additions are required because of requirements of crew schedules, rescheduling rules and AgentPower. For example, AgentPower requires attributes X, Y and self nexus for the purpose of the matching process. Figure 4.2 shows a screen shot from AgentPower that illustrates the visual representation of object crew and object duty and their attributes.

Table 4.8: Attributes for Object Crew

Name	Description	Data Type
Crew ID	Identification number for a crew	String
Route No. 1	The first route assigned to the crew	String
Route No. 2	The second route assigned to the crew	String
Duty Number	The duty number assigned to the crew	Integer
Sign-on Time	The time the crew should sign-on at garage.	Time
Start Work 1 Time	The starting time for the crew's first piece of work.	Time
Finish Work 1 Time	The finishing time for the crew's first piece of work.	Time
Start Relief Time	The starting time for the break.	Time
Finish Relief Time	The finishing time for the break.	Time
Ready Time	Time calculated for the purpose of rescheduling (45 minutes after "Start Relief Time").	Time
Start Work 2 Time	The starting time for the crew's second piece of work.	Time
Finish Work 2 Time	The finishing time for the crew's second piece of work.	Time
Sign-off Time	The sign-off time for the crew at garage.	Time
Status	To indicate the status of a crew for the purpose of reassignment, 0 if not available and 1 if available.	Integer
X	Object position in the scene relative to X-direction	Integer
Y	Object position in the scene relative to Y-direction	Integer
Self Nexus	A unique identifier of the project crew agent (used for agent identification in the scene)	Agent Reference

Table 4.9: Attributes for Object Duty

Name	Description	Data Type
Route No	Number for the route	String
Duty No	Number of the duty	Integer
Start Time	The starting time for the duty to be covered.	Time
Minimum Required Time	A minimum required time to cover the duty.	Time
Late Crew Ready Time	The time when the late-crew is ready.	Time
X	Object position in the scene relative to X-direction	Integer
Y	Object position in the scene relative to Y-direction	Integer
Self Nexus	A unique identifier of the project crew agent (used for agent identification in the scene)	Agent Reference

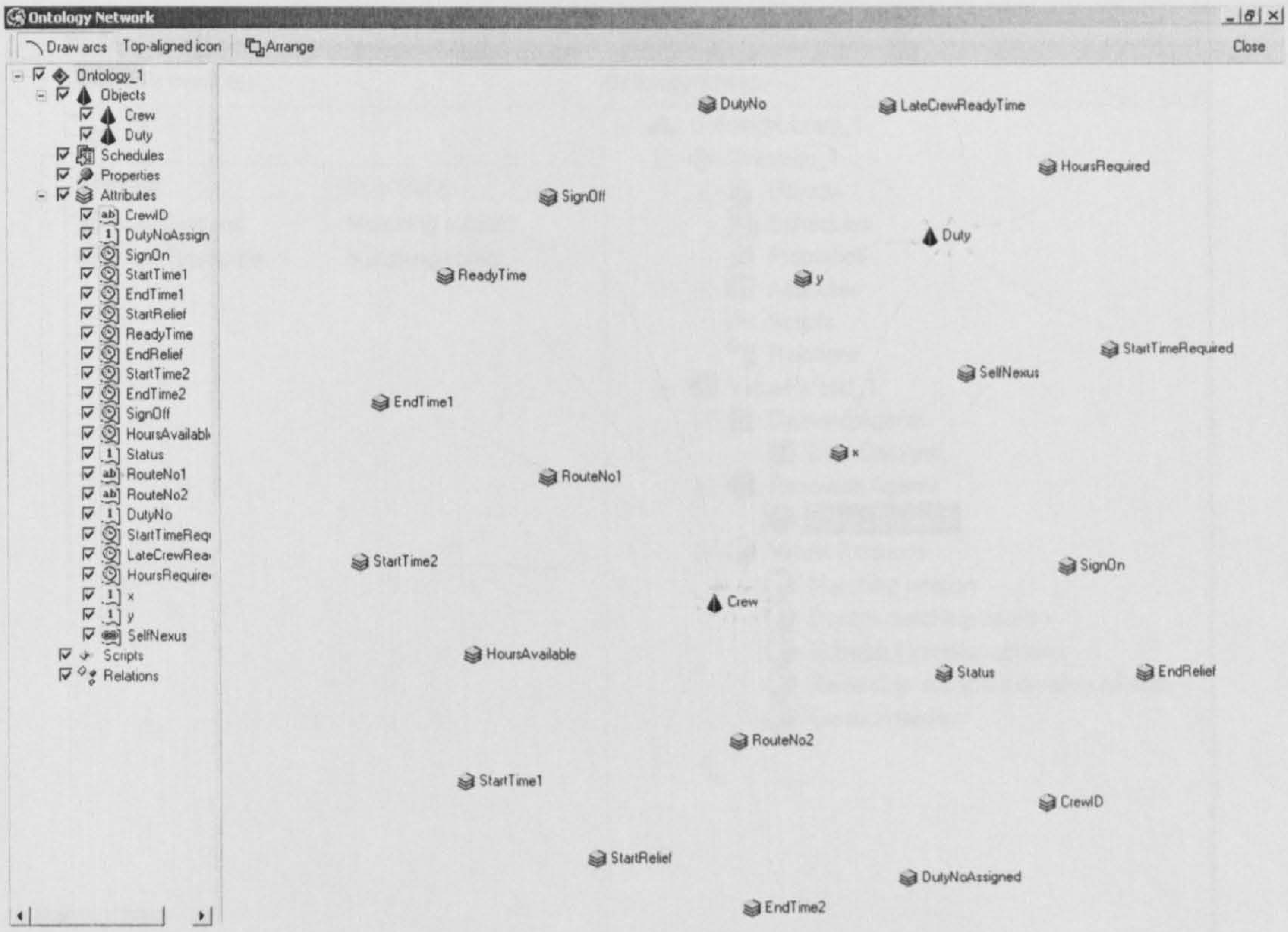

Figure 4.3: Network Representation of Objects and its Attributes in AgentPower

4.3.2 Virtual World

After identifying the objects, the next step is to create a virtual world. In the virtual world, resource and demand agents, and their virtual relations, are specified. There are two objects defined in the above section. One will be assigned as a demand agent and the other as a resource agent. The demand agent represents a task or work to be done. The resource agent represents someone or something that can fulfil the task. In this system, object duty is the demand agent whilst object crew is the resource agent. This is due to the fact that the duty is a task that needs to be done while the crew is the resource able to fulfil the task. Figure 4.3 shows the virtual world where the demand and resource agents are specified.

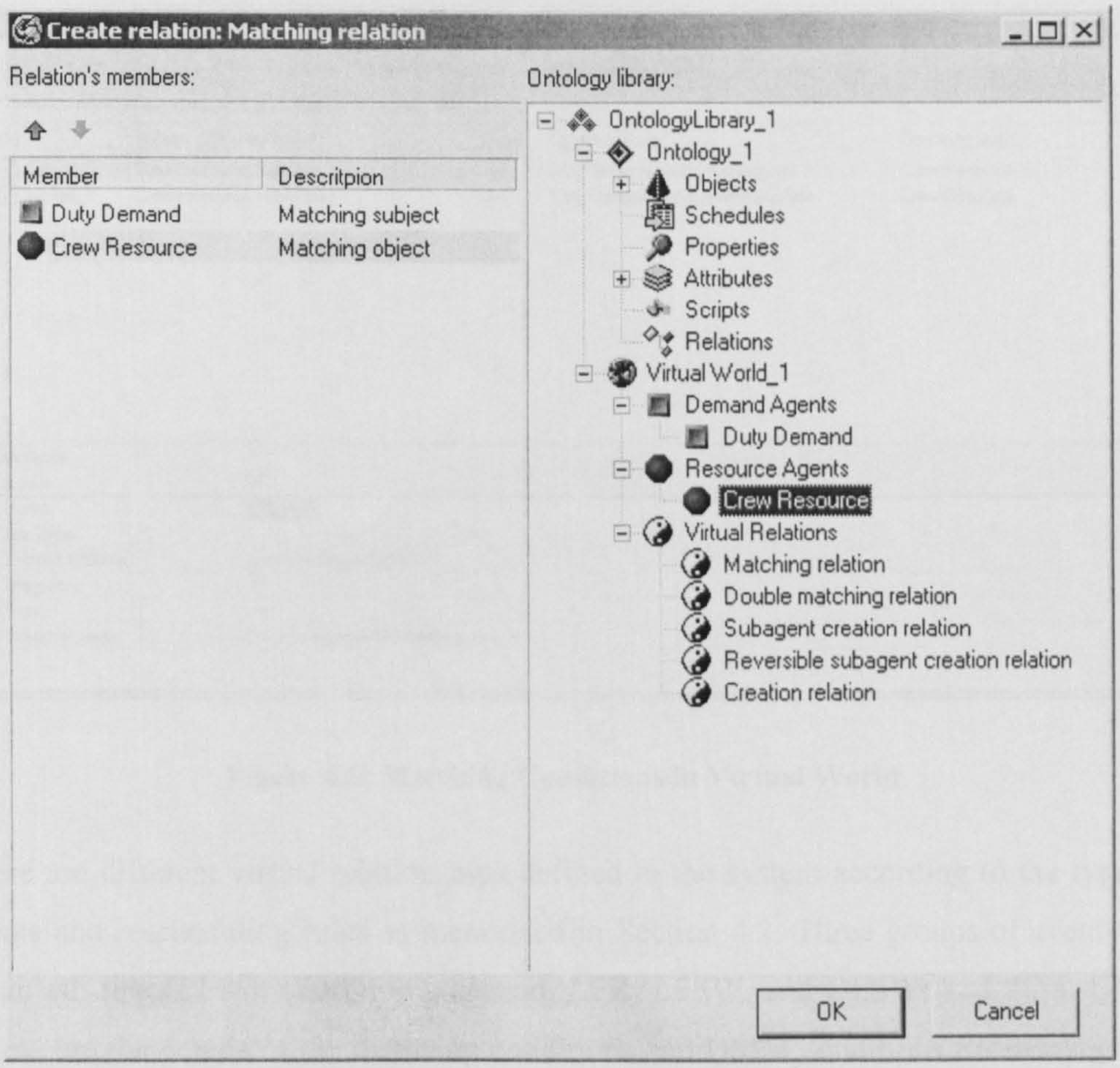

Figure 4.4: Demand Agent and Resource Agent in Virtual World

After specifying the demand and resource agents, the next step is to specify the virtual relationship between them. The purpose of the virtual relationship is to set criteria of matching between the demand agent and resource agent. In this system, we want to reschedule duty to other crews because the crew is late or unavailable. To reschedule the duty, there are rules that need to be followed as presented in Section 4.2. In short, the matching criteria in virtual relationships should be based on the reassignment rules. In AgentPower, there are two types of relationships that need to be defined: *matching condition* and *decision-making machine* (DMM). Matching condition determines the matching criterion for demand agent and resource agent. When there are several matches for an agent, then the DMM condition determines the best from them. Figure 4.4 illustrates the screen shot where the matching conditions are set in the virtual world.

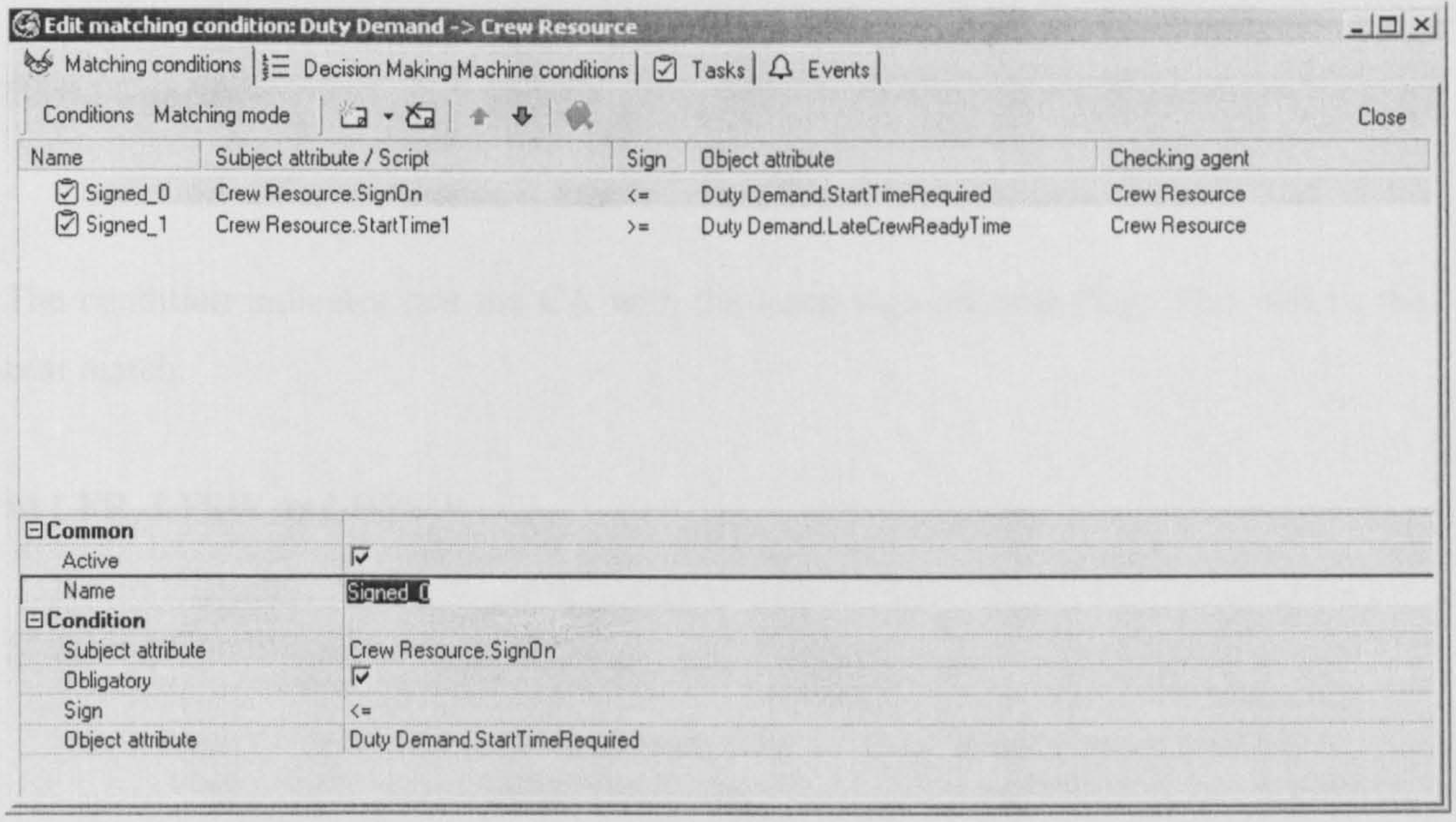

Figure 4.5: Matching Conditions in Virtual World

There are different virtual relationships defined in the system according to the type of events and rescheduling rules as mentioned in Section 4.2. Three groups of events are specified: first, LFSO, and DFSO; second, LFR, LFSW, and DFSW; and third, UNV. Below are the details of the matching conditions and DMM conditions for every group specified above.

a) LFSO and DFSO

Matching conditions

```
Condition 1: Crew Resource.SignOn < = Duty Demand.MinimumRequired Time

Condition 2: Crew Resource.StartTime1 > = Duty Demand.LateCrewReadyTime
```

The first condition specifies that the crew agent (CA) must sign-on (sign-on) before or at the time specified (minimum required time) by the duty agent (DA). The second condition is that the starting time of the first work (start time 1) of CA must be later or equal to the late-crew ready time (late crew ready time). If both conditions are satisfied, there is a match between demand agent (DA) and resource agent (CA).

DMM Condition

```
Condition 1: Crew Resource.SignOn Order: Max (descending) Weight: 100
```

The condition indicates that the CA with the latest sign-on time (Sign On) will be the best match.

b) LFR, LFSW and DFSW

Matching Conditions

```
Condition 1: Crew Resource.CrewReadyTime <= Duty Demand.StartTime

Condition 2: Crew Resource.StartTime2 >= Duty Demand.LateCrewReadyTime
```

The first condition signifies that CA ready time (crew ready time), in this case referring to time after sufficient relief, must be equal or less than the starting time (start time) of the DA. The second condition implies that CA starting time for the second work (start time 2) should be equal or later than the late-crew ready time (late crew ready time). If both conditions are fulfilled there is a match between DA and CA.

DMM Condition

```
Condition 1: Crew Resource.StartTime2 Order: Min (ascending)  Weight: 100
```

The condition designates the CA with the earliest time of *start work 2* to be selected.

c) UNV

Matching Conditions

```
Condition 1: Crew Resource.HoursAvailable > = Duty Demand.HoursRequired

Condition 2: Crew Resource.FinishTime2 < = Duty Demand.StartTime

Condition 3: Crew Resource.SignOff > = Duty Demand.StartTime
```

The first condition specifies that the CA's driving hours available (hours available) in that day should be equal to or more than the driving hours required (hours required) by the DA. Condition 2 indicates the CA finish time 2 should be equal to or less than the start time required by the DA. Condition 3 signifies that the CA sign off time should be equal to or later than the start time required by the DA. If all conditions are fulfilled, then there is a match between the CA and DA.

DMM Condition

```
Condition 1:Crew Resource.HoursAvailable Order:Max(descending) Weight: 100
```

Condition 1 shows that the CA with the highest *hours available* will be the best match.

4.3.3 The Matching Simulation

After specifying the objects, the demand and resource agents, their virtual relationship, and the matching conditions, the next step is to run the simulation. In this simulation, the CA is created based on how many crews are assigned to duties in a crew schedule. However, the number of DA depends on the UE taking place. For example, if a crew schedule has 45 duties and the duties were assigned to 45 crews (normally the number of crews is equal to the number of duties) then the number of CA is 45. And if 5 crews are late then 5 DA will be created. After specifying how many agents are required, the next step is to fill all the attributes of the agents, and then run the simulation. Figure 4.5 shows an example of the running simulation of CA and DA in finding a match. In the matching or negotiation process, the agents communicate by sending messages as described in Section 3.4.2. In AgentPower the messages is display in the central log (see Figure 4.5).

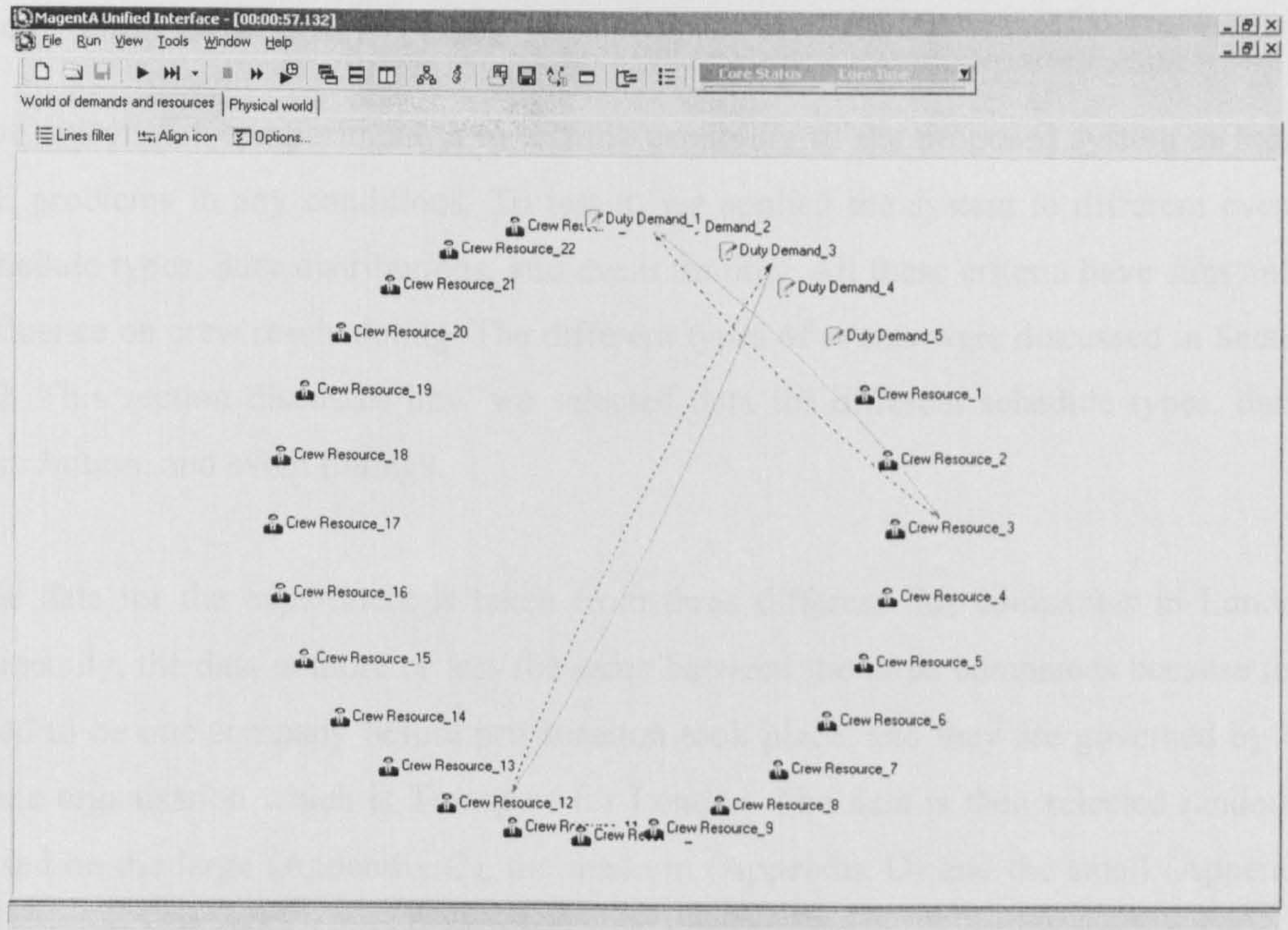

Figure 4.6: Matching Simulation Between CA and DA in AgentPower

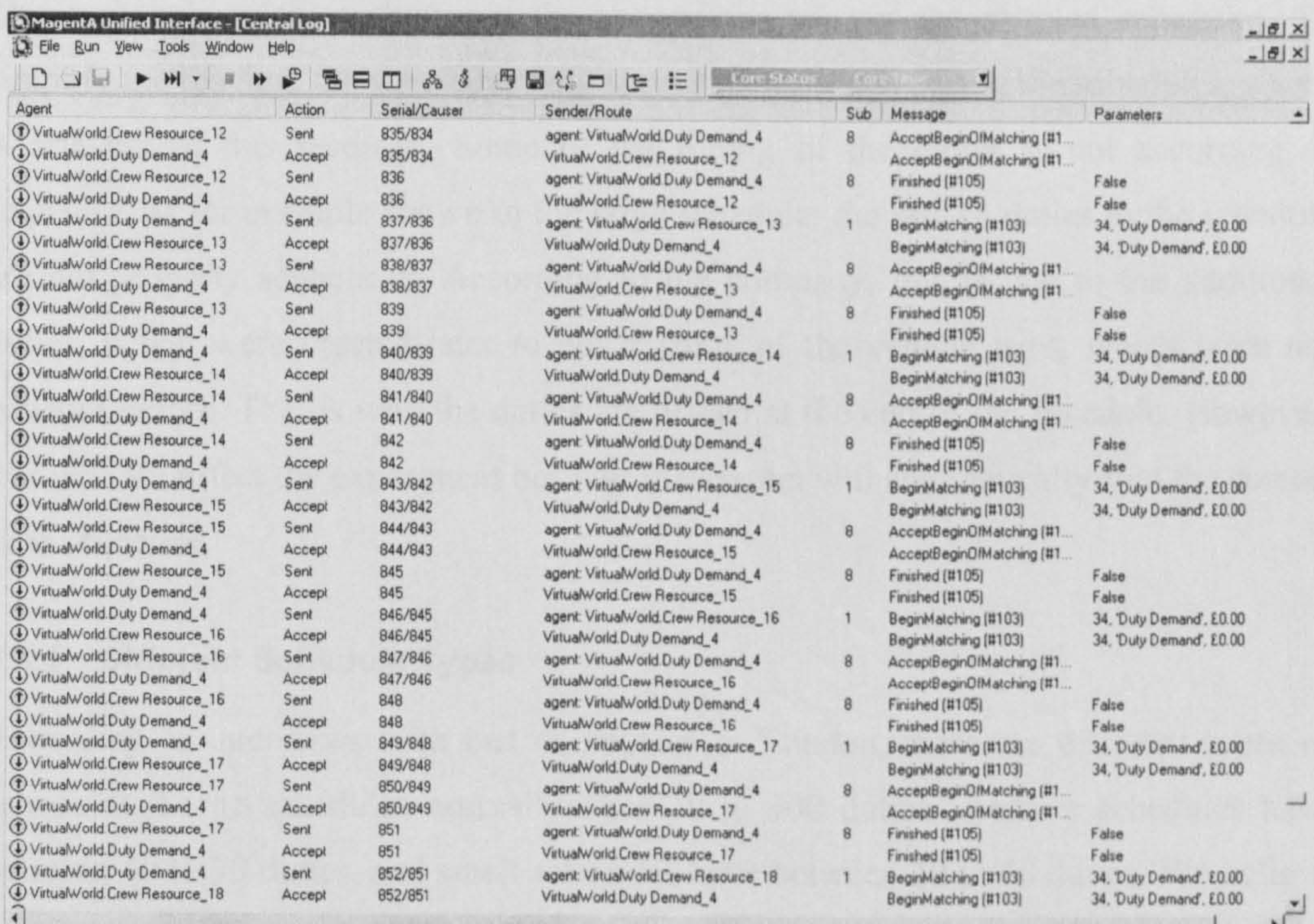

Figure 4.7: Messages Exchanged in Matching Process

4.4 Data Selection Process

The object of the experiment is to test the capability of the proposed system in facing UE problems in any conditions. To test it, we applied the system to different events, schedule types, duty distributions, and event timings. All these criteria have substantial influence on crew rescheduling. The different types of events were discussed in Section 4.2. This section discusses how we selected data for different schedule types, duties distribution, and event timings.

The data for the experiment is taken from three different bus companies in London. Generally, the data is more or less the same between the three companies because they used to be one company before privatisation took place, and they are governed by the same organisation which is Transport for London. The data is then selected randomly based on the large (Appendix C), the medium (Appendix D) and the small (Appendix E) number of duties.

The crew schedules as shown in the appendixes are not the detailed schedules. To simplify the reading, the schedules only show the important part in the schedules, which is relevant to this research. Some of the timing of the duties is not according to sequence, as for example shown in the large schedule; the last 18 duties in the schedule are not properly sequenced. According to the company, this is due to the additional duties, which were created later to cover some of the vehicle trips, which were not covered before. That is why the duties are placed at the end of the schedule. However, this will not affect the experiment because the system will automatically find the correct time sequence.

4.4.1 Different Schedule Types

According to interviews with bus companies in London, there are different types of schedules. Large schedules normally have 70 to 100 duties, medium schedules have between 40 to 70 duties, and small schedules have between 20 to 40 duties. We believe that the type of schedule has a great influence on crew rescheduling. For example, in a large schedule, if a crew is late then there are many crews available compared to in medium or small schedules. For the experiments, three different types of schedules are used: a large schedule consisting of 88 duties (Appendix C), a medium schedule consisting of 51 duties (Appendix D) and a small schedule consisting of 23 duties (Appendix E).

4.4.2 Different Duties Distribution

In this testing we use the term distribution to refer to the number of duties in an hour. We believe that the higher the number of duties in an hour, the higher the possibility of finding a match in crew rescheduling. For this experiment, we classify three different distributions: maximum, median (average), and minimum. For every type of schedule (large, medium, and small), a duty is chosen from maximum, median and minimum distributions. The chosen duty will be used to simulate the occurrence of late and delay. Event scenarios for unavailability are created in the time of maximum, median and minimum distributions. To choose the maximum, median, and minimum distributions in an hour the selection process is carried out as explained below:

1) First, a specific time (for example sign-on time) is selected as a benchmark for different events.
2) Based on the selected specific time, the number of duties is calculated according to the time occurred. The duties are totalled according to the hour time (excluding the minutes). For example, there are 10 duties that have sign-on time at 9 hours (of all the duties that have sign-on times from 9:00 to 9:59).
3) From the total number of duties, the maximum, minimum and median groups are found according to the hours between them. If they are of the same value, then the first is chosen.
4) Based on the selected maximum, median, and minimum hour, a duty is chosen that occurs first in that hour. This duty will be used as test data to simulate events of lateness and delay. However, for unavailability events, scenarios are created in the time of selected maximum, median and minimum hours. The selection process is carried out for all events.

The following paragraphs explain the application of the selection process for every type of event and every type of schedule.

LFSO and DFSO

In the event of LFSO or DFSO, the sign-on time is chosen as a benchmark time. Table 4.10 shows the total number of duties sign-on by hour for large, medium and small schedules. *Sign-on time* shows when the hour of sign-on has happened. *Large, medium and small* refer to the type of crew schedules as discussed in the previous section. For example, at hour 6:00, there are 14, 6, and 2 crews that sign-on for large, medium and small duties respectively. The total shows the total number of duties in every duty type.

Table 4.10: Data Grouping for the Event of LFSO and DFSO

Sign-On	Large	Medium	Small
3:00:00	3	0	0
4:00:00	7	4	1
5:00:00	8	10	2
6:00:00	14	6	2
7:00:00	5	5	1
8:00:00	7	0	5
9:00:00	1	5	0
10:00:00	4	1	0
11:00:00	4	1	2
12:00:00	7	2	2
13:00:00	6	5	0
14:00:00	6	4	1
15:00:00	5	0	3
16:00:00	8	4	2
17:00:00	3	4	1
18:00:00	0	0	1
Total	88	51	23

After the grouping process, the selection process takes place where the maximum, median and minimum data were selected. Table 4.11 shows the results of the selection process. For example, for a large schedule the maximum distribution of duties that sign-on time occurs at 6:00:00 is 14. The median is at 5:00:00 (8 occurrences) and the minimum is at 9:00:00 (1 occurrence). For a medium schedule, the maximum is at 5:00:00 (10 occurrences), the median is at 6:00:00 (6 occurrences) and the minimum is at 10:00:00 (1 occurrence). For a small schedule, the maximum is at 8:00:00 (5 occurrences), the median is at 15:00:00 (3 occurrences) and the minimum is at 4:00:00 (1 occurrence). The first duty that occurred in the chosen hour is selected for the experiment. Table 4.12 shows the test data from every type of schedule (large, medium, and small) and every type of distributions (maximum, median and minimum).

Table 4.11: Data Selection for the Event of LFSO and DFSO

Distribution	Type of Schedule					
	Large		Medium		Small	
Maximum	06:00:00	14	05:00:00	10	08:00:00	5
Median	05:00:00	8	06:00:00	6	15:00:00	3
Minimum	09:00:00	1	10:00:00	1	04:00:00	1

Table 4.12: Test Data for the Event of LFSO and DFSO

Large Schedule				
Distribution	Crew ID	Duty Assigned	Sign On	Start Work 1
Maximum	S	69	06:00:00	6:15:00
Median	K	61	05:03:00	5:18:00
Minimum	CB	140	09:08:00	9:23:00
Medium Schedule				
Maximum	E	205	05:00:00	5:15:00
Median	O	215	06:14:00	6:29:00
Minimum	AE	231	10:31:00	10:46:00
Small Schedule				
Maximum	F	573	08:17:00	8:32:00
Median	O	582	15:26:00	15:41:00
Minimum	A	568	04:56:00	5:11:00

LFR

In the event of LFR, the end time of the first work (end time 1) is chosen as a benchmark time. Table 4.13 shows the grouping of the end time of the first work based on the hour for large, medium and small schedules. For example, at 8:00 there are 6, 4, and 1 crews that finish their first work for large, medium and small duties respectively. After the grouping process, the selection process takes place where the maximum, median and minimum data is selected. Table 4.14 shows the results of the selection process. For example, for a large duty the maximum distribution of end work 1 time occurs at 11:00:00, which is 12 duties at that hour. The median is at 9:00:00 (7 occurrences) and the minimum is at 15:00:00 (1 occurrence). Table 4.15 illustrates the test data selected from every type of schedule (large, medium and small) and every distribution type (maximum, median and minimum).

Table 4.13: Data Grouping for the Event of LFR

End Work 1	Large	Medium	Small
8:00:00	6	4	1
9:00:00	7	4	2
10:00:00	8	11	2
11:00:00	12	4	2
12:00:00	12	5	2
13:00:00	5	3	2
14:00:00	2	4	0
15:00:00	1	1	1
16:00:00	6	2	2
17:00:00	8	4	2
18:00:00	6	1	3
19:00:00	6	3	3
20:00:00	5	3	1
21:00:00	4	2	0
Total	88	51	23

Table 4.14: Data Selection for the Event of LFR

Distribution	Schedule					
	Large		Medium		Small	
Maximum	11:00:00	12	10:00:00	11	18:00:00	3
Median	09:00:00	7	12:00:00	5	09:00:00	2
Minimum	15:00:00	1	15:00:00	1	08:00:00	1

Table 4.15: Test Data for the Event of LFR

Large Schedule				
Distribution	Crew ID	Duty Assigned	Finish Work 1	Start Work 2
Maximum	X	74	11:02:00	12:02:00
Median	M	63	09:05:00	10:10:00
Minimum	AL	88	15:02:00	16:14:00
Medium Schedule				
Maximum	G	207	10:03:00	11:18:00
Median	S	219	12:06:00	14:45:00
Minimum	AO	241	15:43:00	16:37:00
Small Schedule				
Maximum	R	585	18:17:00	19:32:00
Median	B	569	09:15:00	10:11:00
Minimum	C	570	08:43:00	9:52:00

LFSW and DFSW

In the event of LFSW or DFSW, the end time of relief (end relief) is chosen as a benchmark time. Table 4.16 demonstrates the grouping of the end relief time based on hour for large, medium and small schedules. Thereafter, the selection process takes place where the maximum, median and minimum data are selected. Table 4.17 illustrates the results of the selection process, and Table 4.18 shows the test data from every type of schedule (large, medium, and small) and every distribution type (maximum, median and minimum).

Table 4.16: Data Grouping for the Event of LFSW and DFSW

End Relief	Large	Medium	Small
9:00:00	5	0	1
10:00:00	7	7	2
11:00:00	9	5	1
12:00:00	8	4	3
13:00:00	11	3	2
14:00:00	8	8	0
15:00:00	4	5	0
16:00:00	1	1	2
17:00:00	5	2	1
18:00:00	9	4	1
19:00:00	5	1	3
20:00:00	5	3	4
21:00:00	6	4	1
22:00:00	5	1	0
Total	88	48	21

Table 4.17: Data Selection for the Event of LFSW and DFSW

Distribution	Schedule					
	Large		Medium		Small	
Maximum	13:00:00	11	14:00:00	8	20:00:00	4
Median	21:00:00	6	11:00:00	5	12:00:00	3
Minimum	16:00:00	1	16:00:00	1	09:00:00	1

Table 4.18: Test Data for the Event of LFSW and DFSW

Large Schedule				
Distribution	Crew ID	Duty Assigned	End Relief	Start Work 2
Maximum	AD	80	13:03:00	13:08:00
Median	BF	108	21:02:00	21:07:00
Minimum	AL	88	16:09:00	16:14:00
Medium Schedule				
Maximum	AF	232	14:01:00	14:06:00
Median	Y	225	11:08:00	11:13:00
Minimum	AO	241	16:32:00	16:37:00
Small Schedule				
Maximum	O	582	20:06:00	20:11:00
Median	E	572	12:07:00	12:12:00
Minimum	C	570	09:47:00	9:52:00

UNV

In the event of UNV, the end time of second work (end work 2) is chosen as a benchmark time. Table 4.19 illustrates the grouping of the end work 2 based on hour for large, medium and small schedules. Afterwards, the selection process takes place to choose the maximum, median and minimum hour. Table 4.20 shows the results of the selection process. The test data for UNV event are not taken from the selected time (maximum, median and minimum hour) but the UNV scenarios are created in the selected time to test whether rescheduling the uncovered duty at the selected time (maximum, median and minimum hour) is possible or not. Table 4.21 illustrates the scenarios for UNV event according to types of schedules and distributions. There are 4 different types of timing, 30, 60, 90 and 120 minutes and three different starting times, 15, 30, and 45 minutes past any selected hour. The selected hour is based on the selected distribution time (maximum, medium, and minimum). For example (see Table 4.20), in the large schedule type the maximum distribution is at 13:00. So the test scenarios for the large schedule type and maximum distribution (see Table 4.21) will have starting times at 13:15, 13:30, and 13:45 and the ending time depends on the UNV timing. For example, if the UNV timing is 30 minutes (see Table 4.21) then the ending time is 13:45, 14:00, and 14:15 (the starting time plus 30 minutes).

Table 4.19: Data Grouping for the Event of UNV

End Work 2	Large	Medium	Small
11:00:00	3	1	0
12:00:00	3	2	2
13:00:00	12	4	1
14:00:00	12	3	1
15:00:00	5	4	1
16:00:00	4	7	2
17:00:00	3	2	2
18:00:00	3	5	0
19:00:00	5	2	0
20:00:00	6	4	3
21:00:00	9	3	1
22:00:00	7	3	0
23:00:00	0	0	0
00:00:00	8	3	6
1:00:00	8	5	2
Total	88	48	21

Table 4.20: Data Selection for the Event of UNV

Distribution	Schedule					
	Large		Medium		Small	
Maximum	13:00:00	12	16:00:00	7	00:00:00	6
Median	00:00:00	8	13:00:00	4	20:00:00	3
Minimum	11:00:00	3	11:00:00	1	13:00:00	1

Table 4.21: Test Scenarios for the Event of UNV

	Large Schedule						Medium Schedule						Small Schedule					
	Maximum		Median		Minimum		Maximum		Median		Minimum		Maximum		Median		Minimum	
UNV (min)	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
30	13:15	13:45	0:15	0:45	11:15	11:45	16:15	16:45	13:15	13:45	11:15	11:45	0:15	0:45	20:15	20:45	13:15	13:45
30	13:30	14:00	0:30	1:00	11:30	12:00	16:30	17:00	13:30	14:00	11:30	12:00	0:30	1:00	20:30	21:00	13:30	14:00
30	13:45	14:15	0:45	1:15	11:45	12:15	16:45	17:15	13:45	14:15	11:45	12:15	0:45	1:15	20:45	21:15	13:45	14:15
60	13:15	14:15	0:15	1:15	11:15	12:15	16:15	17:15	13:15	14:15	11:15	12:15	0:15	1:15	20:15	21:15	13:15	14:15
60	13:30	14:30	0:30	1:30	11:30	12:30	16:30	17:30	13:30	14:30	11:30	12:30	0:30	1:30	20:30	21:30	13:30	14:30
60	13:45	14:45	0:45	1:45	11:45	12:45	16:45	17:45	13:45	14:45	11:45	12:45	0:45	1:45	20:45	21:45	13:45	14:45
90	13:15	14:45	0:15	1:30	11:15	12:30	16:15	17:30	13:15	14:30	11:15	12:30	0:15	1:30	20:15	21:30	13:15	14:30
90	13:30	15:00	0:30	1:45	11:30	12:45	16:30	17:45	13:30	14:45	11:30	12:45	0:30	1:45	20:30	21:45	13:30	14:45
90	13:45	15:15	0:45	2:00	11:45	13:00	16:45	18:00	13:45	15:00	11:45	13:00	0:45	2:00	20:45	22:00	13:45	15:00
120	13:15	15:15	0:15	1:45	11:15	12:45	16:15	17:45	13:15	14:45	11:15	12:45	0:15	1:45	20:15	21:45	13:15	14:45
120	13:30	15:30	0:30	2:00	11:30	13:00	16:30	18:00	13:30	15:00	11:30	13:00	0:30	2:00	20:30	22:00	13:30	15:00
120	13:45	15:45	0:45	2:15	11:45	13:15	16:45	18:15	13:45	15:15	11:45	13:15	0:45	2:15	20:45	22:15	13:45	15:15

4.4.3 Different Event Timing

Different timing in this context means how long the event is such as, 15 minutes LFSO, or 30 minutes LFR. Timing also can affect the decision to reschedule crew. We believe that the longer the timing is, the harder it is to do crew rescheduling. For example, if a crew happens to come 1 hour late, it is complicated to find an available crew to replace the late-crew. The easy option is to replace it with standby crew, however this is not our objective. In this research we are trying to find an optimum solution by using the available crew instead of standby crew. In this research, for every event we create different timings to test the system. The following paragraph discusses the timing for every event.

For lateness events (LFSO, LFR, and LFSW), the experiment starts from 15 minutes late then increases by 5 minute increments until reaching 60 minutes. In the delay event (DFSO, and DFSW), the experiment starts from 80 minutes late then increases by 20 minutes increments until 180 minutes. In the UNV event (as shown in Table 4.21), the experiment uses 30, 60, 90 and 120 minutes unavailable. For each scenario there are three different times of occurrence in an hour, at 15, 30 and 45 minutes past the hour.

4.4.4 Different Times of Day

Based on the interviews with bus companies in London (as discussed in Chapter Two), traffic is the major cause of UE especially during peak hours. Peak hours are the time when many vehicles are on the road. We believe that the time of day has influence on crew rescheduling. In this experiment, three different times of day are selected that are early, midday, and late. Early is between 7 am. to 9 am., midday is between 12 pm. to 2 pm., and late is between 5 pm. to 7 pm. There are two events (LFSO) which happen at the same time. The periods of lateness are15 and 20 minutes. The data are selected randomly using the random formula in Microsoft Excel to generate random numbers and the numbers are used to refer to the duty numbers. The formula is shown below:

```
RAND( )*(the maximum number-the minimum number) + the minimum number
```

Table 4.22: Data LFSO at Different Times of Day

Large Schedule			
Early			
Crew ID	Duty No	Sign-On	Start Work 1
BS	131	07:32:00	07:47:00
BZ	138	08:39:00	08:54:00
Midday			
AZ	102	13:20:00	13:35:00
CF	144	14:06:00	14:21:00
Late			
BJ	112	16:08:00	16:23:00
BM	115	16:27:00	16:42:00

Medium Schedule			
Early			
Crew ID	Duty No	Sign-On	Start Work 1
U	221	7:00:00	07:15:00
AB	228	9:28:00	09:43:00
Midday			
AK	237	13:13:00	13:28:00
AP	242	14:41:00	14:56:00
Late			
AW	249	17:29:00	17:44:00
AX	250	17:43:00	17:58:00

Small Schedule			
Crew ID	Duty No	Sign-On	Start Work 1
Early			
F	573	08:17:00	08:32:00
I	576	08:56:00	09:11:00
Midday			
K	578	11:56:00	12:11:00
L	579	12:26:00	12:41:00
Late			
T	587	17:37:00	17:52:00
U	588	18:37:00	18:52:00

The maximum number is the total number of duties at different times of day and the minimum number is 1. For example, for a midday time of medium schedule which has 11 duties the formula will look like this:

RAND()*(11-1)+1

Table 4.22 shows the selected data for LFSO at different times of day according to the type of schedule. The full data for the experiment is shown in Appendix F.

4.5 Undertaking the Experiments

As mentioned above, the purpose of a single event experiments is to test the capability of CRSMAS in dealing with different types of events in different types of schedules, duty distributions, and timings, and also to identify the characteristics in crew schedules that influence the possibility of rescheduling. In total there are 54 experiments that need to be carried out. Table 4.22 shows the overall picture of the experiments for each event. For example, in the LFSO event, the experiments are carried out on three different types of schedules (large, medium, and small), and for each type there are maximum, median and minimum distributions. As a result, the total number of experiments for a LFSO event is 9. This is the same for other events.

In these experiments, if there is no match in the first round of rescheduling then manual adjustment is needed for the next round. For example, there may be a match that is a few minutes late. This is acceptable, but the minutes late should be less than the minutes late of the late-crew. For every experiment, the details are recorded for analysis. The information recorded is the timing that shows how late or unavailable the crew is; the time when the late-crew is ready for work; the time the system takes to perform rescheduling; the number of rescheduling rounds; the matching results; minutes late if any due to adjustments to find a match and how many crew are affected by the rescheduling process.

Table 4.22: Overall Picture of the Experiments

Type of Events	Type of Schedules	Duties Distribution	Number of Experiments
LFSO	Large Schedule	Maximum	1
		Median	2
		Minimum	3
	Medium Schedule	Maximum	4
		Median	5
		Minimum	6
	Small Schedule	Maximum	7
		Median	8
		Minimum	9
LFR	Large Schedule	Maximum	10
		Median	11
		Minimum	12
	Medium Schedule	Maximum	13
		Median	14
		Minimum	15
	Small Schedule	Maximum	16
		Median	17
		Minimum	18
LFSW	Large Schedule	Maximum	19
		Median	20
		Minimum	21
	Medium Schedule	Maximum	22
		Median	23
		Minimum	24
	Small Schedule	Maximum	25
		Median	26
		Minimum	27
DFSO	Large Schedule	Maximum	28
		Median	29
		Minimum	30
	Medium Schedule	Maximum	31
		Median	32
		Minimum	33
	Small Schedule	Maximum	34
		Median	35
		Minimum	36
DFSW	Large Schedule	Maximum	37
		Median	38
		Minimum	39
	Medium Schedule	Maximum	40
		Median	41
		Minimum	42
	Small Schedule	Maximum	43
		Median	44
		Minimum	45
UNV	Large Schedule	Maximum	46
		Median	47
		Minimum	48
	Medium Schedule	Maximum	49
		Median	50
		Minimum	51
	Small Schedule	Maximum	52
		Median	53
		Minimum	54

4.5.1 Experiment Environment

A PC with Pentium IV 1.2 GHz and Windows XP operating system was used for the experiments.

4.6 Overview of Experimental Results

This section presents the sample of the results of the experiments for all the events as shown in Tables 4.23 to 4.28 (LFSO (Table 4.23), LFR (Table 4.24), LFSW (Table 4.25), DFSO (Table 4.26), DFSW (Table 4.27) and UNV (Table 4.28)). The full results are shown in 54 tables in Appendix F.

As shown in Tables 4.23 to 4.27, *lateness* illustrates how many minutes the crew is late, *late-crew ready time* shows the time when the late-crew is ready for work, *time* shows how fast in seconds the system performs the rescheduling process, *round* shows how many rescheduling rounds take place to find a match, and *rescheduling* shows which crew is assigned to which duty. For example, in the case of rescheduling result S, V, Z, AB, crew S (which the first from left) is the late-crew and it takes the duty of AB (which is the first from right). Crew V takes crew S's duty, crew Z takes crew V's duty, and crew AB takes crew Z's duty. *Minutes late* shows the late minutes due to adjustments to find a match, and *crew involved* shows how many crews are affected by the rescheduling.

For example, Table 4.23 shows the result for the event of LFSO for large schedule type and maximum distribution. As an example, in the first row, the crew is late by 15 minutes; the late-crew is only ready for work at 6:20; the rescheduling process takes 1.873 seconds and only one round of matching and the result is that crew S (which is the late-crew) takes crew V's duty, and crew V takes crew S's duty. In this process, two crews are affected. For the 60 minutes late example as shown in the last row, the crew is late for 60 minutes, the late-crew is only ready for work at 7:05, and the rescheduling process takes 5.544 seconds and three rounds of matching are needed. The rescheduling results is that crew S (which is the late-crew) takes crew AF's duty, crew V takes crew S's duty, crew Z takes crew V's duty, crew AB takes crew Z's duty, crew AC takes crew AB's duty, crew AD take crew AC's duty, crew AE takes crew AD's duty, and crew AF takes crew AE's duty. In this process, there is 1 minute lateness and 8 crews are affected.

Table 4.23: LFSO (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	06:20:00	1.873	1	S, V	0	2
20	06:25:00	1.912	1	S, V	0	2
25	06:30:00	3.756	2	S, V, Z	0	3
30	06:35:00	1.943	1	S, V, Z	0	3
35	06:40:00	3.866	2	S, V,Z,AB	0	4
40	06:45:00	3.764	2	S, V,Z,AB,AC	0	5
45	06:50:00	1.982	1	S, V,Z,AB,AC	0	5
50	06:55:00	3.655	2	S, V,Z,AB,AC,AD	0	6
55	07:00:00	3.806	2	S, V,Z,AB,AC,AD, AE	0	7
60	07:05:00	5.544	3	S, V,Z,AB,AC,AD, AE, AF	1	8

Table 4.24: LFR (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	12:12:00	1.873	1	X, T	0	2
20	12:17:00	2.123	1	X, T	0	2
25	12:22:00	1.963	1	X, T	0	2
30	12:27:00	1.963	1	X, T	0	2
35	12:32:00	1.933	1	X, T	0	2
40	12:37:00	1.963	1	X, T	0	2
45	12:42:00	1.903	1	X, T	0	2
50	12:47:00	1.862	1	X, T	0	2
55	12:52:00	1.983	1	X, T	0	2
60	12:57:00	1.843	1	X, T	0	2

Table 4.25: LDR (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	13:23:00	1.903	1	AD, BW	0	2
20	13:28:00	1.872	1	AD, BW	0	2
25	13:33:00	1.923	1	AD, BW	0	2
30	13:38:00	1.973	1	AD, BW	0	2
35	13:43:00	1.993	1	AD, AF	0	2
40	13:48:00	1.923	1	AD, AF	0	2
45	13:53:00	1.882	1	AD, AI	0	2
50	13:58:00	1.882	1	AD, AI	0	2
55	14:03:00	1.923	1	AD, AI	0	2
60	14:08:00	1.993	1	AD, AI	0	2

Table 4.26: DFSO(Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	07:25:00	1.873	1	S, V,Z,AB,AC,AD, AE, AF, AG	8	9
100	07:45:00	-	-	No Match	-	-
120	08:05:00	-	-	No Match	-	-
140	08:25:00	-	-	No Match	-	-
160	08:45:00	-	-	No Match	-	-
180	09:05:00	-	-	No Match	-	-

Table 4.27: DFSW (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	14:28:00	1.803	1	AD, AI	0	2
100	14:48:00	1.813	1	AD, AI	0	2
120	15:08:00	1.773	1	AD, AI	0	2
140	15:28:00	3.555	2	AD, AI, AO	0	3
160	15:48:00	-	-	No Match	-	-
180	16:08:00	-	-	No Match	-	-

Table 4.28: UNV (Large)(Maximum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	13:15:00	13:45	I	1.752	0
30	13:30:00	14:00	W	1.802	0
30	13:45:00	14:15	W	1.723	0
60	13:15:00	14:15	I	1.843	0
60	13:30:00	14:30	W	1.943	0
60	13:45:00	14:45	W	1.833	0
90	13:15:00	14:45	I	1.873	0
90	13:30:00	15:00	W	1.853	0
90	13:45:00	15:15	W	1.813	0
120	13:15:00	15:15	I	1.813	0
120	13:30:00	15:30	W	1.792	0
120	13:45:00	15:45	W	1.812	0

In the event of UNV (see Table 4.28), *unavailable* shows in minutes how long the uncovered duty is because of the unavailability of a crew; *start time* shows the start time of the uncovered duty; *end time* shows the end time of the uncovered duty; *rescheduling* shows which crew is assigned to the unattended-duty; *time* shows how fast in seconds the system performs the rescheduling process and *minutes late* shows the late minutes due to adjustments to find a match.

As an example, Table 4.28 shows the results of UNV in large schedule type and maximum distribution. It starts from 30 minutes then followed by 60 minutes, 90 minutes and 120 minutes, and for every minute of UNV three different start and end times (15, 30, and 45 past the hour). For example, in the case of 30 minutes unavailability the start time is 13:15; the end time is 13:45; crew I is reassigned to this uncovered duty; it takes 1.752 seconds for the rescheduling process and is 0 minute late. In the case of 120 minutes UNV, the start time is 13:14; the end time is 15:45; crew W is reassigned to this uncovered duty; it takes 1.812 seconds for the reassignment process and is 0 minute late.

For the full results refer to Appendix F. The next section presents the analysis of the results in detail according to every event.

4.7 Results Analysis

This section presents the analysis of the experiments' results. The objective of this analysis is to measure the results based on certain criteria. As mentioned before, the purpose of the single experiments is to test the capability of CRSMAS in all conditions, and also to identify characteristics in crew schedules that influence the success of rescheduling. The criteria that we used to measure the results are rescheduling capability and times taken to execute it. Rescheduling capability is measured by the number of success in rescheduling (number of matched) and time is measured by the time taken for rescheduling. The best result is a high number of matches with minimum time taken for rescheduling and without or less minutes late. The subsection below presents the analysis according to the events, timing and overall results.

4.7.1 Lateness

LFSO

Figure 4.8 illustrates the number of matched LFSO in different schedule types and duty distributions. The results in Table 4.29 show that the rescheduling is 100% successful (10 out of 10) in *large-maximum* duty, *large-median* duty, *medium-maximum* duty, and *medium-median* duty, while in *small-maximum* duty it is 70% successful (7 out of 10). This reveals that the distribution of a duty plays a major role in determining rescheduling success, regardless of the size of the duty. The average time taken for every rescheduling process is dependent on the type of schedule, as the large schedule takes more than 3 seconds, the medium schedule between 1 to 2 seconds and the small schedule less than 1 second. This is because the bigger the schedule is the more number of duties, and the more time it takes in the matching process. Based on our knowledge, the minutes late are dependent on the distribution of the duty, but the results show that this is not always the case. The table shows average minutes late for large-maximum duty is 0.1 minutes, large-medium duty is 3.5 minutes, medium-maximum duty is 5.1, medium-median duty is 2.6 and small-maximum duty is 15.14. The value for medium-maximum (5.1) is surprisingly high compared to medium-median (2.6) because it supposes that the late minutes are low when the distribution is high. Our further investigation reveals that although the distribution of medium-maximum duty is high (10 duties compared to medium-median duty which is 6 duties as shown in Table 4.11), the starting time of the duties are not spread equally in that hour compared to medium-median. Some of the duties start less than 5 minutes after the previous duty and some of them start more than 10 minutes after the previous duty. Thus, equal distribution of duties in an hour also influences the possibility of finding a match. This is a new factor that we discovered in this experiment.

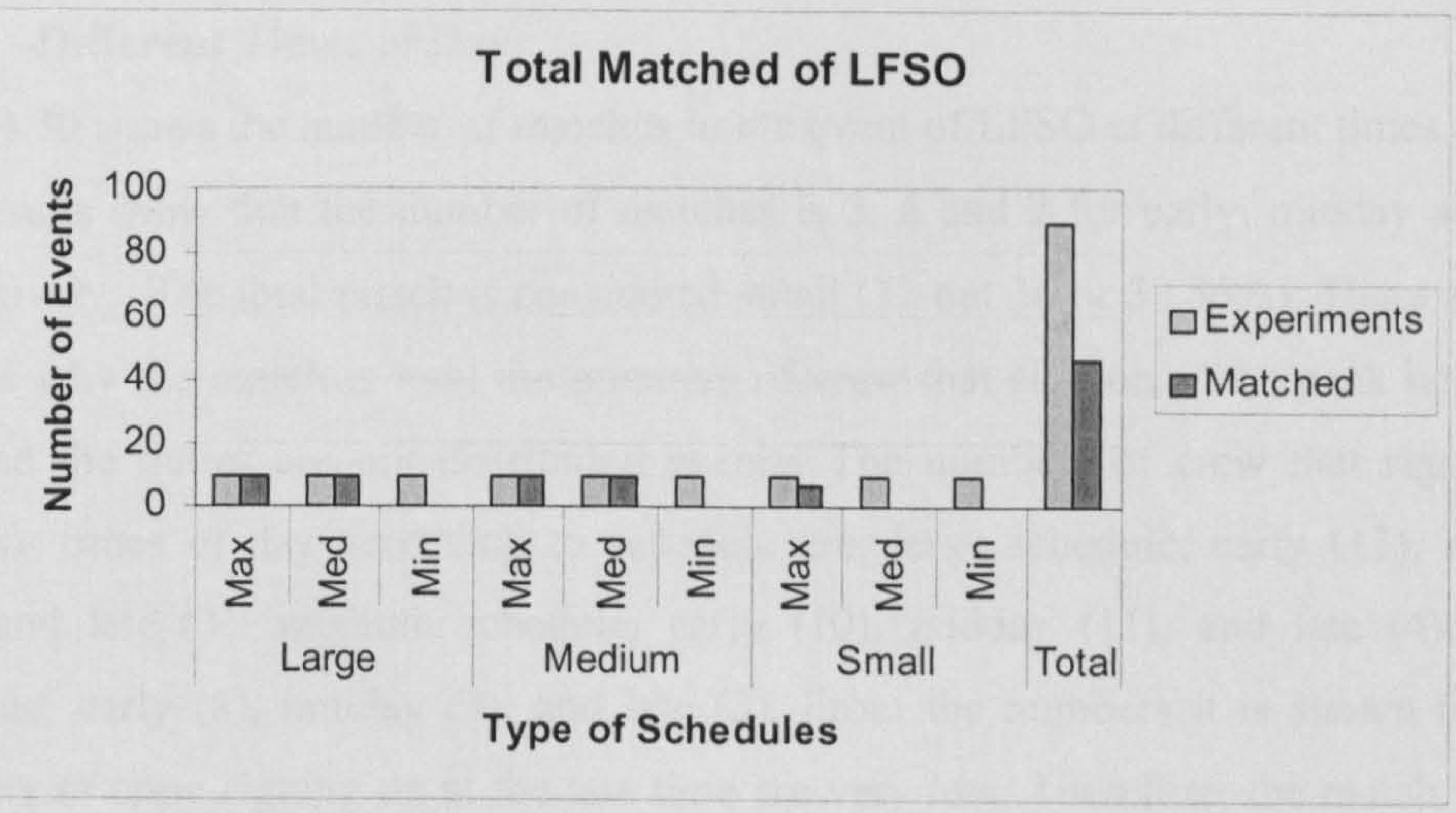

Figure 4.8: Number of LFSO Matched in Different Schedule Type and Distribution

Table 4.29: Rescheduling Analysis for LFSO

	Large Schedule			Medium Schedule			Small Schedule		
	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	10	10	10	10	10	10	10	10	10
Total Successful Matched	10	10	0	10	10	0	7	0	0
Percentage of Successful Matched (%)	100	100	0	100	100	0	70	0	0
Total Time for Successful Matched (S)	32.10	30.92	-	15.44	14.94	-	5.46	-	-
Average Time for Successful Matched	3.21	3.09	-	1.54	1.49	-	0.78	-	-
Total Minutes Late	1	35	-	51	26	-	106	-	-
Average Minutes Late	0.1	3.5	-	5.1	2.6	-	15.14	-	-

Table 4.30: The Analysis of LFSO at Different Times of Day

	Early		Midday		Late		Total Events	Total Match	% Matched
	Event	Match	Event	Match	Event	Match			
Large									
15:00	2	0	2	2	2	0	6	2	33.33
20:00	2	0	2	2	2	0	6	2	33.33
Medium									
15:00	2	1	2	1	2	1	6	3	50.00
20:00	2	1	2	1	2	1	6	3	50.00
Small									
15:00	2	1	2	0	2	0	6	1	16.67
20:00	2	0	2	0	2	0	6	0	0.00
Total	12	3	12	6	12	2	36	11	30.56

LFSO –Different Times of Day

Table 4.30 shows the number of matches in the event of LFSO at different times of day. The results show that the number of matches is 3, 6 and 2 for early, midday and late respectively. The total match is considered small (11 out 36 or 30.56%). There are two reasons why the match is low; the numbers of crew that sign on at the peak hours are few and the duties are not distributed evenly. The numbers of crew that sign on at different times of day according to schedule are: large schedule; early (13), midday (16), and late (3): medium schedule; early (10), midday (11), and late (4): small schedule; early (8), midday (3), and late (3). From the numbers it is shown that the numbers of crew signing on at the late time are very low. Therefore, the match is very low for the late time. Another reason, as mentioned earlier, is the distribution of duties. The large schedule has a large number of crew signing on at the early time but still the number of matches is zero. Further investigation reveals that the distribution of duties is not equal in the large schedule; thus, it decreases the matches. From the results, we conclude that the time of day does not have any effect on rescheduling. The number of available crew and the distribution of duties in an hour have a profound effect on crew rescheduling.

LFR

The analysis in Table 4.31 and Figure 4.9 demonstrates that duty's distribution is a major factor in determining the success of rescheduling. The results show 100% success in large-maximum duty, large-medium duty, medium-maximum duty, and small-maximum duty. The medium-median duty is a unique case because it does not need rescheduling. The reason is the relief time given is long enough to absorb the lateness. The average time for every rescheduling depends on the type of schedule as the results show 1.9 to 2.4 seconds for large schedule, 1.29 seconds for medium schedule, and 0.77 seconds for small" schedule. The average minutes late are according to duty distribution as expected (0 minutes for large-maximum and medium-maximum, 4.4 minutes for large-median, and 9.88 for small-maximum duty).

Table 4.31: Rescheduling Analysis for LFR

	Large Schedule			Medium Schedule			Small Schedule		
	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	10	10	10	10	10	10	10	10	10
Total Successful Matched	10	10	1	10	10*	0	10	0	0
Percentage of Successful Matched (%)	100	100	10	100	100	0	100	0	0
Total Time for Successful Matched (S)	19.41	23.40	-	12.86	-	-	4.19	-	-
Average Time for Successful Matched	1.94	2.34	-	1.29	-	-	0.77	-	-
Total Minutes Late	0	44	-	0	-	-	79	-	-
Average Minutes Late	0	4.4	-	0	-	-	9.88	-	-

** No need for rescheduling*

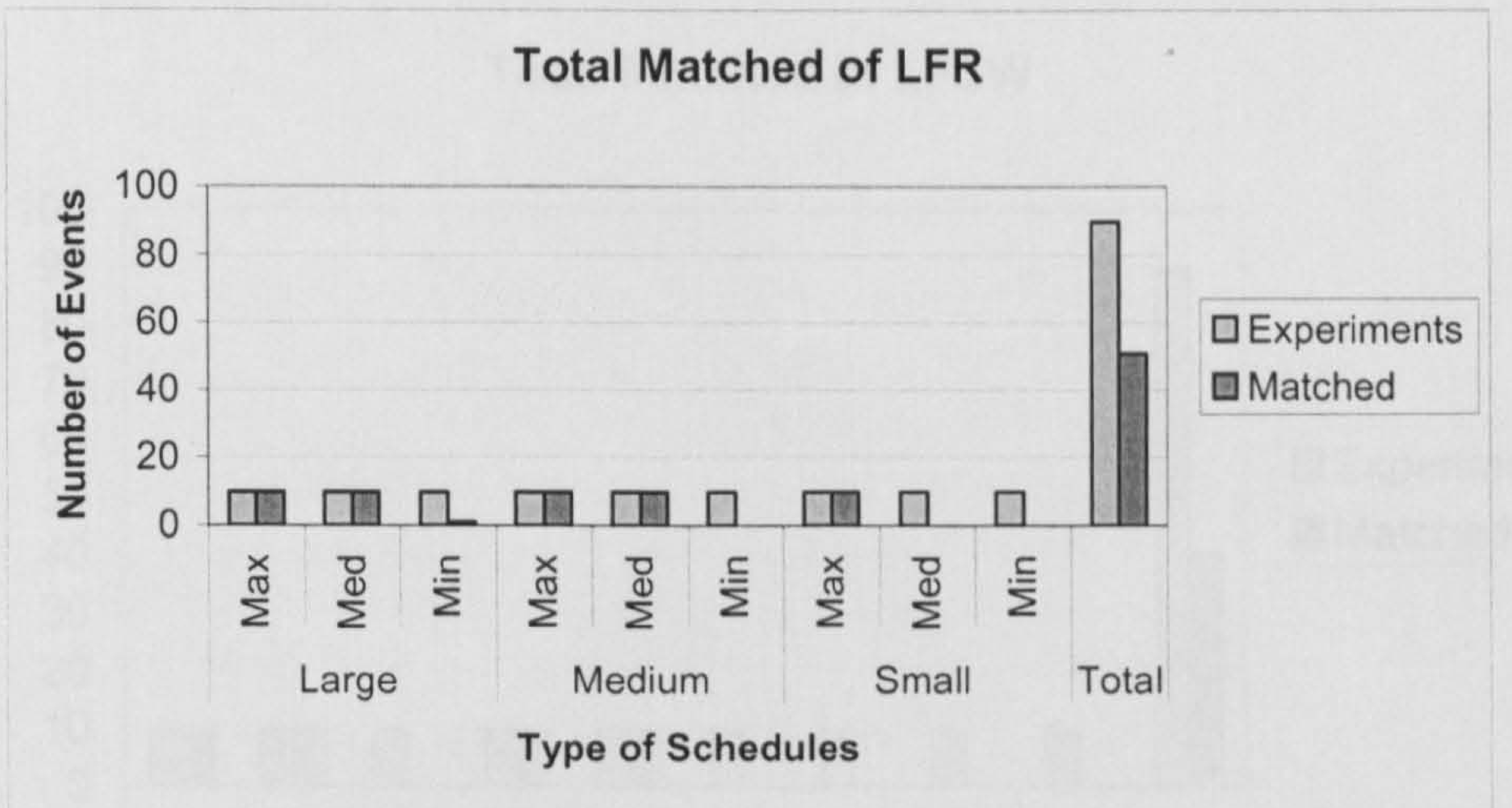

Figure 4.9: Number of LFR Matched in Different Schedule Type and Distribution

LFSW

Table 4.32 and Figure 4.10 illustrate the rescheduling analysis for LFSW where 100% successful matching was achieved in large-maximum duty, large-median duty, medium-maximum duty, and medium-median duty. The average time taken for every rescheduling is 1.93 to 2.26 in the large schedule, and 1.31 to 1.29 minutes in the medium schedule. Surprisingly, there are no minutes late in large and medium schedules. Further investigations reveal that the start of the second work is reasonably spread in the hours. Most of the duties start more than 6 minutes after the previous duty. This enables the rescheduling to succeed without adjustment. This result confirms the finding of the new factor as discussed in LFSO event above.

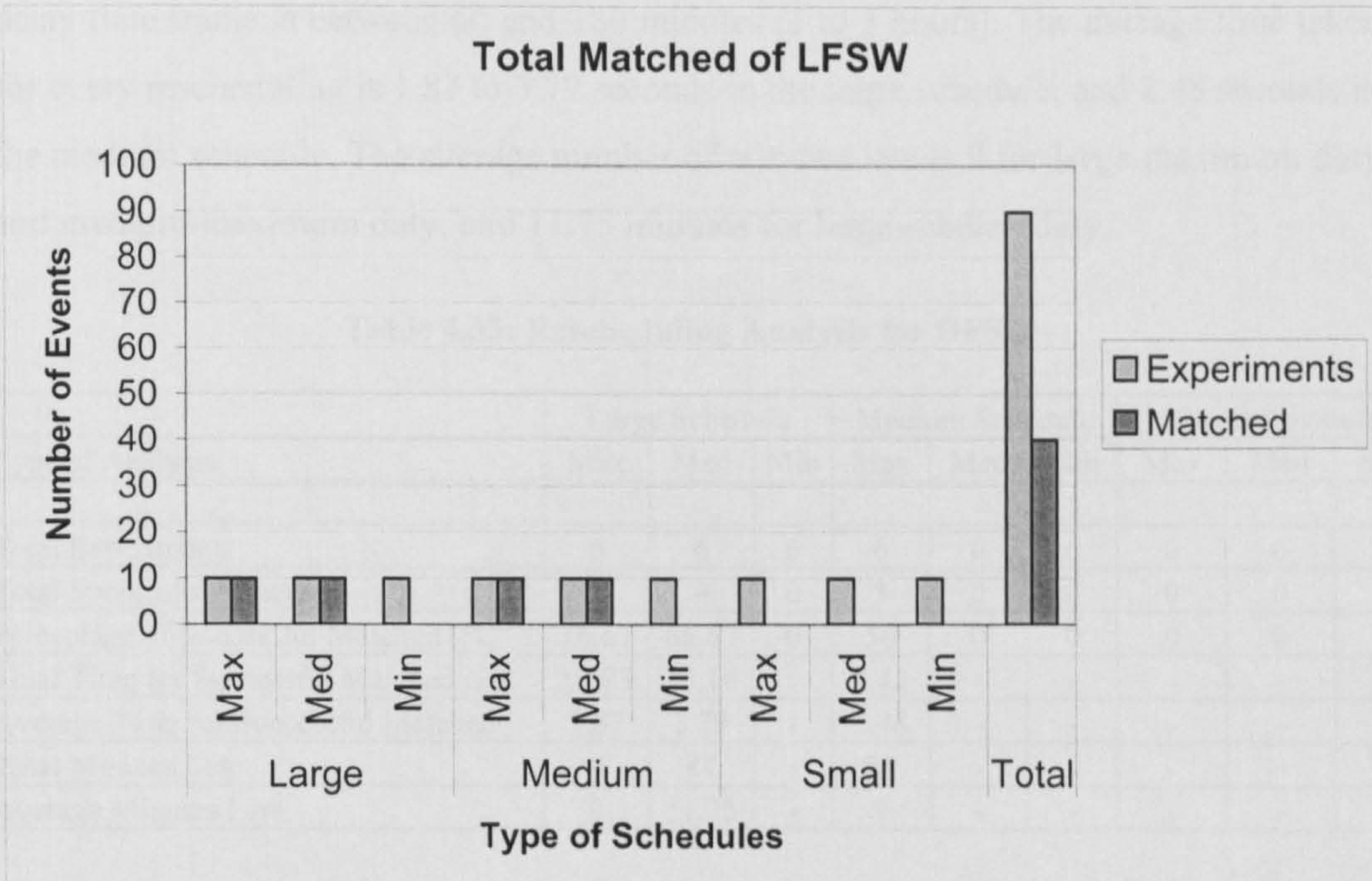

Figure 4.10: Number of LFSW Matched in Different Schedule Type and Distribution DFSO

Table 4.32: Rescheduling Analysis for LFSW

	Large Schedule			Medium Schedule			Small Schedule		
	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	10	10	10	10	10	10	10	10	10
Total Successful Matched	10	10	0	10	10	0	0	0	0
Percentage of Successful Matched (%)	100	100	0	100	100	0	0	0	0
Total Time for Successful Matched (S)	19.27	22.57	-	13.09	12.95	-	-	-	-
Average Time for Successful Matched	1.93	2.26	-	1.31	1.29	-	-	-	-
Total Minutes Late	0	0	-	0	0	-	-	-	-
Average Minutes Late	0	0	-	0	0	-	-	-	-

4.7.2 Delay

DFSO

The results in Table 4.33 and Figure 4.11 demonstrate 16.67% of successful rescheduling in large-maximum duty, 66.67% in large-median duty, and 50% in medium-maximum. The results reveal that in cases of delay, rescheduling does not depend on the frequency in that hour but in the next two hours. This is because the delay time frame is between 60 and 180 minutes (1 to 3 hours). The average time taken for every rescheduling is 1.87 to 3.79 seconds in the large schedule, and 2.48 seconds in the medium schedule. The average number of minutes late is 9 for large-maximum duty and medium-maximum duty, and 11.75 minutes for large-median duty.

Table 4.33: Rescheduling Analysis for DFSO

Type of Analysis	Large Schedule			Medium Schedule			Small Schedule		
	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	6	6	6	6	6	6	6	6	6
Total Successful Matched	1	4	0	3	0	0	0	0	0
Percentage of Successful Matched (%)	16.67	66.67	0	50	0	0	0	0	0
Total Time for Successful Matched (S)	1.873	15.16	-	7.43	-	-	-	-	-
Average Time for Successful Matched	1.87	3.79	-	2.48	-	-	-	-	-
Total Minutes Late	9	47	-	27	-	-	-	-	-
Average Minutes Late	9	11.75	-	9	-	-	-	-	-

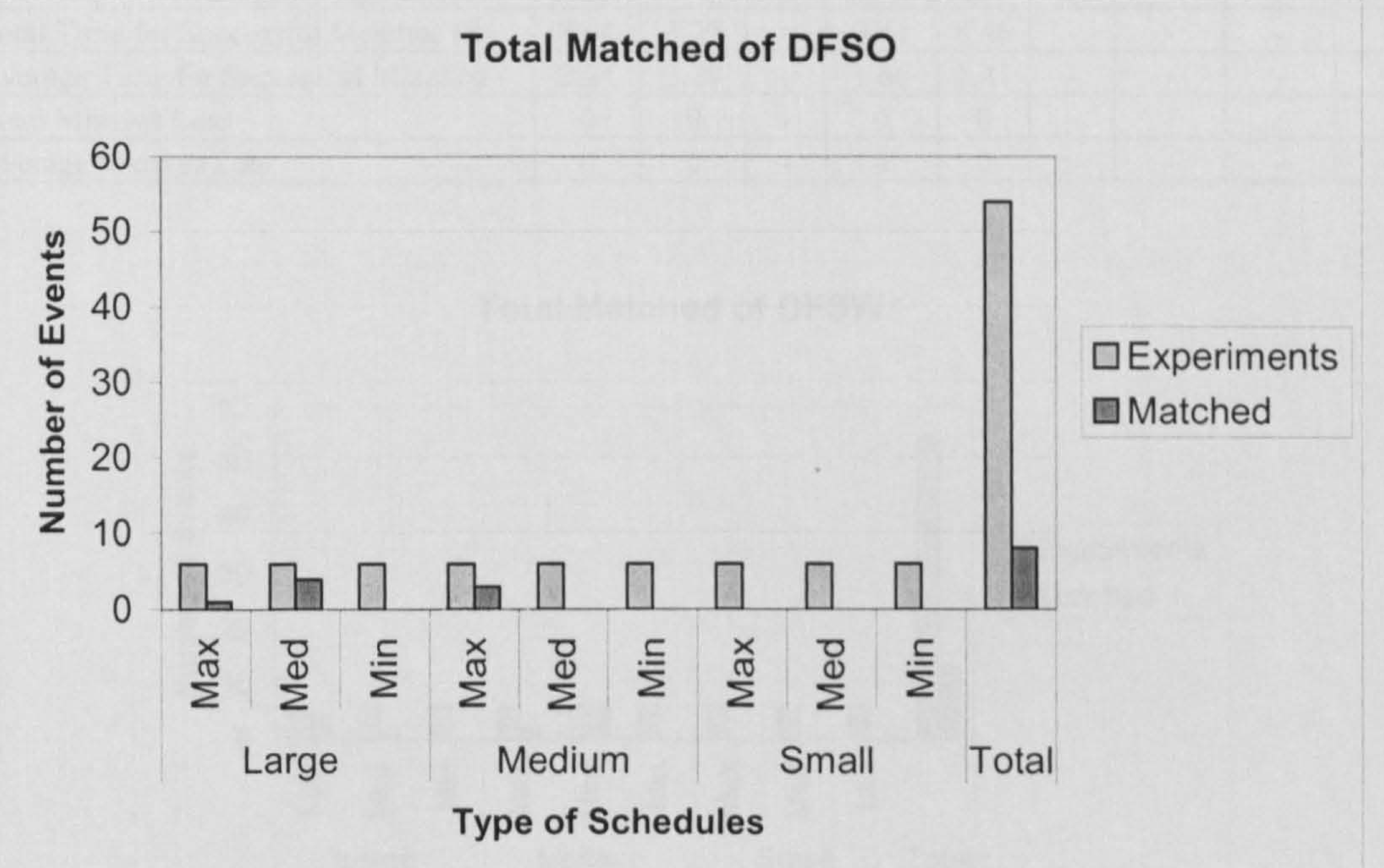

Figure 4.11: Number of DFSO Matched in Different Schedule Type and Distribution

DFSW

The results in Table 4.34 and Figure 4.12 illustrate that 66.67% of successful matches were achieved in large-maximum duty, 16.67% in large-median duty, 33.33% in medium-maximum, and 100% in medium-median. The 100% achievement in medium-median duty is because in the two hours following the delayed start there are many crews beginning their second work. This finding corroborates with DFSO events (as discussed above) that rescheduling for delay event not only depends on the distribution in that hour but also in the next two hours. The average time taken for every rescheduling is 2.24 to 3.29 seconds in the large schedule, and 1.66 to 1.41 seconds in the medium schedule. There are no minutes late in large and medium schedules. The reason for this is that the start of the second work is spread equally in the hours (same case as LFSO and LFSW events as discussed above).

Table 4.34: Rescheduling Analysis for DFSW

	Large Schedule			Medium Schedule			Small Schedule		
Type of Analysis	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	6	6	6	6	6	6	6	6	6
Total Successful Matched	4	1	0	2	6	0	0	0	0
Percentage of Successful Matched (%)	66.67	16.67	0	33.33	100	0	0	0	0
Total Time for Successful Matched (S)	8.94	3.29	-	3.31	8.46	-	-	-	-
Average Time for Successful Matched	2.24	3.29	-	1.66	1.41	-	-	-	-
Total Minutes Late	0	0	-	0	0	-	-	-	-
Average Minutes Late	0	0	-	0	0	-	-	-	-

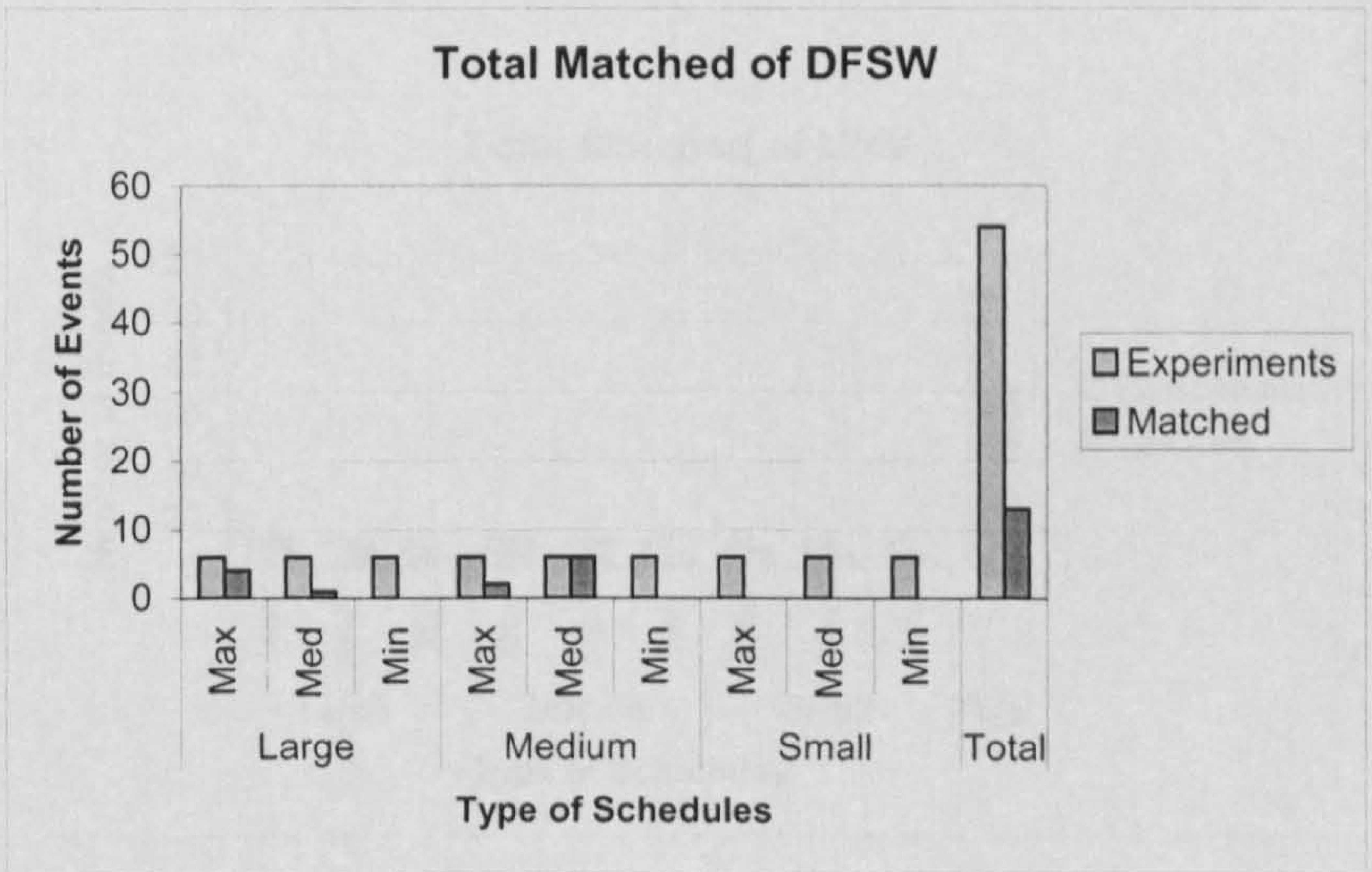

Figure 4.12: Number of DFSW Matched in Different Schedule Type and Distribution

4.7.3 Unavailability

The results (see Table 4.35 and Figure 4.13) explain that 100% of success-reassignment in large-maximum duty and medium-maximum duty, 91.67% in large-median duty and medium-median duty, 58.33% in small-maximum, 50% in small-median duty, and 33.33% in large-minimum duty, medium-minimum duty and small-minimum duty. This is the only experiment where all types of duties have been successfully matched. The reason is that in an UNV event the matching factor is more dependent on the available hours that a crew has and the finishing time of second work than the duty's distribution. The average time taken for every rescheduling is 1.77 to 1.82 seconds in the large schedule, 1.10 to 1.16 seconds in the medium schedule, and 0.57 to 0.59 seconds in the small schedule. The average minutes late is 2 for large-medium duty, 3 for medium-minimum duty and 2.5 for small-median duty.

Table 4.35: Rescheduling Analysis for UNV

	Large Schedule			Medium Schedule			Small Schedule		
Type of Analysis	Max	Med	Min	Max	Med	Min	Max	Med	Min
Total Experiments	12	12	12	12	12	12	12	12	12
Total Successful Matched	12	11	4	12	11	4	7	6	4
Percentage of Successful Matched (%)	100	91.67	33.33	100	91.67	33.33	58.33	50	33.33
Total Time for Successful Matched (S)	21.85	19.47	7.14	12.73	13.67	4.40	4.23	3.448	2.373
Average Time for Successful Matched	1.82	1.77	1.79	1.16	1.14	1.10	0.60	0.57	0.59
Total Minutes Late	0	22	0	0	0	12	0	15	0
Average Minutes Late	0	2	0	0	0	3	0	2.5	0

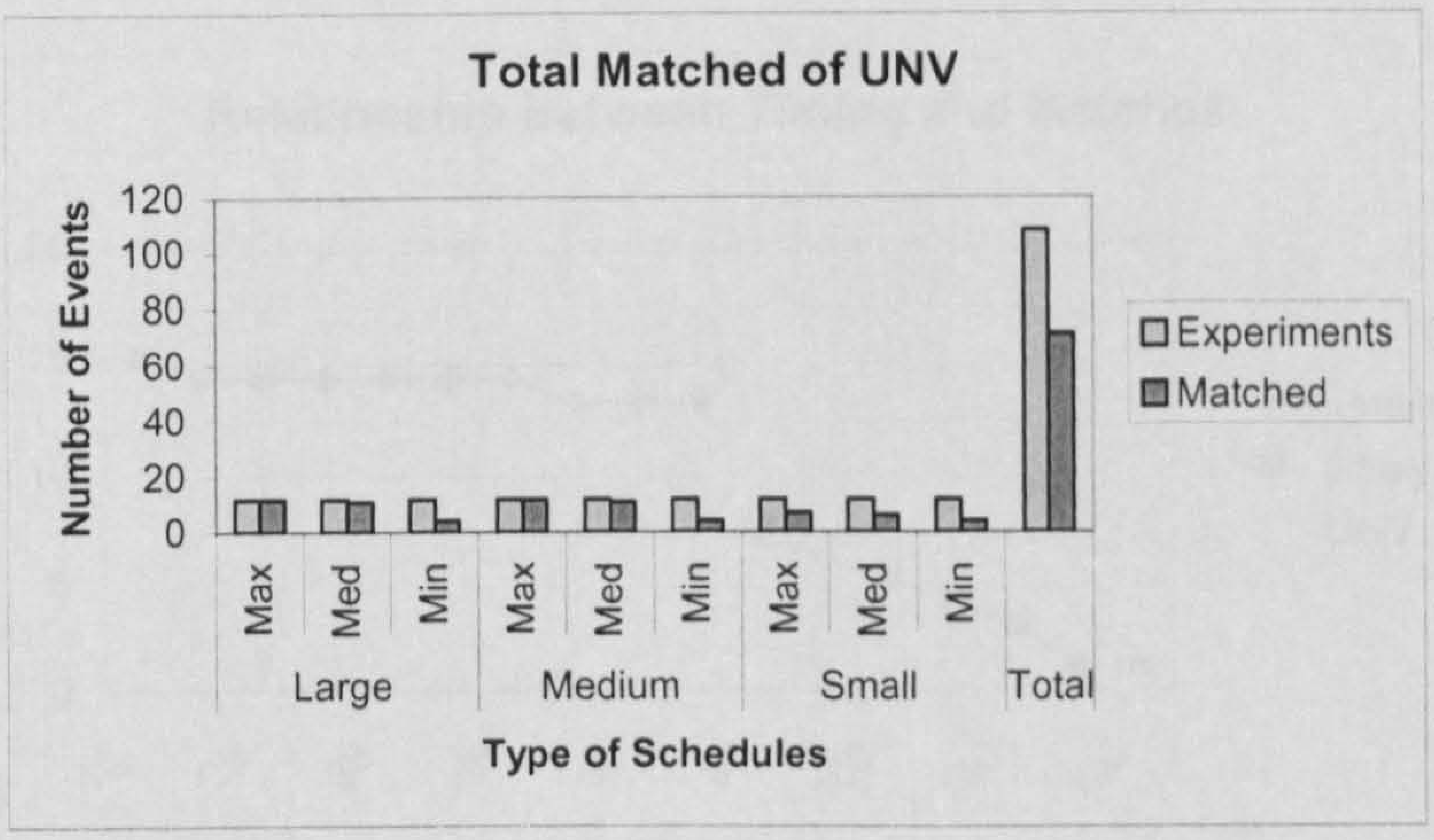

Figure 4.13: Number of UNV Matched in Different Schedule Type and Distribution

4.7.4 Analysis for Different Timing

The purpose of analysing different timing is to discover the relationship between timing and matching. The percentage and numerical figures shown in Table 4.36 and Figure 4.14 demonstrate that the longer the event lasts, the lower the matching. The lateness event gradually decreases, the delay event steadily declines, and the unavailability event remains straight until reaching 90 minutes whereupon it declines sharply.

Table 4.36: Analysis for Different Timing

	Lateness			Delay			UNV			Total		
Minutes	Exp	M	%	Exp	M	%	Exp	M	%	Exp	M	%
15	27	15	55.6	-	-	-	-	-	-	27	15	55.6
20	27	14	51.9	-	-	-	-	-	-	27	14	51.9
25	27	14	51.9	-	-	-	-	-	-	27	14	51.9
30	27	14	51.9	-	-	-	27	19	70.4	54	33	61.1
35	27	14	51.9	-	-	-	-	-	-	27	14	51.9
40	27	14	51.9	-	-	-	-	-	-	27	14	51.9
45	27	14	51.9	-	-	-	-	-	-	27	14	51.9
50	27	13	48.1	-	-	-	-	-	-	27	13	48.1
55	27	13	48.1	-	-	-	-	-	-	27	13	48.1
60	27	13	48.1	-	-	-	27	19	70.4	54	32	59.3
80	-	-	-	18	7	38.9	-	-	-	18	7	38.9
90	-	-	-	-	-	-	27	19	70.4	27	19	70.4
100	-	-	-	18	5	27.8	-	-	-	18	5	27.8
120	-	-	-	18	4	22.2	27	14	51.9	45	18	40
140	-	-	-	18	3	16.7	-	-	-	18	3	16.7
180	-	-	-	18	1	5.56	-	-	-	18	1	5.56
180	-	-	-	18	1	5.56	-	-	-	18	1	5.56
Total	270	138	51.1	108	21	19.4	108	71	65.7	486	230	47.3

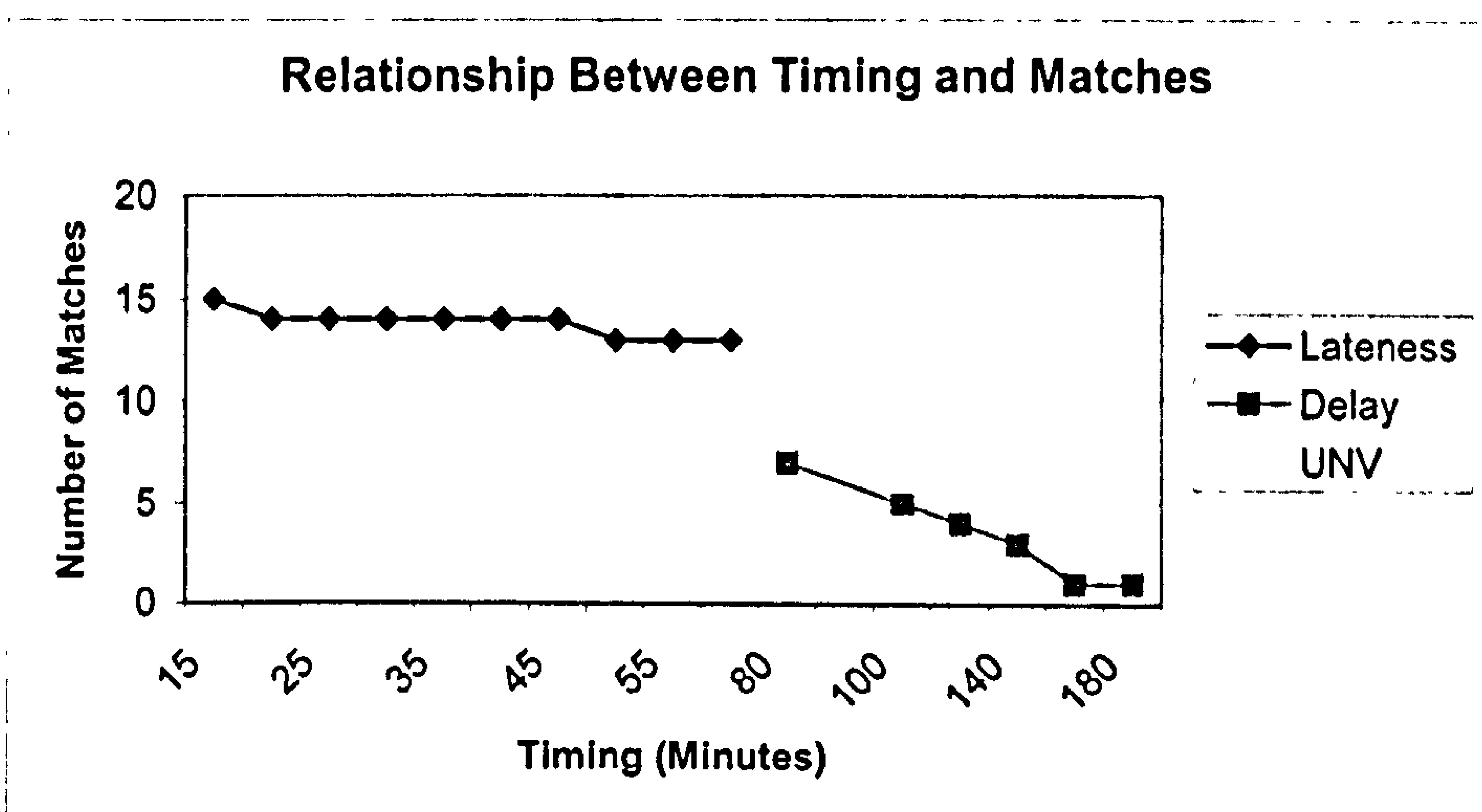

Figure 4.14: Relationship between Timing and Matches for Different Events

4.7.5 Analysis for Total Rescheduling

The results in Table 4.37 show the total experimental analysis. The total percentage of successful matches is 44.07%, which mean that rescheduling is not really possible in all conditions. The highest successful matched (as shown in Table 4.37 and Figure 4.15) is from large-median duty and medium-maximum duty (83.33%). The reason why large-maximum duty (80%) is not as high as we expected is that some of the duties are not equally distributed in an hour. Therefore, the success factors involved in rescheduling are dependent on the distribution of duty (maximum, median, minimum), spreading of the duty (equally distributed or not), and also the types of schedules. The highest duty distribution, equally spreading duty, and in the large schedule offer the best chance of obtaining 100% successful matches. The average time of rescheduling depends on the type of schedules (as shown in Figure 4.16). The larger the schedule, the longer it takes to perform rescheduling because a larger schedule has more duties and more crews assigned. Thus the negotiation has to communicate with all the crew agents to find a suitable match. The average time taken for successful matches is 1.64 seconds, which is quick and acceptable in real time.

Table 4.37: Analysis for Total Rescheduling

	Large Schedule			Medium Schedule			Small Schedule			Total
Type of Analysis	Max	Med	Min	Max	Med	Min	Max	Med	Min	
Total Experiments	60	60	60	60	60	60	60	60	60	540
Total Successful Matched	48	50	5	50	47	4	24	6	4	238
Percentage of Successful Matched (%)	80	83.33	8.33	83.33	78.3	6.67	40.00	10	6.67	44.07
Total Time for Successful Matched (S)	105.3	130	7.14	72.28	50	4.4	15.88	3.45	2.37	390.81
Average Time for Successful Matched	2.19	2.60	1.79	1.45	1.06	1.10	0.66	0.57	0.59	1.64
Total Minutes Late	19	195	0	105	26	12	185	15	0	557
Average Minutes Late	0.40	3.90	0.00	2.10	0.55	3.00	7.71	2.50	0.00	2.34

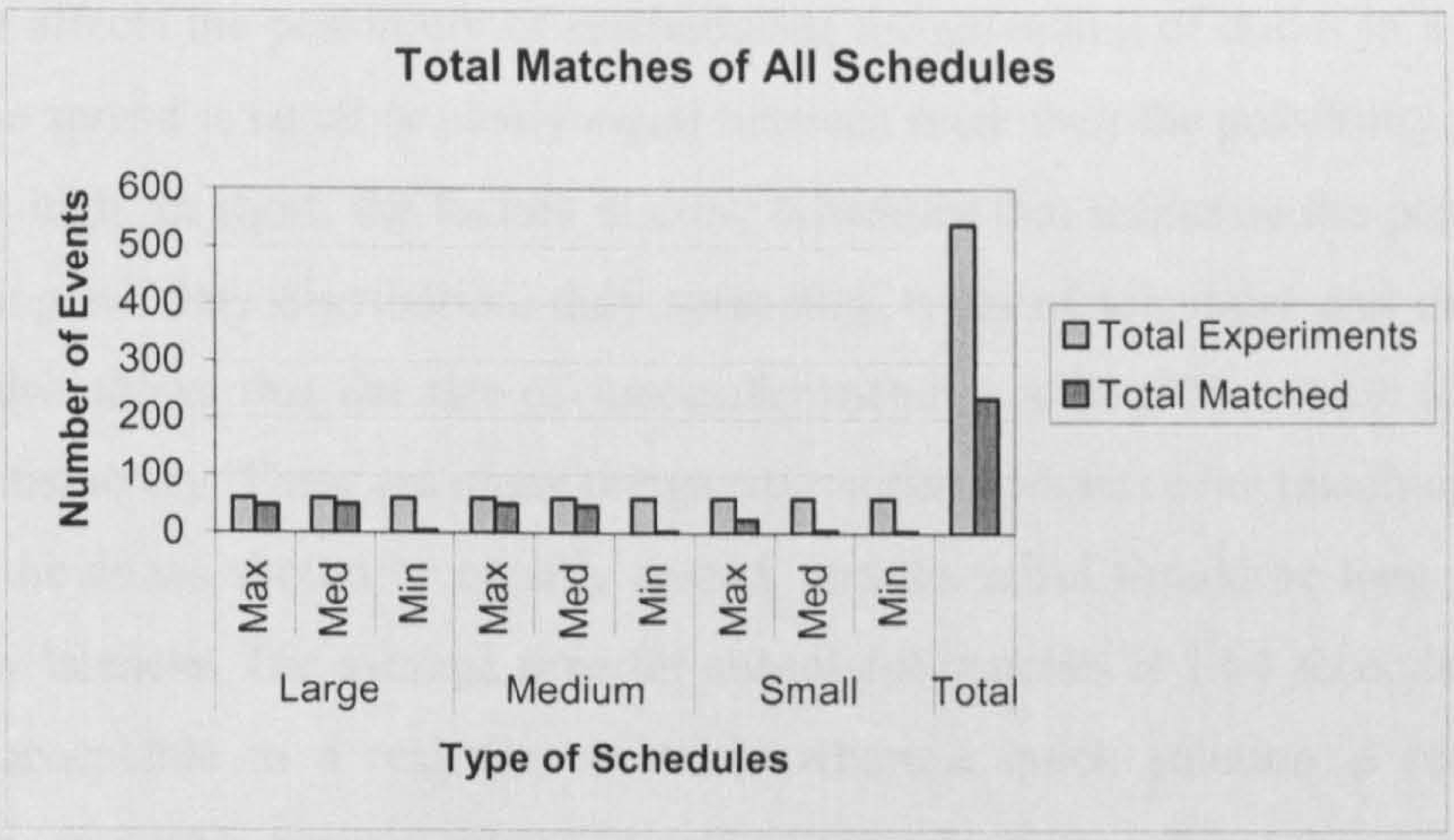

Figure 4.15: Number of Total Matches in Different Schedule Type and Distribution

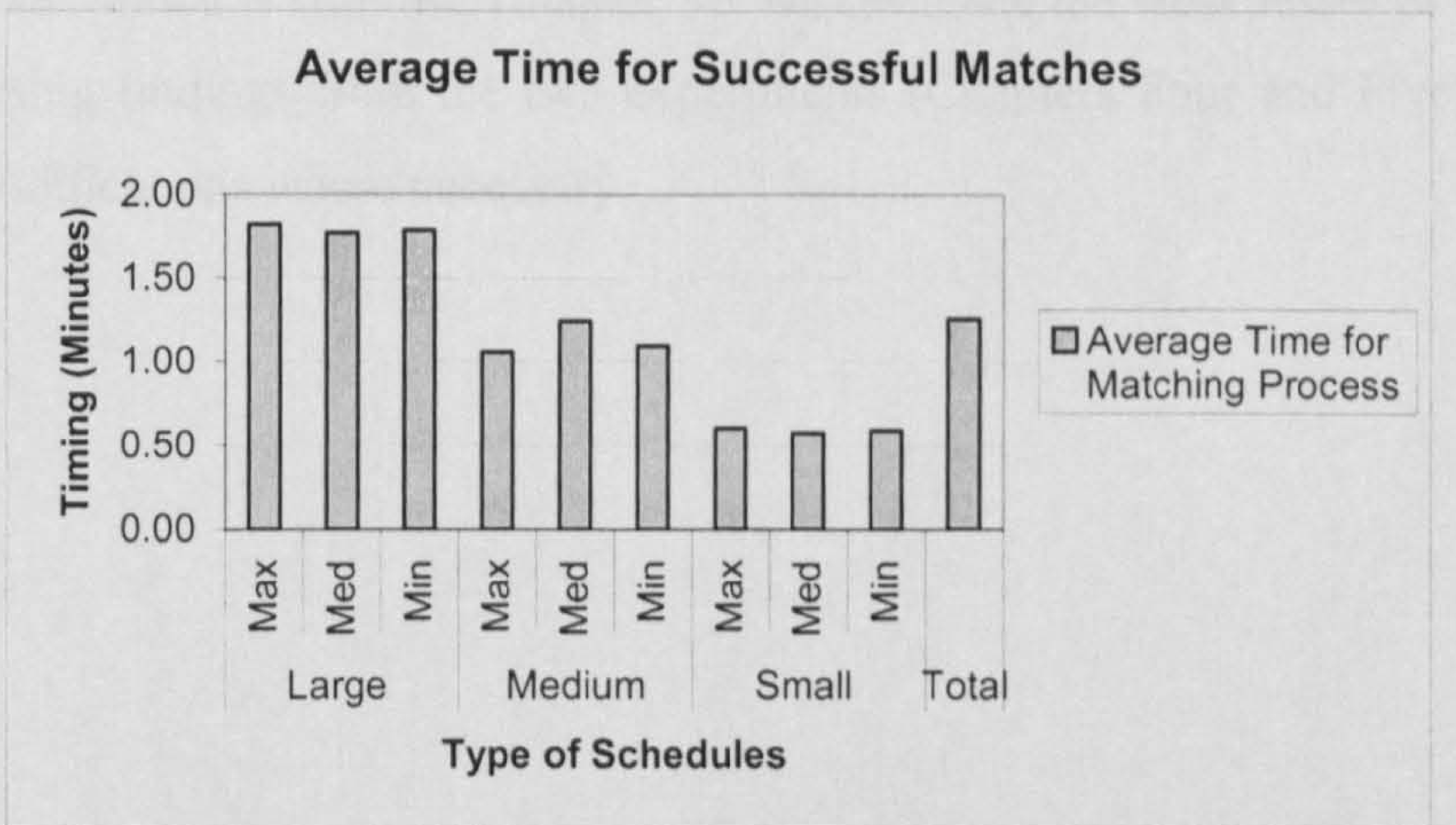

Figure 4.16: Average Time for Successful Matches in Different Type and Distribution

4.8 Summary and Conclusion

This chapter presents the experiment's results and analysis of the proposed system (CRSMAS) that was developed based on the approach presented in Chapter Three. The purpose of the single event experiments is to evaluate the capability of CRSMAS in performing rescheduling in all conditions, and also to identify characteristics in crew schedules that influence the possibility of matching. Different types of events (lateness, delay, and unavailability), different types of schedules (large, medium, and small), different duties distributions (maximum, median, and minimum), and different time of events are used for the experiment's purposes. The analysis of the results reveals a new factor that affects the possibility of rescheduling the spreading of duties in a particular time. If the spread is equal or nearly equal between them then the possibility of finding a match is high. In short, the factors in crew schedules that influence the possibility of rescheduling are duty distribution, duty spreading, types of schedules and timing. The analysis also shows that the rate of successful matches is 44.07%, which is good but still not satisfactory. There are many things we can do to improve the matching rate. For example, the duties should be equally spread, and the relief should be long enough to absorb any lateness. The average time for successful matches is 1.64 seconds, which is fast and acceptable in a real time scenario where a quick solution is required. In conclusion, from this experiment we identified the factors that affect the matching rate and we are satisfied with CRSMAS with regard to time factors but not in relation to the matching rate, which is still low. Chapter Six will evaluate the weaknesses of CRSMAS after analysing findings from the two experiments (Chapters Four and Five) and will propose modifications where necessary.

Chapter Five: Multiple Events Experiments

5.1 Introduction

The previous chapter presented results and analysis from the single event experiments. This chapter presents further experiments where a number of events take place simultaneously and randomly. The purpose is to simulate the real world scenario where UE take place any time and several occur at a time. This will show the robustness of CRSMAS in dealing with different types of events with different types of schedules facing different numbers of events with different event timings at any time. The results will be analysed based on the successful rescheduling and the time taken to execute it. Findings from the two experiments will then form the basis for the approach analysis that is presented in the next chapter where the research evaluates the two outcomes in order to identify the weaknesses in CRSMAS and propose modifications where appropriate.

5.1.1 Chapter Objective

The objective of Chapter Five is to present the results and analysis of the multiple events experiments to the proposed approach (CRSMAS). The purpose of multiple events experiments is to evaluate the capability of CRSMAS in facing different numbers of events taking place with different event timings in different types of schedules at any time. The results will be analysed based on successful matches and the time taken to execute them. The outcomes of the analysis will be used to assess the CRSMAS and proposed modifications wherever appropriate in Chapter Six.

5.1.2 Chapter Outline

The chapter starts with an introduction in Section 5.1 describing the objective of the chapter and its relationship to the rest of the chapters (see Figure 5.1). Section 5.2 presents the experiment plan and discusses types of events and schedules, rescheduling assumptions and rules, data selection process, and experimental environment. There are two types of events, lateness (LFSO, LFR, and LFSW) and unavailability (UNV) and three types of schedules, large, medium, and small. Section 5.3 presents the experimental results and provides an analysis of the results and finally, Section 5.4 concludes and summarises the chapter.

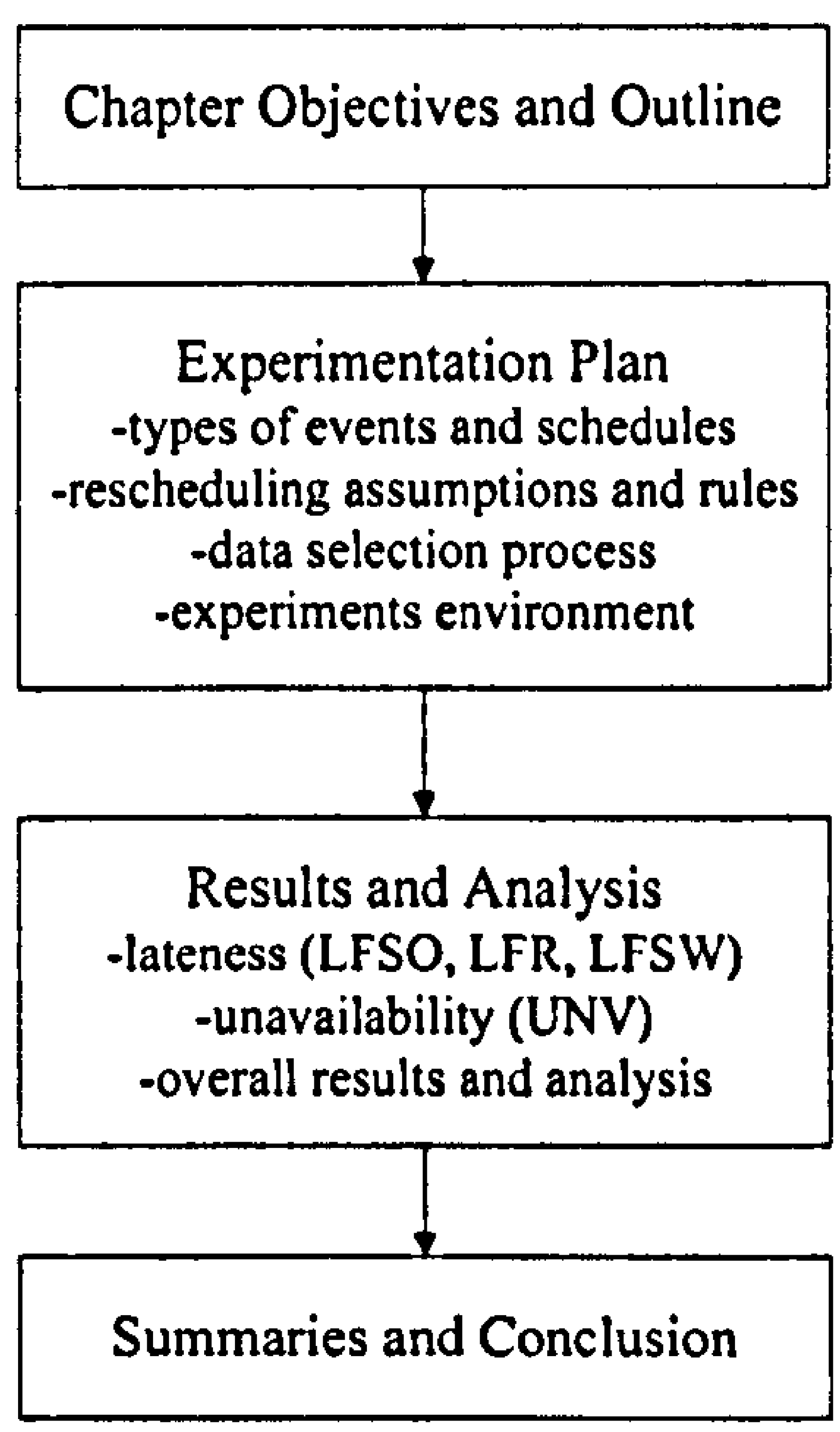

Figure 5.1: The Structure of Chapter Five

5.2 Experiment Plan

This section explains details of types of events, types of schedules, rules and assumptions, the data selection process, and the experimental environment we used for this experiment.

5.2.1 Type of Events and Schedules

The events are the same as discussed in Section 4.2.1 except that there is no delay event. The events are lateness (LFSO, LFR, and LFSW) and unavailability (UNV). The reasons that we do not test delay events is because the duration is quite long and generally it requires more than one round of rescheduling. Two or more than one rounds of rescheduling need manual intervention and adjustments, and when there are many events simultaneously this becomes quite complex. In this experiment, we do not consider more than one round of rescheduling. The types of schedules are the same as in the single event experiments; large, medium and small schedules.

5.2.2 Rescheduling Assumptions and Rules

The rescheduling assumptions and rules are similar to those discussed in Section 4.2.2. The difference is that there is not more than one round of rescheduling because two or more rounds of rescheduling need manual adjustments which are complex. In this experiment, we only consider one round of rescheduling.

5.2.3 Data Selection Process

In these experiments, multiple events take place randomly. Therefore, we should know how to sample the number of events we need and how to select random data. The minimum number of events is 2 and the maximum number is 20% of the total number of duties of the schedule. For a large schedule it is 18 (20% of 88 duties), for a medium 10 (20% of 51) and for a small 5 (20% of 23). To select data randomly, we used the random formula in Microsoft Excel to generate random numbers and the numbers were used to refer to the duty number. For the lateness event we used the formula below:

```
RAND( )*(the maximum number-the minimum number) + the minimum number
```

The maximum number is the total number of duties and the minimum number is 1. For example, for a medium schedule that has 51 duties the formula will look like this:

RAND ()*(51-1) +1

Table 5.1 shows the selected data for a lateness event according to the type of schedule. The full data for the experiments is shown in Appendix G. For the unavailability event, we selected the start time of the event randomly based on the *finish work 2* time. Below is the formula. Table 5.2 illustrates the selected data for an unavailability event.

```
RAND( )*(the latest time for 'Finish Work 2' - the earliest time for
'Finish Work 2') + the earliest time for 'Finish Work 2')
```

Table 5.1: The Selected Data for Lateness Event

No of Events	Large	Medium	Small
	Crew ID	Crew ID	Crew ID
1	E	K	C
2	P	O	H
3	V	Q	L
4	W	T	M
5	X	U	O
6	AB	AG	
7	AC	AH	
8	AD	AL	
9	AL	AP	
10	AQ	AW	
11	AU		
12	AW		
13	AX		
14	BK		
15	BN		
16	BR		
17	BT		
18	CA		

Table 5.2: The Selected Data for UNV Event

No of Events	Large	Medium	Small
	Crew ID	Crew ID	Crew ID
1	11:48:00	14:30:00	19:12:00
2	12:45:00	14:48:00	20:54:00
3	12:54:00	15:00:00	22:18:00
4	14:24:00	16:30:00	23:54:00
5	15:28:00	17:12:00	
6	15:42:00	22:18:00	
7	15:54:00	23:36:00	
8	16:06:00	23:54:00	
9	16:24:00	24:48:00	
10	17:24:00		
11	17:48:00		
12	18:30:00		
13	18:54:00		
14	19:00:00		
15	19:36:00		
16	20:12:00		
17	20:48:00		

In this experiment, we also tested the event with different timing. For lateness (except LFSO) the event timing started from 15 minutes and was increased by 5 minute intervals until 60 minutes was reached. LFSO is only 15 minutes and 20 minutes because when the timing is more it requires second round rescheduling, which is not considered in this experiment. For unavailability, the event started from 30 minutes increasing by 15 minute intervals until 120 minutes was reached. Table 5.3 demonstrates the overall picture of the experiments. For example, in the event of LFSO-Large schedule there were 34 experiments. The maximum number of duties affected in the large schedule was 18 (as discussed in the previous paragraph) but the experiment shows only 17 because the event started from 2 events and went to 18 events. The grand total number of the experiments was 870.

Table 5.3: The Overall Picture of the Experiments

Type of Events	Type of Schedules	Number of Experiments	Total
LFSO	Large Schedule	17 x 2	34
	Medium Schedule	9 x 2	18
	Small Schedule	4 x 2	8
LFR	Large Schedule	17 x 10	170
	Medium Schedule	9 x 10	90
	Small Schedule	4 x 10	40
LFSW	Large Schedule	17 x 10	170
	Medium Schedule	9 x 10	90
	Small Schedule	4 x 10	40
UNV	Large Schedule	17 x 7	119
	Medium Schedule	9 x 7	63
	Small Schedule	4 x 7	28
Grand Total			870

5.2.4 Experimental Environment

A PC with Pentium IV 1.2 GHz and Windows XP operating system was used for the experiments (the same as in single event experiments).

5.3 Results and Analysis

This section presents the results and analysis for every event. Full results are shown in Appendix G.

5.3.1 Lateness

This subsection presents the results and analysis of lateness events. There are three types of lateness, LFSO, LFR, and LFSW, and three types of schedules, large, medium, and small.

LFSO-Large

The results of LFSO-large are shown in Table 5.4. *EV* describes how many events (large schedule is from 2 to 18, medium schedule 2 to 10, and small 2 to 5), *15* and *20* show the minutes that the crews are late, *M* shows the number of matches, *%* explains the percentage of matched crews from the number of events, *T(s)* indicates how fast in seconds the system performed the rescheduling process, and the last row gives the total.

Total is the full results, *TE* refers to total events, *TM* stands for total matched, *TT(s)* explains the total time for rescheduling in seconds, *%* indicates the percentage of total successfully matched, and *AV(s)* shows the average time taken for the rescheduling process in seconds. The percentage of matched is 100% at the beginning, but when more events are incorporated, the number of matched decreases slowly (see Table 5.4 and Figure 5.2). In the event of 6 crews being late for 20 minutes the match is 5 but in the event of 7 crews, the match is reduced to 4. The result is quite strange. Further investigation reveals that one of the crew who is matched in the event of 6 is unavailable in the event of 7 because the crew becomes one of the events, which is the seventh. The overall number successfully matched is 159 out of 340 events and equal to 44%. The average time taken for every event is 1.66 seconds, which is very quick and acceptable for a large schedule.

Table 5.4: LFSO-Large Schedule

EV	15 (Minutes)			20 (Minutes)			Total				
	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	2	100	2.85	2	100	3.86	4	4	6.71	100	1.68
3	3	100	5.20	3	100	5.54	6	6	10.74	100	1.79
4	3	75	5.75	3	75	7.16	8	6	12.91	75	1.61
5	4	80	8.92	4	80	8.84	10	8	17.76	80	1.78
6	5	83	10.59	5	83	10.66	12	10	21.25	83	1.77
7	5	71	12.63	4	57	12.41	14	9	25.04	64	1.79
8	5	63	14.52	4	50	14.21	16	9	28.73	56	1.80
9	5	56	15.46	4	44	15.59	18	9	31.05	50	1.73
10	5	50	17.11	4	40	16.62	20	9	33.73	45	1.69
11	6	55	18.58	4	36	18.76	22	10	37.34	45	1.70
12	6	50	20.90	4	33	18.96	24	10	39.86	42	1.66
13	6	46	21.50	4	31	22.00	26	10	43.50	38	1.67
14	6	43	22.90	4	29	23.23	28	10	46.13	36	1.65
15	6	40	25.74	4	27	23.38	30	10	49.12	33	1.64
16	6	38	26.15	4	25	24.52	32	10	50.67	31	1.58
17	6	35	27.85	4	24	25.73	34	10	53.58	29	1.58
18	6	33	28.66	4	22	28.51	36	10	57.17	28	1.59
170	85	50	285	65	38	280	340	150	565.29	44	1.66

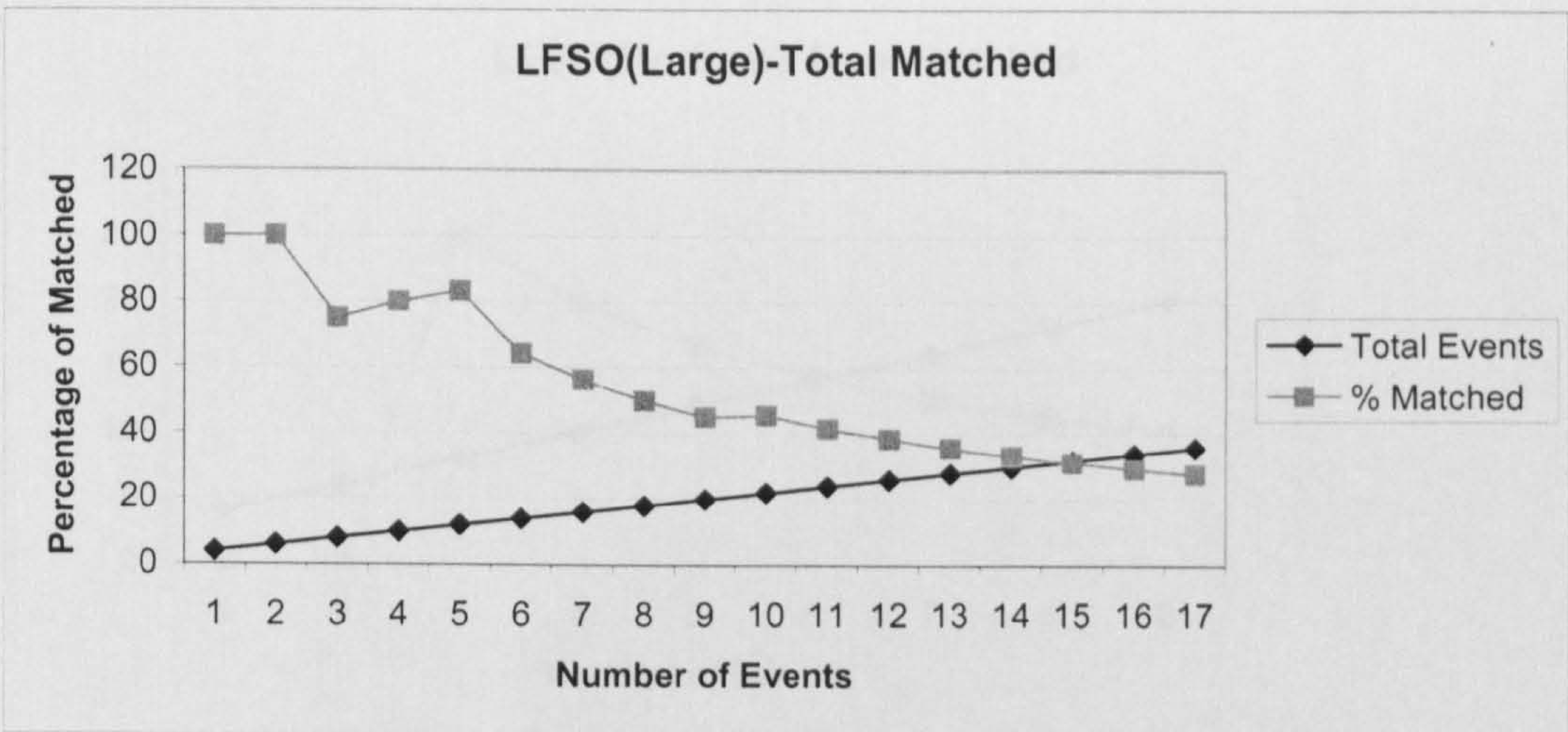

Figure 5.2: The Relationship between Total Events and Total Matches for LFSO (Large)

LFSO-Medium

Table 5.5 and Figure 5.3 show the results for LFSO-medium. The overall matches is very low, only 14 out of 108 events and equates to 13%. The reason for this is that most of the events happen at a time when not many crews sign-on (see Table G.2 in Appendix G). As a result, this is very hard to reschedule. The average time taken for every event is 0.88 seconds; this is very quick and reasonable for a medium schedule.

Table 5.5: LFSO-Medium Schedule

EV	15 (Minutes)			20 (Minutes)			Total				
	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	0	0	1.81	0	0	1.85	4	0	3.66	0	0.92
3	0	0	2.80	0	0	2.75	6	0	5.55	0	0.93
4	1	25	3.73	1	25	3.70	8	2	7.43	25	0.93
5	1	20	4.67	1	20	3.66	10	2	8.33	20	0.83
6	1	17	5.31	1	17	5.28	12	2	10.59	17	0.88
7	1	14	6.15	1	14	5.93	14	2	12.08	14	0.86
8	1	13	6.77	1	13	6.91	16	2	13.68	13	0.86
9	1	11	7.74	1	11	7.46	18	2	15.20	11	0.84
10	1	10	8.52	1	10	8.42	20	2	16.94	10	0.85
54	7	13	47.5	7	13	46	108	14	93.46	13	0.87

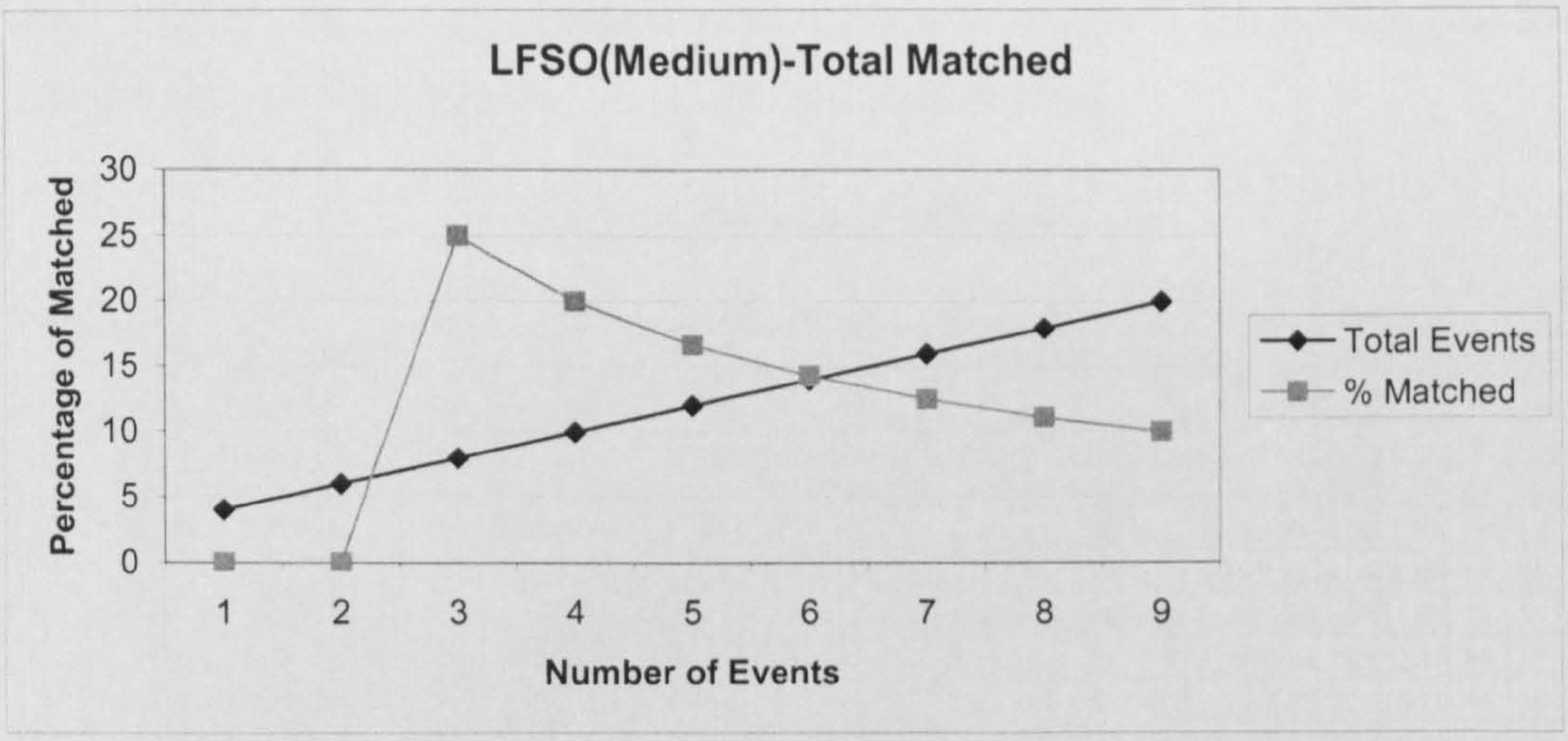

Figure 5.3: The Relationship between Total Events and Total Matched for LFSO (Medium)

LFSO-Small

Table 5.6 shows the results for LFSO-small. Out of 28 events, none were successful. The reason for this is that the schedule is small and the events happened outside peak time (see Table G.3). The average time taken for every event is 0.42 seconds, which is very fast and reasonable for a small schedule.

Table 5.6: LFSO-Small Schedule

EV	15 (Minutes)			20 (Minutes)			Total				
	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	0	0	0.95	0	0	0.91	4	0	1.86	0	0.47
3	0	0	1.28	0	0	1.31	6	0	2.59	0	0.43
4	0	0	1.68	0	0	1.65	8	0	3.33	0	0.42
5	0	0	1.95	0	0	2.04	10	0	3.99	0	0.40
14	0	0	5.86	0	0	5.91	28	0	11.77	0	0.42

LFR-Large

Table 5.7 and Figure 5.4 illustrate the results for LFR-large. The number of matched is 100% when the late time is 15-30 minutes but when the times is longer and the events more the percentage decreases gradually. The overall percentage of matched is only 37%, which is low. The reason is that in the large schedule the relief is not long (just 45 minutes or a bit more) compared to a medium schedule where the relief time is long.

When the relief time is just enough, lateness cannot be absorbed. The average time for rescheduling is 1.5 seconds, which is good for a large schedule.

Table 5.7: LFR-Large Schedule

EV	15 Min.			20 Min.			25 Min.			30 Min.			35 Min.			40 Min.			45 Min.			50 Min.			55 Min.			60 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	2	100	3.27	2	100	3.36	2	100	3.38	2	100	3.15	1	50	3.21	1	50	3.29	1	50	3.50	1	50	3.49	1	50	3.81	1	50	3.43	20	14	33.90	70	1.69
3	3	100	4.66	2	67	4.99	2	67	4.88	2	67	4.59	1	33	4.34	1	33	4.86	1	33	4.42	1	33	4.56	1	33	4.31	1	33	4.71	30	15	46.31	50	1.54
4	4	100	6.45	2	50	6.44	2	50	6.11	2	50	6.45	1	25	6.58	1	25	6.07	1	25	6.76	1	25	6.38	1	25	6.82	1	25	6.72	40	16	64.77	40	1.62
5	5	100	7.74	2	40	8.03	2	40	7.54	2	40	8.14	1	20	8.16	1	20	7.22	1	20	7.88	1	20	7.48	1	20	7.84	1	20	7.43	50	17	77.45	34	1.55
6	6	100	9.56	3	50	9.03	3	50	9.04	3	50	9.48	2	33	9.19	2	33	9.14	2	33	9.02	2	33	9.48	2	33	9.36	1	17	9.35	60	26	92.65	43	1.54
7	7	100	10.65	4	57	10.89	4	57	11.11	4	57	10.59	2	29	10.71	2	29	10.82	2	29	10.53	2	29	11.02	2	29	10.80	1	14	11.07	70	30	108.19	43	1.55
8	8	100	12.91	4	50	11.97	4	50	12.93	4	50	12.72	3	38	13.00	3	38	12.81	3	38	13.20	3	38	12.46	3	38	13.04	2	25	12.37	80	37	127.40	46	1.59
9	9	100	14.03	4	44	14.01	4	44	15.95	4	44	13.43	3	33	13.57	3	33	15.80	3	33	13.88	3	33	15.77	3	33	13.77	2	22	16.11	90	38	146.32	42	1.63
10	10	100	15.57	5	50	15.42	4	40	13.90	4	40	14.45	3	30	14.45	3	30	13.85	3	30	14.25	3	30	13.99	3	30	13.91	2	20	13.77	100	40	143.55	40	1.44
11	11	100	16.97	5	45	16.88	4	36	16.98	4	36	16.41	3	27	16.32	3	27	17.32	3	27	16.17	3	27	17.57	3	27	16.25	2	18	17.44	110	41	168.32	37	1.53
12	12	100	18.37	6	50	18.40	4	33	17.52	4	33	17.37	3	25	17.31	3	25	17.19	3	25	17.19	3	25	17.05	3	25	17.40	2	17	17.36	120	43	175.16	36	1.46
13	12	92	18.75	5	38	19.75	4	31	19.06	4	31	18.99	3	23	18.69	3	23	18.95	3	23	18.42	3	23	18.69	3	23	18.10	2	15	18.63	130	42	188.04	32	1.45
14	13	93	21.25	6	43	20.88	5	36	21.62	4	29	19.98	3	21	20.13	3	21	21.53	3	21	20.06	3	21	21.76	3	21	19.81	2	14	21.96	140	45	208.98	32	1.49
15	14	93	21.47	6	40	21.25	5	33	22.63	4	27	22.11	3	20	22.38	3	20	22.49	3	20	22.09	3	20	22.66	3	20	22.08	2	13	22.99	150	46	222.15	31	1.48
16	15	94	23.20	7	44	23.68	6	38	23.99	5	31	23.19	4	25	23.49	4	25	24.09	4	25	23.14	4	25	24.04	3	19	22.82	2	13	24.20	160	54	235.84	34	1.47
17	16	94	24.75	7	41	24.64	6	35	24.94	5	29	24.64	4	24	24.52	4	24	24.76	4	24	24.86	4	24	24.53	3	18	24.81	2	12	24.21	170	55	246.66	32	1.45
18	17	94	25.20	8	44	24.90	7	39	25.83	6	33	26.63	5	28	27	5	28	25.87	5	28	26.76	5	28	24.8	4	22	26.4	3	17	25.9	180	65	259.16	36	1.44
170	164	96	255	78	46	255	68	40	257.41	63	37	252	45	26	253	45	26	256	45	26	252	45	26	256	42	25	251	29	17	258	1700	624	2544.86	37	1.50

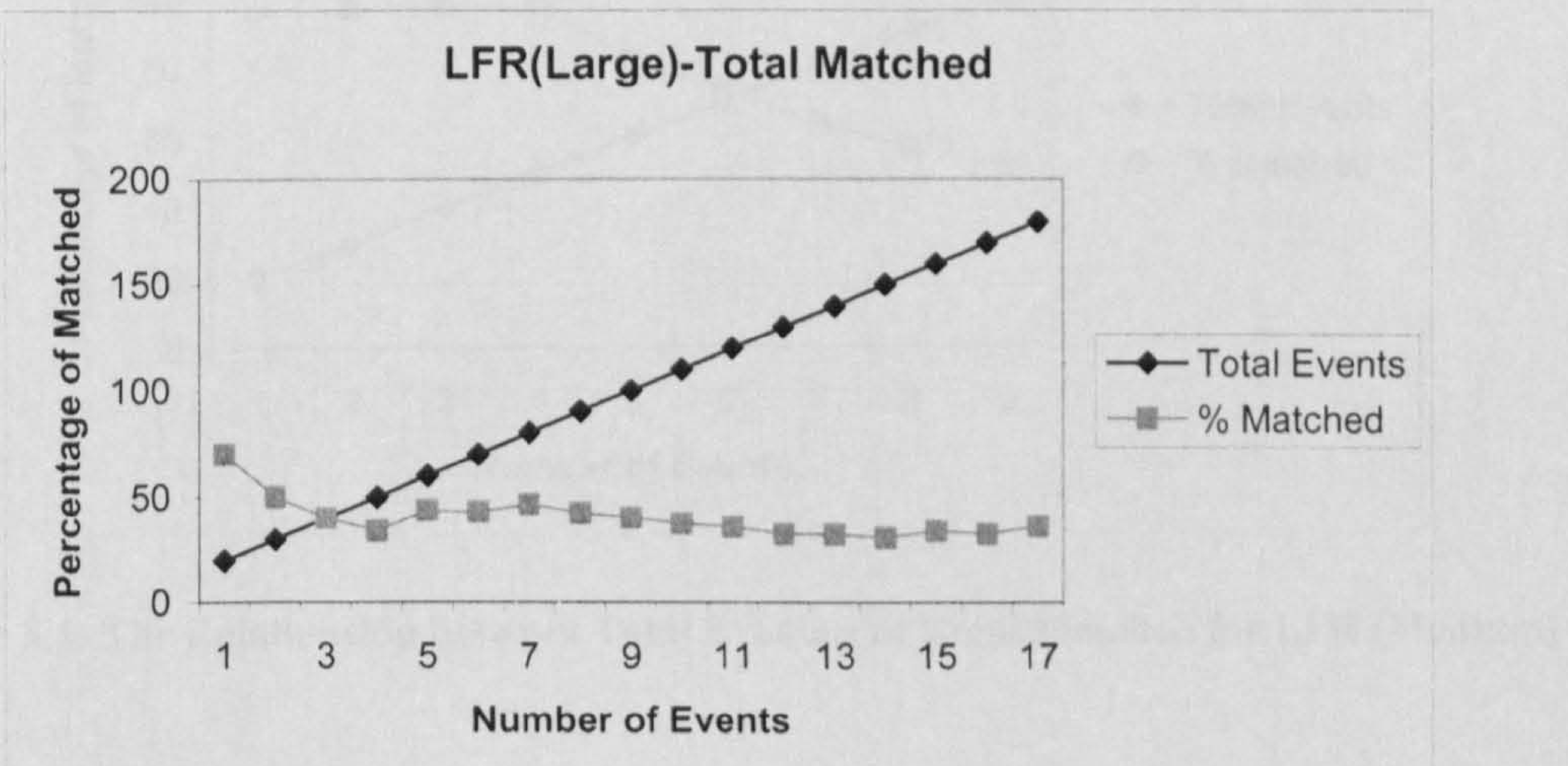

Figure 5.4: The Relationship between Total Events and Total Matched for LFR (Large)

LFR-Medium

The results (see Table 5.8 and Figure 5.5) show that the overall matching rate is very high at 72%. For 15 to 55 minutes from 2 to 5 events, the matching rate is 100%. The results are very encouraging. Further investigation revealed that the relief time is long enough to absorb lateness and increase the possibility of finding another crew for replacement. The average time is 0.90 seconds, which is more or less the same for any type of event in a medium schedule.

Table 5.8: LFR-Medium Schedule

EV	15 Min.			20 Min.			25 Min.			30 Min.			35 Min.			40 Min.			45 Min.			50 Min.			55 Min.			60 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	2	100	2.07	2	100	2.15	2	100	2.23	2	100	2.22	2	100	2.47	2	100	2.38	2	100	2.82	2	100	2.55	2	100	2.45	1	50	2.56	20	19	23.90	95	1.20
3	3	100	2.87	3	100	2.58	3	100	2.71	3	100	2.77	3	100	2.91	3	100	2.69	3	100	3.07	3	100	3.00	3	100	2.89	2	67	3.07	30	29	28.55	97	0.95
4	4	100	3.92	4	100	4.04	4	100	3.77	4	100	3.99	4	100	3.95	4	100	3.86	4	100	3.72	4	100	3.67	4	100	3.88	3	75	3.73	40	39	38.53	98	0.96
5	5	100	4.80	5	100	4.40	5	100	4.45	5	100	4.51	5	100	4.62	5	100	4.83	5	100	4.61	5	100	4.49	5	100	4.43	4	80	4.38	50	49	45.52	98	0.91
6	5	83	5.53	5	83	5.35	5	83	5.55	5	83	5.55	5	83	5.85	5	83	5.61	5	83	5.91	5	83	5.35	5	83	5.87	4	67	5.61	60	49	56.17	82	0.94
7	6	86	6.20	6	86	6.12	5	71	6.02	5	71	6.22	5	71	6.24	5	71	5.94	5	71	6.14	5	71	5.85	5	71	6.21	4	57	5.87	70	51	60.81	73	0.87
8	6	75	7.01	6	75	6.59	5	63	7.14	5	63	6.82	5	63	7.49	5	63	6.86	5	63	7.25	5	63	6.99	5	63	7.38	4	50	7.08	80	51	70.61	64	0.88
9	6	67	7.71	6	67	7.73	5	56	7.48	5	56	7.39	5	56	7.73	5	56	7.28	5	56	7.38	5	56	7.17	5	56	7.64	4	44	7.87	90	51	75.39	57	0.84
10	6	60	8.48	6	60	8.83	5	50	8.58	5	50	8.12	5	50	8.42	5	50	7.99	5	50	8.70	5	50	7.97	5	50	8.79	4	40	8.76	100	51	84.65	51	0.85
54	43	80	48.6	43	80	47.8	39	72	47.9	39	72	47.6	39	72	49.7	39	72	47.4	39	72	49.6	39	72	47	39	72	49.5	30	56	48.9	540	389	484.14	72	0.90

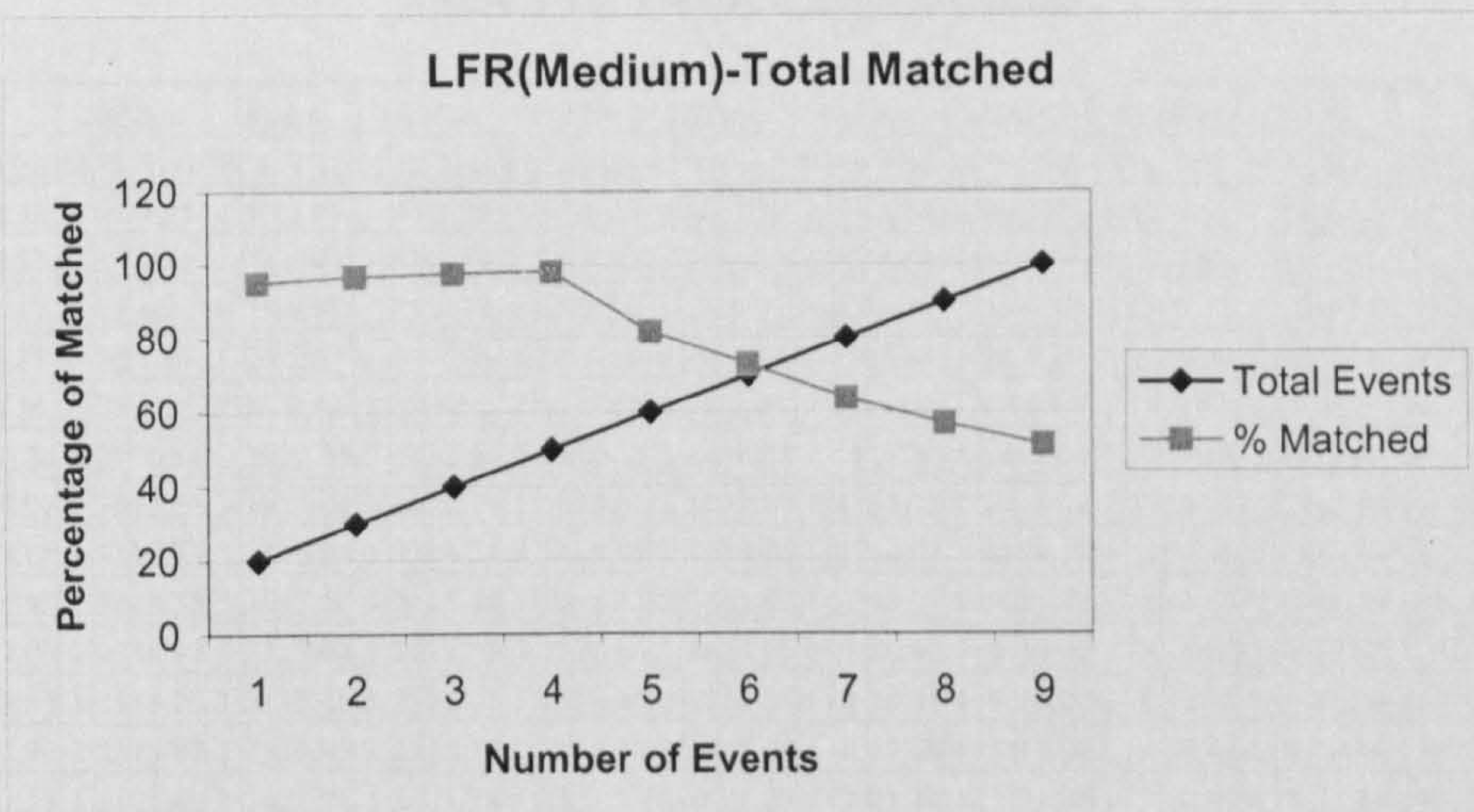

Figure 5.5: The Relationship between Total Events and Total Matched for LFR (Medium)

LFR-Small

Table 5.9 illustrates the results for LFR-small. The overall match is very low at 7% (2 out of 28). The matching rate for a small schedule is expected to be low because there are not many duties in the schedule. The experiments were carried out until 20 minutes only, because there was no single match for 20 minutes late and therefore no point in continuing the experiment.

Table 5.9: LFR-Small Schedule

EV	15 Minutes			20 Minutes			Total				
	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	0	0	0.93	0	0	0.92	4	0	1.85	0	0 46
3	0	0	1.27	0	0	1.13	6	0	2.40	0	0.40
4	1	25	1.75	0	0	1.93	8	1	3.68	13	0.46
5	1	20	2.06	0	0	2.03	10	1	4.09	10	0.41
14	2	45	6.01	0	0	6.01	28	2	12.02	7	0.43

LFSW-Large

Table 5.10 and Figure 5.4 illustrate the results for LFSW-large. The overall matching rate is very low at 18% matched (312 out of 1,700). The reason is same as mentioned for LFR-large, that is the relief time is not long enough and the distribution of the duty is not equally spread in an hour (as discovered in Chapter Four). A large schedule has many duties, but relief timing and spreading also influence the success of rescheduling.

Table 5.10: LFSW-Large Schedule

15 Min.				20 Min.			25 Min.			30 Min.			35 Min.			40 Min.			45 Min.			50 Min.			55 Min.			60 Min.			Total				
E	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	1	50	3.32	1	50	3.25	1	50	3.41	1	50	3.28	1	50	3.45	1	50	3.39	1	50	3.34	1	50	3.28	1	50	3.16	1	50	3.27	20	10	33.16	50	1.66
3	1	33	4.53	1	33	4.49	1	33	4.49	1	33	4.57	1	33	4.53	1	33	4.70	1	33	4 62	1	33	4 68	1	33	4.58	1	33	4 62	30	10	45.83	33	1.53
4	1	25	6.42	1	25	6.46	1	25	6.37	1	25	6.39	1	25	6.36	1	25	6.31	1	25	6.48	1	25	6.32	1	25	6.32	1	25	6.37	40	10	63.80	25	1.60
5	1	20	7.85	1	20	7.81	1	20	7.87	1	20	7.70	1	20	7.94	1	20	7.59	1	20	7.89	1	20	7.89	1	20	8.04	1	20	7.51	50	10	78.09	20	1.56
6	2	33	9.56	2	33	9.55	2	33	9.58	2	33	9.54	2	33	9.69	1	17	9.48	1	17	9.64	1	17	9.81	1	17	9.82	1	17	9.39	60	15	96.04	25	1.60
7	2	29	10.74	2	29	10.81	2	29	10.72	2	29	10.80	2	29	10.75	1	14	10.68	1	14	10.89	1	14	10.99	1	14	10.88	1	14	10.83	70	15	108.08	21	1.54
8	3	38	12.97	3	38	12.83	3	38	13.05	3	38	12.77	3	38	13.01	2	25	12.67	1	13	13.12	1	13	13.04	1	13	13.02	1	13	12.53	80	21	129.02	26	1.61
9	3	33	13.98	3	33	13.88	3	33	13.87	3	33	14.01	3	33	13.95	2	22	13.95	1	11	14.03	1	11	14.18	1	11	14.16	1	11	13.99	90	21	139.99	23	1.56
10	3	30	15.52	3	30	15.55	3	30	15.38	3	30	15.48	3	30	15.37	2	20	15.62	1	10	15.37	1	10	15.43	1	10	15.57	1	10	15.75	100	21	155.03	21	1.55
11	3	27	17.02	3	27	16.97	3	27	17.04	3	27	17.08	3	27	16.96	2	18	16.97	1	9	16.92	1	9	16.92	1	9	16.86	1	9	17.05	110	21	169.79	19	1.54
12	3	25	18.38	3	25	18.25	3	25	18.41	3	25	18.31	3	25	18.45	2	17	18.24	1	8	18.31	1	8	18.24	1	8	18.33	1	8	18.36	120	21	183.29	18	1.53
13	3	23	18.80	3	23	18.87	3	23	18.93	3	23	18.78	3	23	18.91	2	15	18.92	1	8	19.00	1	8	18.90	1	8	18.83	1	8	18.90	130	21	188.85	16	1.45
14	3	21	21.33	3	21	21.42	3	21	21.26	3	21	21.28	3	21	21.13	2	14	21.23	1	7	21.10	1	7	21.05	1	7	20.98	1	7	21.21	140	21	211.99	15	1.51
15	3	20	21.49	3	20	21.63	3	20	21.48	3	20	21.67	3	20	21.34	2	13	21.55	1	7	21.22	1	7	21.17	1	7	21.20	1	7	21.42	150	21	214.17	14	1.43
16	4	25	23.08	3	19	23.03	3	19	23.10	3	19	22.97	3	19	23.14	2	13	23.04	1	6	23.13	1	6	23.03	1	6	23.04	1	6	22.97	160	22	230.53	14	1.44
17	4	24	24.05	3	18	24.06	3	18	24.19	3	18	24.08	3	18	24.09	2	12	24.02	1	6	24.06	1	6	24.00	1	6	24.17	1	6	23.88	170	22	240.61	13	1.42
18	5	28	24.46	4	22	25.26	4	22	24.46	4	22	25.11	4	22	24.42	3	17	25.23	2	11	24 41	2	11	24 31	1	6	24.26	1	6	25.19	180	30	247.11	17	1.37
170	45	26	254	42	25	254	42	25	254	42	25	254	42	25	253	29	17	254	18	11	254	18	11	253	17	10	253	17	10	253	1700	312	2535.38	18	1.49

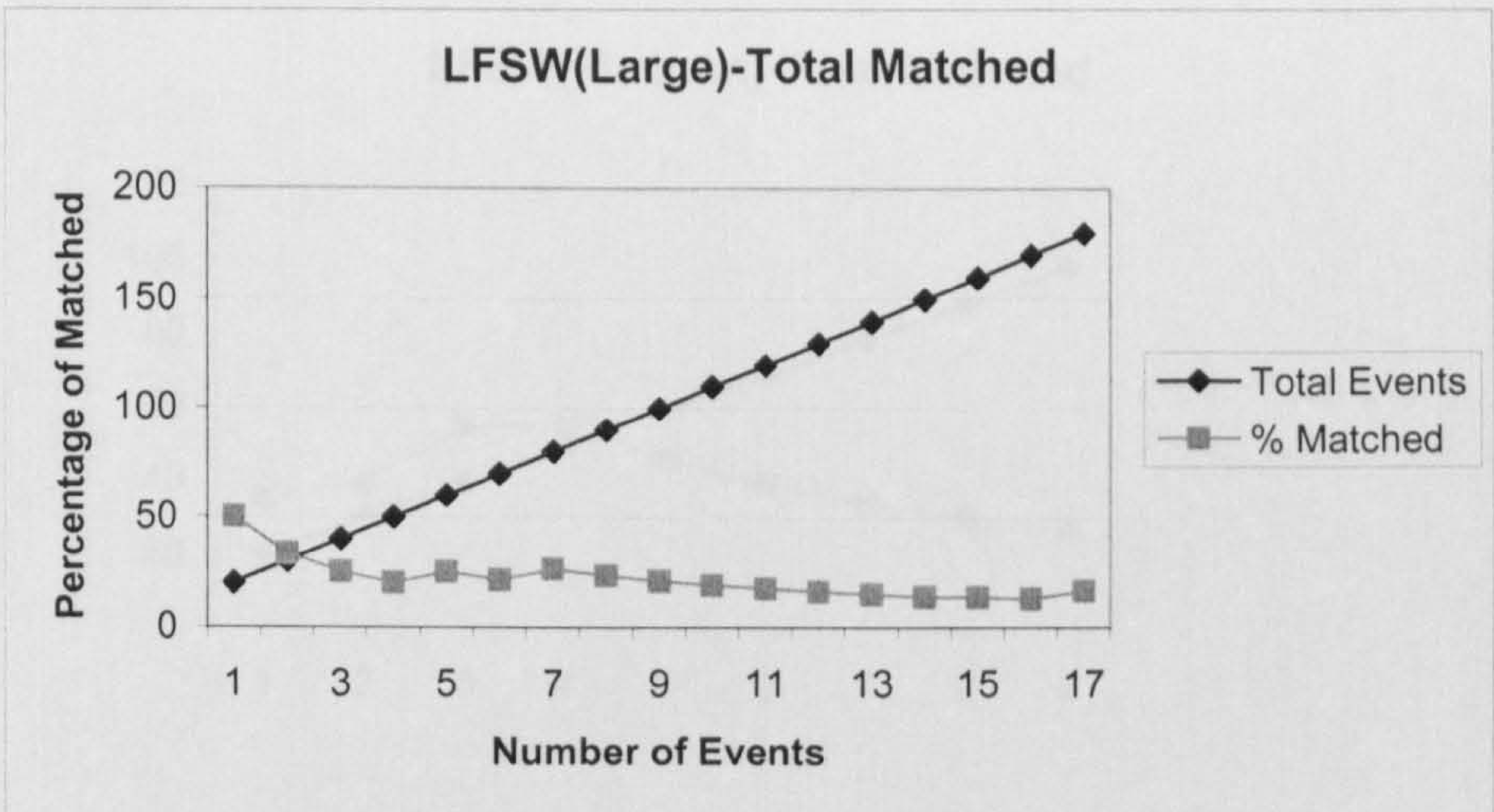

Figure 5.6: The Relationship between Total Events and Total Matched for LFSW (Large)

LFSW-Medium

The matching rate for LFSW-medium (39%) is higher than that of the large schedule (as discussed above) because of the long relief time and spreading of duties in an hour (see Table 5.11 and Figure 5.7). The results show that in the beginning the matching rate is high but when the time is longer and involves more events, the matching rate slowly declines.

Table 5.11: LFSW-Medium Schedule

EV	15 Min.			20 Min.			25 Min.			30 Min.			35 Min.			40 Min.			45 Min.			50 Min.			55 Min.			60 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	2	100	2.00	2	100	2.11	1	50	2.09	1	50	2.04	1	50	1.99	0	0	2.03	0	0	1.97	0	0	2.09	0	0	2.07	0	0	1.98	20	7	20.38	35	1.02
3	3	100	2.24	3	100	2.15	2	67	2.18	2	67	2.12	2	67	2.09	0	0	2.13	0	0	2.04	0	0	2.16	0	0	2.13	0	0	2.29	30	12	21.53	40	0.72
4	4	100	2.93	4	100	2.88	3	75	2.89	3	75	2.72	3	75	2.66	1	25	2.54	1	25	2.42	1	25	2.51	1	25	2.54	1	25	2.46	40	22	26.56	55	0.66
5	5	100	3.60	4	80	3.50	3	60	3.53	3	60	3.60	3	60	3.43	2	40	3.29	2	40	3.31	2	40	3.22	2	40	3.09	2	40	3.21	50	28	33.77	56	0.68
6	5	83	4.28	4	67	4.33	3	50	4.28	3	50	4.20	3	50	4.31	2	33	4.32	2	33	4.20	2	33	4.07	2	33	4.19	2	33	4.09	60	28	42.27	47	0.70
7	5	71	4.57	4	57	4.54	3	43	4.67	3	43	4.72	3	43	4.81	2	29	4.90	2	29	4.84	2	29	4.83	2	29	4.84	2	29	4.92	70	28	47.66	40	0.68
8	5	63	6.87	4	50	6.97	3	38	6.88	3	38	6.71	3	38	6.71	2	25	6.62	2	25	6.67	2	25	6.66	2	25	6.53	2	25	6.37	80	28	66.99	35	0.84
9	5	56	7.91	4	44	7.89	3	33	7.84	3	33	7.98	3	33	7.98	2	22	7.87	2	22	7.96	2	22	7.87	2	22	8.04	2	22	7.70	90	28	79.04	31	0.88
10	5	50	8.24	4	40	8.46	3	30	8.37	3	30	8.61	3	30	8.40	2	20	8.09	2	20	8.30	2	20	8.02	2	20	8.22	2	20	7.96	100	28	82.67	28	0.83
54	39	72	42.6	33	61	42.8	24	44	42.7	24	44	42.7	24	44	42.4	13	24	41.8	13	24	41.7	13	24	41.4	13	24	41.6	13	24	41	540	209	420.87	39	0.78

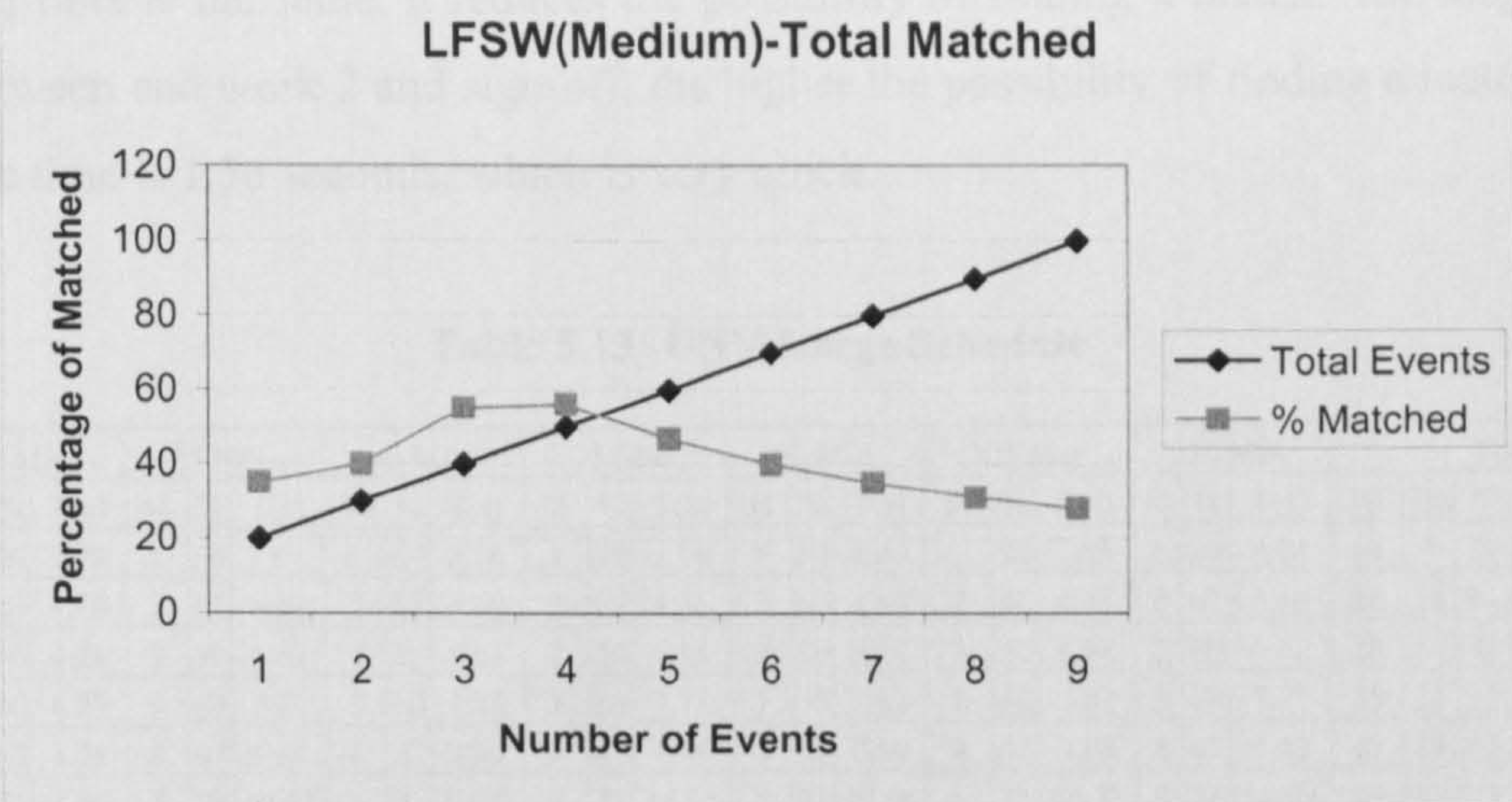

Figure 5.7: The Relationship between Total Events and Total Matched for LFSW (Medium)

LFSW-Small

Table 5.12 shows the results where none of the events find any match. From all the experiments for a small schedule in multiple events for lateness, there is a very low or zero possibility of successful rescheduling.

Table 5.12: LFSW-Small Schedule

EV	15 Minutes			Total				
	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	0	0	0.88	2	0	0.88	0	0.44
3	0	0	1.37	3	0	1.37	0	0.46
4	0	0	1.68	4	0	1.68	0	0.42
5	0	0	2.06	5	0	2.06	0	0.41
14	0	0	5.99	14	0	5.99	0	0.43

5.3.2 Unavailability

This subsection explains the results and analysis for unavailability events for large, medium, and small schedules.

UNV-Large

The results show that the matching rate is average at 67% (see Table 5.13 and Figure 5.8). The reason for this is that some of the sign-off times for the duties are same, and the gap between end work 2 and sign-off is not very consistent in large schedules. If the sign-off time is the same, it reduces the possibility of finding a match. The longer the gap between end work 2 and sign-off, the higher the possibility of finding a match. The average time is 1.56 seconds, which is very quick.

Table 5.13: UNV-Large Schedule

EV	30 Min.			45 Min.			60 Min.			75 Min.			90 Min.			105 Min.			120 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	1	50	2.79	1	50	3.01	1	50	3.16	1	50	2.96	1	50	3.20	1	50	3.03	1	50	3.04	14	7	21.20	50	1.51
3	2	67	4.10	2	67	4.39	2	67	4.60	2	67	4.36	2	67	4.49	2	67	4.48	2	67	4.60	21	14	31.02	67	1.48
4	2	50	4.28	2	50	6.59	2	50	6.63	2	50	6.35	2	50	6.34	2	50	6.54	2	50	6.30	28	14	43.02	50	1.54
5	3	60	6.23	3	60	7.92	3	60	7.71	3	60	7.75	3	60	7.93	3	60	7.87	3	60	7.85	35	21	53.27	60	1.52
6	4	67	6.76	4	67	9.48	4	67	9.56	4	67	9.45	4	67	9.69	4	67	9.58	4	67	9.42	42	28	63.93	67	1.52
7	5	71	8.40	5	71	10.65	5	71	10.76	5	71	10.93	5	71	10.96	5	71	10.71	5	71	10.94	49	35	73.36	71	1.50
8	6	75	8.61	6	75	12.68	6	75	12.98	6	75	12.95	6	75	12.81	6	75	12.96	6	75	12.75	56	42	85.73	75	1.53
9	7	78	9.09	7	78	13.88	7	78	13.81	7	78	13.72	7	78	13.74	7	78	14.03	6	67	14.03	63	48	92.29	76	1.46
10	8	80	13.31	8	80	15.63	8	80	15.59	8	80	15.68	8	80	15.39	8	80	15.55	7	70	15.44	70	55	106.58	79	1.52
11	9	82	15.43	9	82	17.14	9	82	17.02	9	82	16.94	9	82	17.07	9	82	16.98	7	64	16.86	77	61	117.43	79	1.53
12	9	75	16.09	9	75	18.33	9	75	18.26	9	75	18.20	9	75	18.09	9	75	18.35	7	58	18.32	84	61	125.64	73	1.50
13	9	69	17.28	9	69	18.96	9	69	18.79	9	69	18.71	9	69	18.94	9	69	19.02	7	54	18.89	91	61	130.59	67	1.44
14	10	71	18.54	10	71	21.45	10	71	21.36	10	71	21.53	10	71	21.28	10	71	21.38	8	57	21.44	98	68	146.98	69	1.50
15	10	67	19.48	10	67	21.80	10	67	21.47	10	67	22.53	10	67	21.74	10	67	21.76	8	53	21.55	105	68	150.33	65	1.43
16	10	63	20.71	10	63	22.95	10	63	23.11	10	63	23.01	10	63	23.16	10	63	23.03	8	50	22.92	112	68	158.88	61	1.42
17	10	59	21.98	10	59	24.03	10	59	24.14	10	59	23.94	10	59	23.97	10	59	24.07	8	47	23.95	119	68	166.08	57	1.40
18	11	61	24.40	11	61	25.12	11	61	25.04	11	61	24.8	11	61	25.38	10	56	25.29	8	44	25.42	126	73	175.42	58	1.39
170	116	68	217	116	68	254	116	68	254	116	68	254	116	68	254	115	68	255	97	57	254	1190	792	1742	67	1.46

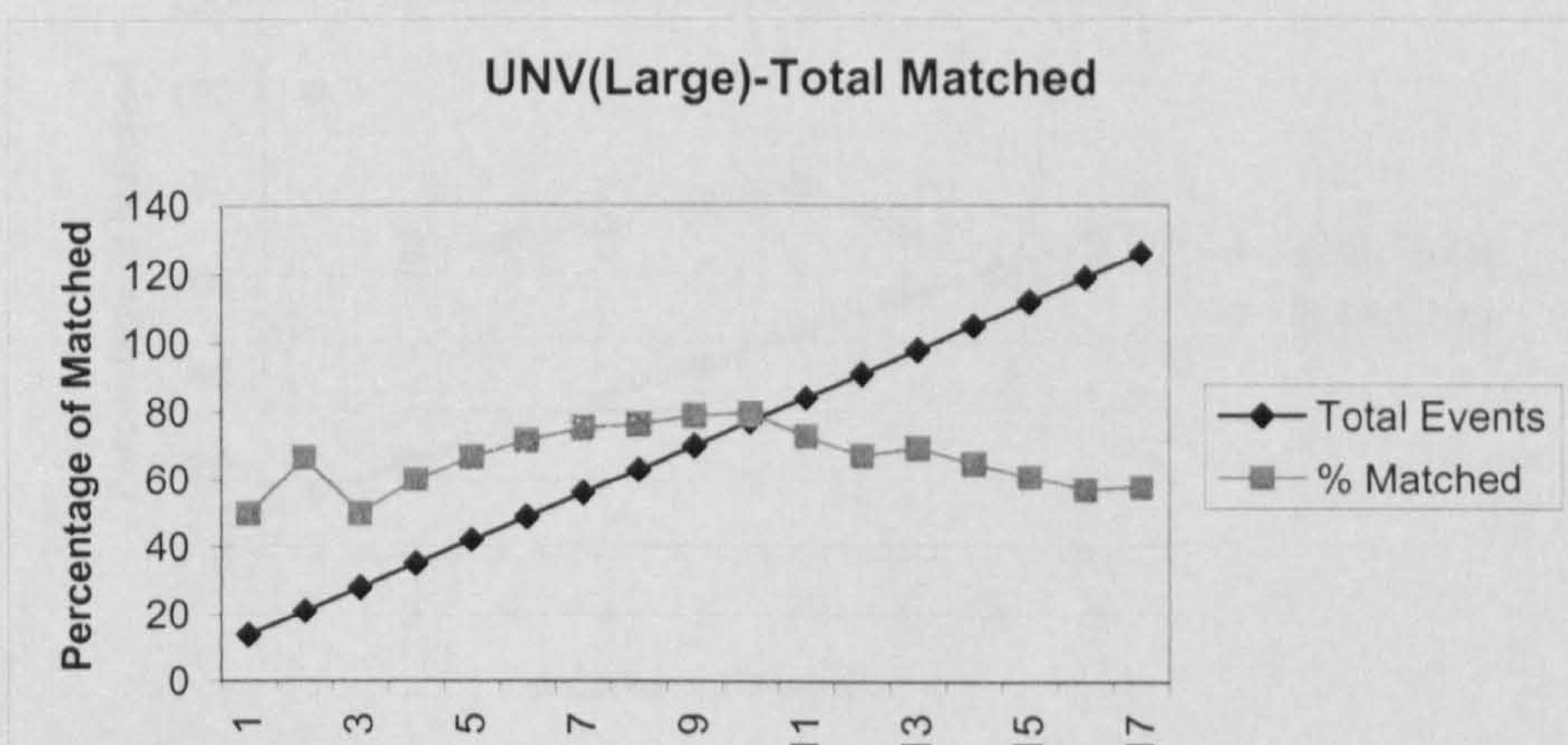

Figure 5.8: The Relationship between Total Events and Total Matched for UNV (Large)

UNV-Medium

Table 5.14 and Figure 5.9 illustrate the results for UNV-medium. The overall matched is 71%, which is higher than for the UNV-large schedule. The explanation for this is that the sign-off time (one of the factors for finding a match in UNV event) for a medium schedule is distributed unlike that of a large schedule where some of the time is the same. When there is different timing, the possibility of finding a match is high. The average time taken is 0.77 seconds, which is very fast.

Table 5.14: UNV-Medium Schedule

EV	30 Min.			45 Min.			60 Min.			75 Min.			90 Min.			105 Min.			120 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	2	100	1.83	2	100	1.87	2	100	2.08	2	100	1.94	2	100	2.01	2	100	1.93	2	100	2.10	14	14	13.75	100	0.98
3	2	67	1.98	2	67	2.13	2	67	2.15	2	67	2.31	2	67	2.10	2	67	2.19	2	67	2.15	21	14	15.02	67	0.72
4	3	75	3.17	3	75	2.89	3	75	3.05	3	75	3.00	3	75	2.84	2	50	3.10	2	50	2.97	28	19	21.01	68	0.75
5	4	80	3.23	4	80	3.50	4	80	3.51	4	80	3.65	4	80	3.75	3	60	3.45	2	40	3.67	35	25	24.76	71	0.71
6	5	83	3.26	5	83	4.31	5	83	4.15	5	83	4.45	5	83	4.17	4	67	4.37	3	50	4.25	42	32	28.96	76	0.69
7	6	86	3.68	6	86	4.41	6	86	4.54	6	86	4.72	6	86	4.40	5	71	4.51	4	57	4.68	49	39	30.94	80	0.63
8	6	75	5.19	6	75	6.86	6	75	6.93	6	75	6.89	6	75	7.02	5	63	6.71	4	50	6.78	56	39	46.37	70	0.83
9	6	67	5.59	6	67	8.02	6	67	7.81	6	67	7.98	6	67	7.80	5	56	8.06	4	44	7.79	63	39	53.06	62	0.84
10	7	70	7.94	7	70	8.41	7	70	8.27	7	70	8.40	7	70	8.41	6	60	8.29	5	50	8.26	70	46	57.98	66	0.83
54	41	76	35.9	41	76	42.4	41	76	42.5	41	76	43.3	41	76	42.5	34	63	42.6	28	52	42.7	378	267	291.8	71	0.77

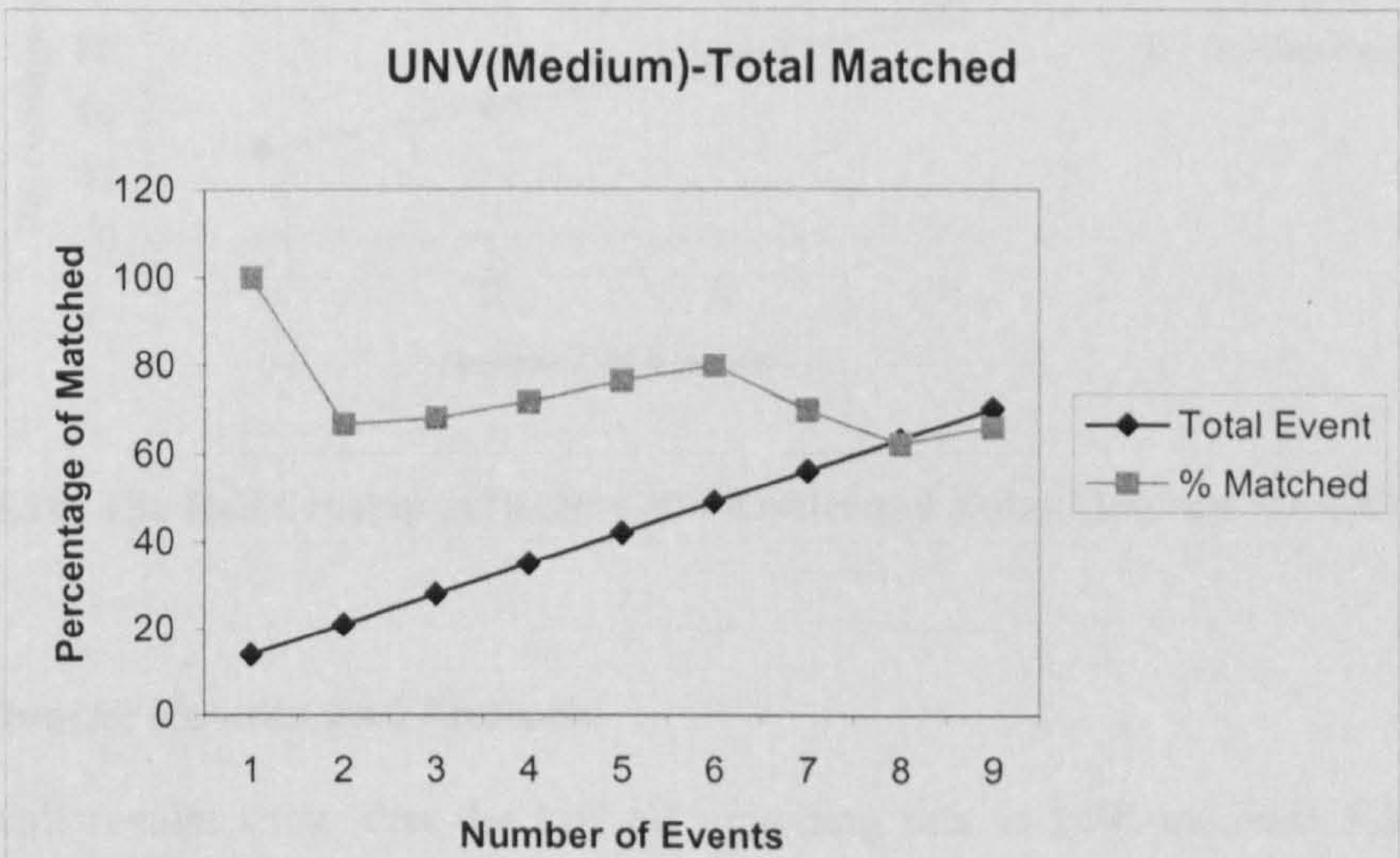

Figure 5.9: The Relationship between Total Events and Total Matched for UNV (Medium)

UNV-Small

Table 5.15 and Figure 5.10 show the results for UNV-small. The overall matched is 47%, which is better than expected for a small schedule. The average time taken is 0.39 seconds, which is very fast.

Table 5.15: UNV-Small Schedule

EV	30 Min.			45 Min.			60 Min.			75 Min.			90 Min.			105 Min.			120 Min.			Total				
	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	M	%	T(s)	TE	TM	TT(s)	%	AV(S)
2	1	50	0.87	1	50	0.72	1	50	0.85	1	50	0.86	1	50	0.87	1	50	0.82	1	50	0.94	14	7	5.93	50	0.42
3	2	67	1.27	2	67	1.40	2	67	1.11	2	67	1.19	2	67	1.30	2	67	1.28	1	33	1.43	21	13	8.98	62	0.43
4	2	50	1.47	2	50	1.60	2	50	1.32	2	50	1.36	2	50	1.42	2	50	1.61	1	25	1.50	28	13	10.28	46	0.37
5	2	40	1.91	2	40	1.85	2	40	1.94	2	40	1.96	2	40	1.95	2	40	1.88	1	20	1.89	35	13	13.38	37	0.38
14	7	50	5.52	7	50	5.57	7	50	5.22	7	50	5.37	7	50	5.55	7	50	5.59	4	29	5.76	98	46	38.57	47	0.39

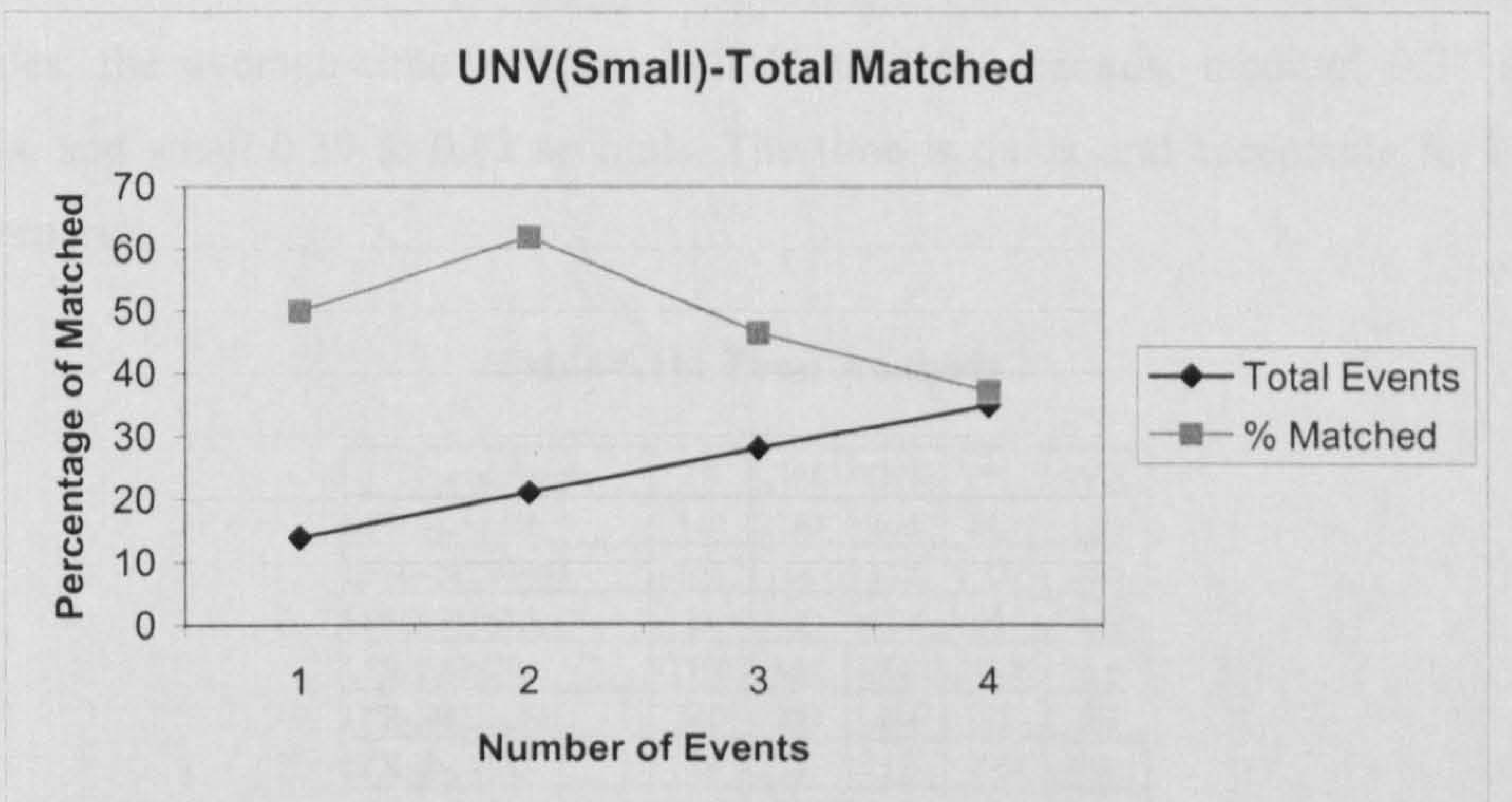

Figure 5.10: The Relationship between Total Events and Total Matched for UNV (Small)

5.3.3 Overall Results and Analysis

The overall results show that the highest matching rate is LFR-medium followed by UNV-medium, UNV-large, and UNV-small respectively. This shows that the type of schedule does not necessarily guarantee a match, but other factors like distribution and the relief period also influence the match. The reason why LFR-medium is the highest is because the schedule has longer break periods so lateness can be absorbed. Unlike in large schedules, the relief period is just enough (more or less than 50 minutes) and gives no chance for lateness absorption. The LFSO event is different because the time is fixed; after sign-on the starting time is after 15 minutes. So the chance to reschedule depends on the size of the schedule. Table 5.16 shows that LFSO-large is 44.1%, LFSO-medium is 13%, and LFSO-small 0%. In the event of UNV, the factor depends on end work 2 and sign-off. In the medium schedule, there are different times for signing off which is why UNV-medium is the highest (70.6%). However, in large schedules, some crews have the same time for sign-off although their end work 2 is different. This reduces the chances for a successful match (UNV-Large is 66.6%). Out of 4 events (LFSO, LFR, LFSW, and UNV), the highest matched is UNV (66%, 70.6%, and 46.9%). The overall match is 42.1%, which gives 2,805 successes out of 6,664 events. The result is good but still not satisfactory. There are many ways of increasing the percentage matched, for example by building the schedule with characteristics that support rescheduling. The next chapter will explain more about this. The time is different with different schedule types and nothing to do with different events. For large schedules, the average time is between 1.46 to 1.66 seconds, medium 0.77 to 0.9 seconds, and small 0.39 to 0.42 seconds. The time is quick and acceptable for a real-time scenario.

Table 5.16: Total Analysis

Type of Events	TE	TM	TT(S)	%	AV(S)
LFSO-LARGE	340	150	565	44.1	1.66
LFSO-MEDIUM	108	14	93.5	13	0.87
LFSO-SMALL	28	0	11.8	0	0.42
LFR-LARGE	1700	624	2545	36.7	1.5
LFR-MEDIUM	540	389	484	72	0.9
LFR-SMALL	28	2	12	7.14	0.43
LFSW-LARGE	1700	312	2535	18.4	1.49
LFSW-MEDIUM	540	209	421	38.7	0.78
LFSW-SMALL	14	0	0	5.99	0.43
UNV-LARGE	1190	792	1742	66.6	1.46
UNV-MEDIUM	378	267	292	70.6	0.77
UNV-SMALL	98	46	38.6	46.9	0.39
TOTAL	6664	2805	8740	42.1	1.31

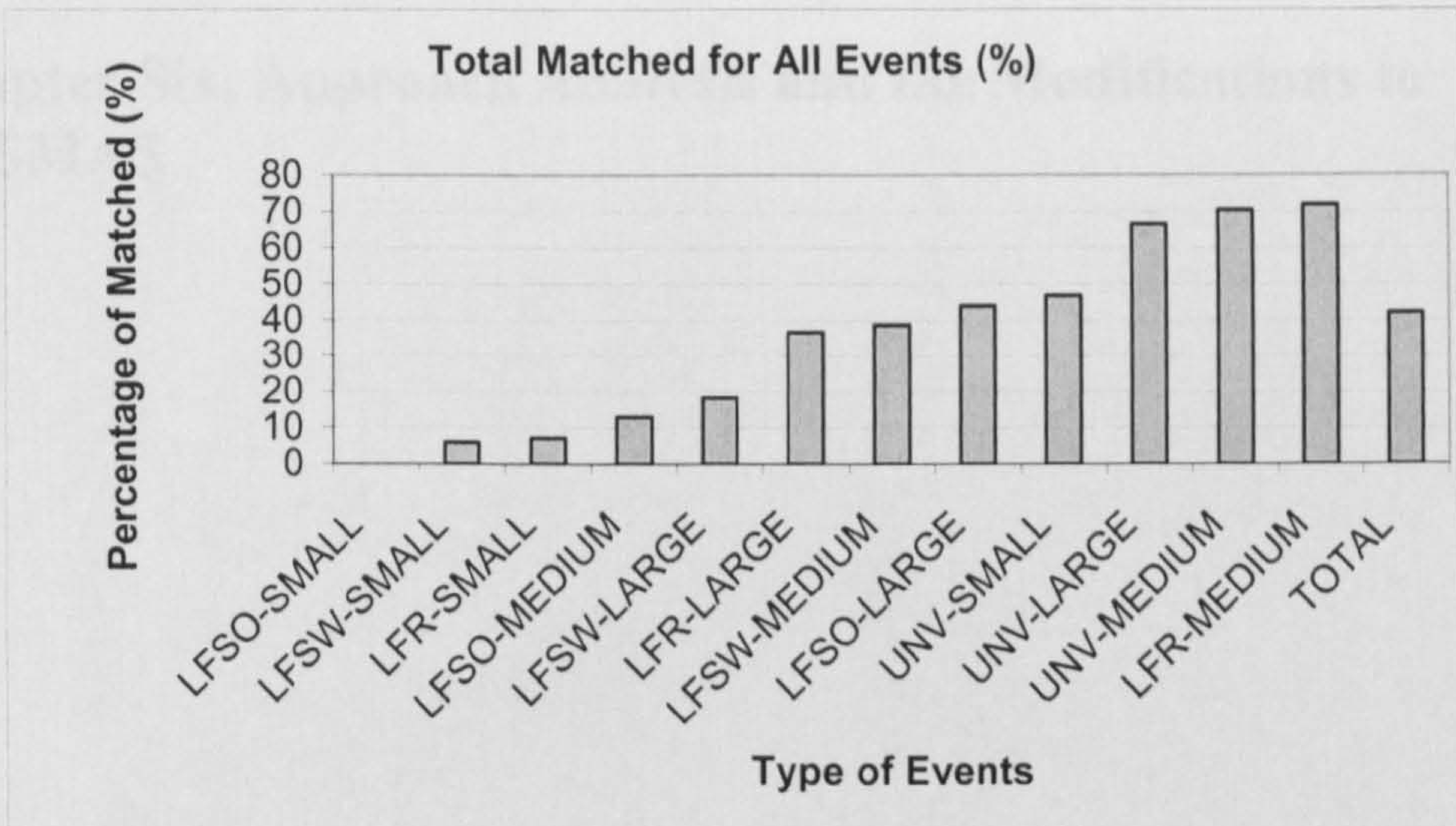

Figure 5.11: The Overall Matched According to Events

5.4 Summary and Conclusion

This chapter presents the results and analysis for multiple events experiments. The purpose of multiple events experiments is to evaluate the capability of CRSMAS (the proposed system) in facing different numbers of events taking place with different event timings in different types of schedules at any time. In these experiments we carried out a total of 870 experiments using four different events - LFSO, LFR, LFSW, and UNV. The analysis of the results shows that the time taken for rescheduling (average is 1.31 seconds) is very quick for all types of schedule and events and excellent for real-time scenarios. CRSMAS is also capable of handling multiple events at a single time. The largest number of events is 18, which takes more or less 25 seconds. However, the percentage of successfully matched (42.1%) is not satisfactory. There are many ways in which we can increase the matching rate, for example, the duties spreading, and the relief timing. In the next chapter these issues will be discussed further. In short, from these experiments, CRSMAS is capable of handling multiple events at any time and giving quick solutions in real-time but with a low matching rate. Chapter Six will evaluate the weaknesses of CRSMAS and propose modifications to it.

Chapter Six: Approach Analysis and the Modifications to CRSMAS

6.1 Introduction

Chapter Three proposed CRSMAS as a system to deal with UE problems related to crew. Chapters Four and Five showed the results and analysis of applying CRSMAS to two different experiments. Based on the analysis of the two experiments, this chapter evaluates CRSMAS, identifies its strengths and weaknesses, and proposes modifications to CRSMAS. To achieve this, the research sets some criteria and then evaluates the results of the two experiments with those criteria. The two criteria that are used are rescheduling capability and rescheduling speed. The number of successful matches determines the rescheduling capability, and the speed is evaluated based on the time taken to perform rescheduling. Based on the evaluation the research then identifies CRSMAS's weaknesses and proposes modifications to improve it, consequently any weaknesses or limitations of CRSMAS can be eliminated or at least minimised to ensure CRSMAS can achieve its aim.

6.1.1 Chapter Objective

The objective of Chapter Six is to present the analysis of the proposed approach (CRSMAS) by analysing the outcome of the two experiments and identifying the weaknesses and limitations of CRSMAS and to take these weaknesses and limitations as a basis for proposing a revised version of CRSMAS.

6.1.2 Chapter Outline

This chapter starts with an introduction in Section 6.1 describing the objective of the chapter and its relations to the rest of the chapters (see Figure 6.1). Section 6.2 sets the analysis and evaluation criteria. Section 6.3 presents the analysis and evaluation of CRSMAS based on the two experiments. Section 6.4 proposes modification to CRSMAS and explains the details. Section 6.5 presents the potential beneficiaries of CRSMAS. Section 6.6 concludes and summarises the chapter.

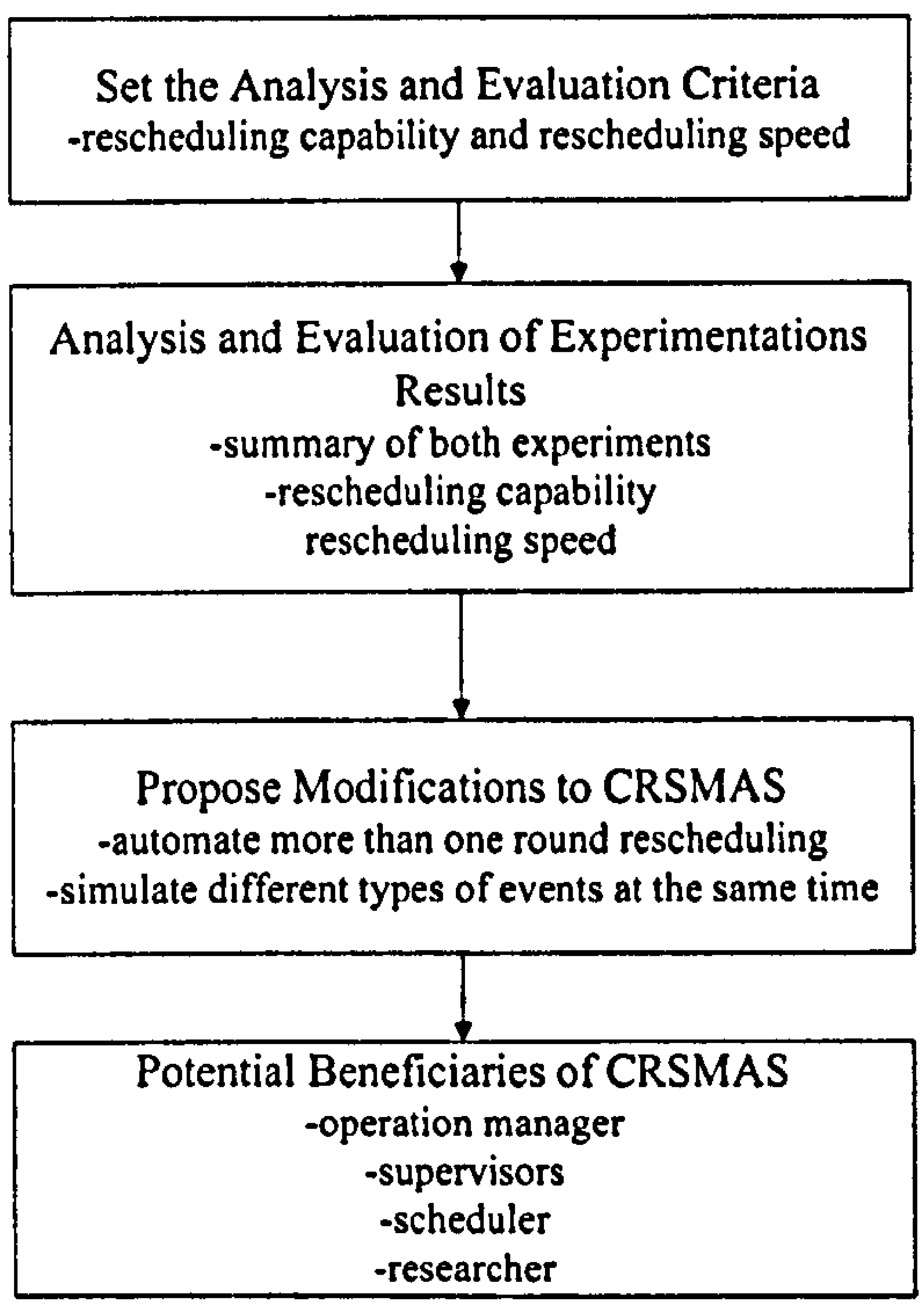

Figure 6.1: The Structure of Chapter Six

6.2 Analysis and Evaluation Criteria

The analysis and evaluation of CRSMAS is based on the aims of the system. The objective of the system is to help supervisors to manage UE and, by doing so, to minimize the effect of UE upon crew schedules and hence to reduce the amount of disruptions to bus operation. Based on this aim the requirements for the selected tool have been identified, as discussed in Chapter Two. The requirement is for a tool that is capable of providing quick results in an uncertain environment. Based on this requirement MAS was chosen and CRSMAS proposed. To measure whether CRSMAS achieves its aim or not, two criteria have been identified, these are: rescheduling capability and rescheduling speed. The rescheduling capability is determined by the number of successful matches and the speed is evaluated based on the time taken to perform rescheduling. As mentioned in Chapter Three, the agents (which in this research refer to CA and DA) achieve their objective through negotiation between agents in Virtual World. There are two types of agents, the demand agent and the supply agent. In CRSMAS the demand agent is DA and the supply agent is CA. When a demand agent negotiates and finds a suitable supply agent that can fulfil its requirements then it is called "matched". In CRSMAS when a duty (DA) loses its driver/crew because of UE then, through the Virtual World, the DA negotiates (rescheduling process) to find a suitable CA (driver/crew) that is available to take the duty. If there is a suitable CA then the match is a success. The matching process is done by CRSMAS. The perfect result is when 100% of the duties find a match. The speed is determined by the time it takes for the agent to find a match. The best result is the least time to find a match.

The experiments (single and multiple events) are done to assess CRSMAS based on these criteria. In addition, the single event experiments' objective is also to identify characteristics in crew schedules that influence the rescheduling capability, so that future crew schedules could be improved to increase their capability of finding crew replacements. The following section addresses the single and multiple event experiences presented in previous chapters, to be analysed and evaluated based on the above-mentioned criteria.

6.3 Analysis and Evaluation of Experimental Results

CRSMAS, as described in Chapter Three, has been examined using two different experiments. The first experiment (single event) is used to test the capability of CRSMAS in all types of schedules, duty distributions and timings, and to identify the characteristics of crew schedules that influence the possibility of successful rescheduling, as based on the matching rate. The second experiment (multiple events) is used to test the capability of CRSMAS to handle many events simultaneously that happen randomly. There are three types of events in Single Event experiments, which are: lateness, delay and unavailability. However, in Multiple Event experiments, the events are the same except there is no delay event because there is only one round of rescheduling for this experiment. More than one round of rescheduling means if in the first round there is no match, then the rescheduling is done manually to find a crew that is the nearest match. Then the duty that belongs to the nearest-matched crew will go to the next round. The matching round will continue until all the unavailable crews get a new duty. For further explanation refer to Section 4.2. In both experiments, three types of schedule (large, medium, and small) were used. Three categories of duty selection were used in the Single Event experiments (maximum, median, and minimum), but in Multiple Event experiments the duties were selected randomly. Table 6.1 shows a summary of the two experiments.

Table 6.1: The Summary of the Two Experiments

	Single Event Experiments	Multiple Events Experiments
Objectives	To test the capability of CRSMAS in all types of schedules, duties distributions and timing. To identify characteristics of crew schedules that influences the possibility of matching.	To test the capability of CRSMAS in handling many events simultaneously that happens randomly.
Events	Lateness (LFSO, LFR, LFSW) Delay (DFSO, DFSW) Unavailability (UNV)	Lateness (LFSO, LFR, LFSW) Unavailability (UNV)
Type of Schedules	Large Medium Small	Large Medium Small
Duty Selection	Maximum Median Minimum	Random

The following subsections present the findings derived from the two experiments. The discussion will be organised according to the evaluation criteria set out in Section 6.2 which are rescheduling capability and rescheduling speed.

6.3.1 Rescheduling Capability

In this research the rescheduling capability was measured based on the number of matches. A match means that a duty which has lost its driver/crew because of a UE finds a driver/crew that is available to take the duty. The matching process is done by CRSMAS. The perfect result is when 100% of the duties find a match. Table 6.2 shows the number of successful matches in the Single Event and Multiple Event experiments. The table shows that the matching rate for Single Event is 47.3% (230 matched out of 486 events) and for Multiple Events is 42.1% (2805 matched out of 6664). The capability of CRSMAS in Single Event is better than in Multiple Events.

Table 6.2: The Matched Results of the Two Experiments

	Single Event	Multiple Events
Total Number of Events	486	6664
Total Number of Matched	230	2805
Percentage of Matched (%)	47.3	42.1

However, as a whole the matching percentage is still low. The reasons are because of the weaknesses and limitations of CRSMAS, crew schedules and the nature of the UE. The details are presented below:

The Weaknesses and Limitations of CRSMAS

In Multiple Events the matching rate is lower than Single Event experiment. One of the reasons for this is that CRSMAS did not support more than one round of rescheduling. This is due to the fact that in Multiple Events, many events happen at the same time; therefore it will take more time to do second or further rounds of rescheduling because the process is done manually. *Automating the multiple rounds (more than one round) of rescheduling process would be useful to increase the matching rate.*

Another limitation of CRSMAS (although not concerning the matching rate) is that CRSMAS cannot simulate different types of events at the same time. In Multiple Events experiment many events are tested, but the events are the same. This limitation is because in different events there are different rules. In MAS, agents can only negotiate with one set of rules at a time. This is one of the limitations of MAS. *One way that may solve this problem is to run the CRSMAS in different windows for different events.*

The Limitations in Crew Schedules

The experimental results of Chapters Four and Five show that the matching percentage of small schedules is much lower. Small schedules have very few duties which is why when UE occurred the probability of finding a match is difficult. *However, this problem may be solved by not restricting the crews according to route. For example, if Crew C is not available then any available crew from the same garage is entitled to take C's duty. But with one condition that is all crews in that garage know all the routes that are managed by the garage.* In both experiments the matches were restricted only to the same crew schedules.

In the Single Event experiment it was discovered that one important factor that influences the matching possibility is duty spreading. If duties are not spread then the possibility of matching them is lower. For example, the large schedule (Appendix C) has many duties, but because the spread of duties in an hour is not equal or distributed then the matches were lower than the medium schedule (Appendix D). The reason why the schedules are different is because they are not both from the same bus company. Apparently, different companies have different policies in constructing their schedules. *By making the duties equally spread or distributed in an hour it increases the possibility of finding a match.*

Based on the analysis of both experiments the period of relief time also influences the possibility of matching. If the relief time is long then the possibility of finding a match is higher because it can absorb the UE such as lateness and delay. For example, the large schedule (Appendix C) allocates just enough relief time in the schedule (more or less than 45 minutes). As a result, the schedule cannot absorb the lateness event and not many crews are available for rescheduling. In contrast, the medium schedule (Appendix D) allocates long hours for relief, so the schedule can absorb the lateness event and many crews are available for rescheduling. *Longer periods of relief time increase the possibility of finding a match.*

The Nature of UE

The longer the period of a UE, the more difficult it is to find a match. For example, the matching rate for a delay event (80 to 180 minutes - that is very long) is very low compared to lateness or short period unavailability events. The reason is that during the long period there has to be more than one rescheduling and the distribution of duties varies from hour to hour. If, in all the hours, the number of duties are large then there is no problem in finding matches although it has to go through many rounds of rescheduling. *One way to solve this problem may be to divide long periods into a few short periods and then do rescheduling to all the parts.*

6.3.2 Rescheduling Speed

The rescheduling speed is measured as the time taken to perform the rescheduling process. Based on the results, the average time taken for a single event is 1.59 seconds and for multiple events is 1.31 seconds (see Table 6.3). The average for Single Event is higher than Multiple Event. One of the reasons for this is that in Single Event there is more than one round of rescheduling and so it takes more time. This average time is considered quick for real-time environments. The analysis in Chapters Four and Five shows that the speed is dependant on the size of schedules; the larger it is, the longer it takes to perform rescheduling. The reason is all the agents have to negotiate with each other and so it takes more time when the number of agents (crews/duties) is large. Based on this evaluation it can be concluded that CRSMAS is capable of performing quick rescheduling in real-time.

Table 6.3: Rescheduling Times of the Two Experiments

	Single Event	Multiple Events
Total Number of Events	486	6664
Total Time Taken (s)	366.35	8740
Average Time (s)	1.59	1.31

6.4 Proposed Modifications to CRSMAS

The previous section mentioned the weaknesses and limitations of CRSMAS, crew schedules and the nature of UE, that cause the percentage of matches generally to be low, and the section also suggested some improvements that may reduce the weaknesses and limitations. In this section some modifications to CRSMAS are proposed, based on the analysis and evaluation in the previous section. The propositions are not tested. The details of the proposition are discussed below.

CRSMAS is not capable of performing rescheduling in more than one round. More than one round of rescheduling is necessary when the period of UE is long, such as in a delay event. In the Single Event experiments more than one round of rescheduling was applied, but it was done manually which is slow and prone to error. The solution is either to automate the manual procedure or to add searching capability to the DA so it can find the next match (the manual way is explained in detail in Section 4.2.2). In this research to proposition to solve this problem is to automate the manual way. Figure 6.2 shows the data flow diagram for the rescheduling process that incorporates more than one round of rescheduling. The process starts with the matching process, if there is no match then it will go to the next process, which is "Find Nearest Match", otherwise the process will stop. In the "Find Nearest Match" process the user can specify how many times the system can go through the same process again (L = looping, X=maximum number of loops). Otherwise, if there is no nearest match, then the loop will not stop until it reaches the maximum number of loops that was set by the user.

Figure 6.3 illustrates the sequence of messages when there is no match and more than one round of rescheduling is required. It starts when a DA needs a driver (crew) to take its duty because the original driver is late or not available. The DA sends messages to all the CAs requesting a driver (*reqDriver* message). In return, CAs will respond back to the DA (*respond* message). Then the DA sends a detailed specification of the duty (*detailsSpec* message). CAs that are available (in this case CA2 and CAn) for the duty will respond and matching will start (*beginMatching* message). Neither of them (CA2 and CAn) will satisfy the requirements of DA. Since there is no match, the DA starts to find a nearest match (*findingNearestMatch* message). If the CA matches to the nearest requirement then DA will put CA into reserve (*reserved* message). DA will continue the matching process with the next CA and put the CA into reserve if it fulfils the nearest requirement. After all the negotiation, the DA will make a decision to choose the best one, which in this case is CAn, and it will receive an acceptance message from DA (*acceptMatch* message).

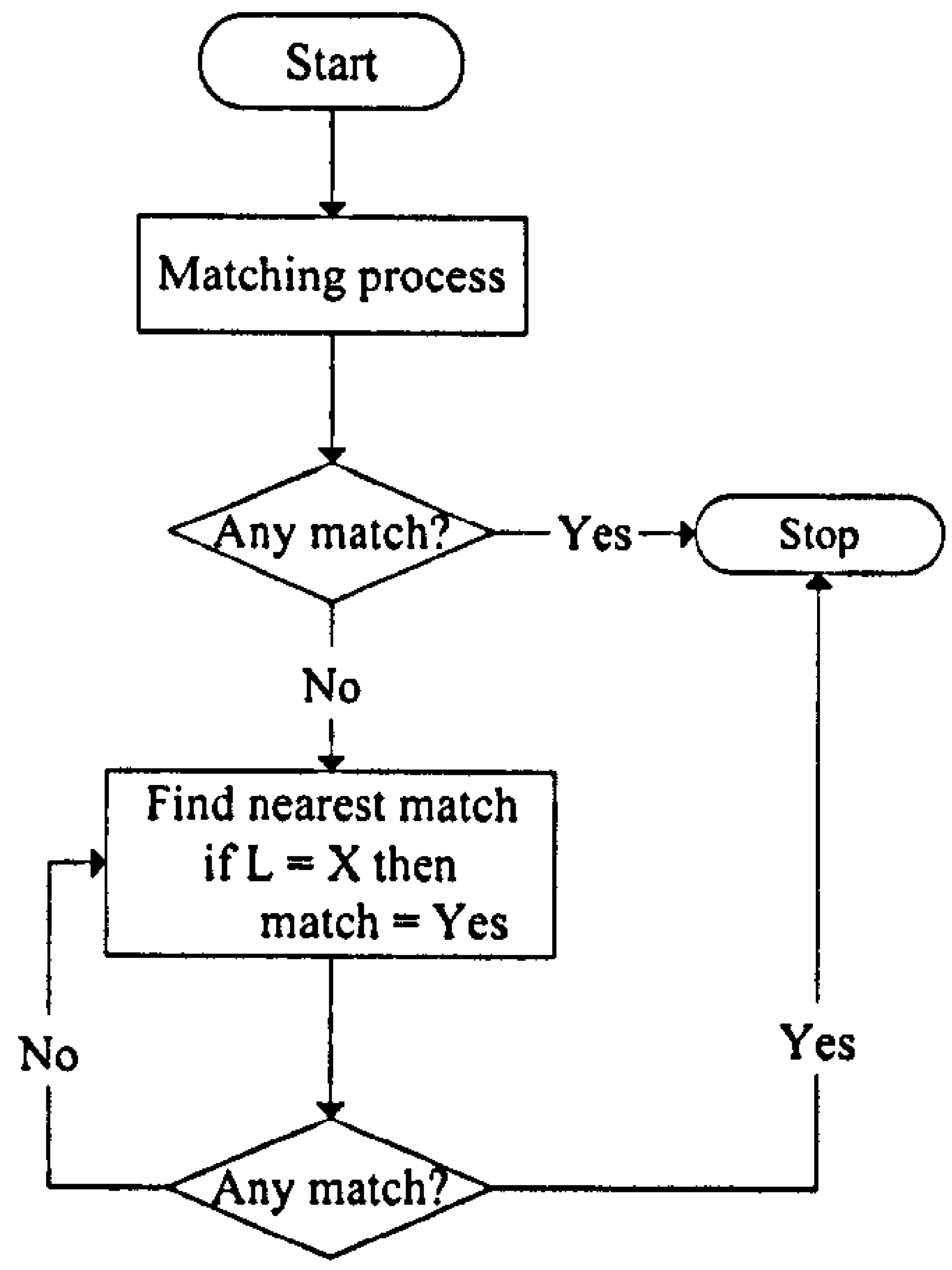

Figure 6.2: The Matching Process for More than One Round of Rescheduling

One of the limitations of MAS is that it cannot simulate different types of event at the same time, because in different events there are different rules. In MAS, agents can only negotiate with one set of rules at a time. One way to deal with this is to run the CRSMAS in different windows for different events. However, there is a problem that multiple matches with the same crew may occur. So to control this we propose adding one attribute to CA, that is "Status", that tells the user the current status of a particular crew. When there is a match the status is updated to "Not Available" in real time. As a result it will stop any matching processes for the particular crew which has turned to "Not Available" in other running windows.

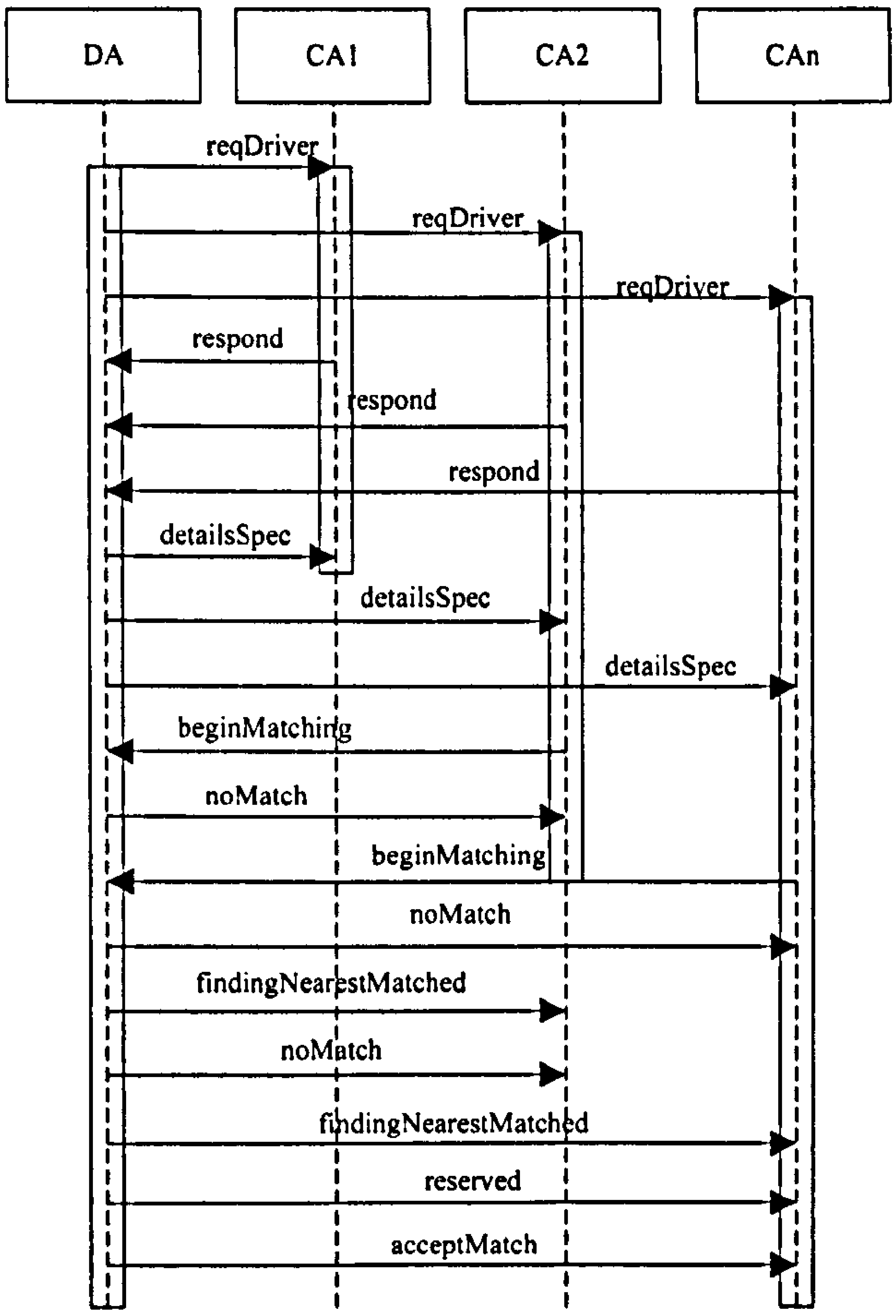

Figure 6.3: The Sequence of Messages for More than One Round of Rescheduling

6.5 Potential Beneficiaries of the System

The CRSMAS that is informed by this research could be a useful decision making tool for several audiences. Such audiences are *Operation Manager, Supervisor, Scheduler, and Researcher*. The *Operation Manager* is a person who is responsible for overseeing the whole bus operation. The Operation Manager can use CRSMAS as a planning tool that is capable of simulating different UE. The simulation results will help the Operation Manager in planning things such as the number of crews needed in everyday operation, and the estimated costs caused by disruption.

The *Supervisor* is a person who is directly involved in day-to-day operations, handling UE, and has to make quick decisions in handling such events. CRSMAS could help the Supervisor in making quick decisions to replace unavailable crew. The *Scheduler* is a person who is responsible for constructing the predetermined schedules. CRSMAS could help the scheduler to construct robust crew schedules that support the rescheduling process. Section 6.3 discusses some of the limitations in crew schedules that reduce the possibility of successful rescheduling and proposes some actions that could increase successful rescheduling. The *Researcher* who is searching for tools or techniques to improve bus or public transport services can also use CRSMAS to simulate the rescheduling process using MAS. The simulation results can help researchers to understand the capability of MAS in rescheduling, the effect of UE to schedules, and identify factors in schedules that support rescheduling.

The potential beneficiaries mentioned above are those who are involved in bus operation. However, the tool also could be of benefit to other domains of scheduling where humans are involved such as workforce scheduling, nurse rostering, truck driver scheduling and air crew scheduling.

6.6 Summaries and Conclusions

This chapter presents the analysis and evaluation of the results from both the Single Event and Multiple Event experiments. The chapter set two criteria for analysis and evaluation which are rescheduling capability and rescheduling speed. Rescheduling capability was measured using the matching percentage and rescheduling speed was measured by the time taken to perform the rescheduling. For the first criterion, CRSMAS is capable of performing rescheduling but the results are still not satisfactory (44.7%) because of weaknesses and limitations in CRSMAS itself, limitations in crew schedules, and the nature of some of the UE (which can be lengthy). CRSMAS's weaknesses and limitations are that it cannot perform more than one round of rescheduling automatically and it cannot reschedule different events at the same time. The limitations in crew schedules are the small number of duties/crews, duties are not equally spread, and the relief time is not long enough. For the rescheduling speed, the ability of CRSMAS is satisfactory because it can perform rescheduling with the average 1.45 seconds. What is still missing is how we can increase the CRSMAS's capability for rescheduling. It is hoped that the proposed modifications to CRSMAS, as mentioned in Section 6.4, would increase the matching percentage. Section 6.3 also suggests ways to deal with the limitations in crew schedules and the lengthy period of some UE. From this analysis and evaluation it has been learned that the successful of rescheduling is not only dependent on the tool but also other factors, such as the design of crew schedules. If crew schedules are designed with the criteria suggested in Section 6.3 taken into account, then it will increase the probability of successful rescheduling. One limitation that has been found with MAS is that MAS is not capable of rescheduling for different events at the same time because there are different rules of rescheduling for different events. In short, in this research the research aim was achieved (although not 100%), which was to reduce the effect of UE to crew schedules. However, there are many potential ways left to maximise the achievement of the aim such as to increase the successful matches, and to design crew schedules that support rescheduling. The chapter suggests potential beneficiaries of the system such as the Operation Manager, Supervisor, Scheduler and Researcher in public transport. The next chapter summarises the whole research and concludes the findings, and suggests further research.

Chapter Seven: Summary and Conclusions

7.1 Introduction

In this research, the literature gap that was found is that most of the current approaches to bus crew scheduling are concentrated on achieving optimum schedules, and they are successful in finding optimum or near-optimum schedules. However, there is very little research considering minimizing the effect of UE problem on crew schedules. The current researches that touch on the issue (managing UE) have limitations such as not being practical in real-world scenarios. In practice, bus companies manage UE manually, which is hard and slow to make decisions, prone to error and not optimum. These limitations necessitate the need for an automated system that supports the process of crew rescheduling to assist supervisors in dealing with UE problems that effect crew schedules. Therefore, as an attempt to cover the literature gap, this research proposed the CRSMAS framework that uses MAS as a tool to automate the rescheduling process of crew rescheduling with the aim of minimizing the effect of UE upon crew schedules, therefore reducing disruption to bus operation. To test CRSMAS we used two types of experiments, namely Single Event and Multiple Events. Based on the results it was found that CRSMAS is capable of quick rescheduling but the success of the rescheduling is still low. Therefore some modifications to CRSMAS were proposed that will make it more effective in achieving successful rescheduling. The work that was done on this research is still not enough fully to cover the literature gap. More research is needed to cover the literature gap. This chapter concludes the research undertaken in this dissertation and recommends directions for further research. It begins with the thesis summary, followed by the conclusions that were based on literature, interviews and experiments carried out. Limitations of this research are offered in the next section. The final section provides recommendations for further research.

7.2 Summary

This dissertation is made up of seven chapters. **Chapter One** served as an introduction to the research problem, outlining the aim and objectives that guided the scope of this thesis. The research described in this dissertation is concerned with UE that cause disruption to bus crew schedules and subsequently bus operation. One way to manage UE is by crew rescheduling. Most of the current approaches, which are based on static schedules, do not provide the capability of crew rescheduling in real time scenarios. In practice, crew rescheduling is managed manually based on supervisors' capabilities and experience in managing UE. There are many limitations to manual crew rescheduling, such as it being hard and slow to make decisions when many UE happen at the same time, the possibility of breaking the EC driving hour rules, and the decisions are not optimum in the use of crew resources. To overcome these limitations, this research proposes an automated crew rescheduling system. The aim of the system is to help supervisors to make decisions about crew rescheduling while managing UE.

Chapter Two provides a review of the UE problem, the current approaches to the bus crew scheduling problems, practical experiences of bus companies in dealing with UE problems, the motivation to use MAS, theoretical description of MAS and the current use of MAS in scheduling. From the analysis of the current approaches, the limitations of the current approaches have been learnt. The limitations in most of the current approaches to bus crew scheduling are concentrated on achieving an optimum schedule. The definition of the optimum schedule is limited to minimum duties and minimum cost. However, crew schedules should be flexible enough to accommodate real-time changes in everyday operation. The UE problem is one of the challenges in bus operation that needs to be tackled. UE will always happen and nothing can prevent them because the world is imperfect. The only way is to minimize the effect of the UE problem. When a UE problem takes place it will cause many effects, and one of them is on crew schedules. One way to handle this is with real-time crew rescheduling that currently is done manually at garages by supervisors. MAS is a promising approach that might be useful to automate the crew rescheduling process. MAS has been known to provide quick solutions in real-time and in uncertain environments. This paved the way for the main research question of this thesis, which is: *Is MAS a suitable approach for automating crew rescheduling process in real-time so that it will help supervisors in dealing with UE problems to crew schedules*?

Chapter Three presents the proposed approach, which is an automated crew rescheduling system. Prior to that, the chapter presents some of the issues regarding the proposed approach. Two issues are discussed, first, whether to reschedule crews or reschedule crew schedules; second, whether to propose a complete crew scheduling system or just an additional to the current system. The research found that crew schedule rescheduling is not suitable for real-time because of the complexity associated with it. The research also concludes that an additional module is suitable for this research since the focus is on solving problems arising with UE that happen in everyday operation on crew schedules, and not on finding optimum schedules. The chapter thereafter models the manual way of crew rescheduling and, based on these models, it proposes the Crew Rescheduling System with MAS (CRSMAS). Then CRSMAS is modelled with the concept of MAS. In CRSMAS architecture there are two types of agents which are: duty agent (DA) and crew agent (CA). CA represents a crew, and DA corresponds to a duty that needs to find a crew because the original crew is late or unavailable. The agent's interactions are modelled with sequence diagrams which show the types of messages passing between agents in different scenarios. CRSMAS can be used to help supervisors in making quick decisions about crew rescheduling whenever a crew is late or unavailable. The decision should not allow the violation of EC driving hour rules, suggest the best, optimum solution, and within a short period of time (within seconds or minutes).

Chapters Four and Five present the two experiments in order to evaluate CRSMAS that are single event and multiple events. The single event experiments only test one event at a time but with different types of event (lateness, delay, and unavailability), different types of schedule (large, medium, and small), different duty distributions (maximum, median, and minimum) and different event timings. The purpose is to test the capability of CRSMAS in all types of events and schedules and also to identify the characteristics of crew schedules that influence the possibility of successful rescheduling. Multiple events testing looked at several events taking place concurrently and randomly. The purpose is to test the robustness of CRSMAS in handling many random events at a time. Chapter Four presents the results and analysis of single event experiments, and multiple events experiments and analysis are presented in Chapter Five. The experiments are conducted using real-world data taken from bus companies in London.

Chapter Six presents the analysis and evaluation of the two experiments in order to identify the weaknesses in CRSMAS and proposes modification wherever appropriate. The chapter sets two criteria for analysis and evaluation that are matching rate and rescheduling speed. The analysis shows that the overall matching rate is low because of a few reasons that are the small number of duties/crews, duties not being equally spread, relief time not being long enough, the event being too long, and only one round of rescheduling. For every reason given, the chapter suggests a way to deal with it. The rescheduling speed is quick and acceptable in the real-time scenario. The chapter then identifies and proposes modifications to CRSMAS to make it better so it can fulfil the aim of its creation. The proposed modifications are the ability to reschedule more than one round, the ability to perform rescheduling of different types of events at the same time, filtering the events before going through rescheduling process, and changing the crew schedules to support the rescheduling process. The chapter suggests potential beneficiaries of the system such as operation manager, supervisor, scheduler and researcher in public transport.

7.3 Conclusions

The main findings and conclusions derived from this research are reported below:

- *MAS can be used as a tool to model and implement the automated crew rescheduling system.* In this research MAS was proposed as a tool to implement the automated crew rescheduling system because MAS can provide a quick solution in real-time and in uncertain environments. Thereafter the research proposed CRSMAS that use the concept of MAS. In the CRSMAS architecture there are two types of agents that are the duty agent (DA) and the crew agent (CA). CA represents a crew, and DA corresponds to a duty that needs to find a crew. The agents perform the rescheduling process through negotiation between them. Based on the experiments it can be concluded that MAS is suitable for automating the crew rescheduling process and is capable of quick rescheduling, whether facing single or multiple events at the same time.

- *MAS has limitations in dealing with different event at the same time.* From the Multiple Events experiment it was found that MAS cannot simulate different types of event at the same time. The limitation is because in different events there are different rules. In Virtual World, agents only can negotiate with one set of rules at a time.

- *Successful rescheduling is not only dependant on the tool.* Findings from the Single Event experiment show that the success of rescheduling is not only dependant on the tool, but also on other factors such as the characteristics of crew schedules and the period of UE. The factors of crew schedules' characteristics are the number of duties, duty spreading, duty distribution and the period of relief time. The longer the period of UE, the less chance there is of rescheduling success.

- *MAS is capable of quick rescheduling.* From the empirical evidence (Single and Multiple Events experiments) MAS is capable of performing quick rescheduling in real-time. The rescheduling speed is measured as the time taken to perform the rescheduling process. Based on the results, the average time taken for Single Event is 1.59 seconds and for Multiple Events is 1.31 seconds. However, the average for Single Event is higher than for Multiple Event. One of the reasons for this is that in Single Event there is more than one round of rescheduling and therefore it takes more time. This average time is considered quick for the real-time environment. The analysis also shows that that the speed is dependent on the size of schedules; the larger a schedule is, the longer it takes to perform rescheduling. The reason for this is that all the agents have to negotiate with each other and as a result it takes time when the number of agents (crews/duties) is large.

7.4 Summaries of Contributions

This dissertation has made four contributions from both its literature and empirical work to both theory and practice:

- *Evaluation of current approaches in dealing with unpredictable events.* The assessment of the strengths and limitations of current approaches, especially in dealing with UE, can be used to improve them by adding the capability of dealing with such events. The findings of the appraisals can also be used to inform researchers and practitioners about the important aspects of a particular approach that may be relevant to their specific research focus.

- *Practical experiences of bus companies in London.* The outcome of the interviews can give an overview of the UE that bus companies face and how they typically manage them. This can guide the researcher in finding what is still missing in bus operation research as a whole and what can be done do to improve it.

- *Proposed Crew Rescheduling System with MAS (CRSMAS).* The aim of the CRSMAS is to minimize the effect of UE upon crew schedules. The results of the experiments show that it is able to do quick rescheduling. However, the success of the rescheduling is still low. From the analysis it was found that there are limitations of CRSMAS which are that it is not capable of performing automated rescheduling more than one round and it cannot perform rescheduling for different events at the same time. To overcome the first limitation, it was proposed to automate the manual way of second and further rounds of rescheduling by introducing the process of finding the nearest match. The user can specify how many times the system can go through the process and CRSMAS will repeat the process until it finds a match or reaches the maximum number of loops that was set by the user. To solve the second limitation, the research proposed to run the CRSMAS in different windows for different events. However, there is a problem that multiple matches may be made on the same crew. So to control this, the research proposed adding an attribute to CA that is "Status" that tells the user of the current status of particular crew. When there is a match then the status is updated to "Not Available" in real-time. As a result it will prevent any other process matching a crew which has its status set to "Not Available" in other running windows. The CRSMAS approach can be used in other applications or problem domains that involve drivers or staff, such as staff scheduling, nurse rostering, and train driver scheduling.

- *The identification of factors in crew schedules that influence the successful match in rescheduling process*. The analysis of the results shows that the factors in crew schedules that influence the possibility of successful rescheduling are its schedule type (large, medium, or small), duty distribution (maximum, median, or minimum), UE period (long or short), and duty spread in an hour. These factors can be a guide for the scheduler to make crew schedules that are more flexible and support crew rescheduling.

7.5 Limitations of Research

A few limitations that were identified:

- *The interviews were carried out in London only.* This limitation means that the approach might be suitable only for bus companies in London only. In other cities in the UK, or elsewhere in the world, the situation might be different such as the bus service frequency might be lower. Thus, in this situation, reassignment may not be possible or suitable.

- *The approach is not tested in real environment setting.* The approach is not tested and implemented in a real environment. There might be other factors that affect the rescheduling process, such as resistance from crews in accepting new duties, and the availability of precise information about UE. These two factors could hinder the smooth process of rescheduling.

- *The research investigates only three types of unpredictable events.* Not all the events were investigated and tested, thus the solution might not be suitable for other events that are not included in the research, such as crews being absent without prior notice or being on strike.

7.6 Further Research

Further research could be directed towards the following:

- *The expansion of the approach to cover other UE.* The approach could be improved by covering other unpredictable events, such as crew absences that need the duty to be totally rescheduled. This can be done by splitting the duty into different parts, then assigning each part to an available crew. More researches are needed to investigate this method. Many issues could rise from this method, for example how to split the schedule, and when it is appropriate to split.

- *Integration of the developed approach with existing scheduling systems.* The integration is one of the important issues that need to be addressed. There are many benefits for the scheduler and supervisor if the CRSMAS integrates with the existing scheduling system. For example, when rescheduling is needed, information about crews and duties can be read immediately from the existing system. This will save time.

- *The expansion of the rescheduling concept in other scheduling problems.* The proposed approach has the potential to be expanded in other scheduling domains, such as workforce scheduling, staff scheduling, nurse rostering, truck driver scheduling and air crew scheduling. Although the proposed approach is meant for bus crews, there are similarities in all types of human scheduling. Humans can be drivers, staff, crew or work forces. For example, when there are human involved, problems such as lateness, delays and unavailability are common. Thus, with small modifications to CRSMAS, the proposed approach might suit other scheduling problems.

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Appendix A: Questions for Interview

Interview with bus companies will be divided to two section A, B,C and D. Each and every section has their own objective(s) :

Section A: The planning and scheduling process
Objective: To know how the company manage the whole planning and scheduling process.

i) Could you please give a brief description on how the planning and scheduling in your company?
ii) How long it takes for the whole planning and scheduling?
iii) What tools do you used?
iv) What are the constraints?
v) What are problems you faced in developing the scheduling?
vi) How do you deal with the problems?

Section B: Bus Crew Scheduling
Objective: To know how the company manage the bus crew scheduling process.

i) Could you please give a brief description on how the crew scheduling in your company?
ii) How long it takes for the crew scheduling?
iii) What is the period for each scheduling?
iv) What tools do you used?
v) What are the constraints?
vi) What are problems you faced in developing the scheduling?
vii) How do you deal with the problems?

Section C: The Problems in Operations
Objective: To know what are the problems in day-to-day operations and how the company manage the problems.

i) What are/ types of problems you faced in implementing the scheduling?
ii) How do you deal with the problems?
iii) Do you need to do the re-scheduling?
iv) What are the costs in handling the problems?
viii) Are the crews satisfied with the solution?
ix) How about the customers' satisfaction?

Section D: The Improvements in Scheduling Packages

i) Are you satisfied with your scheduling package?
ii) What are your suggestions to improve the scheduling package?
iii) Could your package re-schedule when the problems arise?
iv) How about dynamic scheduling? Where the re-schedule is done without disrupting the whole schedule, only 'local' schedule.

Appendix B: Describing the Interviews

The interview was unstructured. The interviewer asked the questions to the interviewee not sequentially. The guide for the questions is shown in Appendix A. The questions consists of 4 section, and total 23 questions, which cover the aspects of planning and scheduling, crew scheduling, everyday operation and scheduling packages. Below are the answers of the interviews.

Section A – Planning and Scheduling Process

The questions are about planning and scheduling. How they do the scheduling and what are the problems faces by them. The questions, and summarized answers, are as follows:

1) Could you please give a brief description on how the planning and scheduling in your company?

Generally, all the three companies have three type of scheduling process; Time Scheduling, Duty scheduling, and ROTA (crew rostering). First, is to do the time scheduling. It will show the running time of buses in particular route. The time will be different, depends on weekday, night or weekend. It will use for tender. On the tender, it is very rough schedule. After that, the duty schedule will be constructed, and with the ROTA as well. ROTA is a roster of names showing the order in which people should perform certain duties. They are different types of rota: light terms, early term, middle term, spread out terms. After the time schedule, duty schedule and ROTA is done then they will send to garage for the comments from trade union, management, road manager, controller/inspector. Then it will be modify, maybe small factors, then fix up. The schedule will be mandate. The schedule will not last for 5 years. It will be amended as it goes. Sometimes the rota or duty schedule needs to be change, because the staffs want to change it. In London, the way they do planning and scheduling is same across all the companies because they inherit the same practices from the parent company.

2) How long it takes for the whole planning and scheduling?

It depends on the route. If the route is operated by the company previously then it will be fast. Otherwise, they have to gather data to determine the times schedule. The route which is high-frequency or vast area, it will takes more time. No specific times given.

3) What tools do you used?

All of the companies used computer software to produce schedule. In Company A, there is a few staff that is comfortable and believes that manual scheduling is still the best. In addition, they are evaluation scheduling software since the current software will no longer supported by the operating system. While in Company B and Company C, the computer software is fully used for developing the schedule and some minor changes is done manually.

4) What are problems you faced in developing the scheduling?

The software is not intelligent enough. According to Company B, one of the example is the system is not able to find the best solution for the driver to travel from garage to relief point because the time is not fixed. Sometimes there is bus travel to that point or sometimes the driver has to take a taxi. Sometimes it takes 10 minutes and sometimes it takes more or less, depends on traffic. Other problem mentioned by Company A is current system is no longer be supported by the current platform by 2006. So the company has to buy new software. Another problem in Company A is paradigm shift. The scheduler has trouble in leaving the current system or the manual system to a new system.

6) How do you deal with the problems?

All the three companies change the schedule manually during the operation stage.

Section B – Bus Crew Scheduling

The questions are about crew scheduling (duty scheduling). How they do the duty scheduling and what are the problems faces by them. The questions, and summarized answers are as follows:

1) Could you please give a brief description on how the crew scheduling in your company?

All company has a same procedure. After the time schedule is constructed, then duty schedule is determined. Duty scheduling is a process of finding an optimum duty to cover the driving task. According to Company A, often what happen is you compiled one route, but it does not always work, sometimes you have to put several routes under one schedules. Small jobs will consist of 20 to 25 duties, average 50 duties, and big one will have 70 to 80 duties. Monday to Friday is bigger schedule while for Saturday to Sunday is smaller schedule. The duty schedule is governed by driving hour rules and agreement with the trade union. They are slightly different rules to different company and sometimes in different garages (though in a same company) also has different rules. The staffs are divided according to certain garages. The duty schedule show the time start at the beginning of the day and end of the day, and the time buses pass the relief point. Relief point is a reasonable time and place, and facilities for the driver. Every route has at least one relief point. They try to make the relief point as nearer to garage as possible. Then the duty is transfer on card. They called it Duty Card. Duty Card is a card that shows all task that the driving task detail for particular day.

2) How long it takes for the crew scheduling?

No exact time. If manual then it will takes longer time than computer.

3) What tools do you used?

All company are using software except in Company A there is a scheduler who still does it manually. According to A, there are five people in charge of scheduling. Some will do it manually, some do manually and put in computer or some will do entirely on computer. Currently, Company A use IMPACS, Company B use TRAPEZE, and Company C use CAP-GEMINI.

4) What are problems you faced in developing the scheduling?

As mentioned in answer number four in Section A above.

Section C – Operations Problem

The questions are about operational problem in everyday operation and how they deal with them. The questions, and summarized answers are as follows:

1) What are/types of problems you faced in implementing the scheduling?

There are varies problem. The problems are from staff, traffic and vehicle. Traffic is the most problematic. No one can predict and control. According to Company C, Friday is the most unpredictable day. It is because Friday is the last day working day. People might want to enjoy or organise a gathering or even a marching. Sometimes a road might be closed due to security alert, demonstration or accident. Motorist use a bus lane and park near the bus stop also add to traffic problem. Some of the problems with staff are; not coming without notice, sick while in duty and comes late. Vehicle is the least problem. Vehicle breakdown either on the road or in the garage are the cause of delay.

2) How do you deal with the problems?

The problem will be solved manually at the garage. Supervisor is a person in charge in handling the entire problem. Everyone agree that there is not absolute solution for traffics problem. The bus will be late and not according to schedule. It is why the times scheduling will take account the recovery time if something happened. It will be solved case by case. For example, if there is a route closed due to accident or etc. then the driver has to re-route the way. If a staff problem comes late for a duty, then the duty will be given to somebody else by pushing up the schedule, until the driver come. If a driver not comes, then give the duty to spare drivers that standby at certain times at the garage. Company A has a policy that the numbers of spare drivers at least 20% from the whole staff. Other company not mention any figure. If the driver sick on duty which is happened very often (according to company A), they have to change driver at the depot or relief point or nearest stop. Put the spare driver on the bus, and changeover. If a bus has a problem then substitutes with other bus. In Company A the policy is at least 20% percent spare buses from the whole buses. Other company not mention any figure.

3) Do you need to do the re-scheduling?

Yes and it is done manually.

4) What are the costs in handling the problems?

No exact figures.

5) Are the crews satisfied with the solution?

It is very hard to quantify the satisfaction.

Section D – The Improvements in Scheduling Packages

The questions in this section are concerning their satisfaction and improvement that they may suggest. The questions, and summarized answers are as follows:

1) Are you satisfied with your scheduling package?

Most of them are not satisfied with the scheduling package. There is a scheduler in Company A that still feel human scheduler is the best. According to him there is no computer system can compiled better than human being. Once the bus company in London had evaluated 60 software packages but none of them satisfy them. However, he agree that with the computer system, it will save 2/3 of the staff..

2) What are your suggestions to improve the scheduling package?

Company A want the scheduling package to be dynamic so that it will help in re-scheduling. Company B want the system to be simple and then can be modified manually. Company C feels that it is good if the scheduling package is dynamic.

3) Could your scheduling package re-schedule when the problems arise?

All of the scheduling package can do re-scheduling, but completely new schedule.

4) How about dynamic scheduling? Where the re-schedule is done without disrupting the whole schedule, only 'local' schedule.

Everyone agree that it is a good idea to have a dynamic schedule that able to re-schedule only the disruption day or week.

Appendix C: Large Schedule

Crew ID	Duty No Assigned	Sign On	Start Work 1	End Work 1	Start Relief	End Relief	Start Work 2	End Work 2	Sign Off
A	51	03:34:00	03:49:00	08:10:00	08:15:00	09:00:00	09:05:00	11:02:00	11:07:00
B	52	03:43:00	03:58:00	08:16:00	08:21:00	09:30:00	09:35:00	11:34:00	11:53:00
C	53	03:53:00	04:08:00	08:52:00	08:57:00	09:51:00	09:56:00	11:58:00	12:17:00
D	54	04:03:00	04:18:00	08:52:00	08:57:00	10:03:00	10:08:00	12:10:00	12:41:00
E	55	04:13:00	04:28:00	09:09:00	09:14:00	10:15:00	10:20:00	12:22:00	12:41:00
F	56	04:23:00	04:38:00	09:22:00	09:27:00	10:27:00	10:32:00	12:34:00	12:53:00
G	57	04:33:00	04:48:00	09:58:00	10:03:00	11:03:00	11:08:00	13:10:00	13:35:00
H	58	04:41:00	04:56:00	10:10:00	10:15:00	11:09:00	11:14:00	13:16:00	13:35:00
I	59	04:48:00	05:03:00	08:26:00	08:31:00	09:24:00	09:29:00	13:02:00	13:21:00
J	60	04:56:00	05:11:00	10:40:00	10:45:00	11:35:00	11:40:00	13:14:00	13:35:00
K	61	05:03:00	05:18:00	10:46:00	10:51:00	11:53:00	11:58:00	13:32:00	13:53:00
L	62	05:11:00	05:26:00	08:53:00	08:58:00	09:53:00	09:58:00	13:34:00	13:53:00
M	63	05:18:00	05:33:00	09:05:00	09:10:00	10:05:00	10:10:00	13:46:00	14:05:00
N	64	05:30:00	05:45:00	09:29:00	09:34:00	10:35:00	10:40:00	14:16:00	14:35:00
O	65	05:47:00	06:02:00	09:56:00	10:01:00	10:57:00	11:02:00	14:38:00	15:05:00
P	66	05:55:00	06:10:00	11:10:00	11:15:00	12:05:00	12:10:00	13:44:00	14:05:00
Q	67	05:56:00	06:11:00	10:08:00	10:13:00	11:05:00	11:10:00	14:46:00	15:05:00
R	68	05:59:00	06:14:00	10:20:00	10:25:00	11:17:00	11:22:00	14:58:00	15:17:00
S	69	06:00:00	06:15:00	11:22:00	11:27:00	12:17:00	12:22:00	13:56:00	14:23:00
T	70	06:05:00	06:20:00	10:32:00	10:37:00	13:17:00	13:22:00	14:56:00	15:17:00
U	71	06:09:00	06:24:00	10:38:00	10:43:00	11:33:00	11:38:00	13:40:00	14:05:00
V	72	06:10:00	06:25:00	09:35:00	09:40:00	10:33:00	10:38:00	14:14:00	14:35:00
W	73	06:13:00	06:28:00	10:50:00	10:55:00	11:47:00	11:52:00	13:26:00	13:53:00
X	74	06:15:00	06:30:00	11:02:00	11:07:00	11:57:00	12:02:00	14:04:00	14:23:00
Y	75	06:17:00	06:32:00	11:08:00	11:13:00	12:03:00	12:08:00	14:10:00	14:35:00
Z	76	06:20:00	06:35:00	11:14:00	11:19:00	12:11:00	12:16:00	13:50:00	14:23:00
AA	77	06:25:00	06:40:00	11:52:00	11:57:00	12:47:00	12:52:00	14:26:00	14:45:00
AB	78	06:26:00	06:41:00	11:26:00	11:31:00	12:33:00	12:38:00	14:40:00	15:05:00
AC	79	06:35:00	06:50:00	11:38:00	11:43:00	12:41:00	12:46:00	14:20:00	14:45:00
AD	80	06:42:00	06:57:00	11:50:00	11:55:00	13:03:00	13:08:00	15:10:00	15:45:00
AE	81	06:46:00	07:01:00	11:56:00	12:01:00	13:15:00	13:20:00	15:21:00	15:45:00
AF	82	06:57:00	07:12:00	12:08:00	12:13:00	13:47:00	13:52:00	15:26:00	15:45:00
AG	83	07:14:00	07:29:00	12:26:00	12:31:00	13:27:00	13:32:00	15:32:00	16:09:00
AH	84	07:20:00	07:35:00	12:38:00	12:43:00	13:45:00	13:50:00	15:50:00	16:09:00
AI	85	08:36:00	08:51:00	12:16:00	12:21:00	15:16:00	15:21:00	19:56:00	20:01:00
AJ	86	10:26:00	10:41:00	12:52:00	12:57:00	14:05:00	14:10:00	19:01:00	19:06:00
AK	87	10:56:00	11:11:00	13:22:00	13:27:00	14:35:00	14:40:00	19:28:00	19:33:00
AL	88	10:56:00	11:11:00	15:02:00	15:07:00	16:09:00	16:14:00	19:39:00	19:44:00
AM	89	11:26:00	11:41:00	13:58:00	14:03:00	15:05:00	15:10:00	19:53:00	19:58:00
AN	90	11:26:00	11:41:00	13:52:00	13:57:00	14:57:00	15:02:00	20:28:00	20:33:00
AO	91	11:56:00	12:11:00	14:28:00	14:33:00	15:27:00	15:32:00	20:05:00	20:10:00
AP	92	11:56:00	12:11:00	14:22:00	14:27:00	15:21:00	15:26:00	20:43:00	20:48:00
AQ	93	12:04:00	12:19:00	16:14:00	16:19:00	17:16:00	17:21:00	20:15:00	20:20:00
AR	94	12:04:00	12:19:00	17:45:00	17:50:00	18:50:00	18:55:00	21:29:00	21:34:00
AS	95	12:26:00	12:41:00	16:27:00	16:32:00	17:40:00	17:45:00	20:36:00	20:41:00
AT	96	12:26:00	12:41:00	16:38:00	16:43:00	17:33:00	17:38:00	21:41:00	21:46:00

AU	97	12:38:00	12:53:00	16:39:00	16:44:00	17:39:00	17:44:00	21:46:00	21:51:00
AV	98	12:46:00	13:01:00	18:27:00	18:32:00	19:24:00	19:29:00	21:57:00	22:02:00
AW	99	12:46:00	13:01:00	16:56:00	17:01:00	18:03:00	18:08:00	22:03:00	22:08:00
AX	100	13:02:00	13:17:00	17:03:00	17:08:00	18:04:00	18:09:00	20:52:00	20:57:00
AY	101	13:20:00	13:35:00	17:21:00	17:26:00	18:16:00	18:21:00	21:03:00	21:08:00
AZ	102	13:20:00	13:35:00	17:26:00	17:31:00	18:22:00	18:27:00	21:09:00	21:14:00
BA	103	13:34:00	13:49:00	17:38:00	17:43:00	18:34:00	18:39:00	21:20:00	21:25:00
BB	104	13:44:00	13:59:00	17:33:00	17:38:00	18:32:00	18:37:00	22:27:00	22:32:00
BC	105	15:26:00	15:41:00	20:36:00	20:41:00	21:49:00	21:54:00	00:04:00	00:09:00
BD	106	15:26:00	15:41:00	17:39:00	17:44:00	18:38:00	18:43:00	00:04:00	00:09:00
BE	107	15:57:00	16:12:00	21:24:00	21:29:00	22:21:00	22:26:00	00:32:00	00:37:00
BF	108	15:57:00	16:12:00	19:52:00	19:57:00	21:02:00	21:07:00	00:47:00	00:52:00
BG	109	15:57:00	16:12:00	21:07:00	21:12:00	22:09:00	22:14:00	01:12:00	01:17:00
BH	110	16:08:00	16:23:00	18:09:00	18:14:00	19:07:00	19:12:00	00:19:00	00:24:00
BI	111	16:08:00	16:23:00	18:43:00	18:48:00	19:47:00	19:52:00	00:48:00	00:53:00
BJ	112	16:08:00	16:23:00	21:15:00	21:20:00	22:17:00	22:22:00	01:20:00	01:25:00
BK	113	16:27:00	16:42:00	20:12:00	20:17:00	21:19:00	21:24:00	00:40:00	00:45:00
BL	114	16:27:00	16:42:00	20:20:00	20:25:00	21:25:00	21:30:00	01:03:00	01:08:00
BM	115	16:27:00	16:42:00	21:30:00	21:35:00	22:25:00	22:30:00	01:34:00	01:39:00
BN	116	16:51:00	17:06:00	19:12:00	19:17:00	20:07:00	20:12:00	00:56:00	01:01:00
BO	117	16:51:00	17:06:00	18:55:00	19:00:00	20:15:00	20:20:00	01:04:00	01:09:00
BP	118	17:09:00	17:24:00	20:44:00	20:49:00	21:41:00	21:46:00	01:19:00	01:24:00
BQ	119	17:09:00	17:24:00	20:52:00	20:57:00	22:05:00	22:10:00	01:35:00	01:40:00
BR	120	17:33:00	17:48:00	19:47:00	19:52:00	21:10:00	21:15:00	01:49:00	01:54:00
BS	131	07:32:00	07:47:00	12:50:00	12:55:00	13:51:00	13:56:00	16:02:00	16:11:00
BT	132	07:33:00	07:48:00	11:20:00	11:25:00	12:27:00	12:32:00	14:34:00	14:43:00
BU	133	07:56:00	08:11:00	11:40:00	11:45:00	13:09:00	13:14:00	16:51:00	17:00:00
BV	134	08:02:00	08:17:00	13:20:00	13:25:00	14:21:00	14:26:00	16:32:00	16:41:00
BW	135	08:12:00	08:27:00	12:02:00	12:07:00	13:33:00	13:38:00	17:15:00	17:24:00
BX	136	08:20:00	08:35:00	13:38:00	13:43:00	14:41:00	14:46:00	16:21:00	16:30:00
BY	137	08:38:00	08:53:00	12:28:00	12:33:00	14:09:00	14:14:00	17:57:00	18:06:00
BZ	138	08:39:00	08:54:00	12:32:00	12:37:00	13:35:00	13:40:00	17:20:00	17:29:00
CA	139	08:55:00	09:10:00	12:46:00	12:51:00	14:23:00	14:28:00	18:08:00	18:17:00
CB	140	09:08:00	09:23:00	12:58:00	13:03:00	14:53:00	14:58:00	18:37:00	18:46:00
CC	141	10:32:00	10:47:00	12:20:00	12:25:00	13:29:00	13:34:00	18:49:00	18:58:00
CD	142	13:50:00	14:05:00	17:44:00	17:49:00	18:44:00	18:49:00	21:46:00	21:55:00
CE	143	14:02:00	14:17:00	19:23:00	19:28:00	20:31:00	20:36:00	22:14:00	22:23:00
CF	144	14:06:00	14:21:00	16:26:00	16:31:00	17:21:00	17:26:00	21:54:00	22:03:00
CG	145	14:08:00	14:23:00	19:29:00	19:34:00	20:39:00	20:44:00	22:22:00	22:31:00
CH	146	14:20:00	14:35:00	19:40:00	19:45:00	20:47:00	20:52:00	22:30:00	22:39:00
CI	147	14:24:00	14:39:00	18:21:00	18:26:00	19:18:00	19:23:00	22:10:00	22:19:00
CJ	148	14:42:00	14:57:00	18:39:00	18:44:00	19:35:00	19:40:00	22:26:00	22:35:00

Appendix D: Medium Schedule

Crew ID	Duty No Assigned	Sign On	Start Work 1	End Work 1	Start Relief	End Relief	Start Work 2	End Work 2	Sign Off
A	201	04:40:00	04:55:00	9:43:00	9:48:00	10:38:00	10:43:00	12:03:00	12:40:00
B	202	04:42:00	04:57:00	9:46:00	9:51:00	10:43:00	10:48:00	12:13:00	12:49:00
C	203	04:55:00	05:10:00	9:33:00	9:38:00	10:23:00	10:28:00	11:48:00	12:25:00
D	204	04:59:00	05:14:00	10:41:00	0:00:00	0:00:00	0:05:00	0:00:00	10:51:00
E	205	05:00:00	05:15:00	10:13:00	0:00:00	0:00:00	0:05:00	0:00:00	10:49:00
F	206	05:02:00	05:17:00	10:06:00	0:00:00	0:00:00	0:05:00	0:00:00	10:43:00
G	207	05:15:00	05:30:00	10:03:00	10:08:00	11:13:00	11:18:00	14:03:00	14:40:00
H	208	05:19:00	05:34:00	10:16:00	10:21:00	11:43:00	11:48:00	13:13:00	13:49:00
I	209	05:20:00	05:35:00	10:28:00	10:33:00	11:58:00	12:03:00	13:28:00	14:04:00
J	210	05:22:00	05:37:00	10:46:00	10:51:00	12:13:00	12:18:00	13:43:00	14:19:00
K	211	05:35:00	05:50:00	10:18:00	10:23:00	11:21:00	11:26:00	14:06:00	14:43:00
L	212	05:39:00	05:54:00	10:56:00	11:01:00	12:01:00	12:06:00	13:56:00	14:33:00
M	213	05:50:00	06:05:00	10:48:00	10:53:00	12:08:00	12:13:00	14:57:00	15:33:00
N	214	05:57:00	06:12:00	11:13:00	11:18:00	14:30:00	14:35:00	16:55:00	17:05:00
O	215	06:14:00	06:29:00	11:18:00	11:23:00	14:30:00	14:35:00	17:00:00	17:10:00
P	216	06:13:00	06:28:00	11:26:00	11:31:00	14:35:00	14:40:00	16:10:00	16:20:00
Q	217	06:25:00	06:40:00	11:58:00	12:03:00	13:08:00	13:13:00	15:51:00	16:28:00
R	218	06:37:00	06:52:00	12:16:00	12:21:00	14:30:00	14:35:00	16:10:00	16:20:00
S	219	06:44:00	06:59:00	12:06:00	12:11:00	14:40:00	14:45:00	16:37:00	16:47:00
T	220	06:45:00	07:00:00	10:43:00	10:48:00	12:43:00	12:48:00	16:52:00	17:29:00
U	221	07:00:00	07:15:00	9:01:00	9:06:00	10:51:00	10:56:00	16:18:00	16:56:00
V	222	07:05:00	07:20:00	8:46:00	8:51:00	10:11:00	10:16:00	15:38:00	16:16:00
W	223	07:07:00	07:22:00	8:49:00	8:54:00	10:13:00	10:18:00	15:46:00	16:24:00
X	224	07:10:00	07:25:00	8:45:00	8:50:00	10:08:00	10:13:00	15:36:00	16:13:00
Y	225	07:10:00	07:25:00	8:53:00	8:58:00	11:08:00	11:13:00	16:37:00	17:14:00
Z	226	09:18:00	09:33:00	12:18:00	12:23:00	13:43:00	13:48:00	17:52:00	18:29:00
AA	227	09:31:00	09:46:00	14:16:00	14:21:00	15:41:00	15:46:00	18:29:00	19:07:00
AB	228	09:28:00	09:43:00	13:48:00	13:53:00	15:31:00	15:36:00	18:26:00	19:03:00
AC	229	09:48:00	10:03:00	12:48:00	12:53:00	13:58:00	14:03:00	18:09:00	18:46:00
AD	230	09:51:00	10:06:00	12:46:00	12:51:00	14:38:00	14:43:00	18:44:00	19:22:00
AE	231	10:31:00	10:46:00	13:26:00	13:31:00	14:52:00	14:57:00	19:55:00	20:05:00
AF	232	11:43:00	11:58:00	13:18:00	13:23:00	14:01:00	14:06:00	18:55:00	19:33:00
AG	233	12:01:00	12:16:00	14:56:00	15:01:00	15:46:00	15:51:00	20:39:00	20:49:00
AH	234	12:31:00	12:46:00	14:36:00	14:41:00	15:38:00	15:43:00	19:56:00	20:06:00
AI	235	13:03:00	13:18:00	14:43:00	14:48:00	15:33:00	15:38:00	20:33:00	20:43:00
AJ	236	13:11:00	13:26:00	18:49:00	18:54:00	19:52:00	19:57:00	22:12:00	22:22:00
AK	237	13:13:00	13:28:00	17:29:00	17:34:00	18:24:00	18:29:00	21:33:00	21:43:00
AL	238	13:28:00	13:43:00	17:44:00	17:49:00	18:39:00	18:44:00	20:55:00	21:05:00
AM	239	13:41:00	13:56:00	16:38:00	16:43:00	17:24:00	17:29:00	20:51:00	21:01:00
AN	240	14:01:00	14:16:00	16:58:00	17:03:00	17:47:00	17:52:00	22:03:00	22:13:00
AO	241	14:21:00	14:36:00	15:43:00	15:48:00	16:32:00	16:37:00	21:18:00	21:28:00
AP	242	14:41:00	14:56:00	17:58:00	18:03:00	18:50:00	18:55:00	21:45:00	21:55:00
AQ	243	14:20:00	14:35:00	17:18:00	17:23:00	18:21:00	18:26:00	22:33:00	22:43:00
AR	244	16:03:00	16:18:00	19:40:00	19:45:00	20:22:00	20:27:00	0:42:00	0:52:00
AS	245	16:23:00	16:38:00	19:59:00	20:04:00	20:52:00	20:57:00	0:54:00	1:04:00

AT	246	16:37:00	16:52:00	19:16:00	19:21:00	20:35:00	20:40:00	1:03:00	1:13:00
AU	247	16:43:00	16:58:00	20:25:00	20:30:00	21:35:00	21:40:00	1:07:00	1:17:00
AV	248	17:03:00	17:18:00	20:38:00	20:43:00	21:22:00	21:27:00	0:47:00	0:57:00
AW	249	17:29:00	17:44:00	21:04:00	21:09:00	22:05:00	22:10:00	1:37:00	1:47:00
AX	250	17:43:00	17:58:00	21:05:00	21:10:00	21:52:00	21:57:00	1:17:00	1:27:00
AY	251	17:54:00	18:09:00	20:22:00	20:27:00	21:05:00	21:10:00	1:33:00	1:43:00

Appendix E: Small Schedule

Crew ID	Duty No Assigned	Sign On	Start Work 1	End Work 1	Start Relief	End Relief	Start Work 2	End Work 2	Sign Off
A	568	4:56:00	5:11:00	10:01:00	10:06:00	10:47:00	10:52:00	12:38:00	12:48:00
B	569	5:00:00	5:15:00	9:15:00	9:20:00	10:06:00	10:11:00	12:01:00	12:11:00
C	570	5:26:00	5:41:00	8:43:00	8:48:00	9:47:00	9:52:00	13:38:00	13:48:00
D	571	6:56:00	7:11:00	9:54:00	9:59:00	11:07:00	11:12:00	14:58:00	15:08:00
E	572	7:27:00	7:42:00	10:58:00	11:03:00	12:07:00	12:12:00	15:58:00	16:08:00
F	573	8:17:00	8:32:00	11:58:00	12:03:00	12:47:00	12:52:00	16:38:00	16:48:00
G	574	8:21:00	8:36:00	11:31:00	11:36:00	12:27:00	12:32:00	16:18:00	16:28:00
H	575	8:26:00	8:41:00	12:31:00	12:36:00	13:27:00	13:32:00	17:18:00	17:28:00
I	576	8:56:00	9:11:00	13:01:00	13:06:00	13:47:00	13:52:00	17:38:00	17:48:00
J	577	11:26:00	11:41:00	15:31:00	15:36:00	16:36:00	16:41:00	20:13:00	20:23:00
K	578	11:56:00	12:11:00	16:01:00	16:06:00	16:47:00	16:52:00	20:10:00	20:20:00
L	579	12:26:00	12:41:00	16:31:00	16:36:00	17:27:00	17:32:00	20:50:00	21:00:00
M	580	12:56:00	13:11:00	17:01:00	17:06:00	18:07:00	18:12:00	21:30:00	21:40:00
N	581	14:57:00	15:12:00	18:50:00	18:55:00	19:36:00	19:41:00	0:12:00	0:22:00
O	582	15:26:00	15:41:00	19:20:00	19:25:00	20:06:00	20:11:00	0:42:00	0:52:00
P	583	15:56:00	16:11:00	19:45:00	19:50:00	20:47:00	20:52:00	1:15:00	1:25:00
Q	584	15:57:00	16:12:00	17:58:00	18:03:00	19:06:00	19:11:00	0:37:00	0:47:00
R	585	16:17:00	16:32:00	18:17:00	18:22:00	19:27:00	19:32:00	0:30:00	0:40:00
S	586	16:56:00	17:11:00	18:58:00	19:03:00	20:07:00	20:12:00	1:10:00	1:20:00
T	587	17:37:00	17:52:00	19:30:00	19:35:00	20:27:00	20:32:00	0:55:00	1:05:00
U	588	18:37:00	18:52:00	20:30:00	20:35:00	21:27:00	21:32:00	0:50:00	1:00:00
V	589	6:57:00	7:12:00	12:18:00	12:23:00	0:00:00	0:00:00	0:00:00	12:28:00
W	590	8:16:00	8:31:00	13:18:00	13:23:00	0:00:00	0:00:00	0:00:00	13:28:00

Appendix F: Single Event Experiments

Table F.1: LFSO (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	06:20:00	1.873	1	S, V	0	2
20	06:25:00	1.912	1	S, V	0	2
25	06:30:00	3.756	2	S, V, Z	0	3
30	06:35:00	1.943	1	S, V, Z	0	3
35	06:40:00	3.866	2	S, V,Z,AB	0	4
40	06:45:00	3.764	2	S, V,Z,AB,AC	0	5
45	06:50:00	1.982	1	S, V,Z,AB,AC	0	5
50	06:55:00	3.655	2	S, V,Z,AB,AC,AD	0	6
55	07:00:00	3.806	2	S, V,Z,AB,AC,AD, AE	0	7
60	07:05:00	5.544	3	S, V,Z,AB,AC,AD, AE, AF	1	8

Table F.2: LFSO (Large)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	05:23:00	1.973	1	K, L	0	2
20	05:28:00	3.936	2	K, L, M	0	3
25	05:33:00	2.023	1	K, L, M	0	3
30	05:38:00	5.827	3	K, L, M, N	2	4
35	05:43:00	1.973	1	K, L, M, N	0	4
40	05:48:00	5.609	3	K, L, M, N, O	7	5
45	05:53:00	1.923	1	K, L, M, N, O	0	5
50	05:58:00	1.943	1	K, L, M, N, O	0	5
55	06:03:00	3.786	2	K, L, M, N, O, Q	0	6
60	06:08:00	1.923	1	K, L, M, N, O, Q	0	6

Table F.3: LFSO (Large)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	09:28:00	-	-	No Match	-	-
20	09:33:00	-	-	No Match	-	-
25	09:38:00	-	-	No Match	-	-
30	09:43:00	-	-	No Match	-	-
35	09:48:00	-	-	No Match	-	-
40	09:53:00	-	-	No Match	-	-
45	09:58:00	-	-	No Match	-	-
50	10:03:00	-	-	No Match	-	-
55	10:08:00	-	-	No Match	-	-
60	10:13:00	-	-	No Match	-	-

Table F.4: LFSO (Medium)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	05:20:00	2.384	2	E, F, G	3	3
20	05:25:00	1.292	1	E, F, G, J	3	4
25	05:30:00	1.312	1	E, F, G, J	3	4
30	05:35:00	1.202	1	E, F, G, J	3	4
35	05:40:00	2.354	2	E, F, G, J, K	6	5
40	05:45:00	1.12	1	E, F, G, J, K, L	6	6
45	05:50:00	1.12	1	E, F, G, J, K, L	6	6
50	05:55:00	2.263	2	E, F, G, J, K, L, M	7	7
55	06:00:00	1.252	1	E, F, G, J, K, L, M, N	7	8
60	06:05:00	1.142	1	E, F, G, J, K, L, M, N	7	8

Table F.5: LFSO (Medium)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	06:34:00	2.334	2	O, Q	1	2
20	06:39:00	1.262	1	O, Q	1	2
25	06:44:00	2.242	2	O, Q, R	3	3
30	06:49:00	1.101	1	O, Q, R, T	3	4
35	06:54:00	1.121	1	O, Q, R, T	3	4
40	06:59:00	1.181	1	O, Q, R, T	3	4
45	07:04:00	2.202	2	O, Q, R, T, U, X	3	6
50	07:09:00	1.172	1	O, Q, R, T, U, X	3	6
55	07:14:00	1.212	1	O, Q, R, T, U, X	3	6
60	07:19:00	1.112	1	O, Q, R, T, U, X	3	6

Table F.6: LFSO (Medium)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	10:51:00	-	-	No Match	-	-
20	10:56:00	-	-	No Match	-	-
25	11:01:00	-	-	No Match	-	-
30	11:06:00	-	-	No Match	-	-
35	11:11:00	-	-	No Match	-	-
40	11:16:00	-	-	No Match	-	-
45	11:21:00	-	-	No Match	-	-
50	11:26:00	-	-	No Match	-	-
55	11:31:00	-	-	No Match	-	-
60	11:36:00	-	-	No Match	-	-

Table F.7: LFSO (Small)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	08:37:00	0.681	2	F, H	0	2
20	08:42:00	1.151	1	F, H	1	2
25	08:47:00	1.222	2	F, H, I	21	3
30	08:52:00	0.6	1	F, H, I	21	3
35	08:57:00	0.601	1	F, H, I	21	3
40	09:02:00	0.601	1	F, H, I	21	3
45	09:07:00	0.601	2	F, H, I	21	3
50	09:12:00	-	-	No Match	-	-
55	09:17:00	-	-	No Match	-	-
60	09:22:00	-	-	No Match	-	-

Table F.8: LFSO (Small)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	15:46:00	-	-	No Match	-	-
20	15:51:00	-	-	No Match	-	-
25	15:56:00	-	-	No Match	-	-
30	16:01:00	-	-	No Match	-	-
35	16:06:00	-	-	No Match	-	-
40	16:11:00	-	-	No Match	-	-
45	16:16:00	-	-	No Match	-	-
50	16:21:00	-	-	No Match	-	-
55	16:26:00	-	-	No Match	-	-
60	16:31:00	-	-	No Match	-	-

Table F.9: LFSO (Small)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	05:16:00	-	-	No Match	-	-
20	05:21:00	-	-	No Match	-	-
25	05:26:00	-	-	No Match	-	-
30	05:31:00	-	-	No Match	-	-
35	05:36:00	-	-	No Match	-	-
40	05:41:00	-	-	No Match	-	-
45	05:46:00	-	-	No Match	-	-
50	05:51:00	-	-	No Match	-	-
55	05:56:00	-	-	No Match	-	-
60	06:01:00	-	-	No Match	-	-

Table F.10: LFR (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	12:12:00	1.873	1	X, T	0	2
20	12:17:00	2.123	1	X, T	0	2
25	12:22:00	1.963	1	X, T	0	2
30	12:27:00	1.963	1	X, T	0	2
35	12:32:00	1.933	1	X, T	0	2
40	12:37:00	1.963	1	X, T	0	2
45	12:42:00	1.903	1	X, T	0	2
50	12:47:00	1.862	1	X, T	0	2
55	12:52:00	1.983	1	X, T	0	2
60	12:57:00	1.843	1	X, T	0	2

Table F.11: LFR (Large)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	10:15:00	1.923	1	M, E	0	2
20	10:20:00	1.973	1	M, E	0	2
25	10:25:00	3.966	2	M, E, F	0	3
30	10:30:00	1.972	1	M, E, F	0	3
35	10:35:00	1.913	1	M, E, N	0	3
40	10:40:00	1.993	1	M, E, N	0	3
45	10:45:00	3.826	2	M, E, N, O	11	4
50	10:50:00	1.913	1	M, E, N, O	11	4
55	10:55:00	1.943	1	M, E, N, O	11	4
60	11:00:00	1.973	1	M, E, N, O	11	4

Table F.12: LFR (Large)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	16:12:00	-	-	No Need	-	-
20	16:17:00	-	-	No Match	-	-
25	16:22:00	-	-	No Match	-	-
30	16:27:00	-	-	No Match	-	-
35	16:32:00	-	-	No Match	-	-
40	16:37:00	-	-	No Match	-	-
45	16:42:00	-	-	No Match	-	-
50	16:47:00	-	-	No Match	-	-
55	16:52:00	-	-	No Match	-	-
60	16:57:00	-	-	No Match	-	-

Table F.13: LFR (Medium)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	11:23:00	1.212	1	G, K	0	2
20	11:28:00	1.202	1	G, H	0	2
25	11:33:00	1.142	1	G, H	0	2
30	11:38:00	1.262	1	G, H	0	2
35	11:43:00	1.122	1	G, H	0	2
40	11:48:00	1.191	1	G, H	0	2
45	11:53:00	1.171	1	G, I	0	2
50	11:58:00	1.122	1	G, I	0	2
55	12:03:00	1.081	1	G, I	0	2
60	12:08:00	2.354	2	G, I, M	0	3

Table F.14: LFR (Medium)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	13:16:00	-	-	No Need Rescheduling	-	-
20	13:21:00	-	-	No Need Rescheduling	-	-
25	13:26:00	-	-	No Need Rescheduling	-	-
30	13:31:00	-	-	No Need Rescheduling	-	-
35	13:36:00	-	-	No Need Rescheduling	-	-
40	13:41:00	-	-	No Need Rescheduling	-	-
45	13:46:00	-	-	No Need Rescheduling	-	-
50	13:51:00	-	-	No Need Rescheduling	-	-
55	13:56:00	-	-	No Need Rescheduling	-	-
60	14:01:00	-	-	No Need Rescheduling	-	-

Table F.15: LFR (Medium)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	16:53:00	-	-	No Match	-	-
20	16:58:00	-	-	No Match	-	-
25	17:03:00	-	-	No Match	-	-
30	17:08:00	-	-	No Match	-	-
35	17:13:00	-	-	No Match	-	-
40	17:18:00	-	-	No Match	-	-
45	17:23:00	-	-	No Match	-	-
50	17:28:00	-	-	No Match	-	-
55	17:33:00	-	-	No Match	-	-
60	17:38:00	-	-	No Match	-	-

Table F.16: LFR (Small)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	19:27:00	-	-	No Need Rescheduling	-	-
20	19:32:00	-	-	No Need Rescheduling	-	-
25	19:37:00	1.192	2	R, N	9	2
30	19:42:00	1.141	2	R, N	10	2
35	19:47:00	0.651	1	R, N, O	10	3
40	19:52:00	0.671	1	R, N, O	10	3
45	19:57:00	0.601	1	R, N, O	10	3
50	20:02:00	0.621	1	R, N, O	10	3
55	20:07:00	0.631	1	R, N, O	10	3
60	20:12:00	0.681	1	R, N, O, S	10	4

Table F.17: LFR (Small)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	10:25:00	-	-	No Match	-	-
20	10:30:00	-	-	No Match	-	-
25	10:35:00	-	-	No Match	-	-
30	10:40:00	-	-	No Match	-	-
35	10:45:00	-	-	No Match	-	-
40	10:50:00	-	-	No Match	-	-
45	10:55:00	-	-	No Match	-	-
50	11:00:00	-	-	No Match	-	-
55	11:05:00	-	-	No Match	-	-
60	11:10:00	-	-	No Match	-	-

Table F.18: LFR (Small)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	09:53:00	-	-	No Match	-	-
20	09:58:00	-	-	No Match	-	-
25	10:03:00	-	-	No Match	-	-
30	10:08:00	-	-	No Match	-	-
35	10:13:00	-	-	No Match	-	-
40	10:18:00	-	-	No Match	-	-
45	10:23:00	-	-	No Match	-	-
50	10:28:00	-	-	No Match	-	-
55	10:33:00	-	-	No Match	-	-
60	10:38:00	-	-	No Match	-	-

Table F.19: LFSW (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	13:23:00	1.903	1	AD, BW	0	2
20	13:28:00	1.872	1	AD, BW	0	2
25	13:33:00	1.923	1	AD, BW	0	2
30	13:38:00	1.973	1	AD, BW	0	2
35	13:43:00	1.993	1	AD, AF	0	2
40	13:48:00	1.923	1	AD, AF	0	2
45	13:53:00	1.882	1	AD, AI	0	2
50	13:58:00	1.882	1	AD, AI	0	2
55	14:03:00	1.923	1	AD, AI	0	2
60	14:08:00	1.993	1	AD, AI	0	2

Table F.20: LFSW (Large)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	21:22:00	1.713	1	BF, BK	0	2
20	21:27:00	3.444	2	BF, BK, BL	0	3
25	21:32:00	3.524	2	BF, BK, BL, BC	0	4
30	21:37:00	1.763	1	BF, BK, BL, BC	0	4
35	21:42:00	1.782	1	BF, BK, BL, BC	0	4
40	21:47:00	1.753	1	BF, BK, BL, BC	0	4
45	21:52:00	1.792	1	BF, BK, BL, BC	0	4
50	21:57:00	3.365	2	BF, BK, BL, BC, BQ	0	5
55	22:02:00	1.713	1	BF, BK, BL, BC, BQ	0	5
60	22:07:00	1.722	1	BF, BK, BL, BC, BQ	0	5

Table F.21: LFSW (Large)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	16:29:00	-	-	No Match	-	-
20	16:34:00	-	-	No Match	-	-
25	16:39:00	-	-	No Match	-	-
30	16:44:00	-	-	No Match	-	-
35	16:49:00	-	-	No Match	-	-
40	16:54:00	-	-	No Match	-	-
45	16:59:00	-	-	No Match	-	-
50	17:04:00	-	-	No Match	-	-
55	17:09:00	-	-	No Match	-	-
60	17:14:00	-	-	No Match	-	-

Table F.22: LFSW (Medium)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	14:21:00	1.252	1	AF, R	0	2
20	14:26:00	1.231	1	AF, R	0	2
25	14:31:00	1.202	1	AF, R	0	2
30	14:36:00	1.232	1	AF, P	0	2
35	14:41:00	1.162	1	AF, AD	0	2
40	14:46:00	2.333	2	AF, AD, AE	0	3
45	14:51:00	1.151	1	AF, AD, AE	0	3
50	14:56:00	1.192	1	AF, AD, AE	0	3
55	15:01:00	1.161	1	AF, AD, AB	0	3
60	15:06:00	1.172	1	AF, AD, AB	0	3

Table F.23: LFSW (Medium)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	11:28:00	1.171	1	Y, H	0	2
20	11:33:00	1.132	1	Y, H	0	2
25	11:38:00	1.231	1	Y, H	0	2
30	11:43:00	1.122	1	Y, H	0	2
35	11:48:00	1.162	1	Y, H	0	2
40	11:53:00	2.313	2	Y, H, I	0	3
45	11:58:00	1.201	1	Y, H, I	0	3
50	12:03:00	1.232	1	Y, H, I	0	3
55	12:08:00	1.182	1	Y, H, M	0	3
60	12:13:00	1.201	1	Y, H, M	0	3

Table F.24: LFSW (Medium)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	16:52:00	-	-	No Match	-	-
20	16:57:00	-	-	No Match	-	-
25	17:02:00	-	-	No Match	-	-
30	17:07:00	-	-	No Match	-	-
35	17:12:00	-	-	No Match	-	-
40	17:17:00	-	-	No Match	-	-
45	17:22:00	-	-	No Match	-	-
50	17:27:00	-	-	No Match	-	-
55	17:32:00	-	-	No Match	-	-
60	17:37:00	-	-	No Match	-	-

Table F.25: LFSW (Small)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	20:26:00	1.272	2	O, T	15	2
20	20:31:00	0.521	1	O, T	15	2
25	20:36:00	1.062	2	O, T, P	23	3
30	20:41:00	0.6	1	O, T, P	23	3
35	20:46:00	0.53	1	O, T, P	23	3
40	20:51:00	0.611	1	O, T, P	23	3
45	20:56:00	-	-	No Match	-	-
50	21:01:00	-	-	No Match	-	-
55	21:06:00	-	-	No Match	-	-
60	21:11:00	-	-	No Match	-	-

Table F.26: LFSW (Small)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	12:27:00	-	-	No Match	-	-
20	12:32:00	-	-	No Match	-	-
25	12:37:00	-	-	No Match	-	-
30	12:42:00	-	-	No Match	-	-
35	12:47:00	-	-	No Match	-	-
40	12:52:00	-	-	No Match	-	-
45	12:57:00	-	-	No Match	-	-
50	13:02:00	-	-	No Match	-	-
55	13:07:00	-	-	No Match	-	-
60	13:12:00	-	-	No Match	-	-

Table F.27: LFSW (Small)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
15	10:01:00	-	-	No Match	-	-
20	10:06:00	-	-	No Match	-	-
25	10:11:00	-	-	No Match	-	-
30	10:16:00	-	-	No Match	-	-
35	10:21:00	-	-	No Match	-	-
40	10:26:00	-	-	No Match	-	-
45	10:31:00	-	-	No Match	-	-
50	10:36:00	-	-	No Match	-	-
55	10:41:00	-	-	No Match	-	-
60	10:46:00	-	-	No Match	-	-

Table F.28: DFSO (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	07:25:00	1.873	1	S, V,Z,AB,AC,AD, AE, AF, AG	8	9
100	07:45:00	-	-	No Match	-	-
120	08:05:00	-	-	No Match	-	-
140	08:25:00	-	-	No Match	-	-
160	08:45:00	-	-	No Match	-	-
180	09:05:00	-	-	No Match	-	-

Table F.29: DFSO (Large)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	06:28:00	3.665	2	K, L, M, N, O, Q, T, W	9	8
100	06:48:00	3.896	2	K, L, M, N, O, Q, T, W, Z, AB, AC	9	11
120	07:08:00	3.806	2	K, L, M, N, O, Q, T, W, Z, AB, AC, AE, AF	11	13
140	07:28:00	3.796	2	K, L, M, N, O, Q, T, W, Z, AB, AC, AE, AF, AG, AH	18	15
160	07:48:00	-	-	No Match	-	-
180	08:08:00	-	-	No Match	-	-

Table F.30: DFSO (Large)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	10:33:00	-	-	No Match	-	-
100	10:53:00	-	-	No Match	-	-
120	11:13:00	-	-	No Match	-	-
140	11:33:00	-	-	No Match	-	-
160	11:53:00	-	-	No Match	-	-
180	12:13:00	-	-	No Match	-	-

Table F.31: DFSO (Medium)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	06:25:00	2.594	2	E, F, G, J, K, L, M, N, P	6	9
100	06:45:00	2.364	2	E, F, G, J, K, L, M, N, P, Q, R	8	11
120	07:05:00	2.468	2	E, F, G, J, K, L, M, N, P, R, T, U	13	13
140	07:25:00	-	-	No Match	-	-
160	07:45:00	-	-	No Match	-	-
180	08:05:00	-	-	No Match	-	-

Table F.32: DFSO (Medium)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	07:29:00	-	-	No Match	-	-
100	07:49:00	-	-	No Match	-	-
120	08:09:00	-	-	No Match	-	-
140	08:29:00	-	-	No Match	-	-
160	08:49:00	-	-	No Match	-	-
180	09:09:00	-	-	No Match	-	-

Table F.33: DFSO (Medium)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	11:56:00	-	-	No Match	-	-
100	12:16:00	-	-	No Match	-	-
120	12:36:00	-	-	No Match	-	-
140	12:56:00	-	-	No Match	-	-
160	13:16:00	-	-	No Match	-	-
180	13:36:00	-	-	No Match	-	-

Table F.34: DFSO (Small)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	09:42:00	-	-	No Match	-	-
100	10:02:00	-	-	No Match	-	-
120	10:22:00	-	-	No Match	-	-
140	10:42:00	-	-	No Match	-	-
160	11:02:00	-	-	No Match	-	-
180	11:22:00	-	-	No Match	-	-

Table F.35: DFSO (Small)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	16:51:00	-	-	No Match	-	-
100	17:11:00	-	-	No Match	-	-
120	17:31:00	-	-	No Match	-	-
140	17:51:00	-	-	No Match	-	-
160	18:11:00	-	-	No Match	-	-
180	18:31:00	-	-	No Match	-	-

Table F.36: DFSO (Small)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	06:21:00	-	-	No Match	-	-
100	06:41:00	-	-	No Match	-	-
120	07:01:00	-	-	No Match	-	-
140	07:21:00	-	-	No Match	-	-
160	07:41:00	-	-	No Match	-	-
180	08:01:00	-	-	No Match	-	-

Table F.37: DFSW (Large)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	14:28:00	1.803	1	AD, AI	0	2
100	14:48:00	1.813	1	AD, AI	0	2
120	15:08:00	1.773	1	AD, AI	0	2
140	15:28:00	3.555	2	AD, AI, AO	0	3
160	15:48:00	-	-	No Match	-	-
180	16:08:00	-	-	No Match	-	-

Table F.38: DFSW (Large)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	22:27:00	3.285	2	BF, BK, BL, BC, BQ, BJ, BM	0	7
100	22:47:00	-	-	No Match	-	-
120	23:07:00	-	-	No Match	-	-
140	23:27:00	-	-	No Match	-	-
160	23:47:00	-	-	No Match	-	-
180	00:07:00	-	-	No Match	-	-

Table F.39: DFSW (Large)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	17:34:00	-	-	No Match	-	-
100	17:54:00	-	-	No Match	-	-
120	18:14:00	-	-	No Match	-	-
140	18:34:00	-	-	No Match	-	-
160	18:54:00	-	-	No Match	-	-
180	19:14:00	-	-	No Match	-	-

Table F.40: DFSW (Medium)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	15:26:00	1.161	1	AF, AD, AB	0	3
100	15:46:00	2.153	2	AF, AD, AB, AA	0	4
120	16:06:00	-	-	No Match	-	-
140	16:26:00	-	-	No Match	-	-
160	16:46:00	-	-	No Match	-	-
180	17:06:00	-	-	No Match	-	-

Table F.41: DFSW (Medium)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	12:33:00	1.251	1	Y, H, T	0	3
100	12:53:00	2.403	2	Y, H, T, Q	0	4
120	13:13:00	1.162	1	Y, H, T, Q	0	4
140	13:33:00	1.282	1	Y, H, T, O	0	4
160	13:53:00	1.162	1	Y, H, T, O	0	4
180	14:13:00	1.201	1	Y, H, T, O	0	4

Table F.42: DFSW (Medium)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	17:57:00	-	-	No Match	-	-
100	18:17:00	-	-	No Match	-	-
120	18:37:00	-	-	No Match	-	-
140	18:57:00	-	-	No Match	-	-
160	19:17:00	-	-	No Match	-	-
180	19:37:00	-	-	No Match	-	-

Table F.43: DFSW (Small)(Maximum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	21:31:00	-	-	No Match	-	-
100	21:51:00	-	-	No Match	-	-
120	22:11:00	-	-	No Match	-	-
140	22:31:00	-	-	No Match	-	-
160	22:51:00	-	-	No Match	-	-
180	23:11:00	-	-	No Match	-	-

Table F.44: DFSW (Small)(Median)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	13:32:00	-	-	No Match	-	-
100	13:52:00	-	-	No Match	-	-
120	14:12:00	-	-	No Match	-	-
140	14:32:00	-	-	No Match	-	-
160	14:52:00	-	-	No Match	-	-
180	15:12:00	-	-	No Match	-	-

Table F.45: DFSW (Small)(Minimum)

Lateness (Minutes)	Late-Crew Ready Time	Time (s)	Round	Rescheduling (Crew ID)	Minutes Late	Crew Involved
80	11:05:00	-	-	No Match	-	-
100	11:25:00	-	-	No Match	-	-
120	11:45:00	-	-	No Match	-	-
140	12:05:00	-	-	No Match	-	-
160	12:25:00	-	-	No Match	-	-
180	12:45:00	-	-	No Match	-	-

Table F.46: UNV (Large)(Maximum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	13:15:00	13:45	I	1.752	0
30	13:30:00	14:00	W	1.802	0
30	13:45:00	14:15	W	1.723	0
60	13:15:00	14:15	I	1.843	0
60	13:30:00	14:30	W	1.943	0
60	13:45:00	14:45	W	1.833	0
90	13:15:00	14:45	I	1.873	0
90	13:30:00	15:00	W	1.853	0
90	13:45:00	15:15	W	1.813	0
120	13:15:00	15:15	I	1.813	0
120	13:30:00	15:30	W	1.792	0
120	13:45:00	15:45	W	1.812	0

Table F.47: UNV (Large)(Median)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	00:15:00	00:45	BH	1.753	4
30	00:30:00	01:00	BE	1.662	2
30	00:45:00	01:15	BK	1.723	0
60	00:15:00	01:15	BH	1.783	4
60	00:30:00	01:30	BE	1.843	2
60	00:45:00	01:45	BK	1.683	0
90	00:15:00	01:30	BH	1.742	4
90	00:30:00	01:45	BE	1.772	2
90	00:45:00	02:00	BK	1.763	0
120	00:15:00	01:45	BH	1.853	4
120	00:30:00	02:00	No Match	-	-
120	00:45:00	02:15	BK	1.893	0

Table F.48: UNV (Large)(Minimum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	11:15:00	11:45	No Match	-	-
30	11:30:00	12:00	No Match	-	-
30	11:45:00	12:15	B	1.662	0
60	11:15:00	12:15	No Match	-	-
60	11:30:00	12:30	No Match	-	-
60	11:45:00	12:45	B	1.873	0
90	11:15:00	12:30	No Match	-	-
90	11:30:00	12:45	No Match	-	-
90	11:45:00	13:00	B	1.813	0
120	11:15:00	12:45	No Match	-	-
120	11:30:00	13:00	No Match	-	-
120	11:45:00	13:15	B	1.792	0

Table F.49: UNV (Medium)(Maximum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	16:15:00	16:45	P	1.152	0
30	16:30:00	17:00	U	1.132	0
30	16:45:00	17:15	Y	1.141	0
60	16:15:00	17:15	P	1.141	0
60	16:30:00	17:30	U	1.151	0
60	16:45:00	17:45	Y	1.212	0
90	16:15:00	17:30	P	1.232	0
90	16:30:00	17:45	U	1.151	0
90	16:45:00	18:00	Y	1.151	0
120	16:15:00	17:45	P	1.141	0
120	16:30:00	18:00	No Match	-	-
120	16:45:00	18:15	Y	1.121	0

Table F.50: UNV (Medium)(Median)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	13:15:00	13:45	H	1.092	0
30	13:30:00	14:00	H	1.152	0
30	13:45:00	14:15	H	1.102	0
60	13:15:00	14:15	H	1.232	0
60	13:30:00	14:30	H	1.141	0
60	13:45:00	14:45	H	1.062	0
90	13:15:00	14:30	H	1.122	0
90	13:30:00	14:45	H	1.133	0
90	13:45:00	15:00	H	1.141	0
120	13:15:00	14:45	H	1.171	0
120	13:30:00	15:00	H	1.151	0
120	13:45:00	15:15	H	1.172	0

Table F.51: UNV (Medium)(Minimum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	11:15:00	11:45	No Match	-	-
30	11:30:00	12:00	No Match	-	-
30	11:45:00	12:15	C	1.061	3
60	11:15:00	12:15	No Match	-	-
60	11:30:00	12:30	No Match	-	-
60	11:45:00	12:45	C	1.102	3
90	11:15:00	12:30	No Match	-	-
90	11:30:00	12:45	No Match	-	-
90	11:45:00	13:00	C	1.151	3
120	11:15:00	12:45	No Match	-	-
120	11:30:00	13:00	No Match	-	-
120	11:45:00	13:15	C	1.081	3

Table F.52: UNV (Small)(Maximum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	00:15:00	00:45	No Match	-	-
30	00:30:00	01:00	R	0.621	0
30	00:45:00	01:15	Q	0.651	0
60	00:15:00	01:15	No Match	-	-
60	00:30:00	01:30	R	0.641	0
60	00:45:00	01:45	Q	0.573	0
90	00:15:00	01:30	No Match	-	-
90	00:30:00	01:45	R	0.471	0
90	00:45:00	02:00	Q	0.641	0
120	00:15:00	01:45	No Match	-	-
120	00:30:00	02:00	R	0.631	0
120	00:45:00	02:15	No Match	-	-

Table F.53: UNV (Small)(Median)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	20:15:00	20:45	K	0.611	0
30	20:30:00	21:00	No Match	-	-
30	20:45:00	21:15	L	0.621	5
60	20:15:00	21:15	K	0.433	0
60	20:30:00	21:30	No Match	-	-
60	20:45:00	21:45	L	0.631	5
90	20:15:00	21:30	K	0.581	0
90	20:30:00	21:45	No Match	-	-
90	20:45:00	22:00	L	0.571	5
120	20:15:00	21:45	No Match	-	-
120	20:30:00	22:00	No Match	-	-
120	20:45:00	22:15	No Match	-	-

Table F.54: UNV (Small)(Minimum)

Unavailable (Minutes)	Start Time	End Time	Rescheduling	Time (s)	Minutes Late
30	13:15:00	13:45	No Match	-	-
30	13:30:00	14:00	No Match	-	-
30	13:45:00	14:15	C	0.591	0
60	13:15:00	14:15	No Match	-	-
60	13:30:00	14:30	No Match	-	-
60	13:45:00	14:45	C	0.581	0
90	13:15:00	14:30	No Match	-	-
90	13:30:00	14:45	No Match	-	-
90	13:45:00	15:00	C	0.611	0
120	13:15:00	14:45	No Match	-	-
120	13:30:00	15:00	No Match	-	-
120	13:45:00	15:15	C	0.59	0

Table F.55: Analysis of Different Timing for Lateness

	LFSO										LFR										LFSW										
	Large			Medium			Small				Large			Medium			Small				Large			Medium			Small				
	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T	GT
15	1	1	0	1	1	0	1	0	0	5	1	1	1	1	1	0	1	0	0	6	1	1	0	1	1	0	0	0	0	4	15
20	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
25	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
30	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
35	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
40	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
45	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
50	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
55	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	1	0	0	5	1	1	0	1	1	0	0	0	0	4	14
60	1	1	0	1	1	0	1	0	0	5	1	0	0	1	1	0	1	0	0	4	1	1	0	1	1	0	0	0	0	4	13

0 = No Match
1 = Matched

Table F.56: Analysis of Different Timing for Delay

	DFSO										DFSW										GT
	Large			Medium			Small				Large			Medium			Small				
	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T	
80	1	1	0	1	0	0	0	0	0	3	1	1	0	1	1	0	0	0	0	4	7
100	0	1	0	1	0	0	0	0	0	2	1	0	0	1	1	0	0	0	0	3	5
120	0	1	0	1	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0	2	4
140	0	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	2	3
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1

0 = No Match
1 = Matched

Table F.57: Analysis of Different Timing for UNV

	UNV									
	Large			Medium			Small			
	Mx	Md	Mn	Mx	Md	Mn	Mx	Md	Mn	T
30	3	3	1	3	3	1	2	2	1	19
60	3	3	1	3	3	1	2	2	1	19
90	3	3	1	3	3	1	2	2	1	19
120	3	3	1	2	3	1	1	0	1	15

0 = No Match
1 = Matched

Table F.58: The Effect of 15 and 20 Minutes LFSO at Different Times(Large Schedule)

Crew ID	Sign On	Start Time 1	Lateness	New Signing On	Ready Time
BS	7:32:00	7:47:00	0:15:00	7:47:00	07:52
	7:32:00	7:47:00	0:20:00	07:52:00	07:57
BZ	8:39:00	08:54:00	0:15:00	08:54:00	8:59:00
	8:39:00	08:54:00	0:20:00	08:59:00	9:04:00
AZ	13:20:00	13:35:00	0:15:00	13:35:00	13:40:00
	13:20:00	13:35:00	0:20:00	13:40:00	13:45:00
CF	14:06:00	14:21:00	0:15:00	14:21:00	14:26:00
	14:06:00	14:21:00	0:20:00	14:26:00	14:31:00
BJ	16:08:00	16:23:00	0:15:00	16:23:00	16:28:00
	16:08:00	16:23:00	0:20:00	16:28:00	16:33:00
BM	16:27:00	16:42:00	0:15:00	16:42:00	16:47:00
	16:27:00	16:42:00	0:20:00	16:47:00	16:52:00

Table F.59: The Effect of 15 and 20 Minutes LFSO at Different Times(Medium Schedule)

Crew ID	Sign On	Start Time 1	Lateness	New Signing On	Ready Time
U	7:00:00	07:15:00	0:15:00	7:15:00	07:20
	7:00:00	07:15:00	0:20:00	7:20:00	07:25
BZ	9:28:00	09:43:00	0:15:00	09:43:00	9:48:00
	9:28:00	09:43:00	0:20:00	09:48:00	9:53:00
AK	13:13:00	13:28:00	0:15:00	13:28:00	13:33:00
	13:13:00	13:28:00	0:20:00	13:33:00	13:38:00
AP	14:41:00	14:56:00	0:15:00	14:56:00	15:01:00
	14:41:00	14:56:00	0:20:00	15:01:00	15:06:00
AW	17:29:00	17:44:00	0:15:00	17:44:00	17:49:00
	17:29:00	17:44:00	0:20:00	17:49:00	17:54:00
AX	17:43:00	17:58:00	0:15:00	17:58:00	18:03:00
	17:43:00	17:58:00	0:20:00	18:03:00	18:08:00

Table F.60: The Effect of 15 and 20 Minutes LFSO at Different Times(Small Schedule)

Crew ID	Sign On	Start Time 1	Lateness	New Signing On	Ready Time
F	08:17:00	08:32:00	0:15:00	8:32:00	08:37
	08:17:00	08:32:00	0:20:00	8:37:00	08:42
I	08:56:00	09:11:00	0:15:00	09:11:00	9:16:00
	08:56:00	09:11:00	0:20:00	09:16:00	9:21:00
K	11:56:00	12:11:00	0:15:00	12:11:00	12:16:00
	11:56:00	12:11:00	0:20:00	12:16:00	12:21:00
L	12:26:00	12:41:00	0:15:00	12:41:00	12:46:00
	12:26:00	12:41:00	0:20:00	12:46:00	12:51:00
T	17:37:00	17:52:00	0:15:00	17:52:00	17:57:00
	17:37:00	17:52:00	0:20:00	17:57:00	18:02:00
U	18:37:00	18:52:00	0:15:00	18:52:00	18:57:00
	18:37:00	18:52:00	0:20:00	18:57:00	19:02:00

Table F.61: The Results for 15 and 20 Minutes LFSO at Different Times (Large Schedule)

Large Schedule	Rescheduling	15:00		Rescheduling	20:00	
		Match	Time		Match	Time
Early						
2 event	-	0	3.35	-	0	4.01
Midday						
2 event	AZ(BA), CF(CH)	2	4.15	AZ(BA), CF(CH)	2	4.64
Late						
2 event	-	0	3.92	-	0	3.62

Table F.62: The Results for 15 and 20 Minutes LFSO at Different Times (Medium Schedule)

Medium Schedule	Rescheduling	15:00		Rescheduling	20:00	
		Match	Time		Match	Time
Early						
2 event	U(X)	1	2.7	U(Y)	1	2.45
Midday						
2 event	AK(AL)	1	2.29	AK(AL)	1	2.68
Late						
2 event	AX(AY)	1	2.65	AX(AY)	1	2.16

Table F.63: The Results for 15 and 20 Minutes LFSO at Different Times (Small Schedule)

Small Schedule	Rescheduling	15:00		Rescheduling	20:00	
		Match	Time		Match	Time
Early						
2 event	F(H)	1	1.21	-	0	1.09
Midday						
2 event	-	0	1.09	-	0	1.12
Late						
2 event	-	0	1.03	-	0	1.05

Appendix G: Multiple Events Experiments

Table G.1: Experimental Data for LFSO(Large Schedule)

			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	1:00:00
CrewID	DutyNo	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO
E	55	04:13:00	04:28:00	04:33:00	04:38:00	04:43:00	04:48:00	04:53:00	04:58:00	05:03:00	05:08:00	05:13:00
P	66	05:55:00	06:10:00	06:15:00	06:20:00	06:25:00	06:30:00	06:35:00	06:40:00	06:45:00	06:50:00	06:55:00
V	72	06:10:00	06:25:00	06:30:00	06:35:00	06:40:00	06:45:00	06:50:00	06:55:00	07:00:00	07:05:00	07:10:00
W	73	06:13:00	06:28:00	06:33:00	06:38:00	06:43:00	06:48:00	06:53:00	06:58:00	07:03:00	07:08:00	07:13:00
X	74	06:15:00	06:30:00	06:35:00	06:40:00	06:45:00	06:50:00	06:55:00	07:00:00	07:05:00	07:10:00	07:15:00
AB	78	06:26:00	06:41:00	06:46:00	06:51:00	06:56:00	07:01:00	07:06:00	07:11:00	07:16:00	07:21:00	07:26:00
AC	79	06:35:00	06:50:00	06:55:00	07:00:00	07:05:00	07:10:00	07:15:00	07:20:00	07:25:00	07:30:00	07:35:00
AD	80	06:42:00	06:57:00	07:02:00	07:07:00	07:12:00	07:17:00	07:22:00	07:27:00	07:32:00	07:37:00	07:42:00
AL	88	10:56:00	11:11:00	11:16:00	11:21:00	11:26:00	11:31:00	11:36:00	11:41:00	11:46:00	11:51:00	11:56:00
AQ	93	12:04:00	12:19:00	12:24:00	12:29:00	12:34:00	12:39:00	12:44:00	12:49:00	12:54:00	12:59:00	13:04:00
AU	97	12:38:00	12:53:00	12:58:00	13:03:00	13:08:00	13:13:00	13:18:00	13:23:00	13:28:00	13:33:00	13:38:00
AW	99	12:46:00	13:01:00	13:06:00	13:11:00	13:16:00	13:21:00	13:26:00	13:31:00	13:36:00	13:41:00	13:46:00
AX	100	13:02:00	13:17:00	13:22:00	13:27:00	13:32:00	13:37:00	13:42:00	13:47:00	13:52:00	13:57:00	14:02:00
BK	113	16:27:00	16:42:00	16:47:00	16:52:00	16:57:00	17:02:00	17:07:00	17:12:00	17:17:00	17:22:00	17:27:00
BN	116	16:51:00	17:06:00	17:11:00	17:16:00	17:21:00	17:26:00	17:31:00	17:36:00	17:41:00	17:46:00	17:51:00
BR	120	17:33:00	17:48:00	17:53:00	17:58:00	18:03:00	18:08:00	18:13:00	18:18:00	18:23:00	18:28:00	18:33:00
BT	132	07:33:00	07:48:00	07:53:00	07:58:00	08:03:00	08:08:00	08:13:00	08:18:00	08:23:00	08:28:00	08:33:00
CA	139	08:55:00	09:10:00	09:15:00	09:20:00	09:25:00	09:30:00	09:35:00	09:40:00	09:45:00	09:50:00	09:55:00

Table G.2: Experimental Data for LFSO(Medium Schedule)

			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	1:00:00
CrewID	DutyNo	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO
K	211	05:35:00	05:50:00	05:55:00	06:00:00	06:05:00	06:10:00	06:15:00	06:20:00	06:25:00	06:30:00	06:35:00
O	215	06:14:00	06:29:00	06:34:00	06:39:00	06:44:00	06:49:00	06:54:00	06:59:00	07:04:00	07:09:00	07:14:00
Q	217	06:25:00	06:40:00	06:45:00	06:50:00	06:55:00	07:00:00	07:05:00	07:10:00	07:15:00	07:20:00	07:25:00
T	220	06:45:00	07:00:00	07:05:00	07:10:00	07:15:00	07:20:00	07:25:00	07:30:00	07:35:00	07:40:00	07:45:00
U	221	07:00:00	07:15:00	07:20:00	07:25:00	07:30:00	07:35:00	07:40:00	07:45:00	07:50:00	07:55:00	08:00:00
AG	233	12:01:00	12:16:00	12:21:00	12:26:00	12:31:00	12:36:00	12:41:00	12:46:00	12:51:00	12:56:00	13:01:00
AH	234	12:31:00	12:46:00	12:51:00	12:56:00	13:01:00	13:06:00	13:11:00	13:16:00	13:21:00	13:26:00	13:31:00
AL	238	13:28:00	13:43:00	13:48:00	13:53:00	13:58:00	14:03:00	14:08:00	14:13:00	14:18:00	14:23:00	14:28:00
AP	242	14:41:00	14:56:00	15:01:00	15:06:00	15:11:00	15:16:00	15:21:00	15:26:00	15:31:00	15:36:00	15:41:00
AW	249	17:29:00	17:44:00	17:49:00	17:54:00	17:59:00	18:04:00	18:09:00	18:14:00	18:19:00	18:24:00	18:29:00

Table G.3: Experimental Data for LFSO (Small Schedule)

			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	1:00:00
CrewID	DutyNo	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO	SO
C	570	5:26:00	05:41:00	05:46:00	05:51:00	05:56:00	06:01:00	06:06:00	06:11:00	06:16:00	06:21:00	06:26:00
H	575	8:26:00	08:41:00	08:46:00	08:51:00	08:56:00	09:01:00	09:06:00	09:11:00	09:16:00	09:21:00	09:26:00
L	579	12:26:00	12:41:00	12:46:00	12:51:00	12:56:00	13:01:00	13:06:00	13:11:00	13:16:00	13:21:00	13:26:00
M	580	12:56:00	13:11:00	13:16:00	13:21:00	13:26:00	13:31:00	13:36:00	13:41:00	13:46:00	13:51:00	13:56:00
O	582	15:26:00	15:41:00	15:46:00	15:51:00	15:56:00	16:01:00	16:06:00	16:11:00	16:16:00	16:21:00	16:26:00

Table G.4: Experimental Data for LFR (Large Schedule)

LFR			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
E	55	09:09:00	10:14:00	10:19:00	10:24:00	10:29:00	10:34:00	10:39:00	10:44:00	10:49:00	10:54:00	10:59:00
P	66	11:10:00	12:15:00	12:20:00	12:25:00	12:30:00	12:35:00	12:40:00	12:45:00	12:50:00	12:55:00	13:00:00
V	72	09:35:00	10:40:00	10:45:00	10:50:00	10:55:00	11:00:00	11:05:00	11:10:00	11:15:00	11:20:00	11:25:00
W	73	10:50:00	11:55:00	12:00:00	12:05:00	12:10:00	12:15:00	12:20:00	12:25:00	12:30:00	12:35:00	12:40:00
X	74	11:02:00	12:07:00	12:12:00	12:17:00	12:22:00	12:27:00	12:32:00	12:37:00	12:42:00	12:47:00	12:52:00
AB	78	11:26:00	12:31:00	12:36:00	12:41:00	12:46:00	12:51:00	12:56:00	13:01:00	13:06:00	13:11:00	13:16:00
AC	79	11:38:00	12:43:00	12:48:00	12:53:00	12:58:00	13:03:00	13:08:00	13:13:00	13:18:00	13:23:00	13:28:00
AD	80	11:50:00	12:55:00	13:00:00	13:05:00	13:10:00	13:15:00	13:20:00	13:25:00	13:30:00	13:35:00	13:40:00
AL	88	15:02:00	16:07:00	16:12:00	16:17:00	16:22:00	16:27:00	16:32:00	16:37:00	16:42:00	16:47:00	16:52:00
AQ	93	16:14:00	17:19:00	17:24:00	17:29:00	17:34:00	17:39:00	17:44:00	17:49:00	17:54:00	17:59:00	18:04:00
AU	97	16:39:00	17:44:00	17:49:00	17:54:00	17:59:00	18:04:00	18:09:00	18:14:00	18:19:00	18:24:00	18:29:00
AW	99	16:56:00	18:01:00	18:06:00	18:11:00	18:16:00	18:21:00	18:26:00	18:31:00	18:36:00	18:41:00	18:46:00
AX	100	17:03:00	18:08:00	18:13:00	18:18:00	18:23:00	18:28:00	18:33:00	18:38:00	18:43:00	18:48:00	18:53:00
BK	113	20:12:00	21:17:00	21:22:00	21:27:00	21:32:00	21:37:00	21:42:00	21:47:00	21:52:00	21:57:00	22:02:00
BN	116	19:12:00	20:17:00	20:22:00	20:27:00	20:32:00	20:37:00	20:42:00	20:47:00	20:52:00	20:57:00	21:02:00
BR	120	19:47:00	20:52:00	20:57:00	21:02:00	21:07:00	21:12:00	21:17:00	21:22:00	21:27:00	21:32:00	21:37:00
BT	132	11:20:00	12:25:00	12:30:00	12:35:00	12:40:00	12:45:00	12:50:00	12:55:00	13:00:00	13:05:00	13:10:00
CA	139	12:46:00	13:51:00	13:56:00	14:01:00	14:06:00	14:11:00	14:16:00	14:21:00	14:26:00	14:31:00	14:36:00

Table G.5: Experimental Data for LFR (Medium Schedule)

LFR			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
K	211	10:18:00	11:23:00	11:28:00	11:33:00	11:38:00	11:43:00	11:48:00	11:53:00	11:58:00	12:03:00	12:08:00
O	215	11:18:00	12:23:00	12:28:00	12:33:00	12:38:00	12:43:00	12:48:00	12:53:00	12:58:00	13:03:00	13:08:00
Q	217	11:58:00	13:03:00	13:08:00	13:13:00	13:18:00	13:23:00	13:28:00	13:33:00	13:38:00	13:43:00	13:48:00
T	220	10:43:00	11:48:00	11:53:00	11:58:00	12:03:00	12:08:00	12:13:00	12:18:00	12:23:00	12:28:00	12:33:00
U	221	9:01:00	10:06:00	10:11:00	10:16:00	10:21:00	10:26:00	10:31:00	10:36:00	10:41:00	10:46:00	10:51:00
AG	233	14:56:00	16:01:00	16:06:00	16:11:00	16:16:00	16:21:00	16:26:00	16:31:00	16:36:00	16:41:00	16:46:00
AH	234	14:36:00	15:41:00	15:46:00	15:51:00	15:56:00	16:01:00	16:06:00	16:11:00	16:16:00	16:21:00	16:26:00
AL	238	17:44:00	18:49:00	18:54:00	18:59:00	19:04:00	19:09:00	19:14:00	19:19:00	19:24:00	19:29:00	19:34:00
AP	242	17:58:00	19:03:00	19:08:00	19:13:00	19:18:00	19:23:00	19:28:00	19:33:00	19:38:00	19:43:00	19:48:00
AW	249	21:04:00	22:09:00	22:14:00	22:19:00	22:24:00	22:29:00	22:34:00	22:39:00	22:44:00	22:49:00	22:54:00

Table G.6: Experimental Data for LFR (Small Schedule)

LFR			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
C	570	8:43:00	09:48:00	09:53:00	09:58:00	10:03:00	10:08:00	10:13:00	10:18:00	10:23:00	10:28:00	10:33:00
H	575	12:31:00	13:36:00	13:41:00	13:46:00	13:51:00	13:56:00	14:01:00	14:06:00	14:11:00	14:16:00	14:21:00
L	579	16:31:00	17:36:00	17:41:00	17:46:00	17:51:00	17:56:00	18:01:00	18:06:00	18:11:00	18:16:00	18:21:00
M	580	17:01:00	18:06:00	18:11:00	18:16:00	18:21:00	18:26:00	18:31:00	18:36:00	18:41:00	18:46:00	18:51:00
O	582	19:20:00	20:25:00	20:30:00	20:35:00	20:40:00	20:45:00	20:50:00	20:55:00	21:00:00	21:05:00	21:10:00

Table G.7: Experimental Data for LFSW (Large Schedule)

LFSW			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
E	55	10:15:00	10:35:00	10:40:00	10:45:00	10:50:00	10:55:00	11:00:00	11:05:00	11:10:00	11:15:00	11:20:00
P	66	12:05:00	12:25:00	12:30:00	12:35:00	12:40:00	12:45:00	12:50:00	12:55:00	13:00:00	13:05:00	13:10:00
V	72	10:33:00	10:53:00	10:58:00	11:03:00	11:08:00	11:13:00	11:18:00	11:23:00	11:28:00	11:33:00	11:38:00
W	73	11:47:00	12:07:00	12:12:00	12:17:00	12:22:00	12:27:00	12:32:00	12:37:00	12:42:00	12:47:00	12:52:00
X	74	11:57:00	12:17:00	12:22:00	12:27:00	12:32:00	12:37:00	12:42:00	12:47:00	12:52:00	12:57:00	13:02:00
AB	78	12:33:00	12:53:00	12:58:00	13:03:00	13:08:00	13:13:00	13:18:00	13:23:00	13:28:00	13:33:00	13:38:00
AC	79	12:41:00	13:01:00	13:06:00	13:11:00	13:16:00	13:21:00	13:26:00	13:31:00	13:36:00	13:41:00	13:46:00
AD	80	13:03:00	13:23:00	13:28:00	13:33:00	13:38:00	13:43:00	13:48:00	13:53:00	13:58:00	14:03:00	14:08:00
AL	88	16:09:00	16:29:00	16:34:00	16:39:00	16:44:00	16:49:00	16:54:00	16:59:00	17:04:00	17:09:00	17:14:00
AQ	93	17:16:00	17:36:00	17:41:00	17:46:00	17:51:00	17:56:00	18:01:00	18:06:00	18:11:00	18:16:00	18:21:00
AU	97	17:39:00	17:59:00	18:04:00	18:09:00	18:14:00	18:19:00	18:24:00	18:29:00	18:34:00	18:39:00	18:44:00
AW	99	18:03:00	18:23:00	18:28:00	18:33:00	18:38:00	18:43:00	18:48:00	18:53:00	18:58:00	19:03:00	19:08:00
AX	100	18:04:00	18:24:00	18:29:00	18:34:00	18:39:00	18:44:00	18:49:00	18:54:00	18:59:00	19:04:00	19:09:00
BK	113	21:19:00	21:39:00	21:44:00	21:49:00	21:54:00	21:59:00	22:04:00	22:09:00	22:14:00	22:19:00	22:24:00
BN	116	20:07:00	20:27:00	20:32:00	20:37:00	20:42:00	20:47:00	20:52:00	20:57:00	21:02:00	21:07:00	21:12:00
BR	120	21:10:00	21:30:00	21:35:00	21:40:00	21:45:00	21:50:00	21:55:00	22:00:00	22:05:00	22:10:00	22:15:00
BT	132	12:27:00	12:47:00	12:52:00	12:57:00	13:02:00	13:07:00	13:12:00	13:17:00	13:22:00	13:27:00	13:32:00
CA	139	14:23:00	14:43:00	14:48:00	14:53:00	14:58:00	15:03:00	15:08:00	15:13:00	15:18:00	15:23:00	15:28:00

Table G.8: Experimental Data for LFSW (Medium Schedule)

LFSW			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
K	211	11:21:00	11:41:00	11:46:00	11:51:00	11:56:00	12:01:00	12:06:00	12:11:00	12:16:00	12:21:00	12:26:00
O	215	14:30:00	14:50:00	14:55:00	15:00:00	15:05:00	15:10:00	15:15:00	15:20:00	15:25:00	15:30:00	15:35:00
Q	217	13:08:00	13:28:00	13:33:00	13:38:00	13:43:00	13:48:00	13:53:00	13:58:00	14:03:00	14:08:00	14:13:00
T	220	12:43:00	13:03:00	13:08:00	13:13:00	13:18:00	13:23:00	13:28:00	13:33:00	13:38:00	13:43:00	13:48:00
U	221	10:51:00	11:11:00	11:16:00	11:21:00	11:26:00	11:31:00	11:36:00	11:41:00	11:46:00	11:51:00	11:56:00
AG	233	15:46:00	16:06:00	16:11:00	16:16:00	16:21:00	16:26:00	16:31:00	16:36:00	16:41:00	16:46:00	16:51:00
AH	234	15:38:00	15:58:00	16:03:00	16:08:00	16:13:00	16:18:00	16:23:00	16:28:00	16:33:00	16:38:00	16:43:00
AL	238	18:39:00	18:59:00	19:04:00	19:09:00	19:14:00	19:19:00	19:24:00	19:29:00	19:34:00	19:39:00	19:44:00
AP	242	18:50:00	19:10:00	19:15:00	19:20:00	19:25:00	19:30:00	19:35:00	19:40:00	19:45:00	19:50:00	19:55:00
AW	249	22:05:00	22:25:00	22:30:00	22:35:00	22:40:00	22:45:00	22:50:00	22:55:00	23:00:00	23:05:00	23:10:00

Table G.9: Experimental Data for LFSW (Small Schedule)

LFSW			00:15:00	00:20:00	00:25:00	00:30:00	00:35:00	00:40:00	00:45:00	00:50:00	00:55:00	01:00:00
CrewID	DutyNo	ET1	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
C	570	9:47:00	10:07:00	10:12:00	10:17:00	10:22:00	10:27:00	10:32:00	10:37:00	10:42:00	10:47:00	10:52:00
H	575	13:27:00	13:47:00	13:52:00	13:57:00	14:02:00	14:07:00	14:12:00	14:17:00	14:22:00	14:27:00	14:32:00
L	579	17:27:00	17:47:00	17:52:00	17:57:00	18:02:00	18:07:00	18:12:00	18:17:00	18:22:00	18:27:00	18:32:00
M	580	18:07:00	18:27:00	18:32:00	18:37:00	18:42:00	18:47:00	18:52:00	18:57:00	19:02:00	19:07:00	19:12:00
O	582	20:06:00	20:26:00	20:31:00	20:36:00	20:41:00	20:46:00	20:51:00	20:56:00	21:01:00	21:06:00	21:11:00

Table G.10: Experimental Data for UNV (Large Schedule)

UNV	0:30:00	0:45:00	1:00:00	1:15:00	1:30:00	1:45:00	2:00:00
ST	ET	ET	ET	ET	ET	ET	ET
11:36:00	12:06:00	12:21:00	12:36:00	12:51:00	13:06:00	13:21:00	13:36:00
11:48:00	12:18:00	12:33:00	12:48:00	13:03:00	13:18:00	13:33:00	13:48:00
12:45:00	13:15:00	13:30:00	13:45:00	14:00:00	14:15:00	14:30:00	14:45:00
12:54:00	13:24:00	13:39:00	13:54:00	14:09:00	14:24:00	14:39:00	14:54:00
14:24:00	14:54:00	15:09:00	15:24:00	15:39:00	15:54:00	16:09:00	16:24:00
15:28:00	15:58:00	16:13:00	16:28:00	16:43:00	16:58:00	17:13:00	17:28:00
15:42:00	16:12:00	16:27:00	16:42:00	16:57:00	17:12:00	17:27:00	17:42:00
15:54:00	16:24:00	16:39:00	16:54:00	17:09:00	17:24:00	17:39:00	17:54:00
16:06:00	16:36:00	16:51:00	17:06:00	17:21:00	17:36:00	17:51:00	18:06:00
16:24:00	16:54:00	17:09:00	17:24:00	17:39:00	17:54:00	18:09:00	18:24:00
17:24:00	17:54:00	18:09:00	18:24:00	18:39:00	18:54:00	19:09:00	19:24:00
17:48:00	18:18:00	18:33:00	18:48:00	19:03:00	19:18:00	19:33:00	19:48:00
18:30:00	19:00:00	19:15:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00
18:54:00	19:24:00	19:39:00	19:54:00	20:09:00	20:24:00	20:39:00	20:54:00
19:00:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00	20:45:00	21:00:00
19:36:00	20:06:00	20:21:00	20:36:00	20:51:00	21:06:00	21:21:00	21:36:00
20:12:00	20:42:00	20:57:00	21:12:00	21:27:00	21:42:00	21:57:00	22:12:00
20:48:00	21:18:00	21:33:00	21:48:00	22:03:00	22:18:00	22:33:00	22:48:00

Table G.11: Experimental Data for UNV (Medium Schedule)

UNV	0:30:00	0:45:00	1:00:00	1:15:00	1:30:00	1:45:00	2:00:00
ST	ET	ET	ET	ET	ET	ET	ET
14:18:00	14:48:00	15:03:00	15:18:00	15:33:00	15:48:00	16:03:00	16:18:00
14:30:00	15:00:00	15:15:00	15:30:00	15:45:00	16:00:00	16:15:00	16:30:00
14:48:00	15:18:00	15:33:00	15:48:00	16:03:00	16:18:00	16:33:00	16:48:00
15:00:00	15:30:00	15:45:00	16:00:00	16:15:00	16:30:00	16:45:00	17:00:00
16:30:00	17:00:00	17:15:00	17:30:00	17:45:00	18:00:00	18:15:00	18:30:00
17:12:00	17:42:00	17:57:00	18:12:00	18:27:00	18:42:00	18:57:00	19:12:00
22:18:00	22:48:00	23:03:00	23:18:00	23:33:00	23:48:00	0:03:00	0:18:00
23:36:00	0:06:00	0:21:00	0:36:00	0:51:00	1:06:00	1:21:00	1:36:00
23:54:00	0:24:00	0:39:00	0:54:00	1:09:00	1:24:00	1:39:00	1:54:00
24:48:00	1:18:00	1:33:00	1:48:00	2:03:00	2:18:00	2:33:00	2:48:00

Table G.12: Experimental Data for UNV (Small Schedule)

UNV	0:30:00	0:45:00	1:00:00	1:15:00	1:30:00	1:45:00	2:00:00
ST	ET	ET	ET	ET	ET	ET	ET
13:42:00	14:12:00	14:27:00	14:42:00	14:57:00	15:12:00	15:27:00	15:42:00
19:12:00	19:42:00	19:57:00	20:12:00	20:27:00	20:42:00	20:57:00	21:12:00
20:54:00	21:24:00	21:39:00	21:54:00	22:09:00	22:24:00	22:39:00	22:54:00
22:18:00	22:48:00	23:03:00	23:18:00	23:33:00	23:48:00	0:03:00	0:18:00
23:54:00	0:24:00	0:39:00	0:54:00	1:09:00	1:24:00	1:39:00	1:54:00

Table G.13: Results for LFSO (Large Schedule)

LFSO-LARGE						
	00:15:00			00:20:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	2	F(E),T(P)	2.85	2	F(E),T(P)	3.86
3	3	F(E),T(P),Z(V)	5.20	3	F(E),T(P),Z(V)	5.54
4	3	F(E),T(P),Z(V)	5.75	3	F(E),T(P),Z(V)	7.16
5	4	F(E),T(P),Z(V),AA(X)	8.92	4	F(E),T(P),Z(V),AA(X)	8.84
6	5	F(E),T(P),Z(V),AA(X),AC(AB)	10.59	5	F(E),T(P),Z(V),AA(X),AC(AB)	10.66
7	5	F(E),T(P),Z(V),AA(X),AD(AC)	12.63	4	F(E),T(P),Z(V),AA(X)	12.41
8	5	F(E),T(P),Z(V),AA(X),AE(AD)	14.52	4	F(E),T(P),Z(V),AA(X)	14.21
9	5	F(E),T(P),Z(V),AA(X),AE(AD)	15.46	4	F(E),T(P),Z(V),AA(X)	15.59
10	5	F(E),T(P),Z(V),AA(X),AE(AD)	17.11	4	F(E),T(P),Z(V),AA(X)	16.62
11	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	18.58	4	F(E),T(P),Z(V),AA(X)	18.76
12	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	20.90	4	F(E),T(P),Z(V),AA(X)	18.96
13	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	21.50	4	F(E),T(P),Z(V),AA(X)	22.00
14	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	22.90	4	F(E),T(P),Z(V),AA(X)	23.23
15	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	25.74	4	F(E),T(P),Z(V),AA(X)	23.38
16	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	26.15	4	F(E),T(P),Z(V),AA(X)	24.52
17	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	27.85	4	F(E),T(P),Z(V),AA(X)	25.73
18	6	F(E),T(P),Z(V),AA(X),AE(AD),AW(AU)	28.66	4	F(E),T(P),Z(V),AA(X)	28.51

Table G.14: Results for LFSO (Medium Schedule)

LFSO-MEDIUM						
	00:15:00			00:20:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	0	NM	1.81	0	NM	1.85
3	0	NM	2.80	0	NM	2.75
4	1	U(T)	3.73	1	U(T)	3.70
5	1	X(U)	4.67	1	Y(U)	3.66
6	1	X(U)	5.31	1	Y(U)	5.28
7	1	X(U)	6.15	1	Y(U)	5.93
8	1	X(U)	6.77	1	Y(U)	6.91
9	1	X(U)	7.74	1	Y(U)	7.46
10	1	X(U)	8.52	1	Y(U)	8.42

Table G.15: Results for LFSO (Small Schedule)

LFSO-SMALL						
	00:15:00			00:20:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	0	No Match	0.95	0	No Match	0.91
3	0	No Match	1.28	0	No Match	1.31
4	0	No Match	1.68	0	No Match	1.65
5	0	No Match	1.95	0	No Match	2.04

Table G.16: Results for LFR (Large Schedule)-15 to 20 Minutes

LFR-LARGE						
	00:15:00			00:20:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	2	E(E),Z(P)	3.27	2	AB(E),J(P)	3.36
3	3	E(E),Z(P),N(V)	4.66	2	AB(E),J(P)	4.99
4	4	E(E),Z(P),N(V),Y(W)	6.45	2	AB(E),J(P)	6.44
5	5	E(E),Z(P),N(V),Y(W),T(X)	7.74	2	AB(E),J(P)	8.03
6	6	E(E),Z(P),N(V),Y(W),T(X),BT(AB)	9.56	3	AB(E),J(P),AC(AB)	9.03
7	7	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC)	10.65	4	AB(E),J(P),BU(AB),AD(AC)	10.89
8	8	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD)	12.91	4	AB(E),J(P),BU(AB),AD(AD)	11.97
9	9	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL)	14.03	4	AB(E),J(P),BU(AB),AD(AD)	14.01
10	10	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ)	15.57	5	AB(E),J(P),BU(AB),AD(AD),CF(AQ)	15.42
11	11	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU)	16.97	5	AB(E),J(P),BU(AB),AD(AD),CF(AQ)	16.88
12	12	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW)	18.37	6	AB(E),J(P),BU(AB),AD(AD),CF(AQ),AX(AW)	18.40
13	12	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW)	18.75	5	AB(E),J(P),BU(AB),AD(AD),CF(AQ)	19.75
14	13	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW),BK(BK)	21.25	6	AB(E),J(P),BU(AB),AD(AD),CF(AQ),BL(BK)	20.88
15	14	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW),BK(BK),BO(BN)	21.47	6	AB(E),J(P),BU(AB),AD(AD),CF(AQ),BL(BK)	21.25
16	15	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW),BK(BK),BO(BN),BR(BR)	23.20	7	AB(E),J(P),BU(AB),AD(AD),CF(AQ),BL(BK),BF(BR)	23.68
17	16	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW),BK(BK),BO(BN),BR(BR),BT(BT)	24.75	7	AB(E),J(P),BU(AB),AD(AD),CF(AQ),BL(BK),BF(BR)	24.64
18	17	E(E),Z(P),N(V),Y(W),T(X),BT(AB),AC(AC),AD(AD),AL(AL),CF(AQ),AS(AU),AW(AW),BK(BK),BO(BN),BR(BR),BT(BT),CA(CA	25.20	8	AB(E),J(P),BU(AB),AD(AD),CF(AQ),BL(BK),BF(BR),AJ(CA	24.90

Table G.17: Results for LFR (Large Schedule)-25 to 40 Minutes

LFR-LARGE											
00:25:00			00:30:00			00:35:00			00:40:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
2	F(E),T(P)	3.38	2	F(E),T(P)	3.15	1	T(P)	3.21	1	T(P)	3.29
2	F(E),T(P)	4.88	2	F(E),T(P)	4.59	1	T(P)	4.34	1	T(P)	4.86
2	F(E),T(P)	6.11	2	F(E),T(P)	6.45	1	T(P)	6.58	1	T(P)	6.07
2	F(E),T(P)	7.54	2	F(E),T(P)	8.14	1	T(P)	8.16	1	T(P)	7.22
3	F(E),T(P),AC(AB)	9.04	3	F(E),T(P),AC(AB)	9.48	2	T(P),BU(AB)	9.19	2	T(P),BU(AB)	9.14
4	F(E),T(P) BU(AB),AD(AC)	11.11	4	F(E),T(P),BU(AB),AD(AC)	10.59	2	T(P),BU(AB)	10.71	2	T(P),BU(AB)	10.82
4	F(E),T(P),BU(AB),AE(AD)	12.93	4	F(E),T(P),BU(AB),AE(AD)	12.72	3	T(P),BU(AB),AE(AD)	13.00	3	T(P),BU(AB),AE(AD)	12.81
4	F(E),T(P),BU(AB),AE(AD)	15.95	4	F(E),T(P),BU(AB),AE(AD)	13.43	3	T(P),BU(AB),AE(AD)	13.57	3	T(P),BU(AB),AE(AD)	15.80
4	F(E),T(P),BU(AB),AE(AD)	13.90	4	F(E),T(P),BU(AB),AE(AD)	14.45	3	T(P),BU(AB),AE(AD)	14.45	3	T(P),BU(AB),AE(AD)	13.85
4	F(E),T(P),BU(AB),AE(AD)	16.98	4	F(E),T(P),BU(AB),AE(AD)	16.41	3	T(P),BU(AB),AE(AD)	16.32	3	T(P),BU(AB),AE(AD)	17.32
4	F(E),T(P),BU(AB),AE(AD)	17.52	4	F(E),T(P),BU(AB),AE(AD)	17.37	3	T(P),BU(AB),AE(AD)	17.31	3	T(P),BU(AB),AE(AD)	17.19
4	F(E),T(P),BU(AB),AE(AD)	19.06	4	F(E),T(P),BU(AB),AE(AD)	18.99	3	T(P),BU(AB),AE(AD)	18.69	3	T(P),BU(AB),AE(AD)	18.95
5	F(E),T(P),BU(AB),AE(AD),BL(BK)	21.62	4	F(E),T(P),BU(AB),AE(AD)	19.98	3	T(P),BU(AB),AE(AD)	20.13	3	T(P),BU(AB),AE(AD)	21.53
5	F(E),T(P),BU(AB),AE(AD),BL(BK)	22.63	4	F(E),T(P),BU(AB),AE(AD)	22.11	3	T(P),BU(AB),AE(AD)	22.38	3	T(P),BU(AB),AE(AD)	22.49
6	F(E),T(P),BU(AB),AE(AD) BL(BK),BF(BR)	23.99	5	F(E),T(P),BU(AB),AE(AD),BF(BR)	23.19	4	T(P),BU(AB),AE(AD),BL(BR)	23.49	4	T(P),BU(AB),AE(AD),BL(BR)	24.09
6	F(E),T(P),BU(AB),AE(AD),BL(BK),BF(BR)	24.94	5	F(E),T(P),BU(AB),AE(AD),BF(BR)	24.64	4	T(P),BU(AB),AE(AD),BL(BR)	24.52	4	T(P),BU(AB),AE(AD),BL(BR)	24.76
7	F(E),T(P) BU(AB),AE(AD),BL(BK),BF(BR),AJ(CA)	25.83	6	F(E),T(P),BU(AB),AE(AD),BF(BR),AJ(CA)	26.63	5	T(P),BU(AB),AE(AD),BL(BR),BY(CA)	27	5	T(P),BU(AB),AE(AD),BL(BR),BV(CA)	25.87

Table G.18: Results for LFR (Large Schedule)-45 to 60 Minutes

LFR-LARGE											
00:45:00			00:50:00			00:55:00			01:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
1	T(P)	3.50	1	T(P)	3.49	1	T(P)	3.81	1	T(P)	3.43
1	T(P)	4.42	1	T(P)	4.56	1	T(P)	4.31	1	T(P)	4.71
1	T(P)	6.76	1	T(P)	6.38	1	T(P)	6.82	1	T(P)	6.72
1	T(P)	7.88	1	T(P)	7.48	1	T(P)	7.84	1	T(P)	7.43
2	T(P),BU(AB)	9.02	2	T(P),BU(AB)	9.48	2	T(P),BU(AB)	9.36	1	T(P)	9.35
2	T(P),BU(AB)	10.53	2	T(P),BU(AB)	11.02	2	T(P),BU(AB)	10.80	1	T(P)	11.07
3	T(P),BU(AB),BW(AD)	13.20	3	T(P),BU(AB),BW(AD)	12.46	3	T(P),BU(AB),BW(AD)	13.04	2	T(P),AF(AD)	12.37
3	T(P),BU(AB),BW(AD)	13.88	3	T(P),BU(AB),BW(AD)	15.77	3	T(P),BU(AB),BW(AD)	13.77	2	T(P),AF(AD)	16.11
3	T(P),BU(AB),BW(AD)	14.25	3	T(P),BU(AB),BW(AD)	13.99	3	T(P),BU(AB),BW(AD)	13.91	2	T(P),AF(AD)	13.77
3	T(P),BU(AB),BW(AD)	16.17	3	T(P),BU(AB),BW(AD)	17.57	3	T(P),BU(AB),BW(AD)	16.25	2	T(P),AF(AD)	17.44
3	T(P),BU(AB),BW(AD)	17.19	3	T(P),BU(AB),BW(AD)	17.05	3	T(P),BU(AB),BW(AD)	17.40	2	T(P),AF(AD)	17.36
3	T(P),BU(AB),BW(AD)	18.42	3	T(P),BU(AB),BW(AD)	18.69	3	T(P),BU(AB),BW(AD)	18.10	2	T(P),AF(AD)	18.63
3	T(P),BU(AB),BW(AD)	20.06	3	T(P),BU(AB),BW(AD)	21.76	3	T(P),BU(AB),BW(AD)	19.81	2	T(P),AF(AD)	21.96
3	T(P),BU(AB),BW(AD)	22.09	3	T(P),BU(AB),BW(AD)	22.66	3	T(P),BU(AB),BW(AD)	22.08	2	T(P),AF(AD)	22.99
4	T(P),BU(AB),BW(AD),BL(BR)	23.14	4	T(P),BU(AB),BW(AD),BL(BR)	24.04	3	T(P),BU(AB),BW(AD)	22.82	2	T(P),AF(AD)	24.20
4	T(P),BU(AB),BW(AD),BL(BR)	24.86	4	T(P),BU(AB),BW(AD),BL(BR)	24.53	3	T(P),BU(AB),BW(AD)	24.81	2	T(P),AF(AD)	24.21
5	T(P),BU(AB),BW(AD),BL(BR),BV(CA)	26.76	5	T(P),BU(AB),BW(AD),BL(BR),AK(CA)	24.8	4	T(P),BU(AB),BW(AD),AK(CA)	26.4	3	T(P),AF(AD),AK(CA)	25.9

Table G.19: Results for LFR (Medium Schedule)-15 to 25 Minutes

LFR-MEDIUM									
	00:15:00			00:20:00			00:25:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)	M	Crew ID	T
2	2	H(K),O(O)	2.07	2	H(K),O(O)	2.15	2	H(K),O(O)	2.23
3	3	H(K),O(O),Q(Q)	2.87	3	H(K),O(O),Q(Q)	2.58	3	H(K),O(O),Z(Q)	2.71
4	4	H(K),O(O),Q(Q),T(T)	3.92	4	H(K),O(O),Q(Q),T(T)	4.04	4	H(K),O(O),Z(Q),T(T)	3.77
5	5	H(K),O(O),Q(Q),I(T),U(U)	4.80	5	H(K),O(O),Q(Q),I(T),U(U)	4.40	5	H(K),O(O),Z(Q),T(T),U(U)	4.45
6	5	H(K),O(O),Q(Q),I(T),U(U)	5.53	5	H(K),O(O),Q(Q),I(T),U(U)	5.35	5	H(K),O(O),Z(Q),T(T),U(U)	5.55
7	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	6.20	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	6.12	5	H(K),O(O),Z(Q),T(T),U(U)	6.02
8	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	7.01	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	6.59	5	H(K),O(O),Z(Q),T(T),U(U)	7.14
9	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	7.71	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	7.73	5	H(K),O(O),Z(Q),T(T),U(U)	7.48
10	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	8.48	6	H(K),O(O),Q(Q),I(T),U(U),AA(AH)	8.83	5	H(K),O(O),Z(Q),T(T),U(U)	8.58

Table G.20: Results for LFR (Medium Schedule)-30 to 40 Minutes

LFR - MEDIUM								
00:30:00			00:35:00			00:40:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
2	H(K),O(O)	2.22	2	H(K),O(O)	2.47	2	H(K),O(O)	2.38
3	H(K),O(O),Z(Q)	2.77	3	H(K),O(O),Z(Q)	2.91	3	H(K),O(O),Z(Q)	2.69
4	H(K),O(O),Z(Q),T(T)	3.99	4	H(K),O(O),Z(Q),T(T)	3.95	4	H(K),O(O),Z(Q),T(T)	3.86
5	H(K),O(O),Z(Q),T(T),U(U)	4.51	5	H(K),O(O),Z(Q),T(T),U(U)	4.62	5	H(K),O(O),Z(Q),T(T),U(U)	4.83
5	H(K),O(O),Z(Q),T(T),U(U)	5.55	5	H(K),O(O),Z(Q),T(T),U(U)	5.85	5	H(K),O(O),Z(Q),T(T),U(U)	5.61
5	H(K),O(O),Z(Q),T(T),U(U)	6.22	5	H(K),O(O),Z(Q),T(T),U(U)	6.24	5	H(K),O(O),Z(Q),T(T),U(U)	5.94
5	H(K),O(O),Z(Q),T(T),U(U)	6.82	5	H(K),O(O),Z(Q),T(T),U(U)	7.49	5	H(K),O(O),Z(Q),T(T),U(U)	6.86
5	H(K),O(O),Z(Q),T(T),U(U)	7.39	5	H(K),O(O),Z(Q),T(T),U(U)	7.73	5	H(K),O(O),Z(Q),T(T),U(U)	7.28
5	H(K),O(O),Z(Q),T(T),U(U)	8.12	5	H(K),O(O),Z(Q),T(T),U(U)	8.42	5	H(K),O(O),Z(Q),T(T),U(U)	7.99

Table G.21: Results for LFR (Medium Schedule)-45 to 60 Minutes

LFR - MEDIUM											
00:45:00			00:50:00			00:55:00			01:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
2	I(K),O(O)	2.82	2	I(K),O(O)	2.55	2	I(K),O(O)	2.45	1	O(O)	2.56
3	I(K),O(O),Z(Q)	3.07	3	I(K),O(O),Z(Q)	3.00	3	I(K),O(O),Z(Q)	2.89	2	O(O),Z(Q)	3.07
4	I(K),O(O),Z(Q),T(T)	3.72	4	I(K),O(O),Z(Q),T(T)	3.67	4	I(K),O(O),Z(Q),T(T)	3.88	3	O(O),Z(Q),T(T)	3.73
5	I(K),O(O),Z(Q),T(T),U(U)	4.61	5	I(K),O(O),Z(Q),T(T),U(U)	4.49	5	I(K),O(O),Z(Q),T(T),U(U)	4.43	4	O(O),Z(Q),T(T),U(U)	4.38
5	I(K),O(O),Z(Q),T(T),U(U)	5.91	5	I(K),O(O),Z(Q),T(T),U(U)	5.35	5	I(K),O(O),Z(Q),T(T),U(U)	5.87	4	O(O),Z(Q),T(T),U(U)	5.61
5	I(K),O(O),Z(Q),T(T),U(U)	6.14	5	I(K),O(O),Z(Q),T(T),U(U)	5.85	5	I(K),O(O),Z(Q),T(T),U(U)	6.21	4	O(O),Z(Q),T(T),U(U)	5.87
5	I(K),O(O),Z(Q),T(T),U(U)	7.25	5	I(K),O(O),Z(Q),T(T),U(U)	6.99	5	I(K),O(O),Z(Q),T(T),U(U)	7.38	4	O(O),Z(Q),T(T),U(U)	7.08
5	I(K),O(O),Z(Q),T(T),U(U)	7.38	5	I(K),O(O),Z(Q),T(T),U(U)	7.17	5	I(K),O(O),Z(Q),T(T),U(U)	7.64	4	O(O),Z(Q),T(T),U(U)	7.87
5	I(K),O(O),Z(Q),T(T),U(U)	8.70	5	I(K),O(O),Z(Q),T(T),U(U)	7.97	5	I(K),O(O),Z(Q),T(T),U(U)	8.79	4	O(O),Z(Q),T(T),U(U)	8.76

Table G.22: Results for LFR (Small Schedule)

LFR-SMALL						
	00:15:00			00:20:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	0	No Match	0.93	0	No Match	0.92
3	0	No Match	1.27	0	No Match	1.13
4	1	M(M)	1.75	0	No Match	1.93
5	1	M(M)	2.06	0	No Match	2.03

Table G.23: Results for LFSW (Large Schedule)-15 to 25 Minutes

LFSW-LARGE									
	00:15:00			00:20:00			00:25:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)	M	Crew ID	T
2	1	T(P)	3.32	1	T(P)	3.25	1	T(P)	3.41
3	1	T(P)	4.53	1	T(P)	4.49	1	T(P)	4.49
4	1	T(P)	6.42	1	T(P)	6.46	1	T(P)	6.37
5	1	T(P)	7.85	1	T(P)	7.81	1	T(P)	7.87
6	2	T(P),BU(AB)	9.56	2	T(P),BU(AB)	9.55	2	T(P),BU(AB)	9.58
7	2	T(P),BU(AB)	10.74	2	T(P),BU(AB)	10.81	2	T(P),BU(AB)	10.72
8	3	T(P),BU(AB),BW(AD)	12.97	3	T(P),BU(AB),BW(AD)	12.83	3	T(P),BU(AB),BW(AD)	13.05
9	3	T(P),BU(AB),BW(AD)	13.98	3	T(P),BU(AB),BW(AD)	13.88	3	T(P),BU(AB),BW(AD)	13.87
10	3	T(P),BU(AB),BW(AD)	15.52	3	T(P),BU(AB),BW(AD)	15.55	3	T(P),BU(AB),BW(AD)	15.38
11	3	T(P),BU(AB),BW(AD)	17.02	3	T(P),BU(AB),BW(AD)	16.97	3	T(P),BU(AB),BW(AD)	17.04
12	3	T(P),BU(AB),BW(AD)	18.38	3	T(P),BU(AB),BW(AD)	18.25	3	T(P),BU(AB),BW(AD)	18.41
13	3	T(P),BU(AB),BW(AD)	18.80	3	T(P),BU(AB),BW(AD)	18.87	3	T(P),BU(AB),BW(AD)	18.93
14	3	T(P),BU(AB),BW(AD)	21.33	3	T(P),BU(AB),BW(AD)	21.42	3	T(P),BU(AB),BW(AD)	21.26
15	3	T(P),BU(AB),BW(AD)	21.49	3	T(P),BU(AB),BW(AD)	21.63	3	T(P),BU(AB),BW(AD)	21.48
16	4	T(P),BU(AB),BW(AD),BL(BR)	23.08	3	T(P),BU(AB),BW(AD)	23.03	3	T(P),BU(AB),BW(AD)	23.10
17	4	T(P),BU(AB),BW(AD),BL(BR)	24.05	3	T(P),BU(AB),BW(AD)	24.06	3	T(P),BU(AB),BW(AD)	24.19
18	5	T(P),BU(AB),BW(AD),BL(BR),CB(CA)	24.46	4	T(P),BU(AB),BW(AD),CB(CA)	25.26	4	T(P),BU(AB),BW(AD),CB(CA)	24.46

Table G.24: Results for LFSW (Large Schedule)-30 to 45 Minutes

LFSW-LARGE											
00:30:00			00:35:00			00:40:00			00:45:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
1	T(P)	3.28	1	T(P)	3.45	1	T(P)	3.39	1	T(P)	3.34
1	T(P)	4.57	1	T(P)	4.53	1	T(P)	4.70	1	T(P)	4.62
1	T(P)	6.39	1	T(P)	6.36	1	T(P)	6.31	1	T(P)	6.48
1	T(P)	7.70	1	T(P)	7.94	1	T(P)	7.59	1	T(P)	7.89
2	T(P),BU(AB)	9.54	2	T(P),BU(AB)	9.69	1	T(P)	9.48	1	T(P)	9.64
2	T(P),BU(AB)	10.80	2	T(P),BU(AB)	10.75	1	T(P)	10.68	1	T(P)	10.89
3	T(P),BU(AB),BW(AD)	12.77	3	T(P),BU(AB),AF(AD)	13.01	2	T(P),AF(AD)	12.67	1	T(P)	13.12
3	T(P),BU(AB),BW(AD)	14.01	3	T(P),BU(AB),AF(AD)	13.95	2	T(P),AF(AD)	13.95	1	T(P)	14.03
3	T(P),BU(AB),BW(AD)	15.48	3	T(P),BU(AB),AF(AD)	15.37	2	T(P),AF(AD)	15.62	1	T(P)	15.37
3	T(P),BU(AB),BW(AD)	17.08	3	T(P),BU(AB),AF(AD)	16.96	2	T(P),AF(AD)	16.97	1	T(P)	16.92
3	T(P),BU(AB),BW(AD)	18.31	3	T(P),BU(AB),AF(AD)	18.45	2	T(P),AF(AD)	18.24	1	T(P)	18.31
3	T(P),BU(AB),BW(AD)	18.78	3	T(P),BU(AB),AF(AD)	18.91	2	T(P),AF(AD)	18.92	1	T(P)	19.00
3	T(P),BU(AB),BW(AD)	21.28	3	T(P),BU(AB),AF(AD)	21.13	2	T(P),AF(AD)	21.23	1	T(P)	21.10
3	T(P),BU(AB),BW(AD)	21.67	3	T(P),BU(AB),AF(AD)	21.34	2	T(P),AF(AD)	21.55	1	T(P)	21.22
3	T(P),BU(AB),BW(AD)	22.97	3	T(P),BU(AB),AF(AD)	23.14	2	T(P),AF(AD)	23.04	1	T(P)	23.13
3	T(P),BU(AB),BW(AD)	24.08	3	T(P),BU(AB),AF(AD)	24.09	2	T(P),AF(AD)	24.02	1	T(P)	24.06
4	T(P),BU(AB),BW(AD),CB(CA)	25.11	4	T(P),BU(AB),AF(AD),AI(CA)	24.42	3	T(P),AF(AD),AI(CA)	25.23	2	T(P),AI(CA)	24.41

Table G.25: Results for LFSW (Large Schedule)-50 to 60 Minutes

LFSW-LARGE								
00:50:00			00:55:00			01:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
1	T(P)	3.28	1	T(P)	3.16	1	T(P)	3.27
1	T(P)	4.68	1	T(P)	4.58	1	T(P)	4.62
1	T(P)	6.32	1	T(P)	6.32	1	T(P)	6.37
1	T(P)	7.89	1	T(P)	8.04	1	T(P)	7.51
1	T(P)	9.81	1	T(P)	9.82	1	T(P)	9.39
1	T(P)	10.99	1	T(P)	10.88	1	T(P)	10.83
1	T(P)	13.04	1	T(P)	13.02	1	T(P)	12.53
1	T(P)	14.18	1	T(P)	14.16	1	T(P)	13.99
1	T(P)	15.43	1	T(P)	15.57	1	T(P)	15.75
1	T(P)	16.92	1	T(P)	16.86	1	T(P)	17.05
1	T(P)	18.24	1	T(P)	18.33	1	T(P)	18.36
1	T(P)	18.90	1	T(P)	18.83	1	T(P)	18.90
1	T(P)	21.05	1	T(P)	20.98	1	T(P)	21.21
1	T(P)	21.17	1	T(P)	21.20	1	T(P)	21.42
1	T(P)	23.03	1	T(P)	23.04	1	T(P)	22.97
1	T(P)	24.00	1	T(P)	24.17	1	T(P)	23.88
2	T(P),AI(CA)	24.31	1	T(P)	24.26	1	T(P)	25.19

Table G.26: Results for LFSW (Medium Schedule)-15 to 30 Minutes

LFSW-MEDIUM												
	00:15:00			00:20:00			00:25:00			00:30:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)	M	Crew ID	T	M	Crew ID	T
2	2	H(K),AE(O)	2.00	2	H(K),AE(O)	2.11	1	I(K)	2.09	1	I(K)	2.04
3	3	H(K),AE(O),Z(Q)	2.24	3	H(K),AE(O),Z(Q)	2.15	2	I(K),Z(Q)	2.18	2	I(K),Z(Q)	2.12
4	4	H(K),AE(O),Z(Q),N(T)	2.93	4	H(K),AE(O),Z(Q),N(T)	2.88	3	I(K),Z(Q),N(T)	2.89	3	I(K),Z(Q),N(T)	2.72
5	5	H(K),AE(O),Z(Q),N(T),Y(U)	3.60	4	H(K),AE(O),Z(Q),N(T)	3.50	3	I(K),Z(Q),N(T)	3.53	3	I(K),Z(Q),N(T)	3.60
6	5	H(K),AE(O),Z(Q),N(T),Y(U)	4.28	4	H(K),AE(O),Z(Q),N(T)	4.33	3	I(K),Z(Q),N(T)	4.28	3	I(K),Z(Q),N(T)	4.20
7	5	H(K),AE(O),Z(Q),N(T),Y(U)	4.57	4	H(K),AE(O),Z(Q),N(T)	4.54	3	I(K),Z(Q),N(T)	4.67	3	I(K),Z(Q),N(T)	4.72
8	5	H(K),AE(O),Z(Q),N(T),Y(U)	6.87	4	H(K),AE(O),Z(Q),N(T)	6.97	3	I(K),Z(Q),N(T)	6.88	3	I(K),Z(Q),N(T)	6.71
9	5	H(K),AE(O),Z(Q),N(T),Y(U)	7.91	4	H(K),AE(O),Z(Q),N(T)	7.89	3	I(K),Z(Q),N(T)	7.84	3	I(K),Z(Q),N(T)	7.98
10	5	H(K),AE(O),Z(Q),N(T),Y(U)	8.24	4	H(K),AE(O),Z(Q),N(T)	8.46	3	I(K),Z(Q),N(T)	8.37	3	I(K),Z(Q),N(T)	8.61

Table G.27: Results for LFSW (Medium Schedule)-35 to 60 Minutes

LFSW-MEDIUM																	
00:35:00			00:40:00			00:45:00			00:50:00			00:55:00			01:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
1	I(K)	1.99	0	No Match	2.03	0	No Match	1.97	0	No Match	2.09	0	No Match	2.07	0	No Match	1.98
2	I(K),Z(Q)	2.09	0	No Match	2.13	0	No Match	2.04	0	No Match	2.16	0	No Match	2.13	0	No Match	2.29
3	I(K),Z(Q),N(T)	2.66	1	R(Q)	2.54	1	R(Q)	2.42	1	R(Q)	2.51	1	R(Q)	2.54	1	R(Q)	2.46
3	I(K),Z(Q),N(T)	3.43	2	R(Q),N(T)	3.29	2	R(Q),N(T)	3.31	2	R(Q),N(T)	3.22	2	R(Q),N(T)	3.09	2	R(Q),N(T)	3.21
3	I(K),Z(Q),N(T)	4.31	2	R(Q),N(T)	4.32	2	R(Q),N(T)	4.20	2	R(Q),N(T)	4.07	2	R(Q),N(T)	4.19	2	R(Q),N(T)	4.09
3	I(K),Z(Q),N(T)	4.81	2	R(Q),N(T)	4.90	2	R(Q),N(T)	4.84	2	R(Q),N(T)	4.83	2	R(Q),N(T)	4.84	2	R(Q),N(T)	4.92
3	I(K),Z(Q),N(T)	6.71	2	R(Q),N(T)	6.62	2	R(Q),N(T)	6.67	2	R(Q),N(T)	6.66	2	R(Q),N(T)	6.53	2	R(Q),N(T)	6.37
3	I(K),Z(Q),N(T)	7.98	2	R(Q),N(T)	7.87	2	R(Q),N(T)	7.96	2	R(Q),N(T)	7.87	2	R(Q),N(T)	8.04	2	R(Q),N(T)	7.70
3	I(K),Z(Q),N(T)	8.40	2	R(Q),N(T)	8.09	2	R(Q),N(T)	8.30	2	R(Q),N(T)	8.02	2	R(Q),N(T)	8.22	2	R(Q),N(T)	7.96

Table G.28: Results for LFSW (Small Schedule)

LFSW-SMALL							
	00:15:00			00:20:00			
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	0	NO MATCH	0.88	0	NO MATCH	0.79
3	0	NO MATCH	1.37	0	NO MATCH	1.42
4	0	NO MATCH	1.68	0	NO MATCH	1.59
5	0	NO MATCH	2.06	0	NO MATCH	1.99

Table G.29: Results for UNV (Large Schedule)-30 to 45 Minutes

UNV-LARGE						
	00:30:00			00:45:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	1	B(E1)	2.79	1	B(E1)	3.01
3	2	B(E1),F(E3)	4.10	2	B(E1),F(E3)	4.39
4	2	B(E1),F(E3)	4.28	2	B(E1),F(E3)	6.59
5	3	B(E1),F(E3),AC(E5)	6.23	3	B(E1),F(E3),AC(E5)	7.92
6	4	B(E1),F(E3),AC(E5),AF(E6)	6.76	4	B(E1),F(E3),AC(E5),AF(E6)	9.48
7	5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	8.40	5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.65
8	6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	8.61	6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.68
9	7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	9.09	7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	13.88
10	8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10)	13.31	8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10)	15.63
11	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11)	15.43	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	17.14
12	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10) BW(E11)	16.09	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.33
13	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11)	17.28	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.96
14	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11),CC(E14)	18.54	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.45
15	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11),CC(E14)	19.48	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.80
16	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11),CC(E14)	20.71	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	22.95
17	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11),CC(E14)	21.98	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	24.03
18	11	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(E10),BW(E11),CC(E14),AP(E18	24.40	11	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14),AP(1	25.12

Table G.30: Results for UNV (Large Schedule)-60 to 75 Minutes

UNV-LARGE					
01:00:00			01:15:00		
M	Crew ID	T	M	Crew ID	T
1	B(E1)	3.16	1	B(E1)	2.96
2	B(E1),F(E3)	4.60	2	B(E1),F(E3)	4.36
2	B(E1),F(E3)	6.63	2	B(E1),F(E3)	6.35
3	B(E1),F(E3),AC(E5)	7.71	3	B(E1),F(E3),AC(E5)	7.75
4	B(E1),F(E3),AC(E5),AF(E6)	9.56	4	B(E1),F(E3),AC(E5),AF(E6)	9.45
5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.76	5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.93
6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.98	6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.95
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	13.81	7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	13.72
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10)	15.59	8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10)	15.68
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	17.02	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	16.94
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.26	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.20
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.79	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.71
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.36	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.53
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.47	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	22.53
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.11	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.01
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	24.14	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.94
11	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14),AP(18)	25	11	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14),AP(18)	24.8

Table G.31: Results for UNV (Large Schedule)-90 to 105 Minutes

UNV-LARGE					
01:30:00			01:45:00		
M	Crew ID	T	M	Crew ID	T
1	B(E1)	3.20	1	B(E1)	3.03
2	B(E1),F(E3)	4.49	2	B(E1),F(E3)	4.48
2	B(E1),F(E3)	6.34	2	B(E1),F(E3)	6.54
3	B(E1),F(E3),AC(E5)	7.93	3	B(E1),F(E3),AC(E5)	7.87
4	B(E1),F(E3),AC(E5),AF(E6)	9.69	4	B(E1),F(E3),AC(E5),AF(E6)	9.58
5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.96	5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.71
6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.81	6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.96
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	13.74	7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9)	14.03
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10)	15.39	8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10)	15.55
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	17.07	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	16.98
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.09	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.35
9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	18.94	9	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11)	19.02
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.28	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.38
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.74	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	21.76
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.16	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.03
10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	23.97	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	24.07
11	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14),AP(18)	25.38	10	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),AH(E9),BX(10),BW(11),CC(E14)	25.29

Table G.32: Results for UNV (Large Schedule)-120 Minutes

UNV-LARGE		
	02:00:00	
M	Crew ID	T
1	B(E1)	3.04
2	B(E1),F(E3)	4.60
2	B(E1),F(E3)	6.30
3	B(E1),F(E3),AC(E5)	7.85
4	B(E1),F(E3),AC(E5),AF(E6)	9.42
5	B(E1),F(E3),AC(E5),AF(E6),AD(E7)	10.94
6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	12.75
6	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8)	14.03
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10)	15.44
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10)	16.86
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10)	18.32
7	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10)	18.89
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10),CC(E14)	21.44
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10),CC(E14)	21.55
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10),CC(E14)	22.92
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10),CC(E14)	23.95
8	B(E1),F(E3),AC(E5),AF(E6),AD(E7),AG(E8),BX(10),CC(E14)	25.42

Table G.33: Results for UNV (Medium Schedule)-30 to 45 Minutes

UNV-MEDIUM						
	00:30:00			00:45:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)
2	2	J(E1),L(E2)	1.83	2	J(E1),L(E2)	1.87
3	2	J(E1),L(E2)	1.98	2	J(E1),L(E2)	2.13
4	3	J(E1),L(E2),M(E4)	3.17	3	J(E1),L(E2),M(E4)	2.89
5	4	J(E1),L(E2),M(E4),U(E5)	3.23	4	J(E1),L(E2),M(E4),U(E5)	3.50
6	5	J(E1),L(E2),M(E4),U(E5),Y(E6)	3.26	5	J(E1),L(E2),M(E4),U(E5),Y(E6)	4.31
7	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	3.68	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	4.41
8	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	5.19	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	6.86
9	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	5.59	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	8.02
10	7	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7),AV(E10)	7.94	7	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7),AV(E10)	8.41

Table G.34: Results for UNV (Medium Schedule)-60 to 75 Minutes

UNV-MEDIUM					
	01:00:00			01:15:00	
M	Crew ID	T	M	Crew ID	T
2	J(E1),L(E2)	2.08	2	J(E1),L(E2)	1.94
2	J(E1),L(E2)	2.15	2	J(E1),L(E2)	2.31
3	J(E1),L(E2),M(E4)	3.05	3	J(E1),L(E2),M(E4)	3.00
4	J(E1),L(E2),M(E4),U(E5)	3.51	4	J(E1),L(E2),M(E4),U(E5)	3.65
5	J(E1),L(E2),M(E4),U(E5),Y(E6)	4.15	5	J(E1),L(E2),M(E4),U(E5),Y(E6)	4.45
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	4.54	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	4.72
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	6.93	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	6.89
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	7.81	6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	7.98
7	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7),AV(E10)	8.27	7	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7),AV(E10)	8.40

Table G.35: Results for UNV (Medium Schedule)-90 to 120 Minutes

UNV-MEDIUM								
01:30:00			01:45:00			02:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
2	J(E1),L(E2)	2.01	2	J(E1),L(E2)	1.93	2	J(E1),L(E2)	2.10
2	J(E1),L(E2)	2.10	2	J(E1),L(E2)	2.19	2	J(E1),L(E2)	2.15
3	J(E1),L(E2),M(E4)	2.84	2	J(E1),L(E2)	3.10	2	J(E1),L(E2)	2.97
4	J(E1),L(E2),M(E4),U(E5)	3.75	3	J(E1),L(E2),U(E5)	3.45	2	J(E1),L(E2)	3.67
5	J(E1),L(E2),M(E4),U(E5),Y(E6)	4.17	4	J(E1),L(E2),U(E5),Y(E6)	4.37	3	J(E1),L(E2),Y(E6)	4.25
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	4.40	5	J(E1),L(E2),U(E5),Y(E6),C(E7)	4.51	4	J(E1),L(E2),Y(E6),C(E7)	4.68
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	7.02	5	J(E1),L(E2),U(E5),Y(E6),C(E7)	6.71	4	J(E1),L(E2),Y(E6),C(E7)	6.78
6	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7)	7.80	5	J(E1),L(E2),U(E5),Y(E6),C(E7)	8.06	4	J(E1),L(E2),Y(E6),C(E7)	7.79
7	J(E1),L(E2),M(E4),U(E5),Y(E6),C(E7),AV(E10)	8.41	6	J(E1),L(E2),U(E5),Y(E6),C(E7),AV(E10)	8.29	5	J(E1),L(E2),Y(E6),C(E7),AV(E10)	8.26

Table G.36: Results for UNV (Small Schedule)-30 to 75 Minutes

UNV-SMALL												
	00:30:00			00:45:00			01:00:00			01:15:00		
EV	M	Crew ID	T(S)	M	Crew ID	T(S)	M	Crew ID	T	M	Crew ID	T
2	1	C(E1)	0.87	1	C(E1)	0.72	1	C(E1)	0.85	1	C(E1)	0.86
3	2	C(E1),L(E3)	1.27	2	C(E1),L(E3)	1.40	2	C(E1),L(E3)	1.11	2	C(E1),L(E3)	1.19
4	2	C(E1),L(E3)	1.47	2	C(E1),L(E3)	1.60	2	C(E1),L(E3)	1.32	2	C(E1),L(E3)	1.36
5	2	C(E1),L(E3)	1.91	2	C(E1),L(E3)	1.85	2	C(E1),L(E3)	1.94	2	C(E1),L(E3)	1.96

Table G.37: Results for UNV (Small Schedule)-90 to 120 Minutes

UNV-SMALL								
01:30:00			01:45:00			02:00:00		
M	Crew ID	T	M	Crew ID	T	M	Crew ID	T
1	C(E1)	0.87	1	C(E1)	0.82	1	C(E1)	0.94
2	C(E1),L(E3)	1.30	2	C(E1),L(E3)	1.28	1	C(E1)	1.43
2	C(E1),L(E3)	1.42	2	C(E1),L(E3)	1.61	1	C(E1)	1.50
2	C(E1),L(E3)	1.95	2	C(E1),L(E3)	1.88	1	C(E1)	1.89

Appendix H: An Example of How the MAS Algorithm Works

The MAS algorithm in AgentPower is works based on the agent's interaction. In CRSMAS there are two types of agent, namely Duty Agent (DA) and Crew Agent (CA). DA acts as a demand agent and CA acts as a supply/resource agent. DA is the main agent that plays a great role in the matching process. Figure H.1 shows the flow of the process in the algorithm. It starts with (Process 1). DA sends a message to all CAs to initialize them. CAs will reply to DA (Process 2). Then DA sends a message to CAs to inform them that the matching process has started (Process 3). Then, each CA replies to DA to indicate that the agent is ready for the matching process (Process 4). DA checks all the properties of each CA in turn, to see whether they match with DA's requirements (Process 5). If there is a match then DA puts the selected CA in the reservation (Process 6); otherwise DA continues to the next CA. The matching process continues until all CAs have gone through the process. Finally (Process 7), if there is one CA in the reservation then the agent is chosen to take the duty. In the case where there is more than one CA in the reservation then DA chooses the best option based on the DMM condition. However, if there is more than one who has the same properties then the first in the queue is chosen.

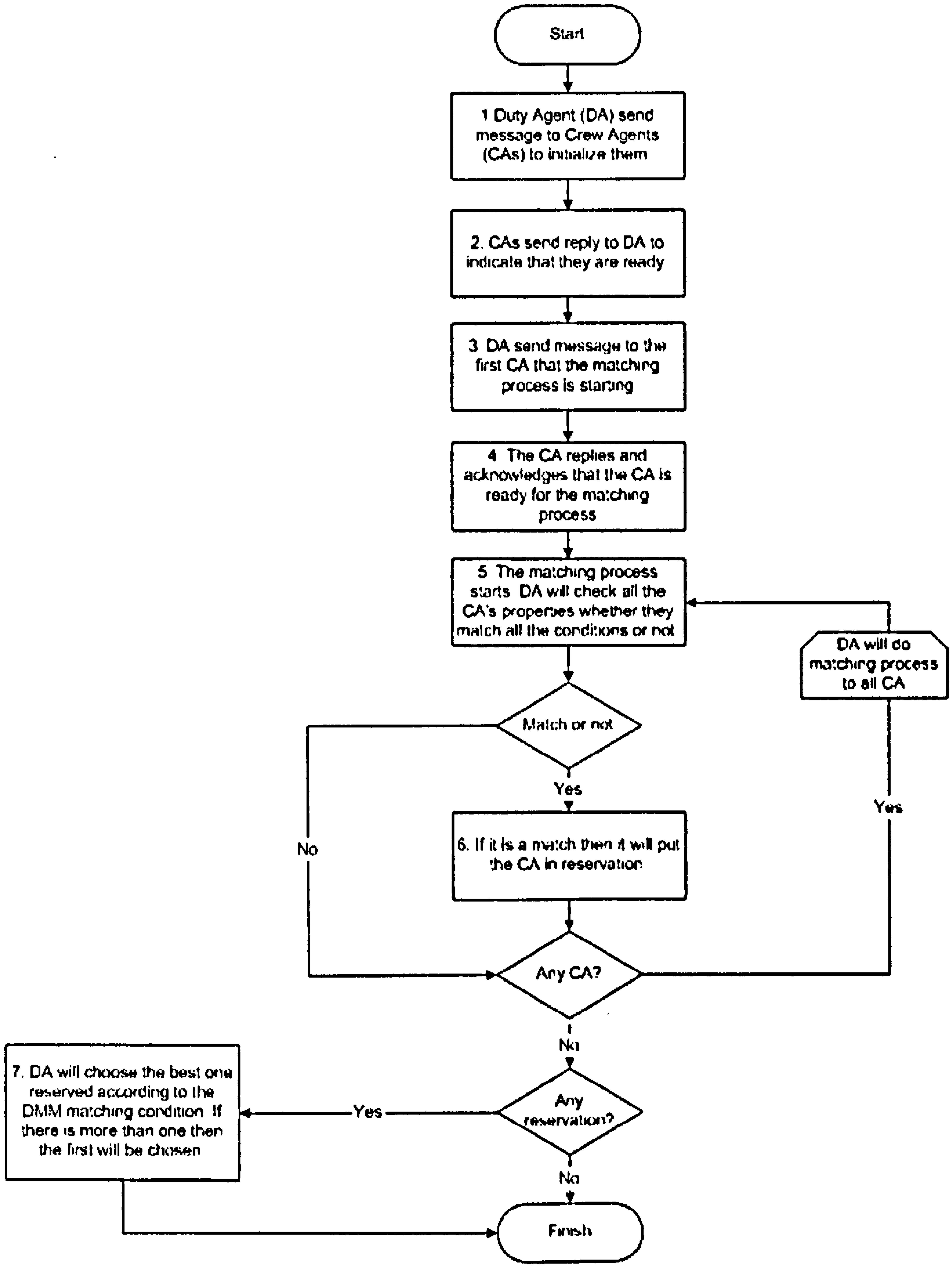


Figure H.1: The Flow of the MAS algorithm

In order to understand how the MAS algorithm works, we can look at a simple example. The example explains the step-by-step process of the algorithm. Consider the situation where there are two crews (C and D). Table H.1 shows the details of the crews. Crew C is late for signing on by 15 minutes and he/she is only ready for work at 6:20 (the arrival time plus 5 minutes to get ready). So, there is a need to find a replacement driver for Duty No. 570, which is the duty number of crew C, In order to make a simulation, we create a new duty based on Duty No. 570 with different attributes. The attributes (for the case of late signing on) are *start time required* and *late crew ready time. Start time required* is the latest signing-on time for any crew who can take the duty. *Late crew ready time* is a time when the late crew is available for duty (the arrival time plus 5 minutes to get ready). Table H.2 shows the details of Duty 1.

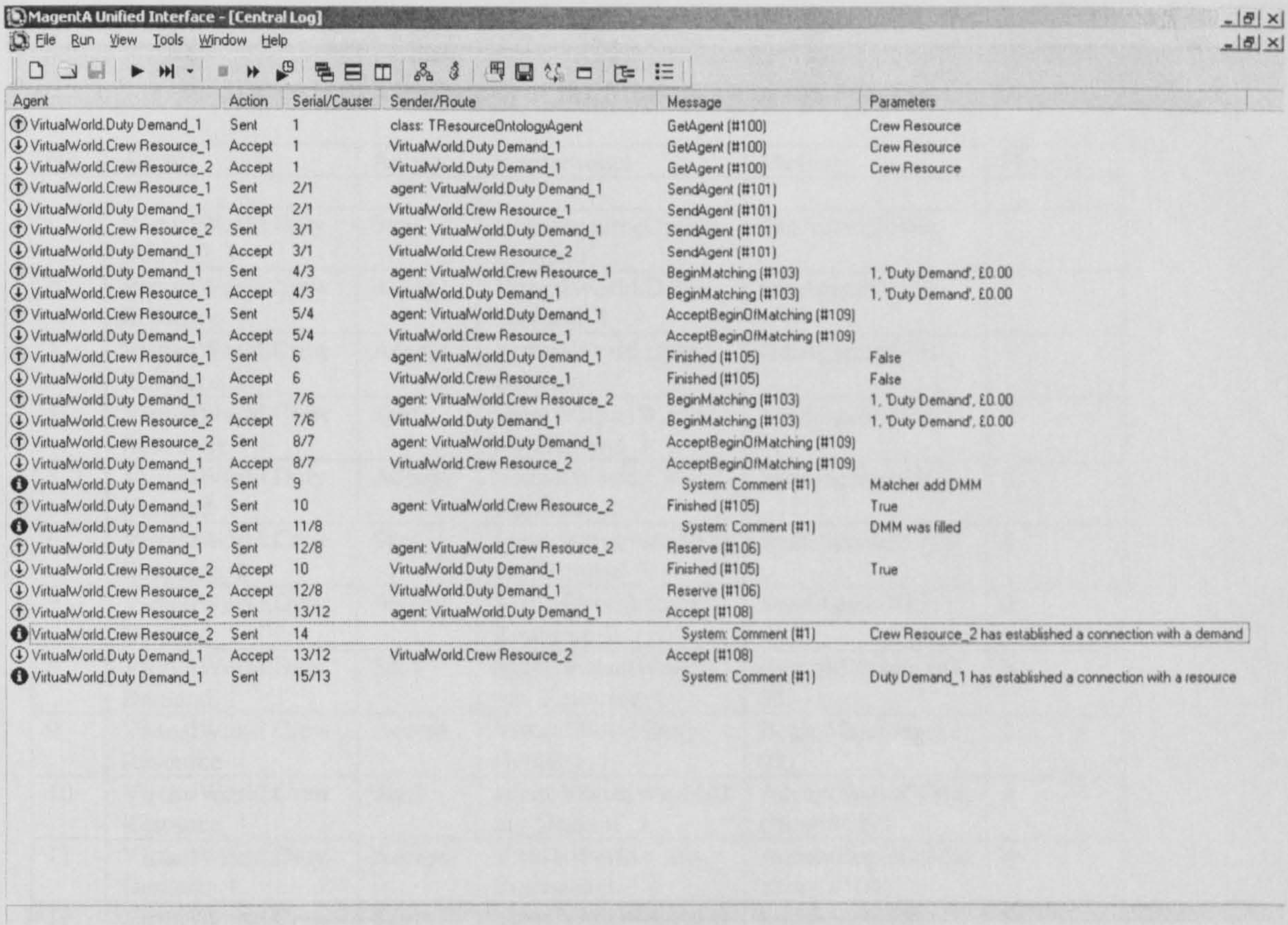
Table H.1: The Details of the Crews

CrewID	Duty No Assigned	SignOn	StartTime1	EndTime1	Start Relief	End Relief	StartTime2	EndTime2	SignOff
C	570	06:00:00	06:15:00	09:43:00	09:48:00	10:47:00	10:52:00	13:38:00	13:48:00
D	571	06:10:00	06:25:00	09:54:00	09:59:00	11:07:00	11:12:00	14:58:00	15:08:00

Table H.2: The Details of the Duty 1

Name	DutyNo	StartTimeRequired	LateCrewReadyTime
Duty 1	570	06:10:00	06:20:00

The next step is to run the simulation. In the simulation the CA is created based on how many crews are assigned to duties in a crew schedule. In this example there are two CAs. The number of DAs depends on the UE taking place. In this example there is one. The simulation shows the agents interact with each other in order to find the best solution. The result of the simulation shows that Duty 1 is matched to Crew D. Crew D takes Duty 1 (No. 570) and Duty C is assigned to Duty No. 571 which originally belonged to Duty D. In AgentPower the messages are displayed in the central log (see Figure H.2). The log shows the messages exchanged between DA and CA.



MagentA Unified Interface - [Central Log]

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Agent	Action	Serial/Causer	Sender/Route	Message	Parameters
VirtualWorld.Duty Demand_1	Sent	1	class: TResourceOntologyAgent	GetAgent (#100)	Crew Resource
VirtualWorld.Crew Resource_1	Accept	1	VirtualWorld.Duty Demand_1	GetAgent (#100)	Crew Resource
VirtualWorld.Crew Resource_2	Accept	1	VirtualWorld.Duty Demand_1	GetAgent (#100)	Crew Resource
VirtualWorld.Crew Resource_1	Sent	2/1	agent: VirtualWorld.Duty Demand_1	SendAgent (#101)	
VirtualWorld.Duty Demand_1	Accept	2/1	VirtualWorld.Crew Resource_1	SendAgent (#101)	
VirtualWorld.Crew Resource_2	Sent	3/1	agent: VirtualWorld.Duty Demand_1	SendAgent (#101)	
VirtualWorld.Duty Demand_1	Accept	3/1	VirtualWorld.Crew Resource_2	SendAgent (#101)	
VirtualWorld.Duty Demand_1	Sent	4/3	agent: VirtualWorld.Crew Resource_1	BeginMatching (#103)	1, 'Duty Demand', £0.00
VirtualWorld.Crew Resource_1	Accept	4/3	VirtualWorld.Duty Demand_1	BeginMatching (#103)	1, 'Duty Demand', £0.00
VirtualWorld.Crew Resource_1	Sent	5/4	agent: VirtualWorld.Duty Demand_1	AcceptBeginOfMatching (#109)	
VirtualWorld.Duty Demand_1	Accept	5/4	VirtualWorld.Crew Resource_1	AcceptBeginOfMatching (#109)	
VirtualWorld.Crew Resource_1	Sent	6	agent: VirtualWorld.Duty Demand_1	Finished (#105)	False
VirtualWorld.Duty Demand_1	Accept	6	VirtualWorld.Crew Resource_1	Finished (#105)	False
VirtualWorld.Duty Demand_1	Sent	7/6	agent: VirtualWorld.Crew Resource_2	BeginMatching (#103)	1, 'Duty Demand', £0.00
VirtualWorld.Crew Resource_2	Accept	7/6	VirtualWorld.Duty Demand_1	BeginMatching (#103)	1, 'Duty Demand', £0.00
VirtualWorld.Crew Resource_2	Sent	8/7	agent: VirtualWorld.Duty Demand_1	AcceptBeginOfMatching (#109)	
VirtualWorld.Duty Demand_1	Accept	8/7	VirtualWorld.Crew Resource_2	AcceptBeginOfMatching (#109)	
VirtualWorld.Duty Demand_1	Sent	9		System: Comment (#1)	Matcher add DMM
VirtualWorld.Duty Demand_1	Sent	10	agent: VirtualWorld.Crew Resource_2	Finished (#105)	True
VirtualWorld.Duty Demand_1	Sent	11/8		System: Comment (#1)	DMM was filled
VirtualWorld.Duty Demand_1	Sent	12/8	agent: VirtualWorld.Crew Resource_2	Reserve (#106)	
VirtualWorld.Crew Resource_2	Accept	10	VirtualWorld.Duty Demand_1	Finished (#105)	True
VirtualWorld.Crew Resource_2	Accept	12/8	VirtualWorld.Duty Demand_1	Reserve (#106)	
VirtualWorld.Crew Resource_2	Sent	13/12	agent: VirtualWorld.Duty Demand_1	Accept (#108)	
VirtualWorld.Crew Resource_2	Sent	14		System: Comment (#1)	Crew Resource_2 has established a connection with a demand
VirtualWorld.Duty Demand_1	Accept	13/12	VirtualWorld.Crew Resource_2	Accept (#108)	
VirtualWorld.Duty Demand_1	Sent	15/13		System: Comment (#1)	Duty Demand_1 has established a connection with a resource

Figure H.2: The Messages Exchanged between Agents

Table H.3 shows the details of the messages in the log and the process related to the MAS algorithm as explained in the first paragraph. *No.* shows the sequence of the message, *Agent* indicates the agent who is doing the process, *Action* refers to the action of the agent, *Sender/route* explains who is sending the message or the route used for the message, *Message* shows what the message is, and *Process* shows the process the agent is using. The process refers to the activity which takes place in the MAS algorithm. For example, the first message is the message from DA. *VirtualWorld.Duty Demand_1* means the DA number 1, which acts as a duty demand in the virtual world. The action is *sent* means DA is sending the message. *Class.resourceOntologyAgent* means DA number 1 is from class resource ontology agent. The message is *GetAgent(#100)* which means DA needs to get the details of CA and the message code is 100. Process *1* is referring to the process in the MAS algorithm, which is "Duty Agent (DA) sends message to Crew Agents (CAs) to initialize them".

Table H.3: The Details of the Messages and the Process

No.	Agent	Action	Sender/route	Message	Process
1	VirtualWorld.Duty Demand_1	Sent	class.resourceOntologyAgent	GetAgent(#100)	1
2	VirtualWorld.Crew Resource_1	Accept	VirtualWorld.Duty Demand_1	GetAgent(#100)	1
3	VirtualWorld.Crew Resource_2	Accept	VirtualWorld.Duty Demand_1	GetAgent(#100)	1
4	VirtualWorld.Crew Resource_1	Sent	agent:VirtualWorld.Duty Demand_1	SendAgent(#101)	2
5	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_1	SendAgent(#101)	2
6	VirtualWorld.Crew Resource_2	Sent	agent:VirtualWorld.Duty Demand_1	SendAgent(#101)	2
7	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_2	SendAgent(#101)	2
8	VirtualWorld.Duty Demand_1	Sent	agent:VirtualWorld.Crew Resource_1	BeginMatching(#103)	3
9	VirtualWorld.Crew Resource_1	Accept	VirtualWorld.Duty Demand_1	BeginMatching(#103)	3
10	VirtualWorld.Crew Resource_1	Sent	agent:VirtualWorld.Duty Demand_1	AcceptBeginOfMatching(#109)	4
11	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_1	AcceptBeginOfMatching(#109)	4
12	VirtualWorld.Crew Resource_1	Sent	agent:VirtualWorld.Duty Demand_1	Finished(#105)	5
13	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_1	Finished(#105)	5
14	VirtualWorld.Duty Demand_1	Sent	agent:VirtualWorld.Crew Resource_2	BeginMatching(#103)	3
15	VirtualWorld.Crew Resource_2	Accept	VirtualWorld.Duty Demand_1	BeginMatching(#103)	3
16	VirtualWorld.Crew Resource_1	Sent	agent:VirtualWorld.Duty Demand_1	AcceptBeginOfMatching(#109)	4
17	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_2	AcceptBeginOfMatching(#109)	4
18	VirtualWorld.Duty Demand_1	Sent	agent:VirtualWorld.Crew Resource_2	Finished(#105)	5
19	VirtualWorld.Crew Resource_1	Accept	VirtualWorld.Duty Demand_1	Finished(#105)	5
20	VirtualWorld.Duty Demand_1	Sent		System: Comment(#1)	
21	VirtualWorld.Duty Demand_1	Sent	agent:VirtualWorld.Crew Resource_2	Reserve(#106)	6
22	VirtualWorld.Crew Resource_1	Accept	VirtualWorld.Duty Demand_1	Reserve(#106)	6
23	VirtualWorld.Crew Resource_1	Sent	agent:VirtualWorld.Duty Demand_1	Accept(#108)	6
24	VirtualWorld.Duty Demand_1	Accept	VirtualWorld.Crew Resource_2	Accept(#108)	7