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Geographical simulation-optimization system for solving subway complex emergency problems

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Abstract

Complex emergency problems are presented in the Mexico City subway due to the breakdown in the train, specifically wheel flat causing the movement of emergency vehicles and firemen that need to select the shortest path from their location to the subway station where the incident is presented. A large number of existing studies in the broader literature have examined the use of optimization techniques to solve the problem of emergencies at subway stations applying the shortest path algorithm and integrating GIS. However, the contributions based on simulation optimization techniques with GIS for solving such problem are limited. This paper addresses the need to establish a framework for a geographical simulation and optimization system that integrates ABMS, GIS, and Dijkstra´s algorithm for solving complex path optimization problems, such as the optimal route finding to support fire emergency service at subway stations and the movement of emergency vehicles, so far lacking in the scientific literature. This system can be used to optimize and simulate a variety of emergency situations at subway stations and design anticipatory scenarios to improve response. First, we present the literature review about the use of optimization algorithms for subway emergency and ABMS used to investigate the dynamic of subway in emergency cases. Second the framework for a geographical simulation and optimization system is formulated and implemented using Netlogo™. Third, the simulation results are analyzed. Finally, the concluding remarks and directions for future research are drawn.

Keywords: ABMS; optimization; GIS; shortest path; Dijkstra´s algorithm.

1. Introduction

According to the Origin-Destination Survey (INEGI, 2017), 15.63 million people make at least one trip during the week in the Metropolitan Zone of Valley of Mexico (MZVM), 50.6% are women and 49.4% are men. The number of people who make at least one trip on Saturdays is 10.35 million. The Mexico City subway (MCS) transport near to 5 million people during the week which represents more than 28% of the total trips in the MZVM (INEGI, 2017).

To offer the public transportation service between the different origin-destination in Mexico City and the Metropolitan Zone, the MCS has a fleet of 384 trains, of which 321 are pneumatic, made up of 292 trains with 9 cars and 29 with 6 cars, as well as 63 with railway tracks, made up of 21 trains with 9 cars and 12 with 6 cars, as well as 30 trains with 7 cars.

Figure 1. Representation of a train with 6 cars, Mexico City subway STC (2021).

Figure 2. Representation of one car, Mexico City subway STC (2021).

The MCS follows a well stablished policy to prevent emergencies or disasters, whether of natural origin such as geological (earthquakes) and hydrometeorological (floods), or of anthropogenic origin (STC, 2017). Despite the MCS was projected, designed and built with risks prevention in mind, being observed in hydraulic systems such as pumping stations to prevent flooding or early detection systems for earthquakes that allow preventive actions to be taken to minimize damage; it maintains the policy of timely risk detection in order to avoid any emergency or disaster.

However, complex emergency problems are presented due to breakdowns in the train, specifically wheel flat, which is a main type of potential dangerous factors of inducing the wheel/rail failure, which is usually generated by the two following factors, according to Jing (2017):

- The sudden lock of a running wheel during the braking process, resulting that the braking force exceeds temporarily the available wheel-rail friction force.
- The sliding of the wheel on the rail under the circumstance of a local reduction of the wheel-rail adhesion force.

Depending on the severity, such complex emergency problems are solved by the authorities of MCS with assistance of external areas as for example emergency vehicles and firefighters which are geographical located along Mexico City. As results, the problem for passengers is dissatisfaction in the quality of service due to long waiting time in transportation caused by this incident. The emergency vehicles and the firefighters need to select the shortest path from their actual location to the subway station where the incident is presented. All this under uncertainty context: high road traffic, danger of fire on tracks, higher irritation level and another psychological feeling that passengers might experience due to delays such as angry, sleepiness, nausea, aggression, stomach pain, increase heartbeat, etc.

A large number of existing studies in the broader literature have examined the use of optimization techniques to solve the problem of emergencies at subway stations applying the shortest path algorithm and integrating geographic information systems (GIS). However, the contributions based on simulation (ABMS) optimization techniques with GIS for solving such problem are limited. This paper addresses the need to establish a framework for a geographical simulation and optimization system that integrates ABMS, GIS, and Dijkstra´s algorithm for solving complex path optimization problems, such as the optimal route finding to support fire emergency service at subway stations and the movement of emergency vehicles, so far lacking in the scientific literature.

The innovative aspect of this system is the way in which ABMS is integrated with GIS, and the management of Dijkstra´s algorithm over a cellular automata platform to address some mobility and human factors for handling complex emergency problems. This system can be used to optimize and simulate a variety of emergency situations at subway stations and design anticipatory scenarios to improve response.

This paper is organized into five sections. In the following section we present the literature review about i) the use of optimization algorithms for subway emergencies including emergency vehicles, fire stations and shortest path, and ii) ABMS used to investigate the dynamic of subway in emergency cases. The framework for a geographical simulation and optimization system is formulated and implemented using Netlogo™ software (Wilensky and Rand, 2015) in Section 3. In particular, we discuss the integration of ABMS with GIS and the adaptations of Dijkstra´s algorithm to handle complex paths in case of emergency situations. The main results of our analysis are presented in Section 4. Concluding remarks and directions for future research are drawn in Section 5.

2. Systematic literature review

In this section, we present the literature review about the use of optimization algorithms for subway emergencies including emergency vehicles, fire stations and shortest path, and ABMS used to investigate the dynamic of subway in emergency cases. We followed the literature review process proposed by Machi and McEvoy (2009). The Figure 3 describes the steps for conducting a literature review.

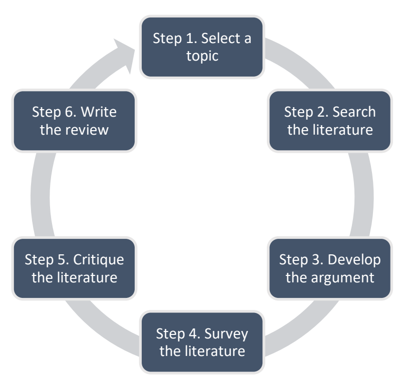

Figure 3. The literature review model, Machi and McEvoy (2009).

2.1. Optimization algorithms for subway emergencies

2.1.1. *Step 1. Select a topic*

We started the literature research by using the keywords *optimization models* AND *ambulances* AND *fire stations*. Another search was conducted by using the keywords *shortest path* AND *emergency* AND *stations*.

2.1.2. *Step 2. Search the literature*

For each manuscript, preliminary relevance was determined by title. We searched Scopus and Science Direct databases. We limited the publication date to 2011 and 2021, so that we can build the review on the literature published in the past ten years.

We started the literature research by using the keywords: *optimization models*. We found 882,706 results. Then, we search by using the keywords *optimization models* AND *ambulances* AND *fire stations*. In this case, we found 1 result. After that, the search was conducted by using the keywords *shortest path.* We obtained 13,541 results. Then, we search by using *shortest path* AND *emergency* AND *stations*. We found 55 results.

2.1.3. *Step 3. Develop the argument*

On the one hand, the search based on keywords "optimization models" and "optimization models AND ambulances AND fire stations" aims to find literature related to the optimization models that are currently used and that are related to fire stations, as well as considering emergency services such as ambulances.

On the other hand, the main objective of the search based on keywords *shortest path* AND *shortest path* AND *emergency* AND *stations* is to find the contributions where the shortest path algorithm is applied to study emergency situations. We recognize that the use of such algorithm could be ideal because in many cities along the world the criteria in emergency cases is time not distance, however it is the first step we consider for optimizing.

2.1.4. *Step 4. Survey the literature*

We downloaded the bibliographical information and analyzed it using VOSviewer™ software for clustering the keywords based on the co-occurrences. VOSviewer™ is a software tool focused on the distance-based visualization of bibliometric networks. In the visualizations provided by VOSviewer™, the distance between two nodes indicates the relatedness of the nodes (Van Eck & Waltman, 2014), see Fig. 4 and Fig 5.

Figure 4 shows the relationship among optimization models, subway stations and emergency services from 2010 to 2020. The optimization models suggested in the literature are mainly genetic algorithms, artificial intelligence and ant colony optimization, the latter being one of the most recent. Figure 5 illustrates the application of the shortest path algorithms such as Dijkstra algorithm, GIS, artificial intelligence, and facility location to the study of subway stations in case of emergency.

2.1.5. *Step 5. Critique the literature*

Based on the analysis of the contributions more relevant, it is important to recognize the importance by using GIS, genetic algorithms, and artificial intelligence in the analysis of subway station issues. In the direction of optimization models, the ant colony was the algorithm that was found in two of the contributions related to the topic of the subway; however, linear programming and assignment problems were found as models most used.

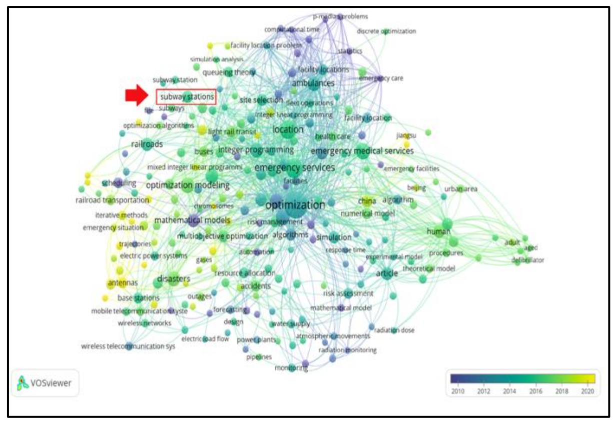

Figure 4. Clustering the keywords: *optimization models* AND *ambulances* AND *fire stations*, based on the co-occurrences using VOSviewer™ software for search based on Scopus and Science direct databases.

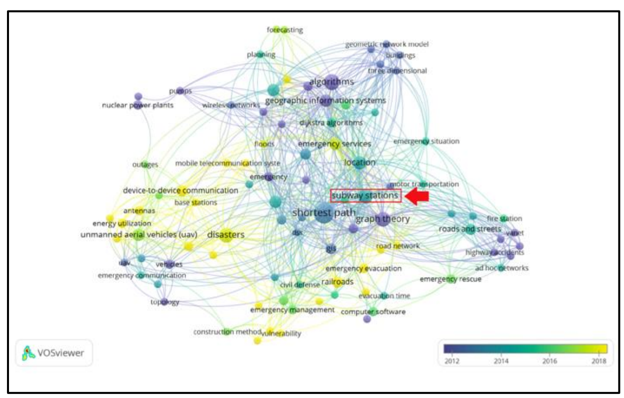

Figure 5. Clustering the keywords: *shortest path* AND *emergency* AND *stations*, based on the co-occurrences using VOSviewer™ software for search based on Scopus and Science direct databases.

The shortest path model was related to the topic of subway stations and emergency situations. Dijkstra's algorithm was the algorithm most closely related to the shortest path model in the search carried out. Additionally, it is important to note that simulation has been used in topics related to subway stations, mainly 3D simulation and ABMS. The optimization algorithms most used with ABMS were genetic algorithms. Also, the use of GIS was an important related topic.

2.2. ABMS and the dynamic of subway in emergency cases

2.2.1. Step 1. Select a topic

In order to investigate the dynamic of subway in emergency cases using ABMS, we carried out the research by using keywords *agent based* AND *simulation* AND *optimization* AND *emergency*.

In this case, the first topic was agent - based modelling and simulation, the second one was agent - based modelling and simulation and optimization in emergency cases, the third topic was agent - based modelling and simulation and optimization applied to study the subway dynamic, and the four topic was agent - based modelling and simulation and optimization applied to study the subway dynamic in emergency cases.

2.2.2. Step 2. Search the literature

For each manuscript, preliminary relevance was determined by title. We searched Scopus and Science Direct databases. We limited literature published in the past ten years, from 2012 to 2022. We carried out the first research by using keywords *agent* AND *based* AND *simulation*. From here, we obtained 63,210 results. Then, we search by using *agent* AND *based* AND *simulation* AND *optimization* AND *emergency*, from here we get 116 results. After that we search by using *agent* AND *based* AND *simulation* AND *optimization* AND *subway* as keywords, so we get 18 results. Finally, we search the string *agent* AND *based* AND *simulation* AND *optimization* AND *subway* AND *emergency*, so we obtained 245 results.

2.2.3. Step 3. Develop the argument

The aim of the of the search based on the topic agent - based modelling and simulation and optimization in emergency cases is to find the contributions where this simulation approach has been used to optimize some criteria in emergency cases located along the subway path. Based on the results found, we consider this topic is not new, however in the last years has been relevant when machine learning algorithms are included such as deep learning combined with energy management aspects.

2.2.4. Step 4. Survey the literature

We downloaded the bibliographical information and analyzed it using VOSviewer™ software for clustering the keywords based on the co-occurrences, the results were (see Fig. 6).

2.2.5. Step 5. Critique the literature

Figure 7 depicts that the subway topic is directly interrelated to agent-based models, passenger flows, multi-agent systems, disaster prevention, autonomous agents, and scheduling methods, in the scientific literature. However, its integration with GIS and optimization algorithms for solving complex path optimization problems is missing.

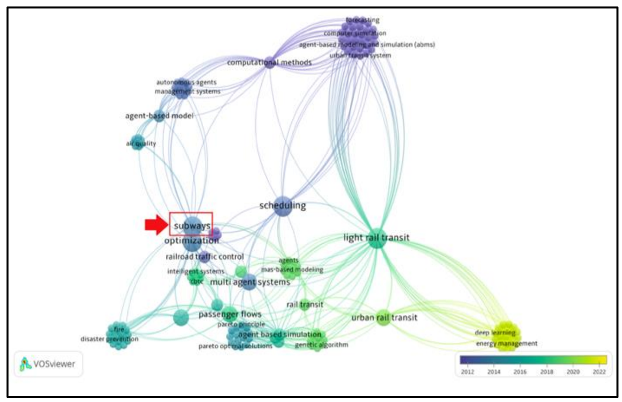

Figure 6. Clustering the keywords: agent based AND simulation AND optimization AND emergency, based on the co-occurrences using VOSviewer™ software for search based on Scopus and Science direct databases.

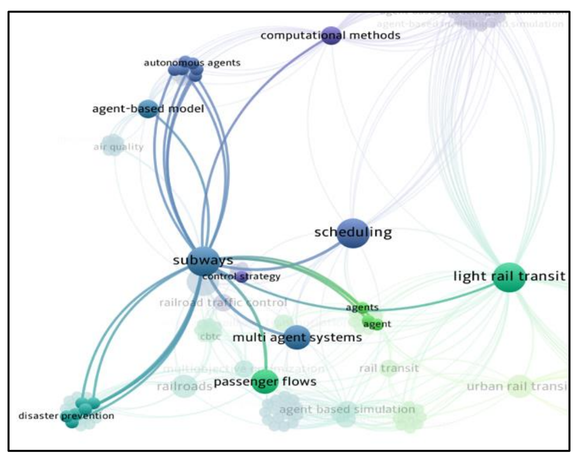

Figure 7. Interrelationship between the keyword subway and agent-based modelling and simulation in emergency cases using VOSviewer™ software, search results on Scopus and Science Direct databases, 2012-2022.

3. Materials and methods

3.1. Materials

3.1.1. The simulation software

Netlogo™ software (Wilensky and Rand, 2015), created by Uri Wilenksy in 1999 it is mostly written in Scala, with some parts in Java. It is a multi-agent programmable modeling environment. The *Logo* part is because NetLogo™ is a dialect of the *Logo* language. *Net* is meant to evoke the decentralized, interconnected nature of the phenomena you can model with NetLogo™, including network phenomena (Wilensky and Rand, 2015).

The Netlogo™ software version used to develop the simulation model included in this was 6.2.0, released on December 22, 2020.

3.2. Methods

In this section, we present the framework for a geographical simulation and optimization system (*GeSiOS*) and their application.

The *GeSiOS* integrates agent-based simulation models (ABMS), cellular automata (CA), Dijkstra's algorithm to solve the shortest path problem, and geographical information systems (GIS) for solving complex path optimization problems as the optimal route to support fire emergency service at subway stations and the movement of emergency vehicles from hospitals (see Fig. 8).

The integration of ABMS and GIS allows the system to address some mobility and human factors for handling complex emergency problems. Another novelty of this proposed system is its capability of integrating simulation models with optimization models that means the management of Dijkstra´s algorithm over a cellular automata simulation platform.

GeSiOS can be used to simulate, analyze, optimize, and design anticipatory scenarios to improve response for complex emergency problems in urban context.

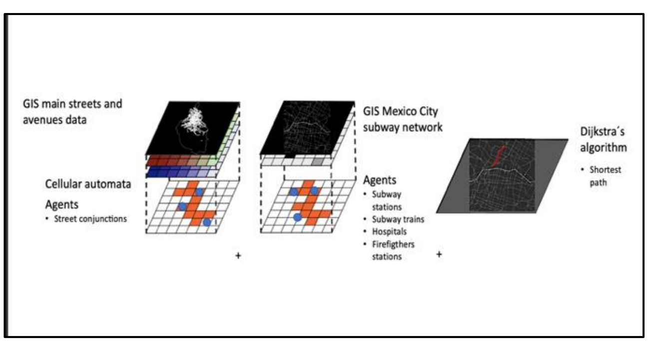

Figure 8. GeSiOS system.

3.2.1. Integrating ABMS and GIS

GIS are computational tools based on the management of information layers whose main characteristic is the reference to a geographic coordinate system.

Complex phenomena can be better understood by representing data in the world which can be indexed via a spatial location. GIS and ABMS can provide rich pictures of both the pattern and process of complex spatial systems (Wilensky and Rand, 2015). The integration of GIS with ABMS allows model developers to think about how agents interact and change in space and time (Crooks et al., 2019).

To integrate GIS into NetLogo™ the GIS extension needs to be used. This extension provides the ability to load vector GIS data (points, lines, and polygons), and raster GIS data (grids) into your model. The extension supports vector data in the form of ESRI shapefiles and GeoJSON files. The shapefile (.shp) and GeoJSON (.geojson) formats are the most common format for storing and exchanging vector GIS data.

3.2.2. The Dijkstra´s algorithm

Computer scientist Edsger Dijkstra developed an algorithm for finding the shortest path for any weighted, directed graph with non-negative weighs. In Flores de la Mota (2010), the Dijkstra's algorithm is described step by step, and in Huang *et* al. (2009), the pseudocode of Dijkstra's algorithm is presented as follows.

```
Dijkstra (Graph G, Vertex S)
    Initialize (G,s);
    Priority_Queue minQ = {all vertices in V};
    while (minQ ≠ ∅) do
     Vertex u = ExtractMin(minQ);// minimum est(u)
     for (each v ∊ minQ such that (u,v) ∊ E)
       Relax (u,v);
      end for
    end while
```

In NetLogo™ the Networks (Nw) extension can be used to find the shortest path by using the primitive "nw:path-to *target-turtle*", which according to Wilenksi (1999), it finds the shortest path to the target turtle and reports the actual path between the source and the target turtle. The path is reported as the list of links that constitute the path. While it is not specified which algorithm is used in the primitive *nw:path-to* of the Networks extension to calculate the shortest path, it was compared to a routine developed by Gil, Alvaro (2012) using the Dijkstra Algorithm in NetLogo ™.

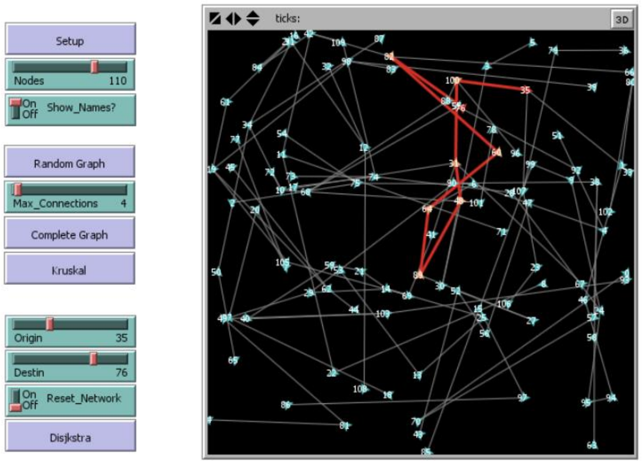

Figure 9. Dijkstra's Algorithm in NetLogo (Gil, Alvaro 2012)

Gil's code of the Dijkstra's algorithm was used and adapted in the model of this study since it had several advantages over the NetLogo's Network extension, mainly that with Gil's routine we could highlight the links in the shortest route between agents, as well as other customization options.

3.2.3. The conceptual model

According to Robinson (2013), conceptual modelling is the abstraction of a simulation model from the real world system that is being modelled. In fact, this is generally agreed to be the most difficult, least understood and most important task to be carried out in a simulation study (Robinson, 2013). In this direction, we identify the requirements for a good conceptual model for solving complex path optimization problems, such as the optimal route finding to support fire emergency service at subway stations and the movement of emergency vehicles. We make various assumptions about the real situation and choose to ignore certain small details in order to present a conceptual model to be useful (easy to use, flexible and quit to run) and to be feasible to be implemented using Netlogo™ software within the constraints of available data and time as suggested by Robinson (2013). Figure 10 depicts the simplified flux of processes and activities included on the conceptual model.

3.2.4. The simulation model

The simulation model's interface consists of seven different groups, as shown in Figure 12. First group is contained in the yellow rectangle in the upper left corner, it has the setup and clear buttons along with the projection chooser.

Inside the red rectangle on the left side are the switches to enable the visualization of the CDMX map and the different metro lines that make up the STC Metro system. The third group consists of the "Zoom L'x'" buttons inside the green rectangle, in which x is the number of the subway line, each of these buttons represent a smaller model of each metro line. On the upper right side inside the pink rectangle are the move buttons, one for each tick and the other for continuous movement. Next, inside the blue box are the sliders (s) and switches (sw) for (top to bottom): number of trains for each line (s), probability of users hurt (s), probability of fire (s), probability of the incident (s), show which train stopped due to incident (sw), number of cars driving on main and secondary avenues (s), visualization of main avenues (sw), visualization of secondary avenues (sw), highlight shortest route in avenues (sw). Inside the orange rectangle are the switches and choosers for visualizing and indicating the resources (low, medium, high) for hospitals and fire stations. Finally, the dark red arrow indicates the output of the simulation model, whenever there is an incident and whether there was a fire and injured users or not, as shown in Figure 12.

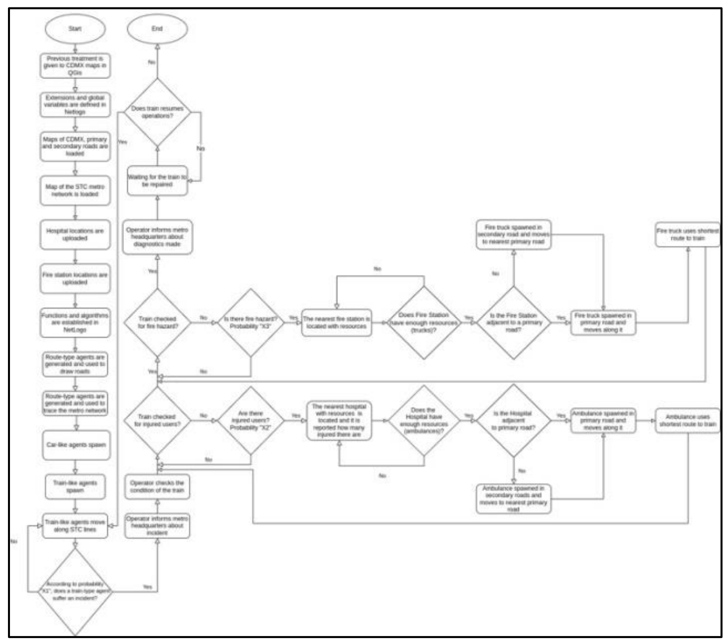

Figure 10. Flux of processes and activities.

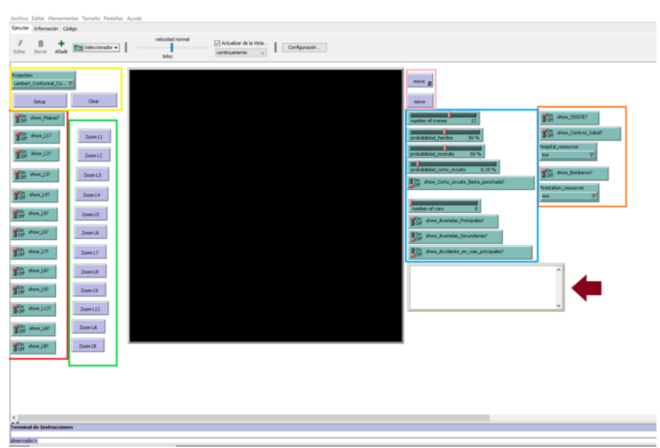

Figure 11. Description of the Simulation Model

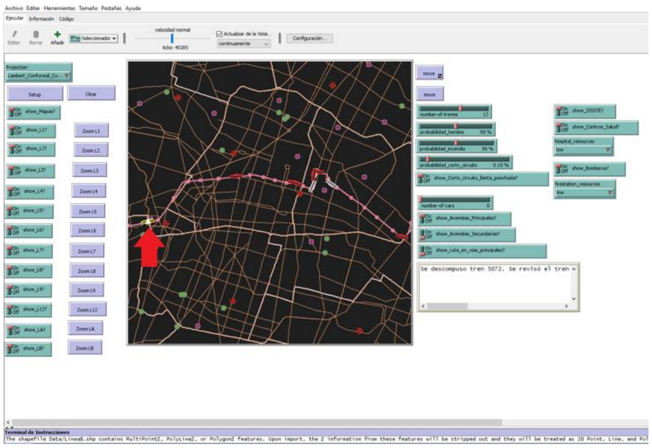

Figure 12. Simulation Model indicating and incident

In Figure 12, the red arrow shows the train from L1 of the STC Metro system (pink line) that suffered the incident, the Output box says the train was checked for injured users which were found so and ambulance was called, and for fire hazard which there also was therefore nearest fire station was called.

3.2.5. The verification method

The verification of the model was achieved by combining three modeling approaches. The first approach was the ABMS Design Principle (Wilensky, U. and Rand, W. 2015): Starting simple and then adding only the necessary layers of complexity as needed to explain the elaborated realistic phenomena. The second approach was based on the *full spectrum modeling*, defined by (Wilensky and Rand, 2015) as "...modeling phenomena at multiple levels of detail — that is, modeling not just at the level of 'simple' and/or 'elaborated and real' but also at the levels in between". The Iterative Modeling approach was used, which is to build the model in incrementally small stages and having frequent feedback between de conceptual model design and the model implementation process. This combination of modeling design approaches could be considered a bottom-up design of the model.

To summarize, it is one large model with many switches which allow different mechanisms to be turned on and off (Full Spectrum), these mechanisms are several smaller and simpler models (ABMS Design Principle) and throughout the whole modeling process it was constantly checked with and compared to the conceptual model, coevolving with it (Iterative Modeling), therefore the model was constantly being verified.

3.2.6. The validation method

According to Wilensky and Rand (2015) "validation is the process of ensuring that there is a correspondence between the implemented model and reality". Furthermore, Rand & Rust (2011) say there are two axes along which to consider validation issues. The first axis of validation is the level at which the process is occurring: microvalidation (important parts of the agent's individual behavior) and macrovalidation (important parts of the system). The second axis is the level of detail of the validation process: facevalidation (properties and mechanisms of the model are look like the real world) and empirical validation (model generates data that corresponds to similar patterns of data of the real world). Validation of a model starts at the lowest level of the model, in other words validation starts from comparing actions and data of agents in a model to those that exist in the real world (same properties, movement, heading, location) and is carried on trough the layers of complexity of the model.

Since the validity of a model is relative to the questions it is being used to answer, validation of a model can be thought more of a spectrum along the axes previously described, however since models are simplifications of reality perfect validation cannot be attained. The validation spectrum of the model presented in this model is presented in Figure 13. The model presented in this study currently has a high face validation (see Figure 14) and microvalidation (see Figure 15 and Figure 16), but data analysis for empirical and macrovalidation is still preliminary.

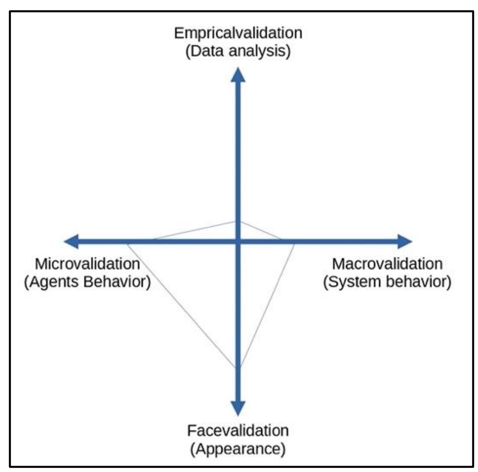

Figure 13. The validation spectrum of the model .

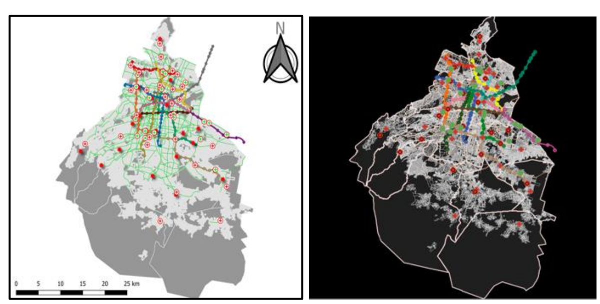

Figure 14. Facevalidation of .shp files loaded and the execution of creation of agents and the drawing of lines that represent primary streets. The image with white background represents the QGIS map. The image with dark background represents the map in Netlogo™.

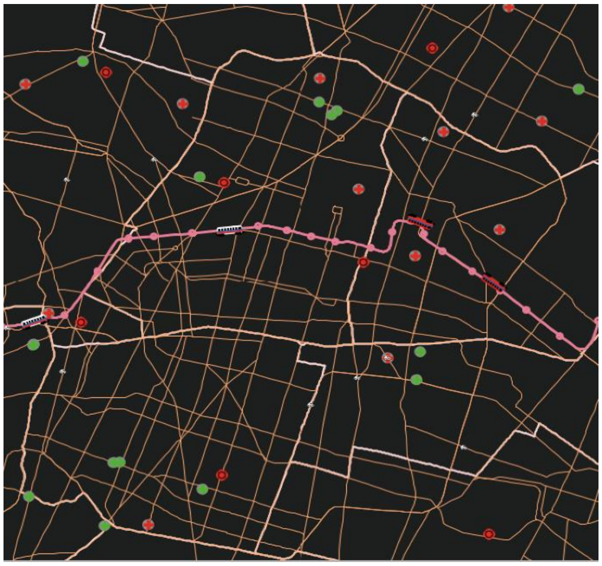

Figure 15. Microvalidation of train´s movement.

```
to movimiento_trenes
  ask trenes[
    ;;;;;;;;;;;;;;;;;;;atención aquí por esto vvvvv no se mueve descompuesto? = true
    if count (trenes with [descompuesto? = true]) = 1 [stop]
    ifelse (descompuesto? = true) [stop] [
    set prob_CC random-float 100
    set prob_heridos random 100
    set prob_incendio random 100
    set newnode one-of [out-link-neighbors] of mynode
      ifelse (newnode = nobody) [renueva] [face newnode ifelse (prob_cc) <= probabilidad_corto_circuito [set descompuesto? true
        set previouscolor color set color yellow output-type "Se descompuso tren" output-type " " output-type who output-type ". "

        create-nodosTrenAcc-with other verticesAP in-radius 2
  ask nodosTrenAcc [set thickness 0.5 set color white
    set hidden? true
        ]
        (ifelse (prob_heridos) <= probabilidad_heridos [set heridos? true llamar_ambulancia] (prob_incendio) <= probabilidad_incendio
          [set incendio? true llamar_bomberos][wait 10 clear-output output-type "El tren ha sido reparado." set color previouscolor set descompuesto? false
            set prob_CC random-float 100

            set prob_heridos random 100
    set prob_incendio random 100
          ask nodosTrenAcc [die] ])][move-to newnode]]
      set previousnode mynode
      set mynode newnode]
  ]

end
```

Figure 16. The Netlogo™ code to ask the train´s movement.

4. Results and Discussion

In this study, the *GeSiOS* that integrates agent-based simulation models (ABMS), cellular automata (CA), Dijkstra's algorithm for solving complex path optimization problems as the optimal route to support fire emergency service at subway stations and the movement of emergency vehicles from hospitals was implemented using Netlogo™ software.

The results are the following:

- Integration ABMS and GIS was successful in this study. Since it has represented big challenges because Netlogo™ software uses patches as spatial reference to agents. However, for this study the patches were not an appropriate representation of maps from GIS. So, it was necessary to implement a network based on agents to represent the subway network and the primary and secondary avenues.
- Train´s movement was achieved considering trains as agents and their movement on a network based on agents. In this direction, the movement is controlled and only on specific agents (agents that are part of the network).
- Incidents on trains. It was implemented as a pseudorandom event. It depends on the probability set by the user and the probability from each train during the movement which is independent of past events. Complementary incidents such as fire hazard and injured users inside the trains are also represented. The duration time of the incidents is variable and is classified in four scenarios: 1. There is only Short Circuit 2. Short Circuit and Fire Hazard 3. Short Circuit and Injured Users 4. Short Circuit, Fire Hazard and Injured Users.

5. Conclusions

We conclude that the aim of this study was achieved. We consider the *GeSiOS* can be useful to support the decision making of the authorities of the subway in Mexico City. But not only, it could support other subway located in different cities as long as the maps (GIS) are available.

The quality of the GIS has a direct impact on the time spent modeling the phenomena. It is advisable to preprocess the information on a program specialized in GIS rather than NetLogo™, since adjustments can be made in NetLogo™ but it is not its main purpose.

The networks of primary and secondary avenues built based on agents in NetLogo™ were simplified since in many cases multiple nodes were generated on the same patch which led to unrealistic movement of cars, ambulances and fire trucks. This was not the case for the networks of the subway lines as they were kept as they were on the .shp files, giving them a 1:1 ratio to the real system. However this also had a direct impact on the velocity of the trains, which appear to be variable but this depends on how the nodes of the GIS were sampled.

The directions for future research are:

a) The integration of traffic congestion on primary and secondary avenues.

b) The integration of alternative routes considering spatial restrictions.

c) The scale of simulation time and real time.

Acknowledgements

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