Capstone Final Project

Real-Time Vehicle Scheduling in Bus Rapid Transit Systems Using Distributed Artificial Intelligence

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Abstract

This project is focused on Bus Rapid Transits Systems (BRTS), which is a modern transportation system important for urban traffic development. In fact, BRT systems have become popular in many countries, reaching 160 cities around the world. BRT systems have two components, design and operational planning. One key problem of operational planning is the Vehicle Scheduling Problem (VSP), which aims to plan vehicle trips. If the VSP is solved in an effective way, it can also have a positive impact on operation costs such as fuel consumption, the carbon foot-print, driver's wages, number of purchased vehicles, and by all means, the quality of service. In this project, the VSP will be analyzed through a decentralized architecture using Distributed Artificial Intelligence (DAI). The main purpose is to allow the VSP to work in real time, making each part of the system capable to adapt and evolve, thus favoring reactivity to perturbations and constant changes. The propose approach will be validated using a case study based on a Colombian BRT.

Keywords: Scheduling, Bus rapid transit, artificial intelligence, real time control.

1. Introduction

Bus Rapid Transit (BRT) systems are high quality transportation systems that combine elements of regular buses and metro systems, in a way that the cost is close to general bus operation, and the speed and capacity is similar to the rail transportation. Accordingly, BRT is a fast, efficient and cost-effective service system. BRT system is composed mainly of articulated buses, stations and corridors. BRT vehicles are large articulated buses with 200-250 people's capacity with an extension of 18-25 meters. The stations are designed to receive the buses by platforms, fitting the buses to allow easy step in-off. The stations also have automatic ticketing and fare collection system outside the vehicles. BRT corridors are in fact bus lanes that prevent busses from getting affected by traffic congestion, and allow them to maintain their speed, with traffic light priority. Significantly, BRT has a short construction period and is an environment friendly system with a low energy consumption (Dong et al., 2011). Additionally, BRT system presents different advantages according to the size of the city. In metropolitan areas, for instance, it could be a complement to the transportation system and in medium sized cities, BRT can link it (Dong et al., 2011).

The efficiency of BRT systems depends on various elements, such as technology, regulations, the planning process, and control strategies. In fact, all these elements together imply highly complex and, most of the time, intractable decision-making problems. In addition, several actors with different objectives are involved: the authorities, users, non-users, and operators (Ibarra-Rojas et al., 2015). In BRT systems, decision-making problems span from strategically, tactical, operational and control decisions, dividing the entire planning and operation into several decision-making sub-problems, as show in Fig. 1.

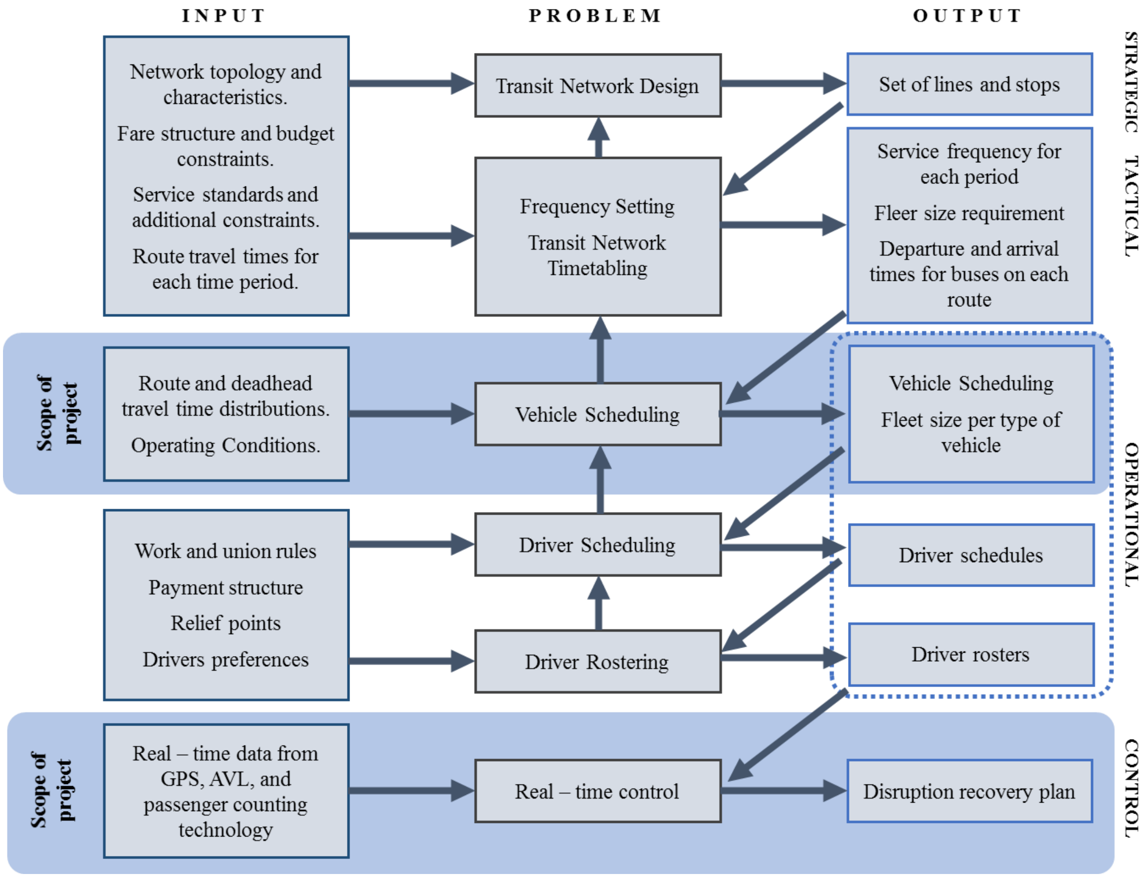

Fig. 1. BRTS sub-problems and their interactions. Taken from (Ibarra-Rojas et al., 2015).

Strategic planning decisions focus on network design. Network design mainly involves station spacing, frequency settings, busways and its routes. From the user perspective, stations must be accessible while covering a large service area to meet the demand, located in strategic spots where the waiting time is ideal, with the smallest possible deviation from the shortest paths. From the system operator perspective, the network must be designed to minimize the number of stations, costs of vehicle usage and drivers' wages. From the authority's perspective, the system must remain within the current budget, be efficient in obtaining revenues and satisfy the demand while providing a good-quality service. Chien and Schonfeld, (1997) proposed an analytical model assuming a rectangular grid and zone dependent passenger demand, to determine the locations of stops and lines, and their headways in order to minimize costs. Medina et al., (2013) presented a non-lineal optimization problem to determine the stop density in a bi-directional corridor and the lines' frequency for several periods. The objective was to minimize costs based on waiting time, in-vehicle travel time, fleet operating costs, and stops installation.

Frequency (or headways) setting *establish the number of trips for a given set of lines, to provide the high level of service in a planning period* (Ibarra-Rojas et al., 2015). Setting headways is one of the critical determinants of system performance and it is one of the most important issues for operation scheduling (Chen et al., 2015). For instance, Strathman et al., (2001) presented a study on bus trajectories and headway dynamics using automatically collected information. Likewise, Shalaby and Farhan, (2004) developed a model that incorporate the notion of headway in its prediction of dwell time.

In turn, busways (or corridors) *"are the most critical elements in determining the speed and reliability of BRT services*" (Diaz, 2004). In other studies, An et al., (2008) used a hybrid heuristic algorithm to solve models for finding a feasible solution for BRT Network design.

Operational planning decisions are composed by vehicle and driver scheduling problems, as well as driver rostering. Ibarra-Rojas et al., (2015) defined the Vehicle Scheduling Problem (VSP) *as the assignment of trips-vehicles to cover all the planned trips such that operational costs based on vehicle usage are minimized*. Variables such as the number of depots where the bus departs from and returns to, resting points, different fleets with different capacities and operating conditions must be included in BRT scheduling problem. It is very important to mention that the maintenance of the buses plays an essential role during vehicle scheduling process. Firstly, if the bus is out of service, it is necessary to find the solution in the real time as to allow the proper functioning of the whole system. Also, it is necessary to maximize the time one bus is in operation and its capacity during its useful life. By lowering the number of buses in usage and, therefore decreasing the costs of maintenance, the costs necessary to maintain the whole system will be lower.

In addition to VSP, operational planning decisions also include driver schedules and roasters. According to Wren and Rousseau, (1995), the process of driver scheduling is to define a set of legal shifts, covering all vehicles in a particular vehicle schedule, which may reflect the whole operation of an organization, or a self-contained part of that operation. Closely related to driver scheduling, the driver rostering problem (DRP) focuses on the assignment of drivers to the daily duties yielded by the driver scheduling for a specific planning period, e.g. a month (Ibarra et al., 2016; Wren and Rousseau, 1995). This assignment, called roster, must comply with labor rules and the company's regulations. For example, Liping Zhao, (2006) took ''morning'' and ''afternoon'' as different problems solving it separately and combining them afterwards to get a solution for the entire day; and Tóth and Krész, (2013) implemented a heuristic to minimize the cost of driver scheduling focusing on labor regulations.

The urban context in which all the aforementioned decisions are taken is very dynamic and often unpredictable. Evidently, the uncertainty of travel times, demand patterns and internal (e.g. vehicle breakdowns, driver-related problems) and external disturbances (e.g. public protests, weather conditions, special events) require real-time control strategies (Ibarra-Rojas et al., 2015). To have real-time control capability, the monitoring functions and control decision-making should be carried out in a negligible time (Chan et al., 2008).

Among all the aforementioned problems, VSP scheduling has a huge impact on service quality. The number of buses assigned to a specific corridor will influence how long a passenger should wait for the bus and how many people are waiting to step in. In addition, such operational problem has been tackled independently from real-time control, with few efforts to integrate both decisions. Mainly, such integration has been constrained by the amount of data and the reactivity required to handle perturbations by real-time controllers. Thus, the classical centralized approaches based on analytical models, heuristics or metaheuristics can hardly handle efficiently VSP operation and control (Wang et al., 2011). Therefore, this project focuses on VSP given its impact on bus usage efficiency, timetable establishment, and crew scheduling (Dong et al., 2011). If the VSP is solved in an effective way, it can also have a positive influence on operation costs such as fuel consumption, the carbon foot-print, driver's wages, number of purchased vehicles, and by all means, the quality of service. Contrary to previous studies, this project aims at proposing a real-time vehicle scheduling approach using a distributed artificial paradigm. The main purpose is to provide a way to deal with vehicle scheduling decisions and real-time control conjointly, to account for randomness coming from internal and external unexpected events.

2. Problem Statement and Objectives

Given the importance of vehicle scheduling and real-time vehicle control in BRT systems, and considered that scheduling and control architecture must face the randomness and uncertainty of the urban context, the following research questions arises: *how can distributed artificial intelligence be used to schedule and control vehicles into a BRT system? What distributed artificial intelligence paradigm is suitable to do so? What would be the main benefits and drawbacks of having a fully distributed approach for the VSP and real-time control compared to a centralized approach, in normal and abnormal conditions?* Then, the main objective of this project is *to propose architecture based on a distributed artificial intelligence paradigm to schedule and control vehicles in BRT systems*. The specific objectives derived from this main objective are:

- Analyze the different paradigms issued from the distributed artificial intelligence field to choose the most suitable one.
- Propose a control architecture for scheduling and controlling vehicles in a BRTS, identifying decisional entities.
- Define the scheduling and control decision algorithms based on the chosen distributed artificial intelligence paradigm.
- Validate the proposed approach against the current centralized approach based on fixed frequencies.

2.1. Design requirements

The following requirements must be fulfilled:

- The proposed control architecture must be implemented in an agent-based simulation environment.
- The simulation environment must allow to validate the proposed control architecture under normal conditions and at least one abnormal condition, which can be determined during the project execution.
- The simulation environment must allow to validate scalability only in terms of number of buses.
- The project must define the service indicator to measure the performance of the proposed architecture. The same service indicator must be used to compare the proposed approach with current centralized approaches.

2.2. Design constraints

The following constraints must be taken into consideration:

- The simulation model will be made using Bogota's BRT, Transmilenio, as reference, for only one sequence of bus corridors linking two bus portals. This constraint does not jeopardize the generality of the proposed approach, but it helps for validation.
- The simulation model will consider regular traffic as deterministic data, e.g. traffic light times. In this project, issues and events related to regular traffic will not be considered (e.g. blockage at intersections).
- The proposed architecture only focuses on vehicle scheduling and control, thus, driver scheduling and rostering are not considered. Therefore, all decisions related to vehicle dispatching considers that the driver and the vehicle are available.

2.3. Norms and standards

The BRT standard *is an evaluation tool for world-class bus rapid transit (BRT) based on international best practices* (ITDP, 2014). The standard establishes a common definition of BRT and guarantee BRT systems to be more uniform aiming to economic benefits and positive environmental impacts. BRT standard evaluates different aspects such us: corridors, service planning, infrastructure, stations, communication, access and integration, obtaining a scorecard based on the criteria and point values (ITDP, 2014). To design the proposed control architecture and the simulation model, all the aforementioned aspects will be evaluated and those necessary will be taken into consideration.

3. Literature Review

This section presents a literature review in tow main areas. First, various studies dealing with the vehicle scheduling problems are presented to give an idea on what exactly has been matter of research and common points. Second, a review on distributed artificial intelligence approaches is given aimed to establish the spectrum of possibilities to be used in the proposed approach.

3.1. The vehicle scheduling problem

The vehicle scheduling problem (VSP) has been studied with different techniques, which it is mainly composed by non-deterministic methods. Pepin et al., (2009) proposed to compare the performance of five different heuristics, a Lagrangian heuristic, a truncated column generation method, a large neighborhood search heuristic using truncated column generation for neighborhood evaluation, and a taboo search heuristic to determine least cost schedules for vehicles assigned to several depots. Zhang and Zhang, (2008) proposed an improvement ant colony algorithm for VPS. It is composed of a new state transition rule, a new pheromone updating rule and diverse local search procedures, to reduce the number of vehicles, and minimize the total distance travelled by all vehicles. Deb and Chakroborty, (1998) focused on minimizing the overall waiting time of transferring and non-transferring passengers while satisfying a number of resource- and service-related constraints using a genetic algorithm. These methods can be integrated as an expert system to facilitate generic usage while improving performance. For this reason, these methods require a detailed study of the problem, but may suffer for low responsiveness since they have to handle large amounts of data, usually communicated to a central dispatching center.

3.2. Distributed artificial intelligence paradigms

As mentioned before, VSP scheduling has several variables which make the optimization problem more complex. Contrary to classical centralized approaches, Distributed Artificial Intelligence (DAI) is a promissory paradigm because DAI seeks for a synergy between decision and information. Distributed Artificial Intelligence (DAI) "*is the study, construction and application of multi-agent systems, that is, systems in which several interacting, intelligent agents pursue some set of goals or perform some set of goals*" (Weiss, 1999). One of the main ideas of DAI is that when separate intelligences of each component are added up, this sum is less than the intelligence of the whole group combined. It is also important for the entities to be able to share the knowledge by common ways of communication. With that, they are able to achieve one same goal. The main distributed artificial intelligence paradigms are presented in Table 1.

The benefits of DAI are that each part of the system or "decisional entity" is capable on its own to adapt and evolve. Decisional entities can learn and adjust to the environment, to attain their local objectives, without affecting the whole system. By doing so, decision entities are highly reactive because they can process only the necessary information, and information that concerns their decision-making processes.

Table 1. DAI paradigms

DAI Paradigm	General Description
Multi-agent Control Approach	This approach uses autonomous entities called " agents", who can act on their own and make independent decisions. By communicating with the environment and other entities they are able to produce complex creative behavior. This interaction is extremely important for this approach (Ferber, 1999)
Holonic Control Approach	This approach is based on real life systems, like solar system which has 8 planets and the sun, but at the same time is a part of group of solar systems which make galaxy. In the same way, holons that make holonic system can be seen in two ways. First, one holon as a whole is made of other entities, and secondly, it makes a part of one bigger system of holons. This holons are able to cooperate with each other. This type of a system is a perfect example of combining pure heterarchy and hierarchy (Van Brussel et al., 1998) .
Bionic and Biological Approach	Based on natural systems, it uses biological characteristics (self-organization, evolution, adaptation) to develop production system. It imitates cells behavior where each entity of bionic production system is autonomous and self-organized. This systems is, most of the time, fully hierarchical (Ueda, 2007)
Stigmergic Approach	The name of this approach comes from a term ¨stigmergy¨ which describes the way insects, specifically ants, organize themselves to perform collective tasks. In production systems, it means that environment is used to support indirect communication between entities. This idea was used as a base to develop potential field concept (Berger et al., 2010).
Potential Fields	This approach was first applied to guide and navigate robots. Robot would avoid obstacle which was emitting repulsive field and move toward goal which was emitting attractive field. In manufacturing systems, resources would attract products to ensure dynamic and optimum resource allocation among set of products. Approach was also used for bus stop allocation, where each bus stop was considered as an agent trying to attract the passenger with its attraction field (Pach et al., 2012; Zbib et al., 2012).

3.3. Case study: Transmilenio

Transmilenio is a Colombian BRT system, implemented in Bogotá, the capital city. Transmilenio was inaugurated in December, 2000 and since then, it has expanded its network by building new stations, portals and busways to cover all major points in the city. Transmilenio system has 12 busways distinguished by colours and letters. As many BRTS, Transmilenio buses use exclusive lanes separating them from the city traffic. Transmilenio stations are exclusive points where buses can pick up and drop off passengers. In total

Transmilenio has 131 stations with a distance ranging from 500 to 700 meters from one station to the next one, making it convenient and easy for passengers to enter system (Transmilenio S.A., 2013).

The system's structure is a closed system. It implies that the corridor access is limited to a prescribed set of operators and restricted number of vehicles. The system control and management is given by frequencies according to demand analyses, considering all restrictions such as corridors, intersections, drivers, trunk line buses, schedules and connections (ITDP, 2014). Trunk line buses basically operate by express and stopping services. Both services operate at about 3 minutes' frequency in peak periods and 5 minutes in others periods. The system operates most of the working days with express services starting from 05:30 - 22:00, and going from 05:00-23:00. At weekends, time coverage is slightly reduced, with 70% service on Saturdays and 50% on Sundays and official holidays (ITDP, 2014).

The design of Transmilenio system is based on busways, stations and buses (Transmilenio S.A., 2013). Fig. 2 shows the Transmilenio system with all the current stations and busways. Through busways, buses can start and end its routes in portals or main stations. Other types of public and private transportation are not allowed to use busways. Busways are designed of two types: one lane and two lanes busways to avoid blocking. Nowadays, Transmilenio has 12 busways distinguished by colors and letters. More, Transmilenio stations are the exclusive points in busways where buses can pick up and drop off passengers. In total, Transmilenio has 131 stations with inter-station distances around 500 to 700 meters, making it convenient and easy for passengers to enter Transmilenio. In average three cards reader are located in the entrance of each station for fee collection, making queues at the station entrance. Transmilenio has three types of stations:

- Standard stations: these stations are the most common, simple and the smallest ones. They allow access to maximum of six buses at the same time (three buses in each direction).
- Intermediate stations: these stations allow passenger transfer with hybrid buses. These intermediate stations are not numerous within the Transmilenio system.
- Portal stations: these stations are located at the beginning and at the end of each busway and allow the transfer between hybrid buses, intercity buses and Transmilenio buses.

In terms of buses, Transmilenio counts with buses of an average capacity of 160 passengers, 18 meters long and 2.6 meters wide. They are equipped with state of the art mechanical features like pneumatic suspension, capacity sensors, four doors on the left side and the most modern motors run by Diesel fuel. In addition, in the second semester of 2009 there was a significant upgrade in the fleet, by adding two-hinged buses to the fleet, increasing passenger capacity up to 260 passengers. Two-hinged buses are 27.2 long and 2.6 wide with seven doors. Transmilenio buses can be assigned to the following services:

- Express service: this service is programmed to serve passengers travelling between various zones of origin and destination in the fastest possible way. To achieve this, buses do not stop at every station on the busway, but only those carefully chosen by the Transmilenio.
- Super express service: this service stops at only few stations making faster the way form the origin station to the destination. Its goal is to serve passengers travelling large distances in the system with higher frequency with less stops than express services.
- Easy-route service: This service is designed to stop at every station in the busway giving passenger greater options for changing lines and less waiting times.
- Hybrid service: this service is operated by specific buses that run on both, busways and regular streets. Hybrid services start on the main stations and finalize in specifics points around the city but stopping on bus stations previously defined.

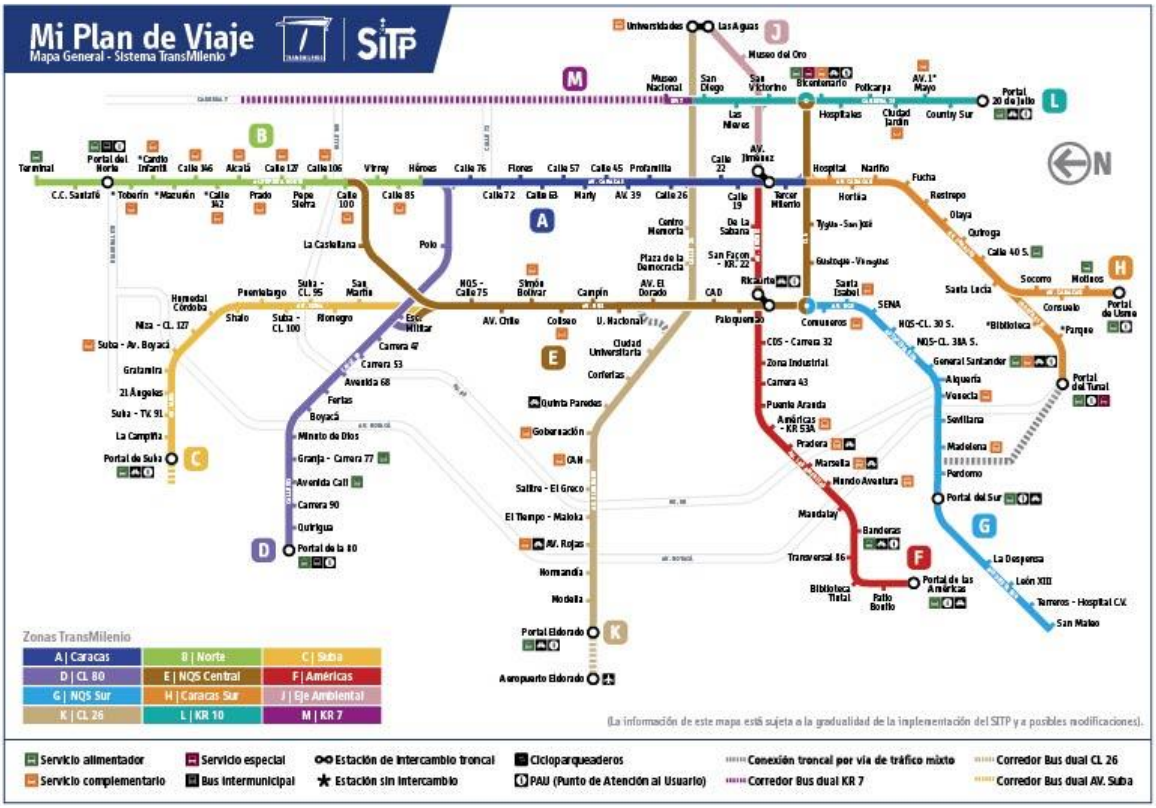

Fig. 2 Transmilenio busways. Taken from (Transmilenio S.A., 2013)

When the system was introduced in 2000, Bogota had a population around 6 million inhabitants and the concept of stations, busways and automatic ticketing was new. Nowadays, Transmilenio seems to struggle to offer a good quality service, since the demand increased 600% in 15 years, first because of the success of the system, then elimination of old buses and the implementation of SITP (SITP - Integrated System of Public Transit), and the proximity of nearby towns, increasing the number of people commuting. Overall, the main problems affecting Transmilenio are (Gómez T. Yolanda, 2016):

- Delays on busway construction: there is a deficit of about 275km.
- Operational costs: 10% of the users do not pay the ticket.
- Non-connected busways: there are 3 busways without connection.
- Overcrowding: the users increased from 410.421 in 2001 to 2'355.000 today and buses have increased from 427 to 2.969.

After evaluating Transmilenio' s busways based on number of stations, number of routes and occupation, the line going from "portal El Dorado" to "Universidades" was chosen for this case study. This choice was made based on simplicity, since other lines would require analyzing more than one busway, which would increase problem complexity. Thus, for the purpose of this undergraduate project, taking the line going from "portal El Dorado" to "Universidades" is sufficient to validate the proposed approach. This chosen busway has the following characteristics:

- Number of stations: the number of stations were checked at urban transportation web sites (www.surumbo.com), phone apps (moovit, transmisipt), giving a total of 15 stations through the chosen busway. Finally, to obtain the parameters of physical distances between stations Google Maps was used.
- Bus stops: bus stops were also checked with different sources since information was not identical for all. This chosen busway has one portal named Portal El Dorado and the ending station is a standard station.

4. Proposed Methodology

4.1. Objective 1

In order to accomplish the first specific objective various criteria were considered for selecting a DAI method. In Table 3 the 6 methods analyzed and their relationship to each criterion are presented, but before such criteria are defined in Table 2.

Table 2. Criteria definition.

Criteria	General Description
Autonomy	Autonomous entities can behave based on their own experience and from their built-in knowledge, which is specific for each environment. Decisional entities have proven to work successfully in unpredictable domains because they are capable of autonomous actions. (*ANEMONA*, 2008)
Cooperation	For advanced intelligence systems, any complete functional model must have cooperation as a built-in requirement. In addition, to accomplish system goals all decisional entities must cooperate with each other. According to Christensen's, (1994) definition, cooperation is achieved when decisional entities mutually agree on their decisions and actions.
Hierarchy	This form is characterized by a "*philosophy of 'levels' of control and contain several control modules arranged in a pyramidal structure* " These distinct levels have their own purpose and function. All activities of the subordinate (slave) levels are dictated by the supervisor (master) levels and the subordinates have no recourse but to comply. At the top of the hierarchy is a single, high-level decisional entity responsible for setting global goals and formulating long-range strategies that "*commit the entire hierarchical structure to a unified and coordinated course of action which would result in the selected goal or goals being achieved* " The control decisions are operated top-down, with status reporting operating bottom up (Dilts et al., 1991).
Scalability	As pointed out by (Badr, 2008) conventional systems are usually designed as customized solutions. Any changes to the structure, for instance, introducing a new decisional entity is only possible with highly complex and costly major modifications. Consequently, scalability should be catered for by control architectures to allow long-term flexibility, particularly to cope with system growth.

Multi-agent Control Approach (MAS)

- Autonomy: Agents can operate without the direct intervention of humans or other agents. Agents have been successfully used in domains where the degree of uncertainty and unpredictability requires processing units that are capable of autonomous action, without the direct intervention of humans or others. (*ANEMONA*, 2008)
- Cooperation: is one of the key characteristics of MAS by means of repeated interaction, incentives, and the need of other agents to achieve local goals (Allen et al., 2010)
- Hierarchical: it is not present in the definition of multi-agent systems but it is also not prohibited. Several MAS have applied the concept of coordinators, supervisors or higher-rank decisional entities with broader view to help the entires MAS to achieve global goals (Isern et al., 2011).
- Scalability: by definition agent-based systems do not limit the number of decisional entities, and the entire system can shrink or expand in terms of agents, and the system can continue working. However, the scalability of the system is only limited by the computing cost and not the underlying principles of MAS (Leitão et al., 2012).

Holonic Control Approach

- Autonomy: is the capability of a holon to create and control the execution of its own plans and/or strategies (and to maintain its own functions). (ANEMONA, 2008)
- Cooperation: the process whereby a set of holons develops mutually acceptable plans and executes them (ANEMONA, 2008)
- Hierarchy: Holonic approaches have within themselves the best of both worlds. They use hierarchy to have stability but at the same time offer essential flexibility by its heterarchical parts (Van Brussel et al., 1998)
- Scalability: As each holon has its own identity that brings to the system the capability to act on its own on and therefore treat specific objectives and local information; and at the same time it is a sub ordinate of a larger group, holonic systems offer scalability to the process without undermining the performance (Leitão and Restivo, 2006)

Bionic and Biological Approach

- Autonomy: Autonomy of unit: High, cells able to define operations changes in environment. Autonomy of group: Predefined functions of organs through genesis and operational autonomy (Tharumarajah, 1996)
- Cooperation: The cooperation between parts is assured through the supervision body and coordination units which make sure that all of them are working towards the same goal. Certain level of cooperation is also required to resolve conflicts between entities, as any of them imposing its own will is not considered appropriate in this approach. (Tharumarajah, 1996)
- Hierarchy: Top-down as task specifications and bottom-up decisions. The top-down process specifies operations (tasks), since a spontaneous action of a unit does not constitute any function of the system and the bottom -up process, units' actions cumulate and manifest in an operation of the whole system. The structure and workings of natural life exhibit autonomous and spontaneous behavior, and social harmony within hierarchically ordered relationships (Tharumarajah, 1996)
- Scalability: As bionic systems are based on real live organisms where each entity representing a cell is autonomous and independent of others, any changes to the structure of the whole system should not have great effect on it. With this said, this approach allows scalability without affecting performance (Tharumarajah, 1996)

Stigmergic Approach

- Autonomy: each individual in the swarm has the capability to act, which means, changing the state of the world (Heylighen, 2016).
- Cooperation: this paradigm is based on cooperation though the environment, which means that each decisional entity left information to other on the environment. In can be then conclude that this paradigm focuses on indirect cooperation (Heylighen, 2016).
- Hierarchy: stigmergical approaches do not consider any kind of hierarchy unless the paradigm is combined with other paradigms that do so (Berger et al., 2010).
- Scalability: as the number of nodes increases in a network, the number of entities needed increases, and consequently, the convergence time also increases. One way to solve this problem would be to use topological information to divide the entire swarm/population into zones and then to use intra- and inter-zone routing.(Sallez et al., 2009)

Potential Fields

- Autonomy: it has its roots in robotics where it was originally intended for robots to find their way. Robots used two different types of potential fields: repulsive potential fields to avoid obstacles in the way, and attractive potential fields to direct themselves and to optimize its best path. Robot's routing decisions are taken autonomously depending on the potential fields they sense. Their decisions are not shared with other robots, however through their actions and the dynamic changes of the potential fields emitted, the whole system organizes itself.
- Cooperation: The cooperation is completely based on heterarchical architectures. Particularly, the potential fields concept was adapted in manufacturing for real-time production control (Zbib et al., 2012). In manufacturing, resources emit potential fields that are relayed through the transportation system, and products sense those fields while on decision nodes. Since fields change dynamically with product decisions (i.e., resource selection for processing and activity), then products may change their decisions at each decision node. Hence, resources cooperate with products by updating their fields so products can make decision with up to date information. In this context, the cooperation is simple and it goes in one way because products do not share information with resources and with other products, they just act based on the information they capture.
- Hierarchy: as mentioned before, the potential fields concept does not require any hierarchical relationships since information is shared from resources to products, indirectly, and from products to products also indirectly. Therefore, since products take the information they need and make their decisions, and there is no need to share those decisions, thence master-slave relationships are not necessary.
- Scalability: is ensured given the lack of hierarchies. Manufacturing resources (or robots in the first case) can be added and withdrawn at any time and the system adjusts itself immediately. An unavailable resource reduced the field it emits to zero and then it stops to be visible to products, hence it will not be used. In addition, since product relationships are not direct, hence products can be introduced as many as the system capacity allows it and they can start immediately sensing fields coming from resources and make their decisions to achieve their manufacturing systems.

Table 3. DAI paradigms

	Autonomy	**Cooperation**	**Hierarchical**	**Scalability**	**Communication rate**
Desired level	↑↑↑	↑↑↑	↓↓↓	↑↑↑	↓↓↓
Multi-agent Control Approach	↑↑↑	↑↑↑	"↑↑"	↑↑	↑↑↑
Holonic Control Approach	↑↑	↑↑↑	↑↑	↑↑	↑↑↑
Bionic and Biological Approach	↑↑	↑	↑↑	↑↑↑	↑↑
Stigmergic Approach	↑↑↑	↑↑↑	↓↓↓	↑↑↑	↓
Potential Fields	↑↑↑	↑↑↑	↓↓↓	↑↑↑	↓↓↓

"↑↑" not required but usually present

After analyzing the different paradigms, the potential fields concept was chosen because of the following reasons:

- The level of autonomy: out of the five paradigms, the potential fields concept has the highest level of autonomy because of the indirect interaction between decision entities. In addition, the simplicity of the indirect interaction and the fact that local decisions are not shared and do not depend on other entities' decisions, make the potential fields more attractive in terms of autonomy. For the BRT case, this is of the outmost importance for having a highly reactive system and low complex interactions, given the size of BRT systems and the amount of information.

- Cooperation: since in the potential fields cooperation is one way, from resources to products, low complexity can be achieved more easily that with other paradigms. Again, this is crucial to have high reactivity in BRT systems, and interactions can be initially thought from buses to stations and stations to portal stations.
- Heterarchy: although other paradigms claim for heterarchical relationships, the implementation always count on hierarchical relationships, making the decision-making structure more complicated. On the contrary, the potential fields implementation in manufacturing showed that no hierarchies are necessary to achieve a system highly performant.
- Communication rate: The flow in the information exchange is given by the low rate of communication that exists between the entities. Potential fields is the only paradigm that gives an increase in the flow of information exchange driven by the low hierarchy and high cooperation. The amount of data that is send per minute must be lower due to the size of the system.

4.2. Objective 2

With the purpose to achieve the second specific objective, the following decentralized control architecture with decisional entities is proposed:

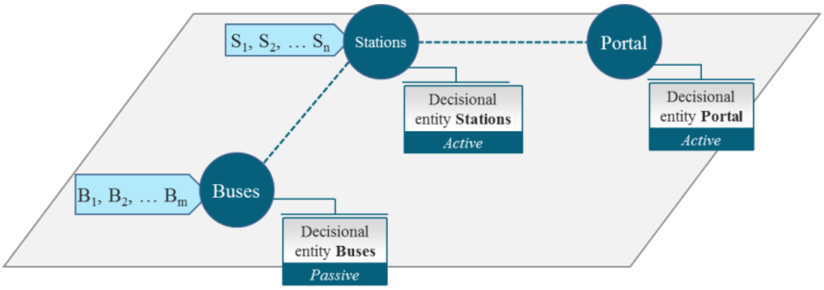

Fig. 3 Decentralized control architecture.

The proposed architecture is heterarchical since there are no hierarchical relationships between the decisional entities. One important characteristic of this architecture is the exchange of information between the decisional entities. For example, the station decisional entities and the portal decisional entities exchange information among each other to determine the frequency of the buses. The station decisional entities change their level of attractiveness depending on the percentage of their occupancy. This attractiveness is sent from all the stations to the portal decisional entity, which makes allocations decisions to assign a line to an available bus, considering the capacity of the system with the number of the available buses. In the same way, the bus decisional entities exchange information with station decisional entities to determine the quantity of passengers stepping in and out of buses at each and every station.

Station decisional entities are active because they can decide whether the station is available or not, to simulate abnormal situations. It is important to highlight that abnormal situation analysis is out of the scope of this project, but one of the main features of the proposed architecture is that is already conceived to deal with perturbations such as:

- Bus unavailability: if the fleet is perturbed at any point of the operation, the vehicle scheduling is capable to adapt to new conditions on a real-time basis.
- Station unavailability: if a station is not available, then all buses that should stop in such station will skip it on a real-time basis.

- Cancelling lines: if at a certain time a line should not be operated, then the model cannot allocate buses to such line. This reactivity must be ensured on a real-time basis.

Perturbation analysis will be carried out in future works.

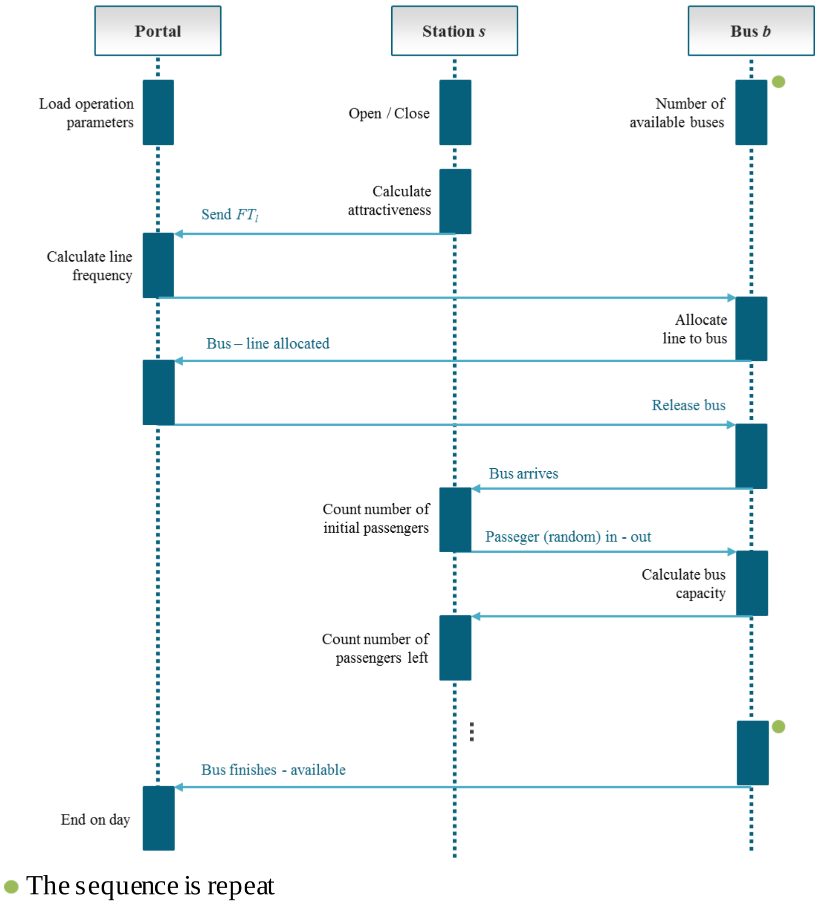

Fig.4 UML Diagram – entities relationship

Table 4. Characteristics of decisional entities

Decisional Entity	Role	Parameters and Decisions
Buses	Passive	Line Number of buses available Number of passengers Occupation Percentage
Station	Active	Location (x,y) Demand Physical structure Attractiveness Availability (decision)
Portal	Active	Basic Frequency Allocation (Line – Bus, decision)

4.3. Objective 3

Taking into account the proposed architecture and the potential fields approach (Pach et al., 2012), in the following the scheduling and control algorithms are described.

The scheduling task in BRT systems is usually carried out at portals, in which an available bus is assigned to a line depending on a fixed frequency. The schedule is done for long periods of time and is not usually updated on a regular basis. Because such scheduling is fixed and based on classical scheduling models and algorithms, such scheduling approach do not adapt well to changes in demand. Herein, the proposed scheduling and control algorithm is inspired on the potential fields approach. Hence, the level of occupancy of stations (i.e., level of demand in real time) is used to calculate the attractiveness of the station to change the frequency of bus lines required by that station. The more passengers waiting for buses in a station, the more attractive the station is and the more frequent those bus lines serving the station should be. Such adaption to real-time conditions ensures the reactivity to the system to unexpected events and constantly changes in demand. The proposed scheduling is done on real-time depending on the number of available buses, capacity of the buses, system infrastructure (i.e., stations) and available lines.

In this model, the portal assumes an active role in making decisions for the allocation process. The portal sense the attractiveness emitted by all stations, and based on this, the portal assigns lines to buses changing the predefined frequency of the lines. This attractiveness has values between 0 and 1, which is used to find a proportion of the predefined frequency. In the following, the parameters, variables and the attractiveness formulation are described.

Parameters

L: Set of lines $L = \{1,2,\dots,|\mathrm{L}|\}$ denoted by the expression $l \in L$.

S: Set of stations: $S = \{1,2,\dots,|\mathrm{S}|\}$ denoted by the expression $r \in S$.

$\boldsymbol{D_l(L)}$: Line's demand $l \in L$ in the moment $m \in M, m$ is a time segment.

$\boldsymbol{FB_l}$: Initial frequency $l \in L$.

$\boldsymbol{B}$: Number of buses on the system $B = \{1,2,\dots,|\mathrm{B}|\}$

Variables

$\boldsymbol{S_{sl}}$: Is a binary value set to 1 if the route j stops in the station s. else 0. $l \in L, r \in S$.

$\boldsymbol{Q_{l(s-1)}}$: Occupancy rate of the line $l \in L$ at the station $s \in S$.

Attractiveness

$$\boldsymbol{\alpha_{rl}(t)} = \forall l \in L \sum_{r \in S} \frac{D_{lr}(t) * S_{rl}(t) * Q_{l(r-1)}}{\sum_{l \in l} D_l(t)}$$

$$\boldsymbol{\beta_l} = \min[(1-\alpha_l), 0{,}7]$$

$$\boldsymbol{FT_l} = \boldsymbol{\beta_l} * \boldsymbol{FB_l}$$

Allocation algorithm

Once the proposed model generates the frequencies of the bus lines, it is necessary to have a control which will assure the correct functioning of the proposed scheduling algorithm. For this, algorithm to assign the lines is used. This algorithm allows to establish the logical order in which the buses are sent, with the assigned routes, depending on the attractivity of the stations. This consist in organize the lines in the ascending order, in accordance with their frequency. The order establishes the list of dispatching the lines, considering that the lines with the lowest frequency do not saturate the system and allow for the dispatching of the lines with the higher frequency. The figure 5 shows in detail the flow of the allocation algorithm.

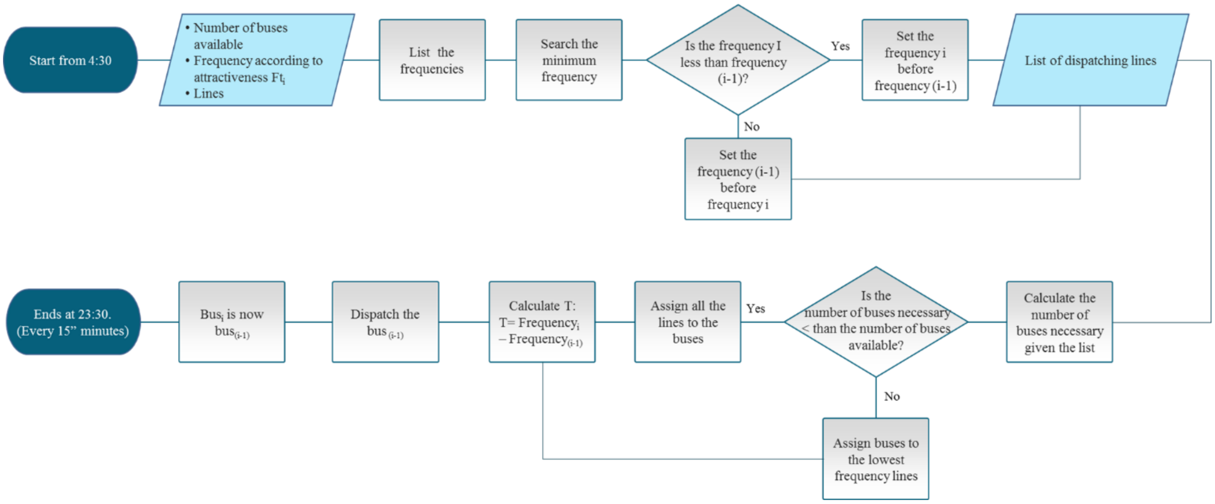

Fig.5 Flowchart allocation algorithmic

Desktop Test

A desktop test for the mathematical model is presented. Line K23 was selected to simulate the model. Table 5 shows the percentage of bus occupancy at the time of arriving at the station at a certain hour. Table 6 presents the historical demand found in reports by Ministry of Transport, for each station in each period. Table 7 represents the demand of the station for each wagons a certain hour, it is assumed that the demand of the station is divided proportionally among the number of wagons. Table 8 shows the number of random passengers waiting for a bus in each wagon. Table 9 shows the attractiveness of the wagons at certain hour. Table 10 shows the values of B which means the factor of attractiveness. Finally, Table 11 shows the theoretical frequency for a given hour.

Table 5. Percentage of occupation at specific time

Percentage of occupation at specific time							
Hour	**Avenida rojas**	**El tiempo - Maloka**	**Salitre - El Greco**	**CAN**	**Gobernación**	**Ciudad Universitaria**	**Plaza de la Democracia**
6:30	0,9	0,85	0,85	0,8	0,8	0,6	0,6
10:45	0,2	0,21	0,235	0,25	0,275	0,25	0,25
12:00	0,6	0,6	0,55	0,55	0,4	0,4	0,45
14:30	0,175	0,19	0,2	0,215	0,245	0,26	0,25
18:00	0,65	0,7	0,7	0,6	0,55	0,5	0,5

Table 6. Demand Station - Hour $D_l\ (t)$

Demand Station - Hour $D_l\ (t)$							
Hour	**Avenida rojas**	**El tiempo - Maloka**	**Salitre - El Greco**	**CAN**	**Gobernación**	**Ciudad Universitaria**	**Plaza de la Domocracia**
6:30	191	250	239	226	201	257	95
10:45	76	99	95	90	80	102	38
12:00	83	109	104	98	87	112	41
14:30	83	109	104	98	87	112	41
18:00	144	189	181	171	152	194	72

Table 7. Demand Station / Docking Bay - Hour $\sum D_{lr}\ (t)$

Demand Station / Docking Bay - Hour $\sum D_{lr}\ (t)$								
Hour	**Avenida rojas**	**El tiempo - Maloka**	**Salitre - El Greco**	**CAN**	**Gobernación**	**Ciudad Universitaria**	**Plaza de la Domocracia**	$\sum D_{lr}\ (t)$
No. Doccking bay	**6**	**4**	**4**	**4**	**4**	**4**	**4**	-
6:30	32	63	60	57	51	65	24	352
10:45	13	25	24	23	20	26	10	141
12:00	14	28	26	25	22	28	11	154
14:30	14	28	26	25	22	28	11	154
18:00	24	48	46	43	38	49	18	266

Table 8. Random Passengers

Random Passengers								
Hour	**Avenida rojas**	**El tiempo - Maloka**	**Salitre - El Greco**	**CAN**	**Gobernación**	**Ciudad Universitaria**	**Plaza de la Domocracia**	$\sum$
6:30	13	35	52	42	0	40	9	191
10:45	13	14	12	8	16	11	10	84
12:00	10	17	20	19	10	9	4	89
14:30	11	18	0	20	11	12	4	76
18:00	1	48	23	4	25	7	3	111

Table 9. Attractiveness $\alpha_{rl}\ (t)$

$\alpha_{rl}\ (t)$								
Hour	**Avenida rojas**	**El tiempo - Maloka**	**Salitre - El Greco**	**CAN**	**Gobernación**	**Ciudad Universitaria**	**Plaza de la Domocracia**	$\sum$
6:30	0,06	0,16	0,23	0,18	-	0,13	0,03	0,78
10:45	0,03	0,04	0,03	0,02	0,05	0,03	0,03	0,24
12:00	0,07	0,11	0,12	0,12	0,04	0,04	0,02	0,53
14:30	0,03	0,05	-	0,06	0,04	0,04	0,01	0,22
18:00	0,01	0,30	0,15	0,02	0,12	0,03	0,01	0,64

Table 10. Attractiveness β_l

β_l	
Hour	**β**
6:30	0,22
10:45	0,70
12:00	0,47
14:30	0,70
18:00	0,36

Table 11. Teoric Frecuency FT_l

FT_l	
Hour	**FT**
6:30	1,55
10:45	4,90
12:00	3,30
14:30	4,90
18:00	2,49

4.4. Objective 4

Plataform NetLogo

The design, test and simulation of decentralized approaches, and particularly those exhibiting adaptation and reactivity, are usually a hard task. The agent-based modelling and simulation platforms (ABM) aim to test and compare various model configurations by allowing to change the parameters and decision-making algorithms of each agent. As pointed out by (Barbosa and Leitão, 2010) a set of modelling and simulation environments are currently available such as MASON (http://cs.gmu.edu/~eclab/projects/mason/), NetLogo (http://ccl.northwestern.edu/netlogo/), Swarm (http://www.swarm.org/) and Repast (http://repast.sourceforge.net/). Babosa and Leitão summarized the main features of the platforms in the following table

Table 12. Characteristics of Some Agente-Based Modeling and Simulation Plataforms

Name	Mason	NetLogo	Swarm	Repast[GMZR1]
Availability (Free)	Yes	Yes	Yes	Yes
Maturity	-	O	+	O
Programming effort	-	+	O	-
Change of properties	-	O	-	+
User interface	-	+	-	+
Simulation speed	+	O	O	+
Documentation	+	+	O	O

Analyzing the characteristics represented in the Table 5, it is possible to conclude that most existing platforms presents general weaknesses and none of them is perfect, i.e. each one has good and weak points. Above the others, the NetLogo platform can be seen as a good solution to develop agent-based solutions that exhibit complex behavior. It provides an easy, intuitive and well-documented programming and modelling language with enough simulation facilities (e.g. a good graphical interface) and processing potentialities. For the decentralized model proposed herein the following advantages can be highlighted:

- Graphical visualization: for a BRT simulation model, it is of the outmost importance to visualize the current state of the system and the behavior of movable entities, in this case, buses.
- Breeds: the three decisional entities proposed can be easily modeled as breeds which decreases the amount of time spent in programming.
- Patches: the concept of patches matches very well with our context since patches allow to model the BRT infrastructure, particularly the streets on which buses move.
- Library: NetLogo has traffic models that can be used as reference.

The following pictures show a view of the NetLogo simulation and how the information about the bus with a specific line is presented. Figure 4.presents the graphic of the demand to the system in an operational day.

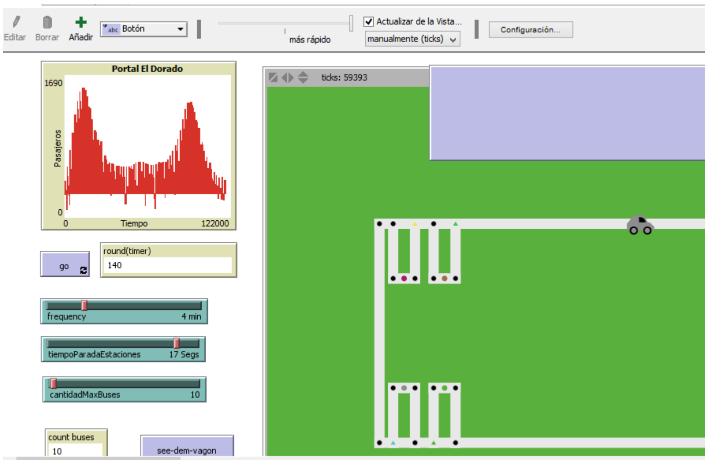

Fig. 6. NetLogo Simulation.- Curve of Demand in the System.

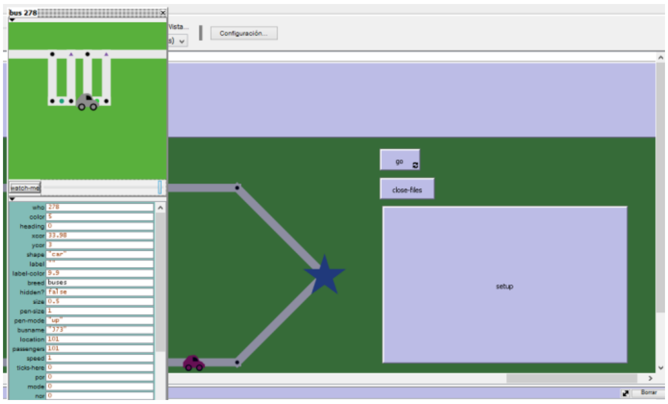

Fig. 7. NetLogo Simulation – Information for buses.

Nodes in the system

To guarantee the simulation works appropriately it is necessary to have four types of nodes which are described in the Table 13.

Table 13. Nodes in the NetLogo Simulation

Node	Function	Characteristics
Step	Offers the information with the respect to the speed of the buses and the position they can be found at. It facilitates continuous movement of the buses with no traffic jams, so that bus does not have to stop in certain stations.	Red /Circle
Station	Gives information on which bus lines stop at certain docking bays.	Green/Circle
Docking Bay	Brings information on passengers. The number of passengers entering and leaving the station until the bus is there and the number of passengers staying at the station after the bus has left.	Blue/Circle
Portal	Establishes the number of buses to send to each station, the demands of the system and properties of each node.	Black/Circle

Estimation of the demand for Transmilenio BRT system

The validation of the proposed decentralized control architecture, and the comparison of this with the actual model, depends on the real data taken from the BRT system in Bogota, Transmilenio. This allows the evaluation of the proposed model and its capacity to respond to a normal scenario in real time. Demand-related information consists of two groups of data: first, all the information about the infrastructure of the system (maximum number of the buses, sequence and the geographical location of the stations, busway infrastructure, docking bays and the duration of the operation). The second set of data refers to the system demand, which needs to be detailed depending on its BRT physical structure (i.e., portals, stations, lines). This information was obtained from the "Statistics of the offer and demand of the Integrated System of Public Transport - SITP monthly report May, 2016[GMZR2]". In this report, the profile of the demand of one typical working day of the BRT system and the graphics of the fluctuation of the demand, in intervals of 15 minutes, can be found. Additionally, the report specifies the demand in each and every of the station. However, the report does not mention the origin/destiny matrix, and so the demand by line is not known.

The proposed model reads the demand of each station in the intervals of 15 minutes during one working day. To calculate the demand, a matrix was made where the average of the people in the system for a certain hour in the day is transferred to the average demand per station. This matrix was made following the next steps:

- The whole demand of all Transmilenio system, for time windows of 15 minutes, was obtained from the report. The duration of operation is from 4:30am to 11:45 pm.
- A weight percentage is found by dividing the demand of the system, in certain time window, by the total demand during the whole day. The total demand of the day for each station was obtained from the report and was multiply by the weight percentage for each hour. This is done for all stations in the El Dorado busway. Demand by station is rounded to work with integer demands
- For validations, the demand of all stations in the El Dorado busway were checked to verify that they had the same behavior as the demand of the system.

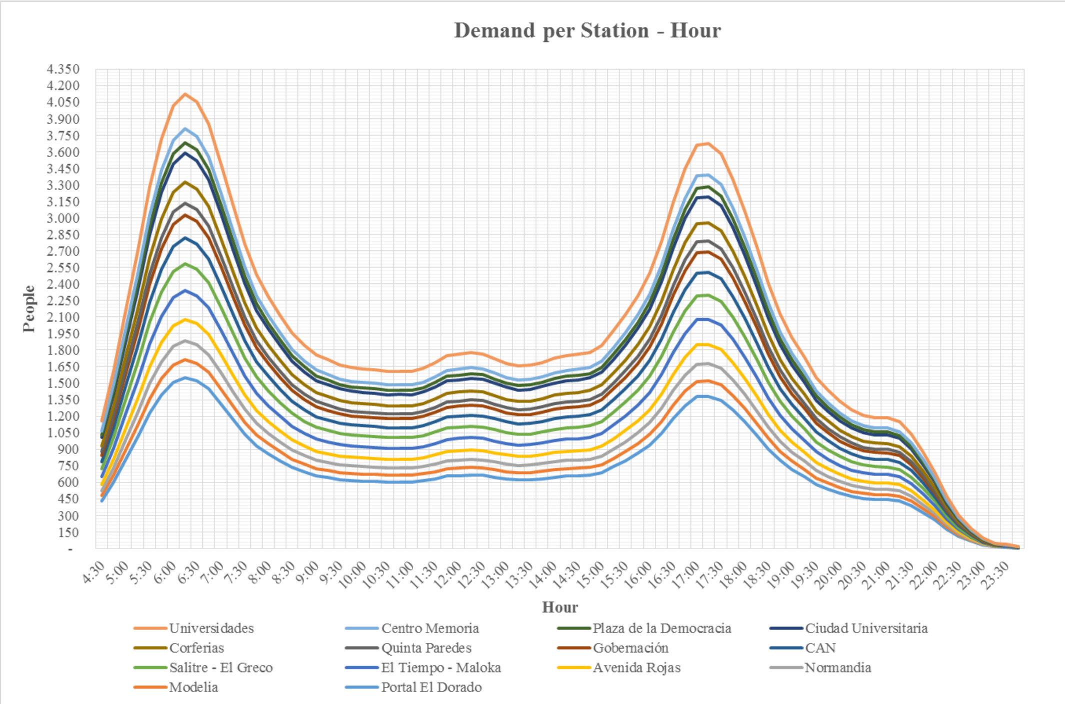

Fig. 8. Demand per Station per Hour in Transmilenio BRT System.

Assumptions

With the goal of simplifying the simulation model of the Transmilenio BRT, the following assumptions were made:

- All the buses have the same capacity and are of the same type.
- The speed is constant and is 20km/h.
- The demand of the stations is equi-probable to the number of the docking bays in the station. Additionally, the docking bays have just one dor.
- The actual structure of the Transmilenio has two pathways in each direction of the busway. For the practical and graphical effect of the simulation, only one busway is considered in each direction. In this way, when one bus is collecting and leaving passengers in one station, it can happen that the other bus, which is not stopping at such station, passes over it.
- The model analyzes only one typical working day.
- Disturbances are not evaluated but the architecture allows to analyze different types of disturbances by only working with few variables.
- Bus lines are simulated only within El Dorado busway; hence the simulation is not carried out for stations out of El Dorado busway.

Results and analysis

The station occupancy is the indicator for comparing the current BRT fixed-frequency system with the proposed real-time potential fields-based system. This indicator shows the number of the people at one station in a certain moment during the day. In Figures 5 and 6, this indicator can be seen for the stations Salitre El Greco at the docking bay number 3, and the station CAN at the docking bay number 1. History of occupancy (i.e., demand reports by Transmilenio) can be observed (shaded cells) as a reference to verify that the simulated models are responding to the real demand of Transmilenio. The green line reflects the occupancy in the station with the fixed-frequency model and the determined frequencies. In the same way, the blue line shows the behaviour of the indicator according to the proposed control architecture for the Transmilenio BRT system.

For the purpose of the explanation, the examples of the previously mentioned stations were taken. But the simulations and the analysis can be done with any station. This is owed to the fact that the BRT system allows to have the same behavior in scale for each station. Based on the simulations of the NetLogo model, it was identified a reduction in the occupancy of the station for the whole working day of 27.8% for the station El Greco and 15.3% for the station CAN. This reductions are result when compared with the occupancy of the current model of Transmilenio. Within these scenarios, the analysis can also be made on critical hours for the system, in other words, rush hours. If this is applied, for the intervals of three hours in the morning and three hours in the afternoon, reductions are 14.3% and 30.7% respectively for the station Salitre at the docking bay number 3; and 13.0% in the morning and 15.6% in the afternoon for the station CAN at the docking bay number1.

By having a lower occupancy, the better the flow of the people and the better the efficiency of the system, since people have to wait less time at the station. The algorithm is also capable of generating more stable occupancy than the current fixed-frequency model, since the occupancy indicator fluctuates less, as seen in figures 5 and 6. This confirms the reactivity of the proposed scheduling and control architecture because stations are less crowed and peaks of occupancy are not as high as in the current system. Additionally, it is possible to confirm that the proposed model of line occupancy has one standard deviation which is not significative. This indicates that there are no atypical points in the simulations and, furthermore, that the fluctuation is smaller than the actual occupancy line of the model.

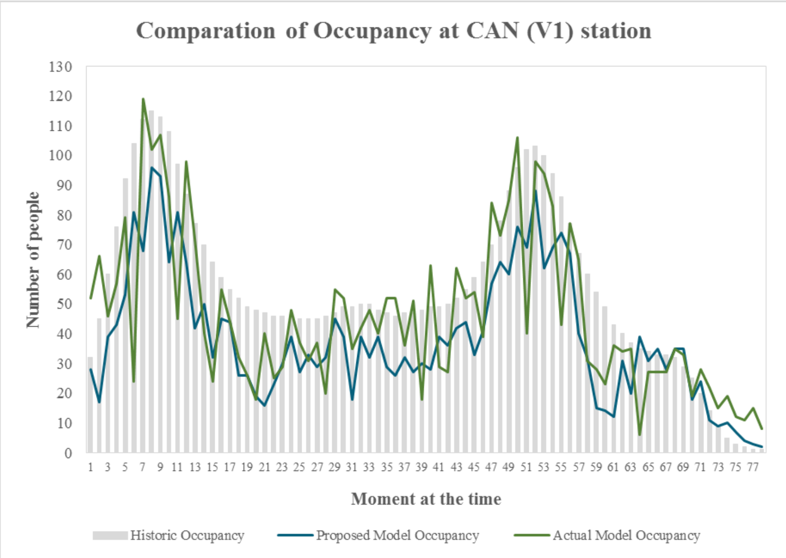

Fig. 9. Comparison of Occupancy at station "CAN"

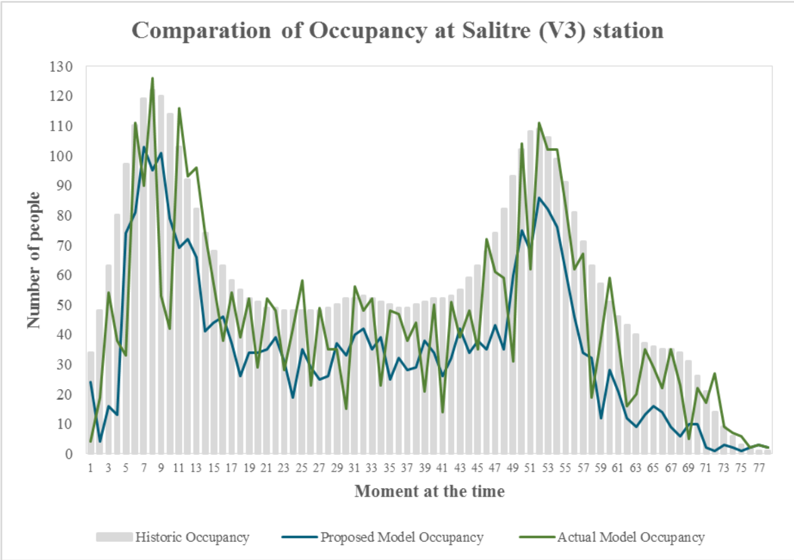

Fig. 10. Comparison of Occupancy at station "Salitre El Greco"

In order to corroborate the significance of the proposed model against the current model, Corferias and El Tiempo stations were selected and an anova analysis was applied. It is possible to choose the stations randomly, since the demand of the system has for each one of the stations a single behavior, in other words, the occupancy level data for each station in a specific moment of the day can be extrapolated from one station to another, this is Evident In Fig. 8.

The number of people in the station at three different times of the day (morning 6:15, afternoon 12:30 pm and night 5:45 pm) were taken as a variable response to perform the anova analysis for both the proposed model as well as the real model. The data collection was performed in the NetLogo software taking into account that both models had the same conditions. Tables 14 and 15 show that the P-values are less than 5%, which means that the proposed model is significantly different in the three times of the day with respect to the current model.

Table 14. Anova for station Corferias

Corferias						
Source of variation	***SS***	***df***	***MS***	***F***	***P-Value***	***F Crit***
Time of the day (Morning, Afternoon, Night)	24646,43	2	12323,22	593,52	1,75E-37	3,17
Models (Centralized and Decentralized)	897,07	1	897,07	43,21	2,03E-08	4,02
Interaction	106,63	2	53,32	2,57	8,60E-02	3,17
Within groups	1121,20	54	20,76			
Total	**26771,33**	**59**				

Table 15. Anova for station El Tiempo.

	El Tiempo					
Source of variation	***SS***	***df***	***MS***	***F***	***P-Value***	***F Crit***
Time of the day (Morning, Afternoon, Night)	35402,70	2	17701,35	878,48	6,47E-42	3,17
Models (Centralized and Decentralized)	380,02	1	380,02	18,86	6,23E-05	4,02
Interaction	12,43	2	6,22	0,31	7,36E-01	3,17
Within groups	1088,10	54	20,15			
Total	**36883,25**	**59**				

In addition to the analysis of the results in the reduction of station occupancy, within a BRT system it is important to contemplate the element of operating costs. Within the methodology of potential fields it is possible to have a factor of measurement of costs by means of a variable to determine the number of hours of use of the bus per day of work and with that to determine the operative costs. This variable can be joined to the allocation algorithm of buses b to lines l. The variable would allow to count how long the bus i is in operation or not according to the lines that are assigned during the operation time. The scope of the Project contemplates VSP and does not contain rostering, the economic analysis is limited only to the bus-related and not to the total operating costs of the System.

Impact of the proposal

The impact of the proposed model was more than evident in the reductions that were found once the analysis was undertaken. These results confirmed that the model is improving the occupancy of the whole lines during the working day and also if we separate certain hours when the number of the passenger spikes up (rush hours). The total reduction of occupancy was 27.9%. This value is very significant for the model and the impact of this model. If we take closer look at the certain hours of the day important for the functioning of the system, as are rush hours, reductions are still significant and persistent.

5. Conclusions

Different models, issued from the distributed artificial intelligence were analyzed with the purpose of choosing the most suitable one. The potential fields approach was chosen for its level of autonomy, cooperation and its hierarchy architecture.

A control architecture for scheduling and controlling vehicles in BRT system was presented, as were all the decisional entities identified (passive and active ones)

A scheduling and control decisional algorithm was defined and the information related to the parameters and variables as well by highlighting the adaptability to changes in variables in the real time.

The algorithm was validated by simulation results that show the reduction in the occupancy of the stations compared to the algorithm with the fixed frequencies. These results confirmed that the model is improving the occupancy of the whole system during the working day and also if we separate certain hours when the number of the passenger spikes up (rush hours). The total reduction of occupancy was 27.9%.

6. Future work

It is necessary to have demand for each line during one working day. This allows to identify more exact frequencies for each line.

It is recommended to introduce different algorithms for bus allocation and control, much more intelligent and structured.

Furthermore, we propose to create scenarios for disturbances to which the system can adapt, which will give it flexibility to the changes in the environment.

It is advised to introduce people as decision entities in the model of potential fields in order to establish criteria for comparison to the present models.

7. Glossary

Scheduling: Scheduling is a decision-making process that is used on a regular basis in many manufacturing and services industries. It deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives (Pinedo, 2008).

Decisional entity: According to the definition proposed by Trentesaux (2009), a *decisional entity* (DE) is a generic term referring to any kind of autonomous unit able to communicate, to make decisions and to act within a manufacturing scenario.

Control architecture: defines the blueprint for the design and construction of FMS control (Smith et al., 1996). Depending on the structure, the control architecture allocates control responsibilities on one or more decisional entities, determines the inter-relationships between them and establishes the coordination mechanisms for the execution of control decisions.

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