SIMULATION OPTIMIZATION OF PEDESTRIAN EVACUATION IN MEXICAN SUBWAY: THE CASE OF PINO SUAREZ STATION

Alma Vera-Morales[(a)], Aida Huerta-Barrientos[(b)]

[(a),(b)]Department of Systems Engineering
National Autonomous Mexico University

[(a)]alma.vera.m@outlook.com, [(b)]aida.huerta@comunidad.unam.mx

ABSTRACT
Mexico City subway started operating in 1961 and actually it is considered the public transport preferred by citizens with an annual ridership of 1.6 billion in 2015. The subway network is geographically located in the seismic areas of high risk in Mexico City. In fact, the subway Line 1 transports users to strategic points from East to West such as workplaces, touristic areas and the Mexico City downtown. The aim of this paper is to develop a simulation model of PINO SUAREZ subway station to optimize the number of passengers evacuating PINO SUAREZ subway station. We implement the simulation model using AnyLogic™ software and it is validated via a sensitivity analysis. We maximize the number of passengers evacuating PINO SUAREZ subway station at the busy hours in a seismic situation. From our results, we conclude that is important for subway authorities to strong the security measures and open new emergency exits.

Keywords: hybrid modeling, Mexican subway, seismic events, pedestrian evacuation.

1. INTRODUCTION
Mexico is located in one of the world´s most seismically active regions. Plate tectonics and volcanic eruptions are the main causes of earthquakes in this country. Given the geographical location and the historical earthquakes that have occurred in the last decades, the governmental authorities have generated official documents as the official map or seismic regionalization to identify regions vulnerable to these natural phenomena in order to protect the life of Mexicans. In this direction, the official map of seismic regionalization classify four seismic zones called A, B, C and D, (see Fig. 1). For instance, Class A represents the geographical region without records of earthquakes in the last 80 years. While, Class B and Class C represent geographical areas where earthquakes are recorded not as frequently as other and Class D represents geographical areas where the largest number of earthquakes has been recorded. Over the last years, the Mexican area that has been most affected by earthquakes is Mexico City. In this case, the soil composition is characterized by clay, which tend to increase the waves when a seismic occurs.

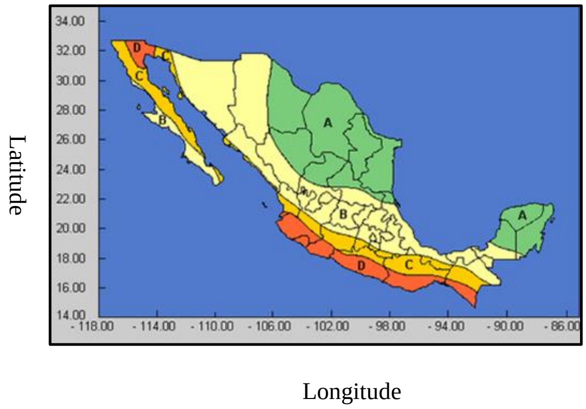


Figure 1: Seismic regionalization of Mexico, location of class A, B, C, and D areas

The earthquake occurred in 1985 was considered a catastrophe that colapsed Mexico City because the amoutn of material and human losses. After that, the governmental authorities published the Building Regulations of Mexico City that includes a map with the three types of soil in order to prevent the construction of tall buildings in susceptibles zones. On the other hand, Mexico City´s population has increased over the last years exponentially, generating a big problem of urban mobility. Mexico City subway started operating in 1961 and there are currently 12 lines in service. (see Fig.2.) It is considered the public transport preferred by citizens with an annual ridership of 1.6 billion in 2015. From the geographical perspective, the Mexico City´s subway network is located over the seismic areas.

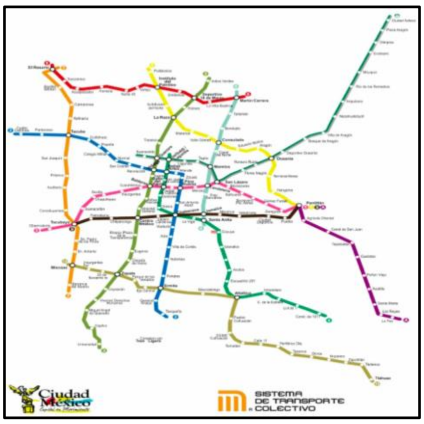


Figure 2: Subway network in Mexico City

We can distinguish three geographical areas based on their seismic risk in Mexico City: high (red), medium high (orange) and medium (yellow) (see Fig. 3). Many subway stations are geographically located over the risk area so this condition represents a warning for citizens and government. For example, work zones are located in the downtown of the city, so a lot of subway´s passengers are in imminent danger if an earthquake occurs when they are in the subway.

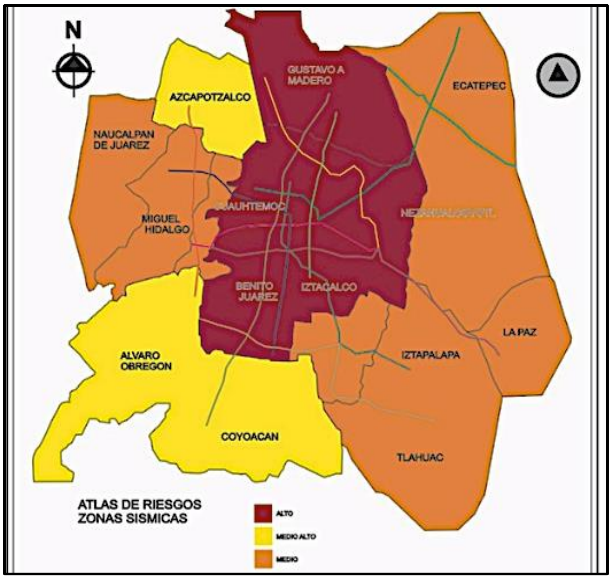


Figure 3: The three geographical areas based on their seismic risk in Mexico City

The subway Line 1 was the first to come into operation. It started in 1969 and consists on 20 subway stations with a total length of 18,828 kilometers. It transports passengers to strategic points running in a East to West direction and vice versa, such as workplaces, touristic areas and the Mexico City downtown. Also, the subway Line 1 has eight intersections with Lines 2, 3, 4, 5, 7, 8, 9, A, and B. Actually, subway Line 1 is considered the second busiest subway line, with an annual ridership of 263, 708, 660 in 2014.

PINO SUAREZ subway station, is located in Mexico City downtown, one of the areas of high seismic risk, and it is the connection between subway Line 1 and subway Line 2. PINO SUAREZ subway station has on average 25,986 riderships per day with two busy periods of time. The firts starts from 5:30 am to 10 a.m. and the second starts from 5:30 to 10:30 pm. At busy hours, the subway platforms are completely full, indeed the ascendt and descent of passengers is very complicated (see Fig. 4). So, if an earthquake occurs during busy hours, pasengers would be seriously affected in the absence of space or better conditions for evacuating. The aim of this paper is to develop a simulation model of PINO SUAREZ subway station to optimize the number of passengers evacuating PINO SUAREZ subway station. We consider our study can help to Mexico City governmental authorities to reinforce the civil protection measurements to preserve the life of subway´s passengers.

Figure 4: PINO SUAREZ subway station Line 1 at busy hour

This paper is prepared as follows: the literature review about simulation models of pedestrian evacuation and simulation software is presented in Section 2. A conceptual model of PINO SUAREZ subway station is developed in Section 3. A hybrid simulation model of PINO SUAREZ station is implemented using AnyLogic™ software and validated via a sensitivity analysis in Section 4. Then we maximize the number of passengers evacuating PINO SUAREZ subway station at the busy hours in a seismic situation and some recommendations for evacuating Mexico City subway in seismic situations are made in Section 5. Concluding remarks are draw in Section 6.

2. PEDESTRIAN MOVEMENT MODELING & SIMULATION

From the quantitative perspective, an increasing amount of literature is devoted to the pedestrian movement and mass evacuation in both indoor and outdoor using simulation. For example, Banos and Charpentier (2007) developed and agent-based prototype, MAGE to simulate pedestrian movements in very constrained and limited spaces, like subway stations. Through “what if scenarios” they explored some fundamentals aspects of complex spatial systems. Their investigations demonstrated the major role played by individual interactions and their influence on the overall behavior of the system.

On the other hand, Yang, Li and Zhao (2014) optimized the opening number of the entrance ticket windows at the Hangzhou subway station. They developed a simulation model based on Anylogic software and study the impact of parameters as the pedestrian arrival rate and the opening number of ticket windows in peak and off-peak periods. From their simulation results, it was observed that during the off-peak period, opening two ticket windows would achieve their best utilization rate.

While in the mass evacuation context, Chen et al. (2016) analyzed the related factors which included the number and width of passage, channelization setting and the number of pedestrians with the evacuation time in the passages of one subway station in Beijing. They recorded the pedestrian evacuation conditions and rom their analysis it was revealed that when the number of pedestrians gets reach to more than 200, the evacuation time increased significantly. Mustafa, Rahman, and Bachok (2013) used SimWalk to plan for an evacuation during a panic situation. It was revealed that when the bottleneck occurred, pedestrians would collide with each other, increasing he friction between them.

There is also a variety of commercial software to simulate the dynamic of pedestrians (see Table 1). For the purpose of this study, we use Anylogic software, a simulation tool that supports discrete event, agent-based and system dynamics simulation (Borshchev and Filippov 2004). The libraries that we use in this study are described in the Section 4.

Table 1: Commercial software used for simulating pedestrian evacuation

Simulation software	
Name	Provider
Egress Section in FPETool	H.E. Nelson National Bureau of Standards, U.S.
EVACNET 4	University of Florida, U.S.
TIMTEX	University of Maryland, U.S.
WAYOUT	Fire Modelling & Computing, AU
STEPS	Mott MacDonald, UK
PedGo	TraffGo
Pedroute and Paxport	Halcrow Fox Associates, UK
SIMULEX	Integrated Environmental Systems, UK
GRIDFLOW	D. Purser & M. Bensilum, UK
ASERI	Integrierte Sicherheits-Germany

3. THE CONCEPTUAL MODEL OF PINO SUAREZ SUBWAY STATION

We develop the conceptual model of the processes involved when a passenger enters to PINO SUAREZ subway station to board the subway. We visited PINO SUAREZ station at busy hours in order to observe the dynamic of daily operations. We identify the access points to understand the behavior of users within the station. In that sense, we identify three areas: the admission ticket, the subway platform and the route through passengers walk to arrive to the subway platform. The first point we focus is the access by turnstile, we find two types of passengers: the first type had ticket and the second one did not. So, once they entered the station, they choose between different directions to reach their final destinations (see Fig. 5).

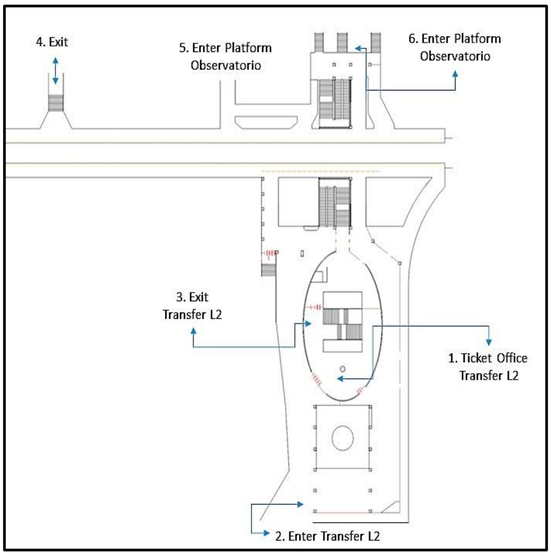


Figure 5: PINO SUAREZ subway station layout

As is observed in Figure 6, passengers sometimes have to wait if the station is too congested or they wait to another user to make the trip or get out of the system together. A lot of users enter the station at busy hour, this situation makes complicated the traffic on it. Sometimes containment measures are applied to make more agile the transit of pedestrians. Another point of interest is the connection between line 1 and line 2 of the PINO SUAREZ station. We describe feasible options that users have to move around the station, sometimes user use to use transfer just to get out of the station, perhaps their destination is closer by that exit or they decide to change the line, to reach their final destination.

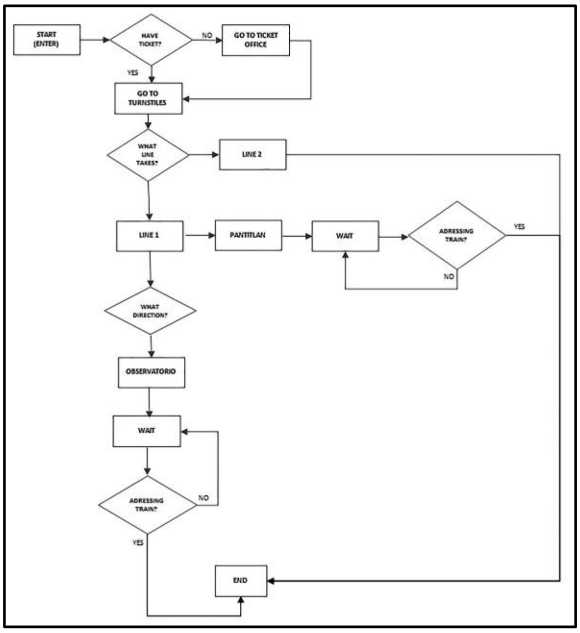


Figure 6: Flow chart of user activities inside the subway station

Finally, we design a flowchart based on Chen (2016) where it can observe how passenger behavior is when an earthquake reaches the station, shares which normally have passengers in a panic situation are: to look around and seek to safety place or to get out of dangerous situation. The station has four emergency exits, in which we optimize the number of passengers evacuating PINO SUAREZ subway station (see Fig. 7).

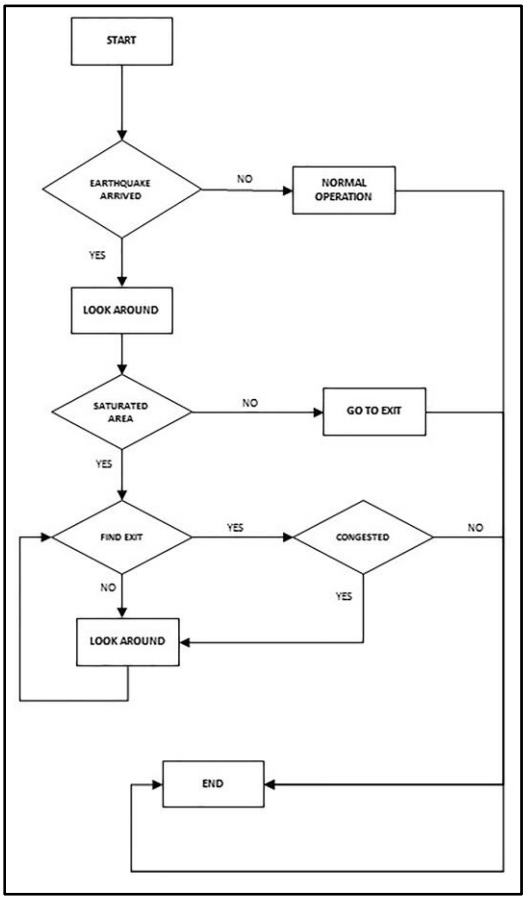


Figure 7: Flow chart of user evacuation inside the subway station during a seismic situation

4. A HYBRID SIMULATION MODEL BASED ON ABM AND DES APPROACHES

We develop the simulation model of pedestrian and subway activities in the PINO SUAREZ subway station using discrete-event simulation (DES) approach (Balci 1994, Banks 1998, Robinson 2004) and agent-based modeling and simulation (ABMS) approach (Grimm and Railsback 2005, Wilensky and Rand 2015). The DES approach uses the top-down perspective, to develop simulation models. In this case, collective phenomena are described at global level. In contrast, ABMS approach uses bottom-up perspective. In this last case, it is possible to understand the interactions rules between elements at local level. Using DES it is not fundamental the definition of a space scale as it is in ABMS. It is important to note that the time scale in DES and ABMS varies at discrete steps.

The hybrid simulation model is implemented using AnyLogic^{TM} Personal Learning Edition software. We used the Pedestrian and Rail libraries. The Anylogic^{TM} Rail Library allows users to efficiently model, simulate and visualize the dynamic of the subway along the PINO SUAREZ subway station. This library integrates well with Anylogic^{TM} Enterprise and Pedestrian libraries (Borshchev 2013). In this simulation model we use the Train Source, Train Move To, and Train Dispose blocks (see Fig. 8).

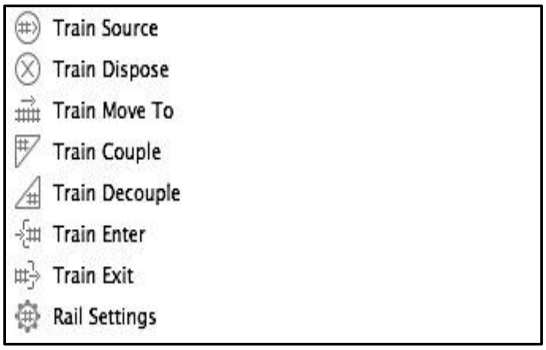


Figure 8: Block of Anylogic´s Rail Library used in the simulation model implemented

On the other hand, the Anylogic^{TM} Pedestrian library simulates pedestrian flows in "physical" environments by allowing to create models of buildings and areas with large numbers of pedestrians such as subway stations (Grigoryev 2015). In this case, we use Ped Source, Ped Sink, Ped Move To, Ped Escalator, Ped Select Output, Ped Area Descriptor, Ped Enter, and Ped Service blocks (see Fig. 9).

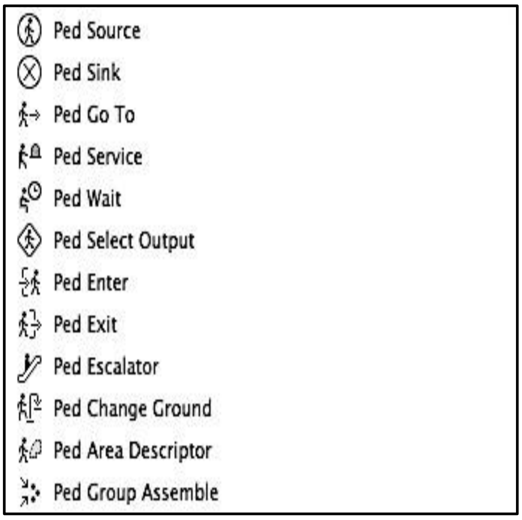
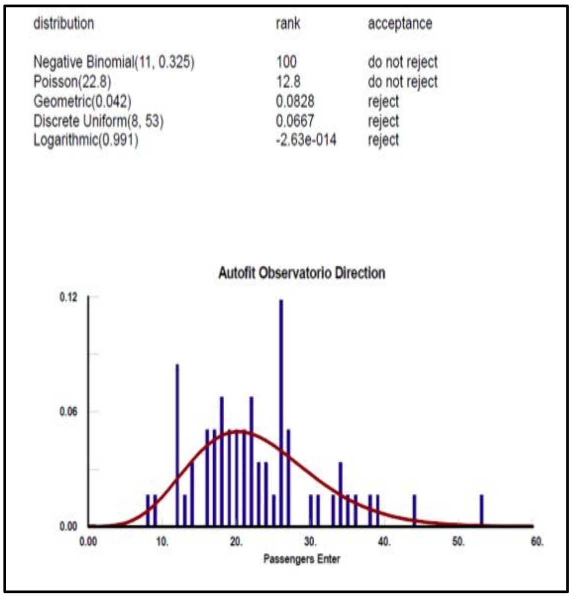


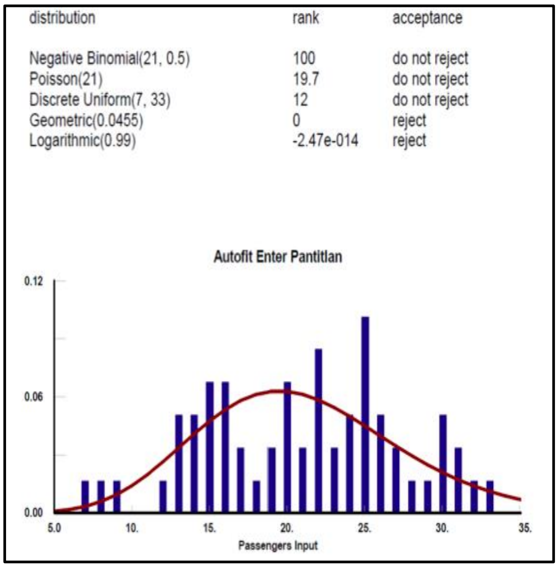
Figure 9: Block of Anylogic´s Pedestrian Library used in the simulation model implemented

4.1. Input data analysis

During the technical visits to PINO SUAREZ subway station we collected the data about passengers entering to the subway station during one hour on Wednesdays. Then, we used Stat::Fit® version 3.0.1.0 Standard to fit probabilistic distributions to our empirical data. Stat::Fit® is a probability distribution fitting software package designed to help users more easily test the fit of hypothesized statistical models to empirical data to identify the best candidate distribution for a given scenario (Benneyan 1998). The flow of passengers is fitted to Negative Binomial and Poisson distributions as can be observed in Fig. 10a and Fig 10b.



(a)



(b)

Figure 10. Autofit of empirical data of flow of passengers a) Observatorio Enter and b) Pantitlan Enter

The layout of PINO SUAREZ subway station is implemented in the simulation model considering real dimensions. We built a 3D animation of the simulation model to visualize in the most realistic way the dynamic of passengers, for example on the platform (see Fig. 11) and at the entrance (see Fig. 12).

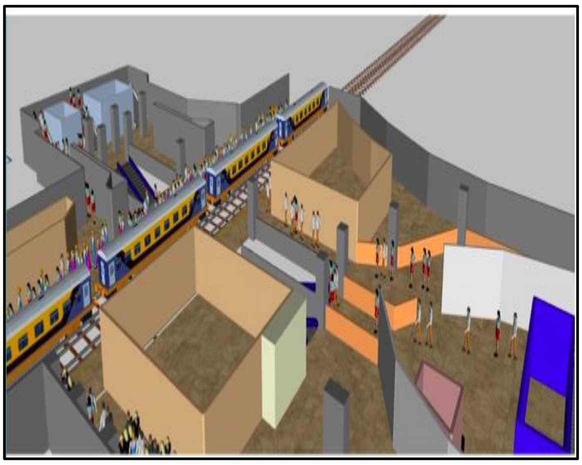


Figure 11: The 3D animation of passenger´s activities in PINO SUAREZ subway platform

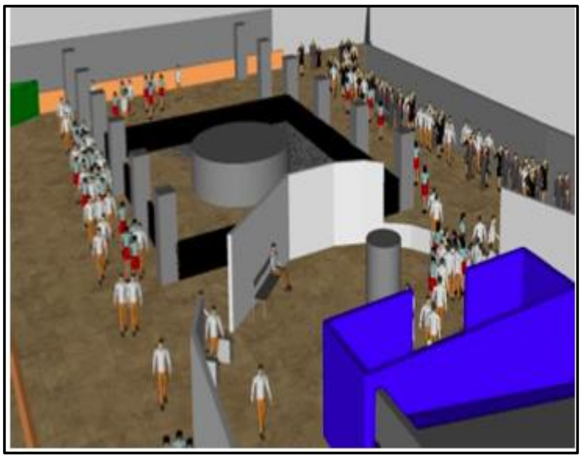


Figure 12: The 3D animation of passenger´s activities in PINO SUAREZ subway station entrance

4.2. Simulation model verification

The process of verification has the goal of elimination of "bugs" from the code, that means, the model needs to be correctly implemented (Wilensky and Rand 2015). In this case, we carry out a check on the Java StackTrace Console included in Anylogic about the warnings. Additionally, as suggested by Banks (1998), we used the 3D animation to detect some logical errors of passengers and convoys. The most common error detected is when passengers look for their final destination and it is unreachable. It was due mainly when the passengers are not adjusted in scale to the subway station dimensions.

4.3. Simulation model validation

As is suggested by Wilensky and Rand (2015), if a model is to be useful for answering real-world questions, it is important that the model provides outputs that address the relevant issues and that the outputs are accurate. In this direction, we are interested in the study of the dynamic of passengers in the PINO SUAREZ subway station, so in order to validate the simulation model, we determine whether the implemented model in Anylogic^{TM} explains such dynamic. We conduct a sensitivity analysis where passenger´s speed is allocated in two extreme values based on a Uniform probability distribution (see Table 2).

Table 2: Input variables for designing the sensitivity analysis

Input variables		
	Low	High
Passenger´s speed	Uniform(0.0, 0.5) m/s	Uniform (0.5, 1.5) m/s

In the case of passenger´s speed distributed as Uniform (0.0, 0.5) meters per second (see Fig. 13), we observe three zones of maximum passenger´s density, that were really crowded, marked in red color. This is due to the bottleneck effect when passenger´s walk slowly. In the bottleneck situation, in both the real and the simulated system, passengers are too close to each other suffering inter personal friction. Contrary, in the case of passenger´s speed distributed as Uniform (0.5, 1.5) meters per second (see Fig. 14), we observe a weak density in the subway station. This preliminary results can suggest that to avoid bottleneck in the subway station, passengers need to move really fast.

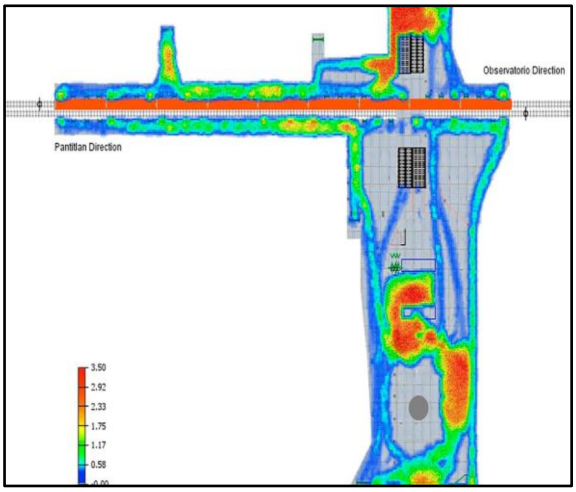


Figure 13: Passenger´s speed at low value, strong density of passengers in red color

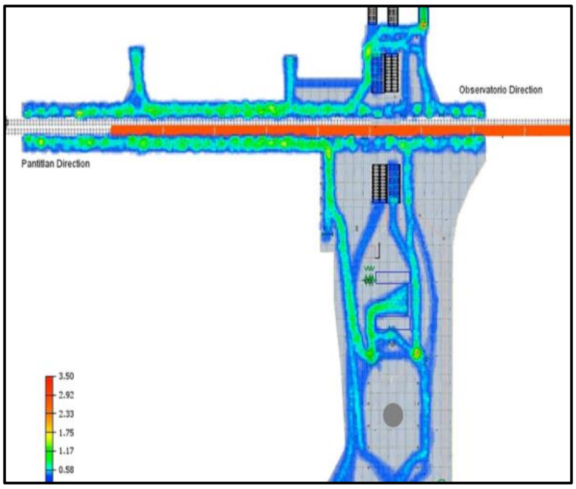


Figure 14: Passenger´s speed at high value, weak density of passengers in green color

5. MINIMIZING THE EVACUATION TIME IN PINO SUAREZ SUBWAY STATION IN SEISMIC SITUATIONS

We maximize the number of passengers evacuating PINO SUAREZ subway station at the busy hours in a seismic situation. We used the OptQuest^{TM} tool that is included in AnyLogic^{TM} software. OptQuest^{TM} is a general purpose optimizer that works with an optimization problem defined outside of the system (Glover, Kelly, and Laguna 1999), which is represented in our case by the implemented model of the PINO SUAREZ subway station (see Fig. 15). In this direction, our simulation model can change while the optimization routines remain the same. The optimization procedure uses the outputs from the simulation model which evaluate the outcomes of the inputs that were fed into the model (Glover, Kelly, and Laguna 1999). OptQuest^{TM} is based on scatter search, tabu search, and neural networks algorithms.

In this study, the outputs from the simulation model are obtained via a design of simulation experiments. To do that, we consider two factors: a) the speed passengers (meters per second) and b) the number of passengers that enter to PINO SUAREZ subway station. From the simulation experiments we obtain the metamodel (Eq. 1) that represents the passengers that evacuate the station when the two factors changes.

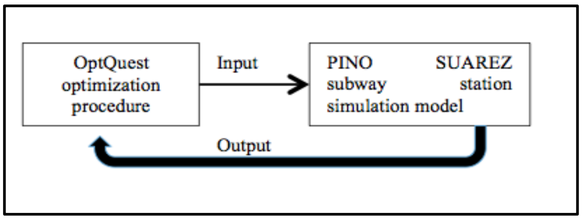


Figure 15: Interaction between OptQuest^{TM} and the simulation model

$$Y = -11.05a + 0.0017b - 0.0033ab + 41.8 \quad (1)$$

We use the metamodel for optimizing the number of passengers that evacuate the subway station during a seismic situation (see Fig. 16). During the optimization execution, agents walk towards the nearest exit area. The path followed for evacuating is not necessarily the fastest route. From the optimization results, we observe that the optimum number of simulated agents that evacuate is 44 and the evacuation time was 10 minutes (see Fig. 17). Most agents remain inside the station. So it is important for subway authorities to strong the security measures and open new emergency exits.

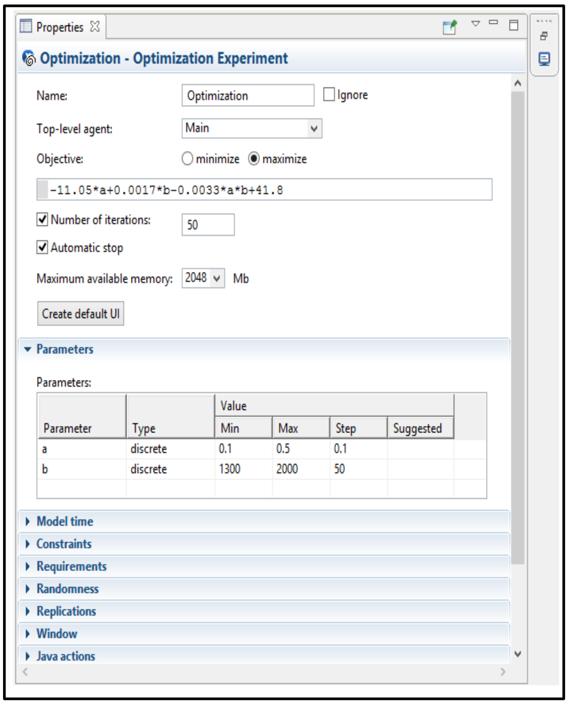
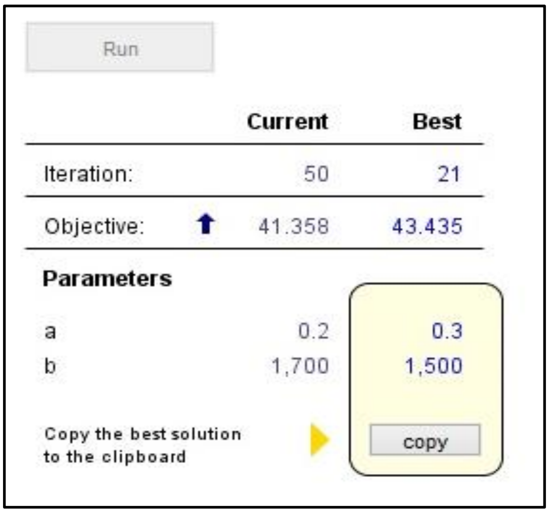
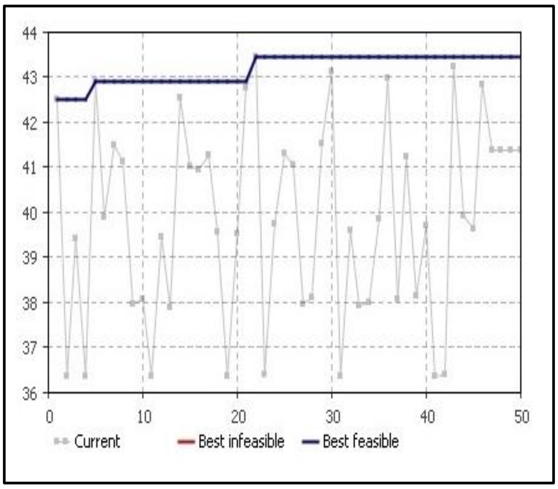


Figure 16: OptQuest™ interface in Anylogic



a)



b)

Figure 17: Passengers that evacuate PINO SUAREZ subway station during a seismic situation a)the best values found, b) the graphical representation

6. CONCLUDING REMARKS

We developed the conceptual model of the processes involved when a passenger enters to PINO SUAREZ subway station to board the subway. The simulation model was implemented based on discrete-event and agent-based modeling and simulation approach. During the technical visits to PINO SUAREZ subway station we collected the data about passengers entering to the subway station during one hour on Wednesdays. The flow of passengers was fitted to Negative Binomial and Poisson distributions using Stat::fit software. We maximized the number of passengers evacuating PINO SUAREZ subway station at the busy hours in a seismic situation. We used the OptQuest™ tool that is included in AnyLogic™ software. From the optimization results, we observed that the optimum number of simulated agents that evacuate is 44 and the evacuation time was 10 minutes. Most agents remain inside the station. In conclusion, this study is useful to optimize and evaluate the layout of PINO SUAREZ subway station for evacuating situation.

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AUTHORS BIOGRAPHY

ALMA VERA MORALES currently is Master student of the Department of Systems Engineering at the School of Engineering, UNAM. Her research interests are planning and project management, simulation and optimization of complex systems.

AIDA HUERTA-BARRIENTOS received her Ph.D. in Operations Research from National Autonomous Mexico University (UNAM), and currently is Associate Professor of the Graduate Department of Systems Engineering at the School of Engineering, UNAM and she is an invited young researcher at the Center for Complexity Sciences, UNAM, in the Program for Social Complexity.