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Analysis of massive crowd dynamics during special events: 2026 FIFA World Cup as a case study

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Abstract

The study of massive crowd dynamics during the World Cup 2026 is essential because it will be the biggest tournament yet in more ways than one. The Azteca stadium, located in Mexico City, is one that will host the World Cup 206. The Azteca stadium, despite being a venue with large areas where people can wait for access to the event, is located in a fairly troublesome area since the growth of the city in the surrounding areas has caused complicated access to the stadium. So, it is important to Mexican authorities to management and control massive crowd dynamic during World Cup 2026 in the Azteca stadium access. This paper proposes a methodological approach based on simulation modeling for analyzing massive crowd dynamics during 2026 FIFA World Cup to support the massive crowd dynamic management and control. First, a systematic literature review about the use of agent-based simulation modeling on the study of massive crowd dynamic is presented. Second, a methodological approach based on agent simulation modeling to analyze massive crowd dynamics during 2026 FIFA World Cup is formulated and implemented using Vissim™software. Third, the main results of the analysis and the discussion about the crowd dynamic are presented.

Keywords: ABMS; Vissim; sports stadiums; crowd simulation; behavioral research.

1. Introduction

The FIFA (Fédération Internationale de Football Association) World Cup 2026™ Canada, Mexico and USA final date was set for Sunday 19 July. The 2026 World Cup will be the biggest tournament yet in more ways than one. Never 48 teams have been involved in a single edition, while this is also the first World Cup to be held across three countries (FIFA, 2023b). On Thursday, 16 June 2023, FIFA announced the 16 cities which will host matches at the FIFA World Cup 2026™ across Canada, Mexico and the USA (FIFA, 2023b). Eleven cities from the USA, three from Mexico and two from Canada were successful (see Table 1).

1.1. Azteca stadium

According to CDMX (2023), Azteca stadium, the biggest, most famous stadium in Mexico, is sometimes known as the "Colossus of Santa Ursula", the third biggest football stadium in the Americas, it is the 11th biggest in the world. It is the only stadium in the world to have hosted two FIFA World Cup finals. As suggested by CDMX (2023), Azteca stadium, currently the home field of Club America, has been the scene of countless massive rock concerts, and has frequently been noted as the most emblematic football stadium.

Table 1. FIFA World Cup 2026 venues.

City	Stadium	Capacity (seats)
Atlanta	Mercedes-Benz Stadium	71,000
Boston	Guillete Stadium	65,878
Dallas	AT&T Stadium	80,000
Guadalajara	Akron Stadium	49,850
Houston	NRG Stadium	72,200
Kansas	Arrowhead Stadium	76,416
Los Angeles	SoFi Stadium	70,240
Mexico City	Azteca Stadium	87,523
Miami	Hard Rock Stadium	64,767
Monterrey	BBVA Stadium	53,500
New York	MetLife Stadium	82,500
Philadelphia	Lincoln Stadium	69,796
San Francisco	Levi´s Stadium	68,500
Seattle	Lumen Stadium	69,000
Toronto	BMO Stadium	30,000
Vancouver	BC Stadium	54,500

2026 FIFA World Cup will not only be a great opportunity for Mexico in the economic and tourism fields but will also mark a historical milestone for the country and football, since Mexico will become the first country to house three different FIFA World Cup events, the first time being the 1970 FIFA World Cup and the second time being the 1986 FIFA World Cup.

1.2. The massive crowd safety risks in sports facilities

According to the Citizen Security and Protection Bureau, the National Civil Protection Coordination (CNCP), and the National Center for Disaster Prevention (CENAPRED) in their Civil Protection Manual (2021), a disturbing phenomenon is that in which emergencies, disasters or catastrophes are caused by different phenomena, which, according to their cause are classified as natural or anthropic. Massive concentrations of people belong to the category of "Anthropic Phenomena", being described as follows: *Anthropic Phenomena: this type of phenomena is directly triggered by human activity.* Table 2 describes the classification of this phenomena.

Massive concentrations of people (Socio-Organizational Phenomena) do not represent a risk by themselves, however, when combined with another natural or anthropic phenomenon, they would represent a very elevated risk that threatens the lives of assistants to these events. Table 3 shows various tragedies that have occurred all over football history related to massive concentrations of people (AS, 2020), were the emotions and importance given to these events are key triggers that mostly generate dangerous situations for the assistants.

Table 2. Anthropic phenomena.

Category	Description
Chemical-Technological	Caused by leaks or spills of dangerous chemical substances like solvents, gases, and gasolines, also extending to fires, explosions, toxic outbreaks or radioactive accidents.
Sanitary-Ecological	Caused by pollution of the air, soil, acid rain and volcanic ash as well as plagues from rats, cockroaches, ants or bees.
Socio-organizational	Caused by human error or premediated action taking place in large concentration or people or large population movements. Their type can be religious, sports, cultural, traditional, official, touristic or entertainment.

The Azteca stadium, despite being a venue capable of hosting a large number of people and having large areas where people can wait for access to the event, it is located in a fairly troublesome area since the growth of the city in the surrounding areas has caused access to the stadium to become complicated since fans are not the only ones that circulate through the area, but they coexist with other people who use the roads surrounding the stadium as well as the residents of the Santa Ursula neighborhood that travel through streets and areas adjacent to the access of the Azteca stadium.

Table 3. Accidents related to mass gatherings.

Stadium	Year	Balance
Ibrox Park	1902	25 deceased and 57 injured
Bulden Park	1946	44 deceased and 500 injured
Naples	1955	152 deceased
National Lima Stadium	1964	More than 300 deceased
Buenos Aires Monumental Stadium	1968	71 deceased and 113 injured
Ibrox Park	1971	66 deceased
Luzhniki Stadium, Moscow	1982	340 deceased and 100 injured
Bradford Stadium	1985	53 deceased and 200 injured
Heysel Stadium Brussels	1985	39 deceased
Hillsborough Stadium	1989	96 deceased
Ghana	2001	130 deceased
Port Said, Egypt	2012	74 deceased and 1000 injured
Olembre Stadium, Cameroun	2022	8 deceased and 50 injured
Indonesia	2022	125 deceased and 300 injured

To provide the necessary security to sporting events attendees, there is a collaboration between the authorities of Mexico City and the Liga BBVA (Mexican Soccer League) through external security protocols provided by the Citizen Security and Protection Bureau, and the internal protocols provided by the Liga BBVA and the Azteca stadium, where before and after match action protocols are previously established as well as those safety measures that have to be adapted in case an emergency presents itself, however, due to the very nature of the sports events or other special events that are carried out at the Azteca Stadium, both formal and informal trade are present in the surroundings, from food, shirts, balls, souvenir stalls, etc., to the official stores within the Azteca stadium itself cause the few spaces where the fans can travel to be blocked by them or by the same fans who attend to these stalls, causing security protocols not to achieve planned efficiency and therefore, attendees experiencing unpleasant situations, such as:

- Poorly organized access to the stadium.
- Excess of informal trade.
- Late entrance protocols.
- Long transfers to enter the event.
- Elevated access and egress times.

There is little scientific and empirical evidence of how to manage and control crowds in the context of massive sports events. Previous research has focused on simulation of crowd dynamics; on fluid flow models; on social force models; and on Cellular Automata. Studying massive crowd dynamics during sports events as FIFA World Cup 2026 is challenging, given the lack of a widely accepted methodological approach for modeling and simulating, for instance, using CAD files and hundreds of agents. This paper proposes a methodological approach based on agent simulation modeling for analyzing massive crowd dynamics during special events such as 2026 FIFA World Cup.

This paper is organized into five sections. In the following section the systematic literature review about agent-based modeling and simulation (ABMS) of massive crowd dynamic is presented. The methodological approach based on agent simulation modeling to analyze massive crowd dynamics during 2026 FIFA World Cup is formulated and implemented using Vissim™ software (PTV Group) in Section 3. The main results of the analysis and the discussion about the agent-based simulation model are presented in Section 4. Concluding remarks and recommendations for future research work that can happen in agent-based simulation for the study of massive crowd dynamic are drawn in Section 5.

2. Systematic literature review

In this section we present a systematic literature review about ABMS of massive crowd dynamic. We followed the literature review process proposed by Machi and McEvoy (2009). The Figure 1 describes the steps for conducting a literature review.

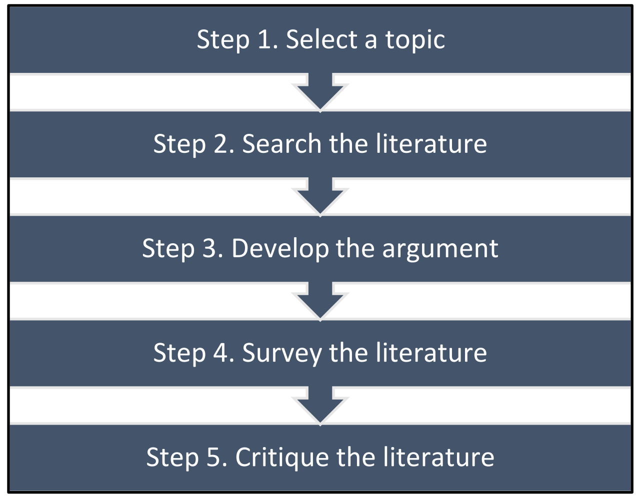

Figure 1. The literature review model, Machi and McEvoy (2009).

2.1. Select a topic

The topic selected was the use of modeling and simulation on the study of massive crowd dynamic management and control.

2.2. Search the literature

For the literature research we used Scopus™ database. We started the literature research using as keywords: *mass* AND *gathering*. For our first iteration we got 3872 results, then we followed the research using the keywords: *mass gathering* AND *management*, getting 733 results, after that the next research was using the keywords: *mass gathering* AND *management* AND *sports* AND *safety*, getting 15 results. Afterthat we changed the keywords: to *mass* AND *gathering* AND *simulation*, getting 235 results, after that we used the keywords: *mass* AND *gathering* AND *simulation* AND *agent* AND *crowd*, getting 13 results, then we used the keywords: *simulation* AND *crowd* AND *agent* AND *event*, getting 164 results. Finally we used the keywords: *simulation* AND *pedestrian* AND *agent* AND *sport*, getting 6 results.

2.3. Develop the argument

The main objective of the search in the literature was to find the literature related to mass gatherings and the related simulation methods that are being used to study this and see how is related this topic to sporting events.

On the second part of the search in the literature, the objective was to find the relation between modeling and simulation, mass gathering and sporting events, identifying the agent-based simulation as the most viable simulation perspective for the mass gathering management.

2.4. Survey the literature

We downloaded the biographical information from Scopus™ database, and we used the VOSviewer ™ software visualizing through cluster the keywords based on the co-occurrence. The VOSviewer™ software is a tool for visualizing bibliometric networks and the relatedness of specific terminology and keywords based on their distance in the network (Van Eck & Waltman, 2014). Figure 2 shows the agent-based simulation, artificial intelligence, and pedestrian dynamics as the most recent methods for crowd and pedestrian simulation. Figure 3 and 4 shows the principal applications of the agent-based simulation on evacuation simulation, crowd safety, urban planning, large scale events, etc. Figure 5 presents the interrelations we found in the literature among agent-based simulation, sports stadium, multiagent systems, and college buildings.

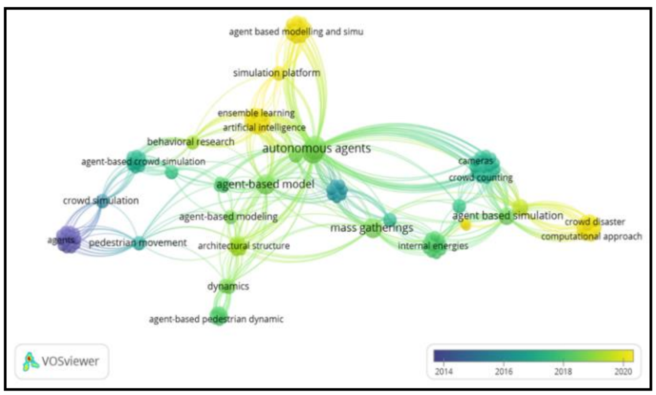

Figure 2. Clustering the keywords: *mass* AND *gathering* AND *simulation* AND *agent* AND *crowd*, based on the co-occurrences using VOSviewer™ software for search based on Scopus™ database.

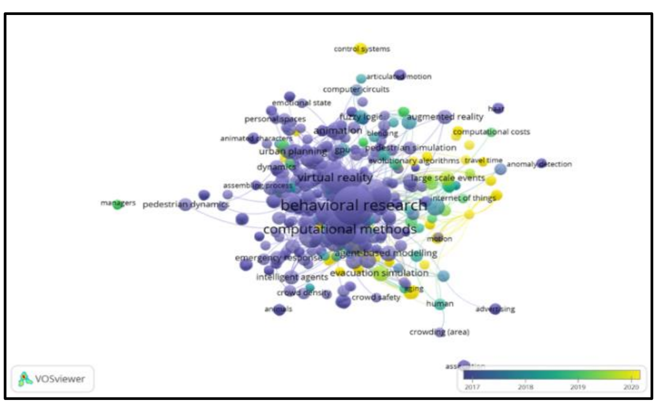

Figure 3. Clustering the keywords: *simulation* AND *crowd* AND *agent* AND *event*, based on the co-occurrences using VOSviewer™ software for search based on Scopus™ database.

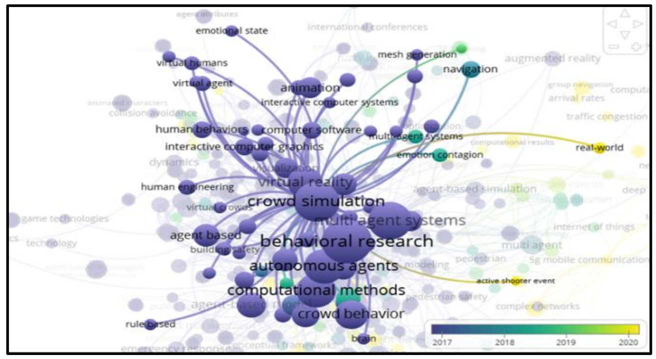

Figure 4. Zoom in of clustering the keywords: *simulation* AND *crowd* AND *agent* AND *event*, based on the co-occurrences using VOSviewer™ software for search based on Scopus™ database.

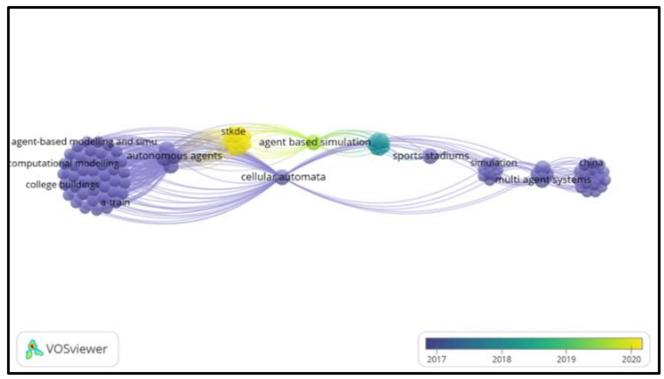

Figure 5. Clustering the keywords: *simulation* AND *pedestrian* AND *agent* AND *sport*, based on the co-occurrences using VOSviewer™ software for search based on Scopus™ database.

2.5. Critique the literature

Based on the research made on *Scopus* database and the related studies, we can identify the importance of using the simulation to understand the crowd and pedestrian dynamics for a better planning of massive events, preventing emergencies and ensuring crowd safety. In the simulation topic, the agent-based modeling was the most common method used for crowd simulation, however we could identify other trends on artificial intelligence and evolution algorithms combining this with real time data to make bottleneck prediction models. Also, cellular automata are related to the study of massive crowds. After our literature review, we have noticed that in recent years, the ABMS has been applied to control and understand mass gatherings, but such research has been focused more on medical area, related to disease propagation in context of the Covid-19 pandemic. However, there are some investigations related to humanitarian logistics in search of pedestrian safety specifically, analysing cases of religious events. Jian Ma *et al.* (2015) proposed an evaluation method for bottlenecks by measuring the volume and occupation of the streets and comparing the time travel of the pedestrian in different scenarios. Also, Karbovskii *et al.* (2021) and Karthika *et al.* (2020)

used machine learning and image recognition to predict possible bottlenecks by measuring the time travel and density of the streets. This gives us a strong support for the study of the mass gathering in special events, such as sports events by using ABMS as a way to understand the pedestrian dynamics.

3. Materials and methods

3.1. Materials

3.1.1. Data

The data used in the analysis of massive crowd dynamics during 2026 FIFA World Cup, was be based on past events in the Azteca stadium. Some real data have been collected visiting the surrounding area, so we could better understand the behavior of the assistants to this kind of events, so that we could recreate this behavior in the simulation software as accurately as possible, by programming agents in each entrance and in each point of interest and giving them the necessary characteristics to have better results.

3.1.2. The simulation software

There are several software tools focused on ABMS such as Anylogic™ or Pathfinder™, however, there is a tool that specializes in agent dynamics and therefore can provide us with better results, this software is called Vissim™ and it has been developed by PTV Group, which is a company dedicated to the development of software for traffic, transport, mobility and logistics analysis. With its wide range of products, two software stand out that may be useful for this paper: Vissim™ and Viswalk™. Vissim™ is a software focused on traffic simulation and analysis while Viswalk™ focuses on pedestrian simulation and analysis. Although this two software have different purposes, the integration of both is very important to analyze complex situations such as a city, which is why PTV Group has a version that includes both tools, which despite referring to this version as Vissim™, it does not limit the functions of Viswalk™ when using it and it is the version that will be used for agent-based simulation.

3.1.3. Methods

This study presents a methodological approach that integrates ABMS, computer-aided design (CAD) files, and geographical information systems (GIS) for analyzing massive crowd dynamics during massive events such as 2026 FIFA World Cup.

3.1.4. Integrating ABMS and CAD

Figure 6 presents the integration platform of ABMS, CAD and GIS in the case of Azteca stadium. First, the 3D object is computer-aided designed. Second, it is geographically located in a virtual environment. Third, agents are modelled and simulated in the virtual environment.

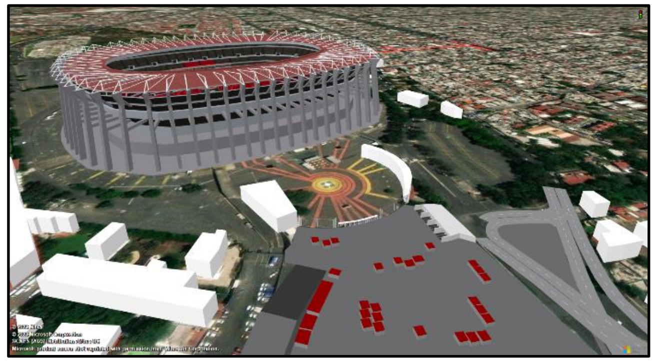

Figure 6. Integrating ABMS, CAD, and GIS using Vissim™ software for modeling the Azteca stadium located in Mexico City.

3.1.5. The conceptual model

For the development of the conceptual model, we used the map of the Azteca Stadium (as it can be seen in Figure 7) so we can define the principal access to the stadium and the routes that cars, public transport systems and pedestrians will use to get to the stadium on the last mile route, also we defined the possible action courses that the pedestrians will take, considering that in the surrounding areas of the Azteca stadium are also another public spaces that can get the attention of the people before and after the match, so it is important to define the areas around the stadium that are destined for food and trade stalls and where the people can stay there for a long time obstructing the flow of entry to the stadium, being a reason why massive concentrations of people may occur . In this case, there are three principal ways to get to the stadium. Figure 8 shows the route that pedestrians use if they arrive by the public transport system called "Tren Ligero" (Lightweight Train) to the stadium and the possible decisions that they can make before entering the stadium.

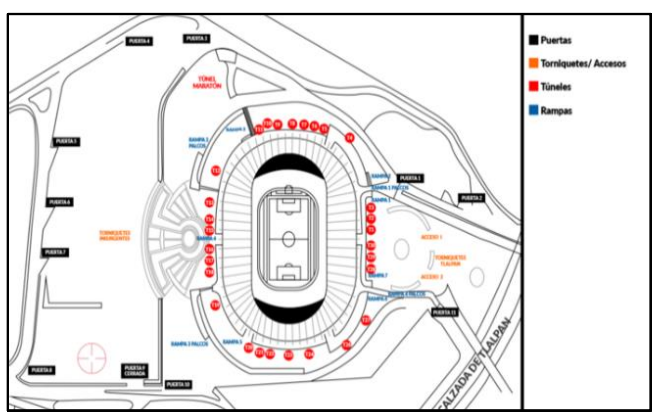

Figure 7. Conceptual model of main streets around Azteca stadium, using Vissim™ software.

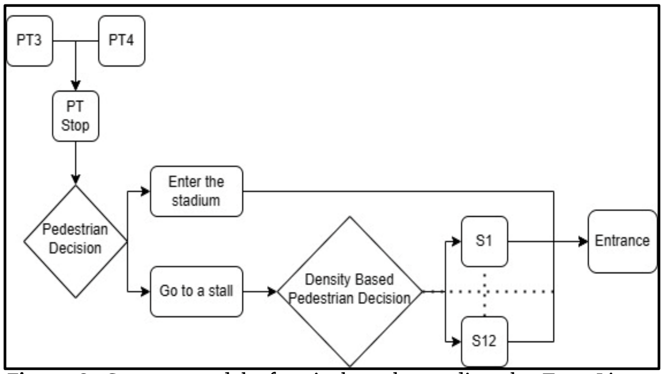

Figure 8. Concept model of arrival to the stadium by Tren Ligero system.

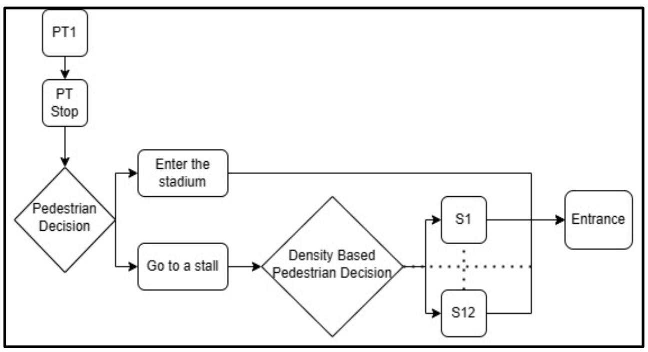

Figure 9. Concept model of arrival to the stadium by public transport system.

Figure 9 shows the route that pedestrians use if they get to the stadium by one of the Public Transport system routes and all the possible decisions they can make before entering the stadium. The simulation model was implemented using Vissim™ software. Figures 10 and 11 presents the design of different avenues and main streets around the Azteca stadium.

3.1.6. The agent-based simulation model

Figure 10. Simulation model of main streets around Azteca stadium, using Vissim™ software.

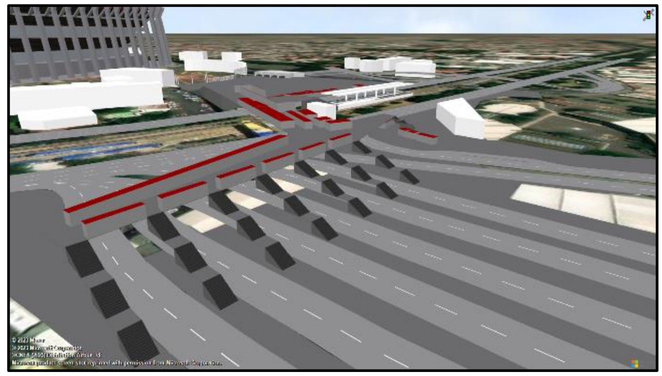

Figure 11. Simulation model of main bus stations around Azteca stadium, using Vissim™ software.

3.1.7. The verification of agent-based simulation model

The verification process was carried out using the iterative modeling, that means the simulation model was built incrementally in small stages and having feedback between conceptual model and the implementation process (Wilensky and Rand, 2015). Figure 12 shows the dynamic of agents that represents people. Figure 13 shows the dynamic of vehicles arriving to the Azteca stadium. Figure 14 shows the interaction between public transport and people.

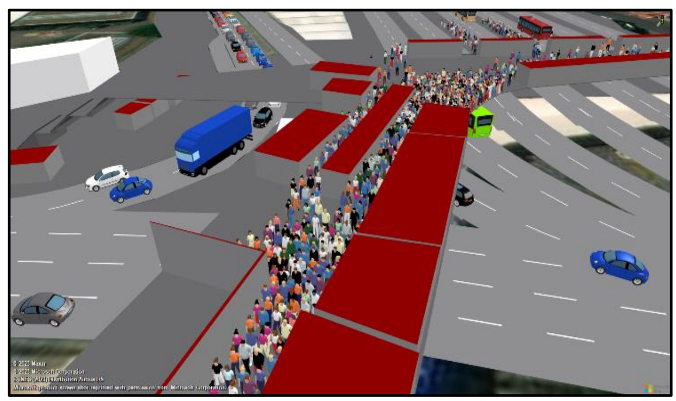

Figure 12. Simulation of dynamic of pedestrians at the Azteca stadium, using Vissim™ software.

Figure 13. Simulation of dynamic of vehicles at the Azteca stadium, using Vissim™ software.

Figure 14. People and transport system interacting around the Azteca stadium, using Vissim™ software.

Table 4. Public transport characteristics.

Public transportation path	Public transportation speed	Vehicle type	Capacity (person)
PT 1	60 km/h	Van	17
PT 2	60 km/h	Bus	70
PT3	60 km/h	Train	374
PT 4	60 km/h	Train	374
PT 5	60 km/h	Bus	70
PT 6	60 km/h	Van	17
PT 7	60 km/h	Bus	70
PT 8	60 km/h	Bus	70
PT 9	60 km/h	Bus	70
PT 10	60 km/h	Bus	70
PT 11	60 km/h	Bus	70
PT 12	60 km/h	Bus	70

3.1.8. The validation of agent-based simulation model

To ensure that the simulation model represents the real dynamic of people and cars, we used the scenarios technique. We consider the following variables: speed of people and cars, number of people and cars, and decisions for the agents based on density.

4. Results and Discussion

4.1. Preparation

The purpose of this study is to analyze the dynamics of pedestrians during a massive event in the Aztec stadium, for this, we selected 4 areas that are considered to be conflictive and can cause problems for the safety of those attending the event, the results obtained will show us what would happen in these areas in different situations, and thus observe if they can indeed be considered as conflictive areas or not (or the degree of conflict that each area has) and in case of finding conflictive areas we can observe under which situations the greatest number of conflicts can arise.

For this, we identified 12 possible routes using the public transport system to the surroundings, for our simulations a speed of 60 km/h was established for each of the transport path, being this a fixed parameter throughout the experimentation process, as well as the arrival frequency of each transport, being in a range between 90 and 190 seconds depending on the path. Table 4 shows the characteristics for each transport route such as vehicle type, capacity and speed.

For the study of pedestrian dynamics, we focused on 4 main variables, pedestrian speed (5 and 12 km/h), vehicular speed (80, 60 and 40 km/h), alighting percentage on each public transport stop (100, 50 and 30%) and the volume of vehicles on the roads (Maximum, medium and low).

With each of these variables and their possible options, a total of 54 simulation experiments were obtained in order to validate and observe the behavior of pedestrians with each of the possible combinations. Table 6 shows the combinations that were considered for the experiments with a maximum vehicle volume, as can be seen in Table 5. The remaining experiments used the same order and combination of variables, modifying the vehicle volume by medium and low, having three blocks with 18 experiments each, with a total of 54 experiments as mentioned above.

Table 5. Public transport characteristics.

Road Type	high	Medium	Low
Primary road	7500	5000	2500
Secondary road	3750	2500	1250

Table 6. Simulation experiments.

Number of experiment	Pedestrian speed	Vehicle speed	Alighting percentage	Vehicle volume
1	5 km/h	80 km/h	1	High
2	5 km/h	80 km/h	0.5	High
3	5 km/h	80 km/h	0.3	High
4	5 km/h	60 km/h	1	High
5	5 km/h	60 km/h	0.5	High
6	5 km/h	60 km/h	0.3	High
7	5 km/h	40 km/h	1	High
8	5 km/h	40 km/h	0.5	High
9	5 km/h	40 km/h	0.3	High
10	12 km/h	80 km/h	1	High
11	12 km/h	80 km/h	0.5	High
12	12 km/h	80 km/h	0.3	High
13	12 km/h	60 km/h	1	High
14	12 km/h	60 km/h	0.5	High
15	12 km/h	60 km/h	0.3	High
16	12 km/h	40 km/h	1	High
17	12 km/h	40 km/h	0.5	High
18	12 km/h	40 km/h	0.3	High

For the simulation model, the shortest path process was defined, in addition, 2 stages were programmed for the decision-making process of pedestrians in the simulation model, the first defines the number of people who choose to immediately access the stadium and the number of people seeking to go to one of the commercial stalls in the surroundings, in this case it was considered that 60% of people seek to go first to a commercial stall and 40% go directly to the stadium. The second decision-making process was programmed using a function of the Vissim™ software that allows pedestrians to choose between several zones or routes depending on the pedestrian density on each in "real time", we also included the option to decide if pedestrians accessed a service point or not depending on the number of people waiting, in our case it was limited to a wait of no more than 20 people. With these last decision processes, what was sought is to provide agents with a more realistic behavior.

The parameters that were analyzed in each of the measurement areas were: density, experienced density and number of pedestrians. The difference between the parameter density and experienced density lies in the point of view within the simulation process, that is, being an external or an internal agent to the process. The density refers to the number of people per square meter in the areas that were delimited, and the experienced density refers to the density that each pedestrian experiences individually when making their journey, basically it is how the pedestrian perceives the density in their surroundings, for the latter, a 2-meter radius was defined as the personal zone (perception zone) for each pedestrian, so this data shows us the number of people within a 2-meter radius of each pedestrian. Finally, each of the experiments carried out lasted 1200 seconds of simulation, that is, an equivalent to 20 minutes in real life.

4.2. Results

The results are presented in Figure 15 – 20 as follows.

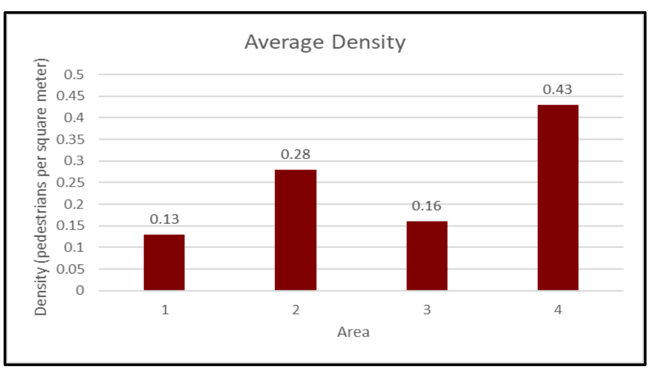

Figure 15. Average density on each area considered.

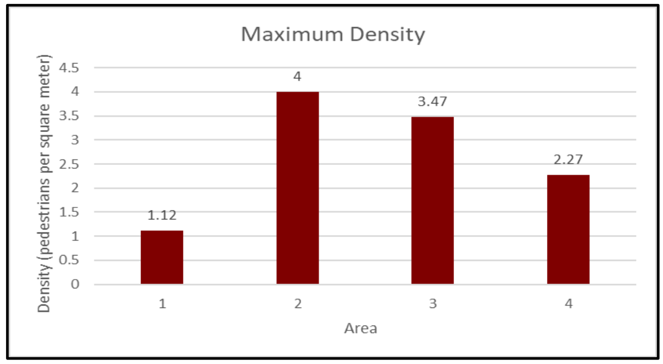

Figure 16. Maximum density on each area considered.

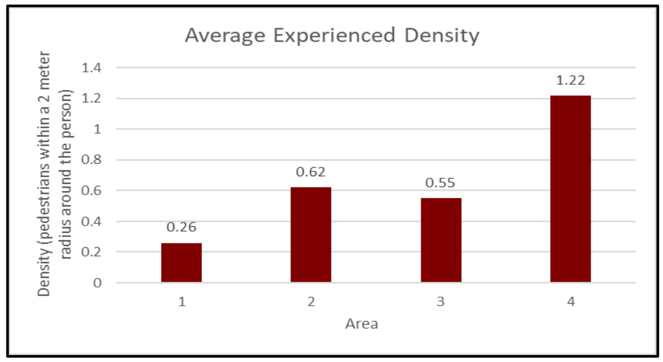

Figure 17. Average experienced density on each area considered.

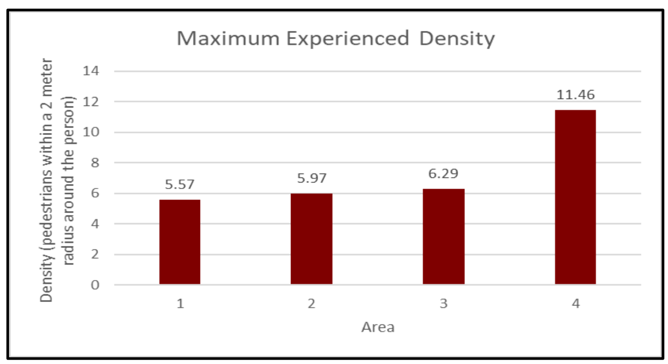

Figure 18. Maximum experienced density on each area considered.

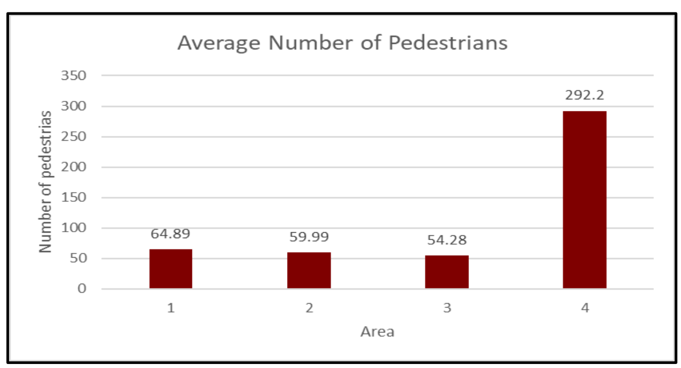

Figure 19. Average number of pedestrians on each area considered.

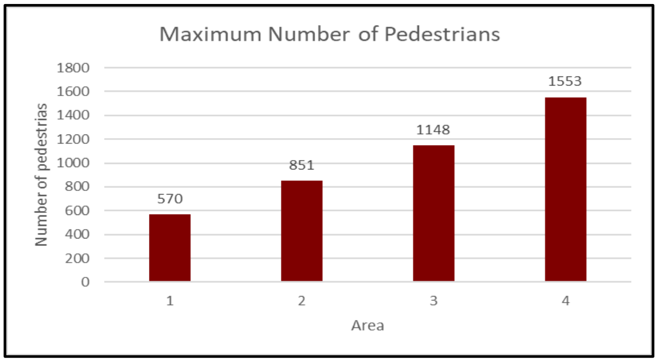

Figure 20. Maximum number of pedestrians on each area considered.

As mentioned by Keith (2014) it is recommended that a quantity of 4.7 pedestrians per square meter (density) not be exceeded to ensure the safety of the crowds, in the same way mentions that from 3 pedestrians per square meter is when the crowd flow begins to decrease and from 5 pedestrians per square meter the flow becomes unstable, generating congestion and limiting the movement of people. Observing the Graphs on Figures 15 and 17, which show the average density and average experienced density of each area, we can see that these values are low enough to represent a risk for attendees, however if we observe the maximum values on Figures 16 and 18, it shows that under certain circumstances the situation can become dangerous since two areas exceed the density value of 3 pedestrians per square meter and one stays at a value close to 2.27 pedestrians per square meter, while on the side of the density experienced, the situation becomes slightly more complicated, where all the areas show values above 5 pedestrians per square meter, including area 4, becoming more than double.

Figures 19 shows the average number of pedestrians per area, and we can see that the values are similar in area 1,2 and 3, but area 4 is the one that has the highest value and is the larger in comparison with the values of the other areas. To understand the simulation results in more detail, the results of area 4 were analyzed, since this was the one that showed one of the highest density values and the highest number of pedestrians in the area as it can be seen in Figures 16 and 20. If we look at the Figures 21 and 22, a comparison is shown between the variables used in the simulation and how they affected the density values, observing the 54 results of the experiments in this area. If we compare the density values, we can observe that neither the volume nor the vehicular speed seems to be a significant parameter for the density, since the values remain very close between each combination and even obtaining similar results, varying slightly between these two parameters. On the other hand, the parameters that do seem significant in density are the pedestrian speed and the level of descent at each public transport stop.

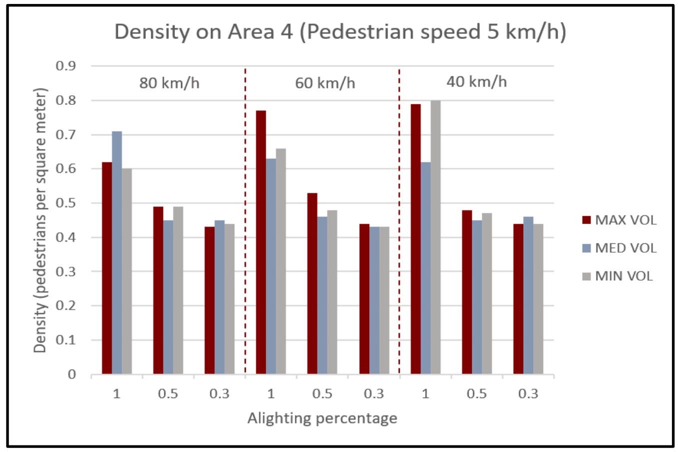

Figure 21. Maximum number of pedestrians on each area considered.

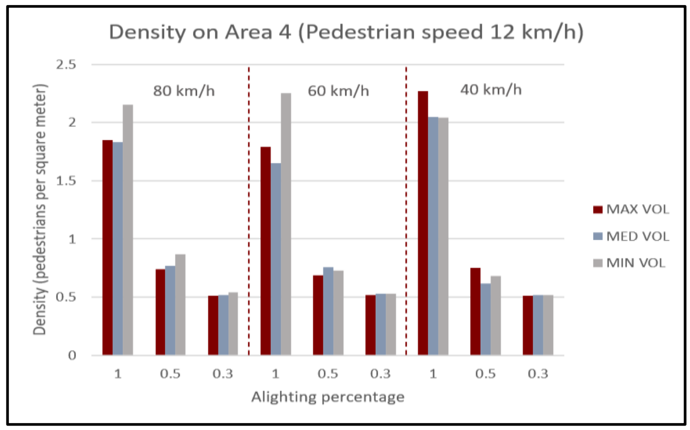

Figure 22. Maximum number of pedestrians on each area considered.

4.3. Conclusions and future research

As it can be seen in Figures 23, 24, 25 and 26, there are areas where a large pedestrian flow is generated causing bottlenecks, so in future researches it is expected to have access to a more detailed information on the behavior of visitors to the stadium, as well as the means of transport that allow us to improve the results of the simulation, thus being able to improve humanitarian logistics for those attending the stadium in order to safeguard the integrity of people. The implementation of new technologies such as machine learning and image recognition is also recommended, in order to implement a pedestrian counting model and density prediction to facilitate the decision-making process by the authorities producing the event.

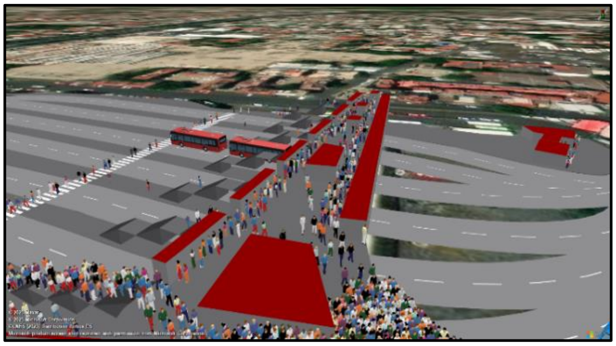

Figure 23. Density of pedestrian on area 1.

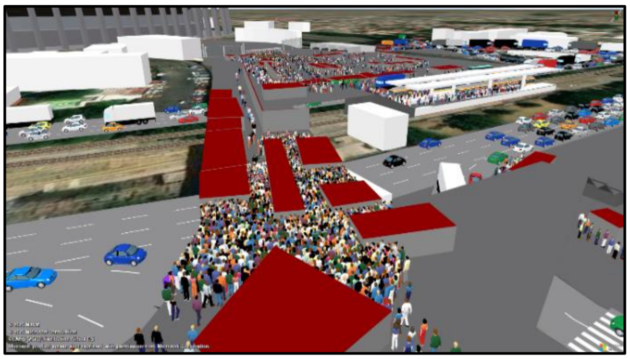

Figure 24. Density of pedestrian on area 2.

Figure 25. Density of pedestrian on area 3.

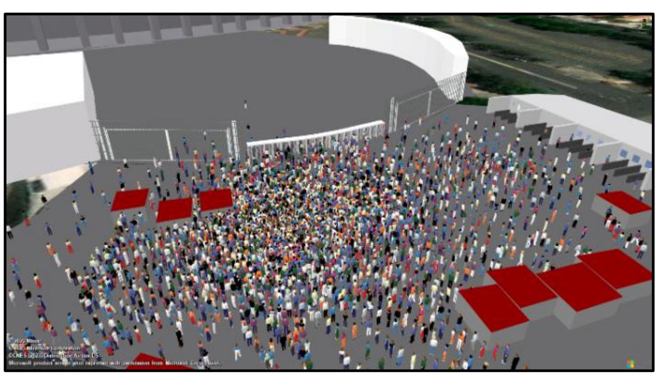

Figure 26. Density of pedestrian on area 4.

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