Real-Time Bus Crew Scheduling Using Multi-Agents System

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Abstract

Bus crew scheduling problem is notoriously difficult to solve because of the large number of resources that need to be allocated, very complex rules for the allocation of crew shifts, high cost of overtime and unpredictability of the urban traffic and crew availability. Current schedulers are reviewed and critiqued. The paper considers an alternative approach to the bus crew allocation based on the use of multi-agent systems capable of real-time scheduling and dynamic re-scheduling whenever an unpredictable change of resources or demands occurs.

1.0 Introduction

Public transport crew scheduling is an ever growing issue in terms of complexity, cost and political pressure. The complexity aspect can be attributed to the fact that public transport crew scheduling involves many variables, such as the availability of personnel, social and cultural factors and a high level of dynamics and unpredictability of the problem itself; the cost aspect is attributed to the fact that the crew expenses can raise the overall cost of public transport quite significantly [{21 Yunes,T.H. 2000}]. One of the main issues related to that is possible miscalculation of shifts which could lead to high rates for overtime, a factor that is commonly known to increase the cost of drivers. Politically, public transport is an important factor for enhancing or demolishing policy makers’ credibility in the eyes of the public. Having buses not coming on time or frequent delays in school transportation is a serious source of discontent. Given such importance, crew scheduling has been extensively studded by academics as well as bus operators. Many techniques have been applied – primarily those belonging to the family of Mathematical Programming and Optimisation techniques - for example, Genetic Algorithms [{116 Wren, A. 1995}]; Fuzzy Genetic Algorithms [{115 Li,J. 2003}]; Integer Programming [{110 Valouxis,C. 2002}]; Dynamic Programming [{81 Beasley,J.E. 1998}]; Hybrid Integer Programming and Heuristics [{125 Fores, S. 2002}].

This paper discusses the above methods in more detail with respect to their theoretical underpinnings, context, practical usefulness and limitations. Before describing the existing methods a general description of the crew scheduling problem is given. Although the emphasis is on bus crew, some of the methods are generic in nature and may be used for scheduling crew for different types of transport, such as aircraft and trains.

In the second part of the paper a consideration is given to a very promising technology of multi-agent systems, which offers considerable advantages when compared to conventional methods.

2.0 The Crew Scheduling Problem

Before delving deeper in the theoretical issues of this paper, it is beneficial to understand first the meaning of terminology that will be used. The basic terminology of bus crew scheduling is as follows:

- A depot / garage is a parking place for vehicles that are not in use for some time.
- A trip is movement with passengers between two relief points or depot at a specified departure and arrival time.
- A deadhead is a movement in time between two trips, from a depot to the first trip and from the last trip to a depot, usually without passenger.
- A relief point is a location and time where and when a change of crew may occur.
- A shift (or duty) is a sequence of trips assigned to the same crew.
• An idle interval is an interval between two consecutive trips in a shift
• The sum of idle intervals in a shift is a rest time
• The sum of durations of trips in a shift is a working time
• Major constraints include minimum rest time, idle limit (if the idle time exceeds the idle limit, it counts as an interruption in a shift and the crew is considered to work a split shift) and workday (is the shift hours exceed a workday, the crew is paid overtime)

Referring to the above terminology, the bus crew scheduling can be described as the allocation of crews to trips within given constraints and with the aim of minimising the cost of transportation.

If the scheduling of bus crew is done separately from the scheduling of busses, additional constraints are the number of busses and bus schedules. For example, the number of trips is mainly related to the number of available busses and routes as well as to the time of the day the trip is scheduled for. One of the major issues to consider is the unpredictable events. Bus drivers like any other human beings get ill without prior notice, and this means that the schedule should take into consideration contingency plans for unpredictable events. Traffic and road conditions are usually important as an aspect of unplanned activities.

A typical requirement from a scheduling tool is the ability to provide the optimal schedules (i.e. minimum cost) in a short time and coupled with the ability to cope with unplanned events (i.e. the ability to reschedule accordingly). These requirements have been the driving force behind most of the attempts to provide reliable schedulers which are also practical and easy to use. There is no point having a good scheduler if it does not provide the results on time and with self-explanatory features.

Another important issue that adds to the complexity of the crew scheduling is its interdependence on the bus scheduling. Naturally, bus crews are scheduled in accordance with bus and trip schedules and this means that if there are any problems with the bus schedule then this will have a ripple effect on the crew schedule. Valouxis and Housos (110 Valouxis, C. 2002) show an example of a combined bus and crew scheduling problem. In cases like this, sometimes part of the requirements is to keep the driver to the same bus. This is often very difficult to maintain due to the dynamic nature of transportation.

Fores et al (125 Fores, S. 2002) give a background on how crews are scheduled as a part of multi-stage planning process of bus operations. The authors stress that these stages are not necessarily independent or sequential. The stages are: plan the network; design the routes, including travel time; decide the departure times; allocate busses to the journeys; integrate schedules to cover a larger network, including odd special journeys; compile crew schedules to cover all busses; construct roster to include all crew duties over a period of weeks, produce documentation. The drivers plan is usually subject to constraints such as meal breaks after a certain time, maximum length of shifts and minimum length of breaks. These features are important to notice as they are not applied when scheduling vehicles which add to the complexity of scheduling crews. Schedules for bus drivers will have to be developed bearing in mind these issues and the vehicles schedule. Each shift incurs a specific cost rising or decreasing given the circumstances of the shift, for example, unpopular shifts are sometimes given higher cost. This schedule is for a typical day; however, schedules are also mapped over longer periods. Rosters, usually run over a period of weeks, are constructed by including rest days whilst taking into account weekends and public holidays.

In many cases, as mentioned earlier, scheduling of bus drivers is closely linked to bus schedules (110 Valouxis, C. 2002). In this particular case the driver is required to stay with the same bus at all times. The main problem is due to possible cycling between shift creation and assignment steps, where assignments are usually limited by rules and legalities.

3.0 Current Schedulers

In this section we discuss current methods used to solve the above problems, observing that most of these methods are developed to solve specific problems rather than being independent tools. For example, consider Beasley and Cao (81 Beasley, J.E. 1998) who use Dynamic Programming for crew scheduling. Desaulniers (485 Desaulniers, G. 2003) proposes a dynamic fixed-cost strategy that can be integrated into the existing branch-and-price approaches to speed them up. The aim of the paper is to drive the fixed cost that is associated with vehicles and waiting. Traditionally cost is assigned in an arbinal fashion for the purpose of optimisation.

Computer-Aided Scheduling of Public Transport (CASPT) is a conference that is held every three years dedicated to all issues related to public transport, including crew scheduling. This is possibly the most important conference totally dedicated to these types of problems. CASPT 2000 (479 Voß, S. 2001) included a number of papers that describe solutions and tools for scheduling. For example, Banihashemi and Hagiani (480 Banihashemi, M. 2000) produced a model for mass transit driver scheduling which is based on existing Linear Programming models yet with some important alterations. One of the main points
related to this paper is that it gives a comprehensive glossary for the variables in the model which is quite useful for replicating the runs. Borndörfer et al. \cite{Borndorfer2000} present Adaptive Column Generation method for scheduling. The paper claims that column generation is one of the best established optimisation approaches to duty scheduling. This paper gives a brief description of methods of column generation for creating duties. The adaptability is defined by using a probing method (Lagrangian Probing) which fixes variables and assesses the optimality which is then iteratively refined until the optimum situation is achieved. The paper also provides pseudo codes for the algorithms used in the scheduling process. Emden-Weinert et al. \cite{EmdenWeinert2000} describe a driver scheduling system for public transport (DISSY) in Germany. This is a European funded project – details about the project can be found at \url{http://people.freenet.de/Emden-Weinert/DISSY}.

DISSY is a simulation and decision support system for the bus and driver duty rostering in urban public transport. There are two main issues to note in this paper; firstly, that simulation allows experimenting with different scenarios to be tested, especially with regard to unpredictable events. Secondly, and stemming from the first point, DISSY uses Simulated Annealing meta-heuristics to optimise local neighbourhoods. This includes moving, deleting and swapping duties. The package is claimed to process 2000 moves per second. Ernst et al. (2000) present a staff optimisation toolkit (SORT) in Australia. The authors belong to the OR department of the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The paper provides a brief review and description of the different types of rosters and rostering. It mentions SORT toolkit, which provides flexible means allowing individual drivers preferences to be entered. However, it is mentioned in the paper that the speed of the scheduling process is inversely related to the size of input. Meliton \cite{Meliton2000} present an experience of selecting computer aided scheduling software. This paper represents the user side of the equation. The author is the scheduling manager of FirstGroup plc, which is the biggest bus company in the UK. The paper describes the steps taken to evaluate and select scheduling tools. It gives information on what users are looking for in schedulers, reviews lessons learned from experience, and provides a set of scenarios and conditions used to assess the different software in the market. Lourenço et al. \cite{Lourenco2000} explain the use of multiobjective metaheuristics for crew scheduling in Portugal. The paper provides a good background to the different systems and projects dedicated to this problem.

### 4.0 Theory behind Scheduling Methods

In this section we discuss the theoretical underpinnings of main scheduling methods which are currently implemented. Only fundamental concepts of each method, with brief mathematical explanations when required, are included. The purpose is to explain the theory to scheduling practitioners who do not posses deep mathematical knowledge but need to understand how these methods work.

Four scheduling methods have been chosen here due to their commercial prevalence. Those are, as mentioned earlier, Genetic Algorithms \cite{Wren1995}; Fuzzy Genetic Algorithms \cite{LiJ2003}; Integer Programming \cite{Valouxix2002}; and Hybrid Integer Programming with Heuristics \cite{Fores2002}. The list is not exhaustive, yet it provides a comprehensive picture of major methods used for crew scheduling.

#### 4.1 Genetic Algorithms

Wren and Wren \cite{Wren1995} present driver shifts as a series of consecutive trips in a given day or a specified period of time. This structure represents the main inspiration behind the use of Genetic Algorithms. In their paper Wren and Wren \cite{Wren1995} state that principles of genetic algorithms are based on strings in artificial systems which are similar in structure to natural chromosomes consisting of strings of genes. In this case, the frame of reference is the string of shifts in a target period of time during which scheduling is to be performed. The assumed length of a shift is from the time a driver reports to the station/depot to the end of the last job of the day. The shift is made of spells, which are divided by breaks and bus changes. The spell is made of work units, where each unit is based on driving a single bus or several buses. Bus drivers may have to drive more than one bus during the shift because of legally imposed breaks. For example, if a driver has to stop for a break, another driver takes over and drives the bus, whilst the original driver, after the break, is given a different bus. Units could also be used as overtime. This happens when a unit is covered by two shifts, which is called over-cover. The over-cover is usually a result of slack schedules.

The solution is produced by generating an initial set of solutions followed by repeatedly generating offspring sets until the desired solution emerges. The initial set is generated by randomly varying the order in which shifts are considered for discarding. The evolution to the next generations is processed by taking the units in chronological order whilst taking the corresponding shifts in random order. Offsprings are
usually generated by mating two or more values from the previous generation.

According to Wren and Wren \cite{116 Wren, A. 1995} the credibility of this method would be better established if it was tested for larger population. The authors believe that this method would be workable for larger population if intelligently biased evaluation was incorporated. The method was subsequently modified and, in fact, the next method described below could be considered as its extension.

4.2 Fuzzy Genetic Algorithms

Li et al \cite{115 Li, J. 2003} present another scheduling method which is based on a combination of Genetic Algorithms and Fuzzy Set Theory. Sets of shifts are collected using greedy heuristic method. 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 shift cover with minimum cost using the minimum number of shifts. 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. This method is based on the same problem formulation as described in the previous section.

Li et al \cite{115 Li, J. 2003} state that there is a major concern about finding an optimum situation using heuristics. This is because the true optimum solution is not known, which makes it difficult to evaluate the achieved solution. To deal with that the authors suggest a near optimal solution, which can be realised by comparing the heuristic optimum with the best known solution. This is done by applying a relative percentage deviation (RPD) over the best known schedule to measure the quality of the heuristic schedule.

The authors stress that this is the first time the fuzzy set theory has been applied in the field of scheduling bus crews. The main finding is that the approach produces a near-optimal weight distribution for large size real life problems.

It must be noted here that authors of most scheduling methods do not claim that their methods can achieve the optimum schedule – only a near-optimal one.

4.3 Integer Programming

Valouxis and Housos \cite{110 Valouxis, C. 2002} use integer programming as their scheduling method. The general setup is slightly different from that used by the previous methods. In this case the crews are scheduled in conjunction with the bus schedule rather than based on it, which is important if bus companies may require the bus and the driver to stay together all the time, which is not the case usually. The mathematical model is based on zero-one integer programming. The starting point and search mechanism are distinguishing features. The procedure starts from all feasible legs that each bus could use and considers all possible segments until all possible shifts for all busses are formed. The work rules are checked during and throughout the creation of the shift.

The solution procedure follows a combination of Column Generation and Quick Shift approaches (CGQS). The steps followed can be summarised as: (1) generate the initial solution, which is based on using QS solution by dividing all trip segments into levels and optimise these levels repeatedly as long as shifts can be improved; (2) solve the linear relaxation of the model and (3) use QS to get an integer solution (at this stage some variables are selected for freezing) and (4) generate additional columns in order to improve the quality of the linear program. Note that steps two to four are repeated until one of the stopping criteria is triggered.

4.4 Hybrid Integer Programming and Heuristics

Fores et al \cite{125 Fores, S. 2002} present the theoretical building blocks of the TRACS II software – possibly a base for the majority of tools for public transport crew scheduling in the UK. TRACS II uses a hybrid method of mathematical programming and heuristics. The main steps for TRACS II procedures are: generate a large number of possible shifts, use heuristics to reduce this number to a manageable set and select from the remaining shifts a suitable schedule using linear programming. The first step is more or less similar to the work of Valouxis and Housos \cite{110 Valouxis, C. 2002}, however, the discarding method for shifts reduction is following the steps of Wren and Wren \cite{116 Wren, A. 1995}. One of the many features in shifts reduction is discarding shifts which do not make use of relief opportunity. This shows that the method incorporates legal rules for work practices. The speed of this method can be assessed from the fact that, when run on a workstation with 650 MHz Pentium III processor, it requires four hours to process 1500 work pieces and 1.5 million shifts. Authors do not claim that the method achieves the optimum schedule. They make a point that the system saves 1% – 5% of the cost of the crews. This is a huge sum of money when considering millions of pounds spent on crews and crew scheduling.

4.5 A Critique of Current Methods
In this section we will provide a brief critique of the methods described in this paper. The aim is to establish an understanding of the basic principles behind the existing practice and how they can be improved. The list of methods mentioned here is not exhaustive, yet these methods represent the most important methods currently used for scheduling bus crews and are cited in most of the relevant literature.

Possibly the most important issue to consider when assessing a scheduling method is to question whether it takes into account all intricate crew scheduling rules. It is important to note that different companies have different operating rules based on many factors, such as the local environment, culture, and operational practices and therefore there are no generally adopted standards. One of the rules, which cause difficulties, is the rule specifying the legal duration of a shift. It appears wasteful to search for the optimum set of shifts if the length of each shift is restricted by legal limits. The rules add considerably to the level of scheduling complexity. Nevertheless, all of the methods discussed above place a significant emphasis on legal limits to shifts and employ techniques that attempt to deal with that restriction. What is not clear from the literature is the level of flexibility associated with such methods when rules are frequently changed or modified.

Current methods are, on the whole, based on the Integer Linear Programming and heuristics optimisation. This means that they require the problem to be expressed mathematically, which could be quite complex at times, especially when issues such as unplanned activities have to be taken into consideration. This increases the number of variables and the level of variability. It has to be said that the problem of unpredictability of certain events has been tackled by many authors over a considerable period of time. Various approaches have been used to reduce the complexity due to the unpredictability, and it is quite clear from this review that the optimisation of bus and crew schedules is very difficult to achieve – if not impossible – with a single method. That explains the effectiveness of hybrid techniques. In summary, although mathematical methods have been employed very elegantly, yet more research is needed to develop approaches that would effectively cope with the dynamics and uncertainty of the scheduling problem.

When considering scheduling of public transport systems, the frequent changes of rules and regulation and the occurrence of unpredictable events, such as no-shows and failures, are of paramount importance. To cope with these conditions the scheduling software needs to have some mechanism for dynamically re-planning previously agreed shift schedules in real-time. It appears from the literature that the proposed mathematical models are not capable of coping with situations where the number of shift distortions reaches a high level without significantly decreasing the speed of the optimisation process. This may be a minor factor for off-line schedulers. However, when it comes to running the software in real time then the speed is very important.

An important aspect of crews scheduling is the human factor. This may be the biggest source of unplanned events. If, for example, drivers do not turn up on time for their shift, what is going to happen? To be able to cope with this situation a scheduler must be capable of re-planning the affected shifts without disrupting the entire schedule. There is no indication of this feature in most of the reviewed papers. This issue was only mentioned by Emden-Weinert et al.\{482 Emden-Weinert, T. 2000\} where Simulated Annealing meta-heuristics method was used for local optimisation. The accepted practice of re-starting the global optimisation after every change has two major problems: firstly, it takes a long time to reach the global optimum point whilst remedial decisions often must be made rapidly; and secondly, it causes more ripple effects and disruptions for crew members. If the re-planning generates many changes in crew schedules in order to attempt to find the minimum cost of the global operation, there is no guarantee that the exercise will not cause practical problems for crews who planned their time around previously agreed shifts, and thus make the implementation of the modified schedule very difficult.

It is highly desirable also to design into software capabilities for asking and answering various what-if questions with a view to re-examining the effectiveness of the whole transportation network including available resources such as busses, routes and crews. No method reviewed in this paper offered any help in this direction.

Generally, mathematical approaches proved to be quite efficient when developing crew schedules given legal labour obligations, operational rules, and human factors. However, the ability to deal with dynamic and changeable environments, specifically in relation to these factors has not been achieved yet. It must be also remembered that most reviewed methods do not claim to reach optimal schedules - only near-optimal situations.

5.0 Multi-Agent System (MAS) Approach to Bus Crew Scheduling

Technological evolution has now reached a stage that enables the design and implementation of small networks of intelligent agents (IA) to be created to act autonomously upon the users/resources behalf, furthermore they are capable of competing or collaborating, depending on how best to accomplish
tasks {{9 Wooldridge, Michael J. 2002}}. MAS are systems that contain a large number of these IA, resolving tasks through the interaction of these agents. MAS are especially competent for solving resource allocation and scheduling problems. It creates virtual markets in which agents representing available resources negotiate with agents representing demands for resources until a satisfactory matching is achieved {{486 Rzevski, G. 2002}}.

In this paper, we propose a new decentralized approach to bus crew scheduling using MAS. The proposed MAS consists of Schedule Agent (SA), Crew Agent (CA), Bus Agent (BA), Rule Agent (RA) and Trip Agent (TA). Figure 1 shows the proposed multi agent bus crew scheduling architecture. As shown in this figure, the system is constructed with matchmaker architecture. Schedule Agent (SA) acts as a broker/matchmaker between CA, BA, RA and TA. CA and BA are providing the supply. CA gives the supply of driver that will drive a bus, while BA provides the service of bus. TA is agent of request. It requests a bus and a driver to serve the trip. RA is an agent that ensure the schedule created are according to the EU rules (concerning driving hours, break and others) and comply with the TU agreement. The next sections describe more detail on objectives, attribute and state for each agent, and a brief on negotiation process.

![Figure 1: Propose Multi Agent System Architecture](image)

**Bus Agent**

BA is corresponding to a bus uses in operation. BA pursues an objective to provide service. Its attributes are registration number, model, type, capacity and year. BA methods are in used, ready to use, under repair/maintenance or fault.

**Crew Agent**

CA is representing a bus driver who pursues objectives such as obtain a salary and work in a safe and healthy environment. Its attribute are social security number, name, age, address, telephone number, year of experience, and license number. CA methods are on duty, on leave and stand by.

**Trip Agent**

TA is corresponding to a trip and deadhead in bus operation. TA objective is to serve the bus route. A trip is movement with passengers between two relief points or depot at a specified departure and arrival time, while a deadhead is a movement in time between two trips without passenger. TA attributes are route number, trip number, start point, end point, start time, end time and duration. TA methods are on, off and jam.

**Rule Agent**

RA models the rules and regulation, and agreement with the TU. Its objectives are follow drivers’ hours rules and follow agreement with staff union. RA attributes are rule identity, rule name, rule detail and rule date. RA methods are new, update, edit and delete.

**Schedule Agent**

SA is an abstraction of scheduling manager. SA acts as a broker/matchmaker between CA, BA and TA. Its objective is to create an optimum crew scheduling and rota, and minimise the total cost. SA attributes are route number, garage, date, rota number and reference number. SA methods are schedule, global reschedule, local reschedule and off schedule. When creating or updating the schedule, SA has to check the compliance of the schedule with the TU agreement and EU rules.

**Negotiation Process**

Negotiation process is one of the key processes for the MAS to successfully achieve its goal. Various agent negotiation strategies can be employed to achieve the best practical schedule. In this research, we use contract net protocol (CNP) by Smith {{488 Smith, R.G. 1980}}. but with some modifications that suit the crew scheduling environment. The allocation negotiation may start by TA sending messages to SA describing their requirements. SA then broadcasts an offer to CA. Each CA would then compare features of available trips and select the most appropriate offer.
taking into consideration any specific demand that the crews may have. Exchange of messages continues until the minimum cost matching is achieved. While forming the schedule, SA would refer to RA to make sure the schedule is legal.

MAS are particularly good at handling changes that inevitably occur during bus operation such as no-show of drivers, bus failures or trip delays. Let us assume that a driver failed to arrive on duty. The TA representing the trip that has suddenly lost a crew sends messages to CA of eligible drivers asking them if anyone could undertake the duty. In most cases the re-planning triggered by an unexpected change can be accomplished locally, without the need to reconsider the whole schedule. However, if local re-planning is not possible (e.g., if there are no free drivers that can undertake new request), agents begin a more comprehensive re-planning process (although still not on a global scale), which may necessitate some changes in the allocation of previously booked drivers. Throughout the allocation process SA attempt to minimise the cost of operation by making sure that drivers and trips are matched in such a way that no driver works a shift longer than prescribed, the overtime payment being usually the major cost factor.

6.0 Conclusions

Two radically different classes of methods for bus crew scheduling have been reviewed in this paper. The first is a class of hybrid mathematical methods, which rely on the mathematical representation of the bus crew scheduling problem and combine a number of well known mathematical techniques to generate and adjust, if necessary, the schedule. All bus crew scheduling software available on the market appears to be based on one or another method belonging to this class. The main limitation of these approaches is their inability to cope effectively, in real-time, with numerous unpredictable changes which regularly occur in all transportation systems.

The second is rather different. It is based on the notion of the separation of domain knowledge from processes that make use of this knowledge and produce a schedule. The actual scheduling as well as dynamic re-planning is done by negotiations among agents representing resources and demands in a so-called virtual market. Agents negotiate the best matches, that is, the minimum-cost allocations of crews to trips, which satisfy, as far as possible, specific requirements of each trip and every crew member. MAS approach although very novel and not yet tried in the area of bus crew scheduling, has been tested and evaluated on other scheduling problems domains such as manufacturing scheduling {354 Jia, H.Z., 2004}, logistic management and scheduling {356 Karageorgos, A. 2003}, and meeting scheduling {366 Lee, C.S. 2004}.

References


