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A multi-agent approach to Intelligent Transportation Systems modeling with combinatorial auctions

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ABSTRACT

Challenges of urbanization require new, more flexible approaches to design of public transportation systems. Demand Responsive Transport systems (DRT) that provide a share transportation services with flexible routes and focus on optimizing of economic and environmental value are becoming an important part of public transportation. In this paper we propose a new approach to design of DRT models which considers DRT as a multi-agent system (MAS) where various autonomous agents represent interests of system's stakeholders. The distributed nature of the MAS facilitates design of scalable implementations in modern cloud environments. We also propose a planning algorithm based on combinatorial auctions (CA) that allows to express commodity of multiple transportation scenarios by evident means of the bids. Using the mechanism of CA we may fully take into account the presence of complementariness and substitutability among the items that differ across bidders. Further, we describe design principles of our proposed software with a prototype implementation. We believe that our approach to multi-agent modeling is general enough to provide the flexibility necessary for adoption of DRT-services modeling into real-world scenarios. The results of modeling have been compared against several cases of a local bus provider and validated in a set of computational experiments.

1. Introduction

The world is urbanizing rapidly and the population density is increasing. A United Nations report estimates approximately 80% of the world's population will live in cities by 2050 (United Nations: World urbanization prospects, 2011). One of the important problems which arise under such circumstances is the problem of effective and efficient public transportation systems. Even nowadays traffic congestion costs the European Union over 1% of GDP, US road traffic congestion in 2007 wasted 2.8 billion gallons of fuel and 4.2 billion hours, the total cost of wasted fuel and time was $87.2 billion (IBM: The case for smarter transportation, 2011). Experts agree that simple development of cities infrastructure cannot meet the growing demand for transportation services. In this situation more and more attention is being paid to investigations of better models of transportation systems. Researchers are looking for a new, flexible solution which would take into account the interests of all system's stakeholders, would be efficient from economic perspective and reduce the transportation network load.

Intelligent Transportation Systems (ITS) or Flexible Transportation Systems (FTS) are general terms which cover transportation services that are flexible in terms of route, vehicle allocation, vehicle operator, type of payment, passenger's payment, etc. There is an important subclass of ITS called Advanced Public Transportation Systems (APTS) whose goal is "to greatly enhance the accessibility of information to users of public transportation as well as to improve scheduling of public transportation vehicles and the utilization of bus fleets" (Sussman, 2005, chap. 1). A Demand Responsive Transportation service (DRT) is a form of APTS that provides a set of functions including trip reservations, vehicle dispatching, routing, etc. The objective of the DRT system is to manage vehicles in an intelligent way, increase the efficient number of passengers in every vehicle, decrease the number of vehicles on streets and build vehicle's routes in response to the customers' demand. By doing this DRT solutions pursue the goals of transportation companies spending optimization, increasing customers' satisfaction, environmental care, filling in gaps in transportation networks and so on. The flexibility of each element can vary from services where all variables are fixed a considerable time before operation to "online" services where all variables are changed in real-time.

Interest to the FTS systems in general, and to the DRT systems, in particular, has been growing over last decades and the trend of positioning of such systems in the overall picture of public

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transportation is shifting. Initially FTS were positioned as niche players for specific cases like elderly people services, premium value services or public transportation in areas with low demand (Rural Transportation Systems – RTD) (Schofer et al., 2003). Since that time DRT were proven to be 'economically' and 'environmentally' successful in a number of scenarios (Brake & Nelson, 2007; Mageean & Nelson, 2003). With a broader definition of an intermediate form of public transportation that falls between "classic" transportation systems (with fixed routes and schedule) and taxi systems the DRT services became an important form of public transportation and probably will be stated as an "essential" part in the future (Mulley & Nelson, 2009).

Development of DRT systems is a challenging field both in terms of algorithmic complexity and system design. From scheduling/vehicle routing perspective the underlying model of a DRT system usually represents an instance of so-called Dial-a-ride problem (DARP) (Cordeau, 2006) with domain-specific constraints and the target function. From a system design perspective the complexity is a matter of choosing of the proper abstraction model which would allow the correct representation of system elements and interactions between them. Different authors suggest application of such formal methods as a hierarchical system or system of systems (Babkin, Abdulrab, & Satunin, 2010; Xu, Yin, & Huang, 2009), decision support system (Sprenger & Moench, 2014), discrete optimization models (Muelas, LaTorre, & Peña, 2013), etc.

We believe that the DRT services can be properly modeled as multi-agent systems as they take into account conflicting interests of stakeholders who represent "different autonomous embedded complex systems" (Vaquerizo García, 2009), and stakeholders themselves can be considered as agents with partial knowledge about the system. On the other hand such system requires an efficient resources allocation: resources of transportation companies (vehicles) should be used in a best way and if we took a look at the system from the vehicle's point of view we would find that customers (passengers) become an attractive resource because every served passenger brings money. So we can think of the vehicles as agents who willing to struggle for passengers. The best way to resolve their conflicts is to provide a fair way to get really valuable resources, provide a transparent and computationally tractable process of resource allocation, taking into account private values of participating agents. Combinatorial auctions (CA) are proven tools for this type of the problems (Cramton, Shoam, & Steinberg, 2005).

In this paper we introduce a new multi-agent model of the DRT service for public transportation. In this model we offer a new CA-based approach to distributed routes planning for such a system and provide an overview of our software prototype which can be considered as operational control software system for the DRT services.

The rest of the paper is composed as follows: the next Section 2describes typical issues of DRT-services development and links to related research works. Section 3 contains a high-level representation of our multi-agent model of a DRT-service, introduces agents and schema of their collaboration. Section 4 devoted to the formalization of the problem statement and the description of planning algorithms. Section 5 provides some guidance on software prototyping of the model, overviews results of our initial experiments. Section 6 highlights results and roadmap of the future work.

2. DRT services – overview and implementation issues

DRT services are those public transportation services characterized by the flexible routing and scheduling of relatively small vehicles (occupancy of four to 20 persons) to provide shared-occupancy, personalized transportation on demand. DRT belongs to a family of services called "paratransit", which also includes conventional exclusive-ride taxis, ride-sharing, and bicycling. DRT is distinguished from conventional taxi service by its ride-sharing feature, which poses difficult control problems. In general, DRT operations require a core set of functions which must be performed whether computer software is utilized or not (Sussman, 2005, chap. 1). These core functions are:

– eligibility determination;
– trip reservation;
– service (trip/vehicle) scheduling;
– vehicle dispatching;
– vehicle routing;
– management reporting and statistics

In a nutshell the DRT system provides to customers a way to place an order for a trip and after it calculates a quasi-optimal solution taking into account all requests. All incoming requests should be processed by the system and at last the solution should be put into action – every request should be satisfied by adding it to the route of a vehicle. Though complexity and design of such systems may vary significantly depending on selected approach they also have some common properties. Analysis of publications (Brake & Nelson, 2007; Cubillos, Gaete, Guidi-Polanco, & Demartini, 2007; Xu et al., 2009) shows that following attributes are considered by many researchers as essential for the DRT systems. These are:

– *Modularity* – i.e. understanding of DRT as a system of sub-components which provide services in the scope of the whole system and can be relatively easily changed by other components serving the same function.
– *High Computational Load* – the DRT system provides nearly real-time service and consumes internally a combination of algorithms to provide a feasible solution.
– *Decentralization* – because of computational load, the large number of system's stakeholders and other influencing factors many papers proposed a multi-agent approach to the modeling of the DRT system.
– *Scalability* – in a real world the DRT systems are dealing with uncertain information, unreliable communications, real-time issues and other problems and the model which works fine on a small data set may fail with a bigger one. The answer is organizing of multi-agent architecture in a number of layers which allows considering it as a "system of systems", i.e. as a collection of task-oriented or dedicated systems that pool their resources and capabilities together to obtain a new, more complex, "meta-system" which offers more functionality and performance than simply the sum of the constituent systems.

Practical implementation of DRT services is a complex task and an open space for research in a number of areas:

– *Service Design* – includes general questions of modeling and designing of service architecture. Formalism of multi-agent models works well in the case of DRT due to a convenient representation of a system in the form of interacting intelligent agents. Such approach was utilized in a number of publications including (Babkin et al., 2010; Cubillos et al., 2007; Sprenger & Moench, 2014; Xu, Abdulrab, & Itmi, 2008; Xu et al., 2009).
– *Algorithmization* – searching for optimal combination of routing and planning algorithms for DRT-services. Usually it implies resolution of the underlying DARP. Approaches may vary significantly depending on a particular model and include exact branch-and-cut algorithms (Cordeau, 2006; Ropke, Cordeau, & Laporte, 2007) usage of various heuristics to reduce the computational load: evolutionary (Carballedo, Osaba, Fernández, &