Pedestrian agent-based simulation for urban mobility planning

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ABSTRACT

The paper presents a study on pedestrian mobility strategies through an agent-based simulation. The pilot study is carried out in the context of the Poblenou neighbourhood (Barcelona) where the first Superblock was established in 2016. Regeneration strategies such as the Superblock have a great impact on the dynamics of urban space. Analysing changes in mobility and specifically in pedestrian flow when pedestrianization strategies are implemented, allows to quantify dynamic behaviours. Pedestrianization policies can contribute to the improvement of the built environment by creating increased safety, visual attractiveness, and environmental health. The paper looks at the link between the pedestrian activity and the spatial configuration and studies the relation between pedestrian flow and walkable area.

The simulation is developed with the Unity engine. Walking paths are computed with the NavMesh tool. Agent behaviours are programmed based on goals and mimic standard pedestrian behaviour varying according to a time schedule. The simulation environment is used for the generation of location datasets, renders and animations. The datasets are analysed further and more accurate visualizations in 2D and 3D are developed with Rhino's Grasshopper.

The main contribution of the paper is the development of a tool that simulates pedestrian activity and flow in urban spaces within a cross-platform graphic environment. The outcome can be easily visualized in real-time with the high-definition render pipeline (HDPR) and communicated to authorities, stakeholders, and policy makers.

Author Keywords
pedestrian; agent-based simulation; impact prediction; pedestrianization; urban regeneration; simulation; data visualization; walkability; mobility plan; Superblock.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING: Model Development; 1.3.7 COMPUTER GRAPHICS: Rendering

1 INTRODUCTION

Pedestrians have a great impact on the shape of a city starting from the first urban structures. The everyday routines of the local people formed the development of road networks in settlements and cities. The size and spread of pre-industrial cities were limited to less than one million inhabitants by the maximum walking distance of its inhabitants [1]. Since the industrial revolution, globalization and rapid urbanization have reshaped modern cities by promoting economic gain and density which have sequentially sheltered various issues with traffic, pollution, inequity, and social segregation, among others.

In the last decades, several planning methods have been adopted to promote sustainable urban approaches able to satisfy the key aspects of sustainability (Ecological, Economic, and Social) and reduce the human impact on the earth [2]. One of the recently embraced urban regeneration concepts throughout many European cities is the increase of pedestrian space by reclaiming street area and repurposing it for pedestrian use. Known as pedestrianization, the concept is not new, it has been in practice as a traffic policy since the 1960s. By 1975, all major European cities banned cars from historic and retail areas within the central business district reviving the concept of the "main street" as a centre for not only trading but an area of social gathering to revive the inner city [3]. The pedestrianization of selected streets is introduced as a measure to counter air, noise, and visual pollution in central areas, to encourage walking and socializing, to boost tourism, and to ensure the financial viability of inner-city retail stores [4]. It is argued that "urban regeneration through pedestrianized spaces" contributes to a decrease in car-dependency, an increase in pedestrian activity levels, and greater economic activity particularly in city centres [5].

The city of Barcelona (Spain) is implementing the concept of pedestrianization through the "Superblock" project. The city authorities attempt to move away from car hegemony and reduce traffic by 21%, meanwhile mitigating excessive air and noise pollution by freeing up to 60% of streets currently used by cars to turn them into so-called "citizen spaces" [6].

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Barcelona's regeneration plan consists of creating superblocks through a series of gradual interventions that will repurpose existing infrastructure (see Figure 1). A superblock will consist of nine existing blocks of the urban grid. Car, scooter, lorry, and bus traffic will then be restricted to the roads in the superblock perimeters, and the allowed speed in the internal streets is the reduced speed of 10km/h [6]. The Superblock model would promote the complexity of the urban system, going beyond the functional division of the city imposed by the modernist architectural movement. It would encourage the democratization of urban space, applying the idea of urban habitability in the same way to all the neighbourhoods, to avoid discrepancies within the urban system. It is the bearing structure of the "Ecological Urbanism" application, and will change the people's rights to the city, making the public spaces accessible to everyone and turning 'pedestrians' into 'citizens' [7].

Figure 1. The new Barcelona superblock plan for expansion of the existing car-free spaces in the city. Map: Ajuntament de Barcelona.

There are several limitations to be considered when dealing with changes in the urban fabric. Spatial configuration, once established, is static making it difficult and cost-ineffective to reflect the dynamic change in the needs of inhabitants. As cities are common spaces that must facilitate a wide variety of functions, establishing a balanced and efficient environment can be challenging. Urban interventions and changes in policies are associated with delays, as multiple parties are involved in the decision process. Innovation in technology, digital tools, and computational practices have made it possible to speed those processes by testing or simulating scenarios and proposing informed interventions on a city or a neighbourhood scale. Nevertheless, within a computational framework it is challenging to account for all biases that can occur within the developed set-up. It is possible to partially mitigate that by accounting for the hierarchy of the study parameters and providing a clear aim of the research. To build up a holistic framework for studying urban regeneration strategies an in-depth research on each aspect of urban planning should be developed.

The main contribution of the paper is the development of a tool that simulates pedestrian activity and flow in urban spaces within a cross-platform graphic environment where the outcome can be easily visualized and communicated to authorities, stakeholders, and policy makers. Such tools facilitate fast change implementation and provide insights in a intelligible and visual manner. Multiple factors can be studied but this paper focuses on the urban regeneration policy: pedestrianization, where space is reallocated from vehicle to pedestrian traffic. This allows us to understand how the transition from vehicle to pedestrian prioritized streets is going to impact pedestrian flow and experience in the city. Walkable cities are linked to various benefits such as healthier life, spending less time in traffic, and gaining time for recreational activities.

The paper aims at providing evidence of the impact on pedestrian flow caused by interventions in the spatial organization of the mobility network. It also looks at how to inform transitional strategies towards a pedestrian prioritized mobility model. The navigational model used in the study is of stochastic nature and provides an abstraction rather than a realistic approximation of the public space utilization. The navigation model has a large impact on the overall simulation. It has to be accounted that the individual components of the framework (e.g. the simulator and the analyser) are not novel but through the case study they become meaningful and gain impact. The main contribution of this paper is the application of the pipeline and development of a framework which is capable of highlighting the impact of two pedestrian mobility strategies on the flow of pedestrian agents.

2 BACKGROUND

Many platforms for urban simulation have been developed and are in use by companies and authorities. Most of these tools are created for the use of experts and highly technically trained urban planners. Although the advancement of urban simulators and tools for policy assessment is irrefutable, it is evident that specialization often excludes pedestrian activity and flow. However, a number of platforms have faced the problem of simulating mobility within metropolitan areas altogether (e.g. UrbanSim [8], UrbanApi [9]). Understanding the consequences of urban decisions is the main purpose of urban simulators. Different strategies and focuses are implied, but the core principle is to provide a framework for informed decision making. Platforms such as Urbano touch upon the topic of walkability. Their approach is based on the allocation of density, program, and amenities without simulating traffic activity but rather creating quantifiable dependencies [10].

Other platforms that focus on mobility have proven to have merit in simulating traffic and its complexities. SUMO (Simulation of Urban Mobility) [11] is an open-source microscopic traffic flow simulation package that can simulate large cities on a single vehicle and single traveller basis. Since 2001, SUMO has been enhanced to simulate intermodal traffic, and it can be used to simulate the communication between the different entities. Therefore, it allows to simulate new modes in a transport system, and to execute the trips being generated by a demand modelling and see their effects in terms of time, traffic, energy, pollutants, etc. Successively, MATSim [12] provides a framework to implement large-scale agent-based transport simulations. MATSim offers a toolbox for demand-modelling, agent-based mobility-simulation (traffic flow simulation), re-planning, a controller to iteratively run simulations as well as methods to analyse the output generated by the modules.

In addition to platforms and tools, there are many advancements in the logics behind crowd simulation and agent-based simulation. Studies provide agents with their own original timeliness functions and need to learn how to coordinate their actions with those of other agents. This presents a focus on the importance of the social aspects of agent's decision making [13]. Social and organizational models are being studied under the scope of multi-agent systems (MAS) to regulate the autonomy of self-interested agents. The functioning of a MAS is determined not only by the degree of deliberativeness but also by the degree of sociability. The assignment of individuals to an organization generally occurs in Human Societies [14], where the organization can be considered as a set of behavioural constraints that agents adopt.

Occupant behaviour is often modelled using deterministic models where the output of the model is fully determined by the parameter values and the initial conditions. These models can be used to obtain control over the collected data to determine hourly information of space usage [15]. Stochastic models, on the contrary, possess inherent randomness and use probability theory to represent observed behavioural patterns that include occupants' presence in a space [16]. Within stochastic models the same set of parameter values and initial conditions will lead to different outputs. Stochastic behaviour distribution approaches use optimization techniques to tune occupant behaviour parameters to meet specific behaviour constraints [17]. Various research projects focusing on building occupancy discuss the benefits and limitations of both deterministic and stochastic models for agent occupancy simulations [15,16,17,18,19]. The method used in this paper is of stochastic nature and gives an abstraction of the possible space use which is sufficient to investigate how changes in the ground floor program (in terms of pedestrian area) will affect the pedestrian agent space occupancy.

However, most studies on agent-based pedestrian simulations in the urban space are focusing on large crowds' mitigation [20] and emergency scenarios of evacuation [21] rather than everyday scenarios. Such platforms are dealing pedestrian movement in high-densities and investigate the physics of pedestrian movements rather than urban planning. In this paper the focus is gaining insight into urban planning strategies without dealing nether with high-density nor evacuation strategies.

Additionally, most platforms developed to deal with the topic are highly specialized, not user friendly, and lack the ability to provide real-time high-resolution rendering that can be effectively used to communicate the finding to authorities.

3 METHODOLOGY

The research challenges the necessity of specialized assistance when pedestrian data needs to be either acquired or simulated. The available tools for pedestrian flow simulation in urban spaces are complex and heavy in terms of computation. In most cases pedestrian activity is included as part of the mobility network. Whereas this may bring to a more comprehensive and complete understanding of the urban system, for architects, urban planners and designers it is often difficult to utilize the existing tools and come up with fast informed solutions for urban regeneration or enhancement.

This paper provides a tool for urban space analysis and explores the impact of pedestrianization on the pedestrian activity in the public realm. The tool allows you to expand the width of the pathways by including sections of the street that are conventionally dedicated to vehicle traffic and observe the effects this change has on pedestrian activity. Additionally, the location, quantity, and type of functions within the area can be changed if there is an update into the real state or if it is needed to investigate how new activities will affect the pedestrian flow. The aim is to predict how the changes in the urban fabric will influence the walkability, pedestrian density, and flow.

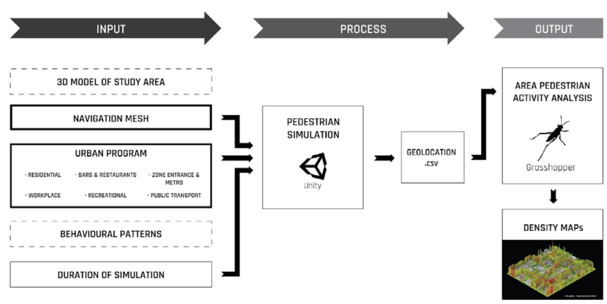

Figure 2. Overview of the developed method

The paper explores urban planning within a virtual environment that allows to observe the effects of modifications in the urban fabric on pedestrian density and spatiotemporal distribution. Accordingly, a tool for an agent-based pedestrian simulation is developed with Unity. The Unity game engine provides a working environment that can be easily used to create high resolution renders, animations, and videos. Additionally, it is accessible for architects and designers to communicate the simulated activity during the process and gain insights. This proved to be useful to communicate the simulated behaviour. Furthermore, as the

Unity community is thriving, the available on-line support makes it easy for beginners to understand how to use the platform.

The developed workflow allows for multiple inputs to be adjusted and used to test various aspects and effects of spatial configuration, program, and agent behaviour on pedestrian activity (Figure 02). The simulation has to be provided with an accurate 3D mesh model of the study area that the Unity Navigation System computes into a NavMesh (Navigation Mesh), points of interest based on the urban program (separated in six categories: Residential, Workplace, Bars and Restaurants, Zone Entrances and Metro, and Public Transport) set as goals and behavioural patterns associated with each category of goals. The convenience of using Unity in this case is that the NavTool AI embedded in the engine computes the paths where agents can move based on collisions with static objects. This makes it particularly easy to change the floor area that pedestrians use and therefore test concepts such as pedestrianization. With a custom script the simulation involves agent parameters that compose simple behavioural patterns in connection with each cluster of attractors based on their function.

When the parameters are set and the simulation is run for a given period, a comma separated values (csv) text file with each agent coordinates (per flame) is recorded. During this time, it is possible to create video recordings, renders of frames or complex visualizations in order to communicate the findings. The generated agent location data is further analysed in Rhinos Grasshopper to obtain controlled visualizations such as pedestrian density maps, flow maps and infographics.

3.1 Area and Program

The impact that pedestrianization has on pedestrian mobility is demonstrated with a case study. Two main strategies towards urban resilience are tested with the developed simulation. The study area is 0,6 square kilometres, located in the neighbourhood of Poblenou, Barcelona (Spain). This area is of interest for various reasons but first and foremost because it is where the pilot of the Superblock urban regeneration concept was first implemented in 2016. Over 25% of the area is predominantly prioritizing pedestrians making it attractive to investigate how more radical pedestrianization will impact the activity and spatial use. Furthermore, the neighbourhood of Poblenou is going through gentrification and has low but steadily increasing pedestrian activity, triggered by the emergence of office/coworking spaces, restaurants, bars, universities, and nightclubs. The area has a diverse ground floor program with predominantly mixed use (Figure 3).

An in-depth analysis of the study area provided sufficient information for the modelling of a precise ground floor plan. The data is used to develop an accurate 3D model where physical data is translated into digital, creating the bases for the simulation. To simplify the variability in functions, they are clustered in 6 main categories: residential, office, food, recreational, public transportation stops, and zone entrance points. Agents are spawn from residential buildings, public transport stops and zone entrances. They are attracted to all indicated points at different times.

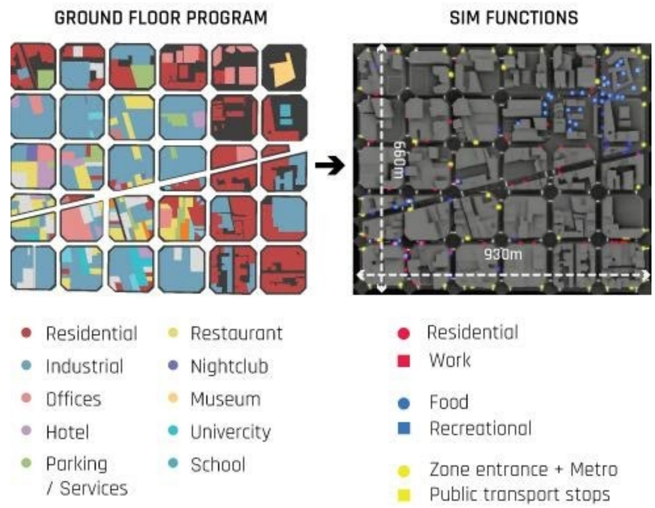

Figure 3. Study area program. Investigation and translation of data from physical to digital - clustering of goals based on functions.

The established workflow allows for easy update in the spatial information when alterations in the area occur. It is also possible to test the effect of changes such as addition or removal of places or change in function of existing places.

3.2 Agent and Behavior

One of the core inputs, that adds a sense of realism to the generated walkability patterns, are the agent behavioral patterns allocated to each functional element (goals) in the 3D space. The virtual environment mimics plausible patterns of behavior within a 24h period based on a standard working week. There are two main differentiations in the modes of agent behavior: working days and weekends. The timeframes and their attraction value (on the scale from 0 to 3) are indicated in Figure 4.

Some of the functionality that Unity's Navigation System provides, within the NavMesh Agents tool, is the ability to set agent velocity and avoidance priority to various rigid bodies. There is no need to add physics colliders to NavMesh Agents for them to avoid each other. The navigation system simulates agents and their reaction to obstacles and the static world - the baked NavMesh.

The NavMesh Agent component handles both the pathfinding and the movement control of a character. The navigation is based on setting a range of desired destination points (goals) that have a range of attractiveness from 0 to 3 depending on the timeframe (Figure 4.). The NavMesh Agent handles all internal computation to achieve both the movement and the pathfinding.

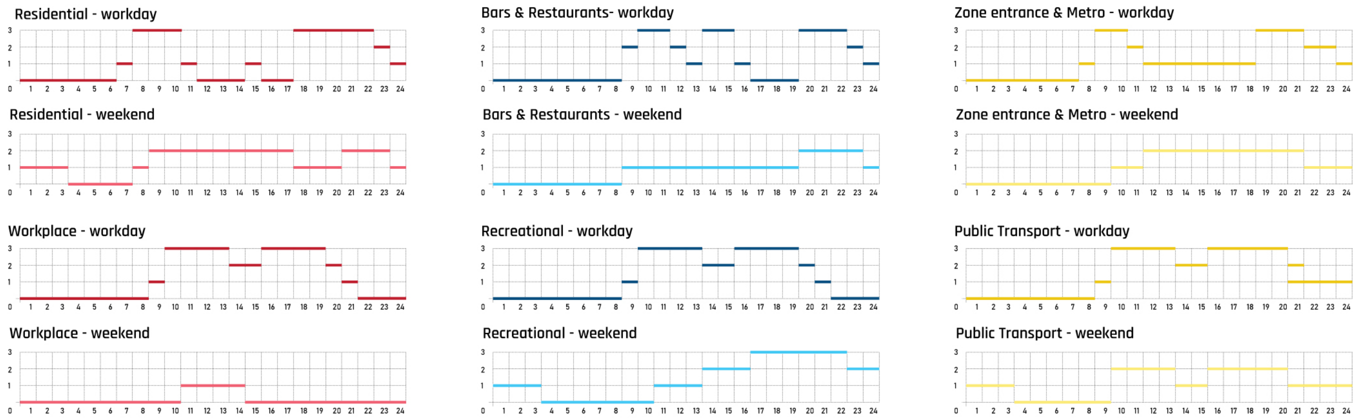

Figure 4. Agent input patterns for each goal category, with three degrees of attraction indicated for 24h

The agents are instantiated at the residential, zone entrance and public transport points. Initially the spawn of agents begins at when the simulation is initiated (by default 7:00h in the morning) and agents are spawn in a set interval until the maximum amount of active agent is reached. For this study, the maximum number of agents that the simulation could support was limited to 500. When an agent reaches a residential, zone entrance and public transport point it is removed from the list of agents and a new agent can spawn in its place.

However, as previously mentioned, the developed model is of stochastic nature and there is a great amount of randomness generated upon the selection of goals. For example, if an agent is assigned to a goal type with the function of workplace because it has the highest attractiveness value at this time, it will nether get assigned on the principle of the shortest path nor get assigned to the same goal multiple times. It has to be accounted that the movement varies, and the goal assignment is random within the indicated goal functions associated with time inputs. As an agent completes a goal it is allocated to another goal with high attractiveness value. This method has limitations in terms of realism of the generated data it can be revised at another iteration of the simulation.

3.3 Simulation and Criteria

As previously stated, the simulation is constructed with the Unity game engine. The environment works with 3D mesh objects and is optimized for efficient and fast workflow in real-time with complex geometries, materials, and animations. The simulation is developed based on an accurate 3D mesh model of the study area done with Rhino and several scripts developed within Unity. The aim is to create an approximation of the pedestrian activity within the study area that requires minimal computational power and can be modified to investigate a range of parameters. To obtain rapid results individual agent profiles are not encoded in the simulation. The general behaviour is an approximation rather than an exact pattern. It is considered that in comparison to the simulation of notarized traffic, pedestrians are not bound to lanes or sidewalks. Pedestrian movement is influenced by both configuration and the location of attractions (goals).

The pedestrian simulation is based on goal exploration, where the goals are organized and located according to the real functions of the area. Agents move to/from and spend time on goals according to their functions. Within the simulation, agents do not have set interaction goals but follow sequential instructions. A simplified example of that during the working days would be going to work in the morning, followed by a bar or restaurant during lunch hours, leaving work in the afternoon, and going to a recreational or residential point in the evening.

To achieve a sensible walkway topology, the Navigation AI tool embedded in Unity is used. Most of the computation is internal which makes it accessible for professionals with basic coding experience. The choice of the navigational model has a large impact on the overall flow depending on its robustness and on factors such as the agent density. As for this study it was not intended to develop a navigational model that can accommodate for a large amount of agents and it was not of interest to include large crowd evacuation analysis, the Navigation AI tool provided by Unity was suitable for the study.

Additionally, it allows for bidirectional and multidirectional flow to be generated. The navigation system in Unity provides powerful pathfinding and generation of walkways for the agents. The Navigation tool requires the generation of a simplified geometrical plane, referred to as a navigation mesh (NavMesh). The NavMesh enables characters to plot walkways around the various complex items in a scene. The NavMesh Agent is responsible for moving agents around the scene and allocating paths between goal based on the NavMesh. The software is very versatile and suitable for professionals with experience in 3D modelling, computation and visualization, as such it has merit to be applied in architecture and design to solve more complex tasks.

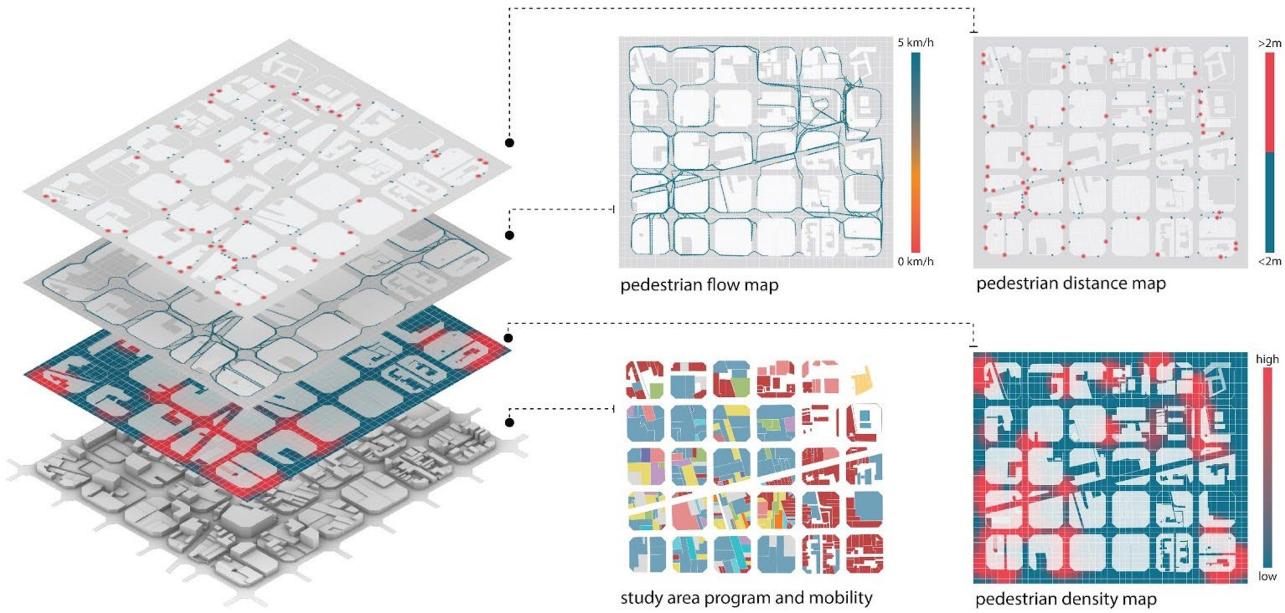

Figure 5. Demonstration of the analysis of the simulated pedestrian activity for 60 consecutive frames representing 1h

3.4 Observation and Assessment

The simulation developed in Unity can be run for any period, generating a diverse data set of agent locations. The randomness within the walkability patterns is visible when you run the same set-up multiple times. This brings to a more realistic findings but has limitations when compared to physically obtained data. The geolocations of the agents are recorder each frame. The generated data sets are then visualized, analyzed, and compared in Rhino's Grasshopper. The visualization of the simulated activity is based on an orthogonal grid with resolution of 1x1m. The insights gained and envisaged based on the generated pedestrian data include but are not limited to:

- Flow maps (based on the speed and direction)
- Density maps (based on number of agents within a certain area)
- Proximity maps (based on distance between agents)

To understand the effect of pedestrianization on the distribution of pedestrian densities, moving and static activity is simulated over 5 week and 2 weekend days. Once the data acquired by the simulation analysis is combined with ground floor analysis and goal locations various valuable insights can be extracted (Figure 5).

3.5 Strategy and Impact

The study area is 6x5 urban blocks and holds a Superblock (3x3 blocks) with the area of 9500sqm. The Superblock zone is an established community area with low to no vehicular traffic and diverse functions attracting pedestrian activity. With more than a quarter of the area having a predominantly pedestrian friendly mobility plan, it is curious to understand the spatial dynamics and walkability patterns within the district. The research looks at how creating other pedestrian zones would affect the spatial dynamics of the area. The NavMesh is the only study variable and the other factors such as agent behaviour or area program are control variables. Within the research framework, the simulation is used to investigate two distinct pedestrianization strategies (figure 06, 07). The effect of the strategies was additionally tested against a ranging quantity of agents aiming to minimize inconsistencies and errors. Both 2D and 3D heat maps are used to visualize the spread and density of agents within the area.

The first strategy proposes the creation of long continuous walkways where more space is dedicated to pedestrian activity. This strategy was tested with two mobility plan reconfigurations one taking place along Carrer d'Àlaba (increasing the pedestrian area by 1150sqm) and the other along Carrer de Pujades (increasing the pedestrian area by 1250sqm). Creating a continuous element that connects the area and generates pedestrian traffic has effects on the use of the entire area. It was observed that in both cases more agents populated the newly dedicated walkable area.

The second strategy gradually extends the Superblock project to the entire district. Two stages are investigated, where the first one creates a second Superblock adjacent to existing one (increase in pedestrian area by 4000sqm) and the second creates two other smaller Superblocks covering the entire area (increase in pedestrian area by 7000sqm). This leaves two main vehicular operational streets in the middle of the study area.

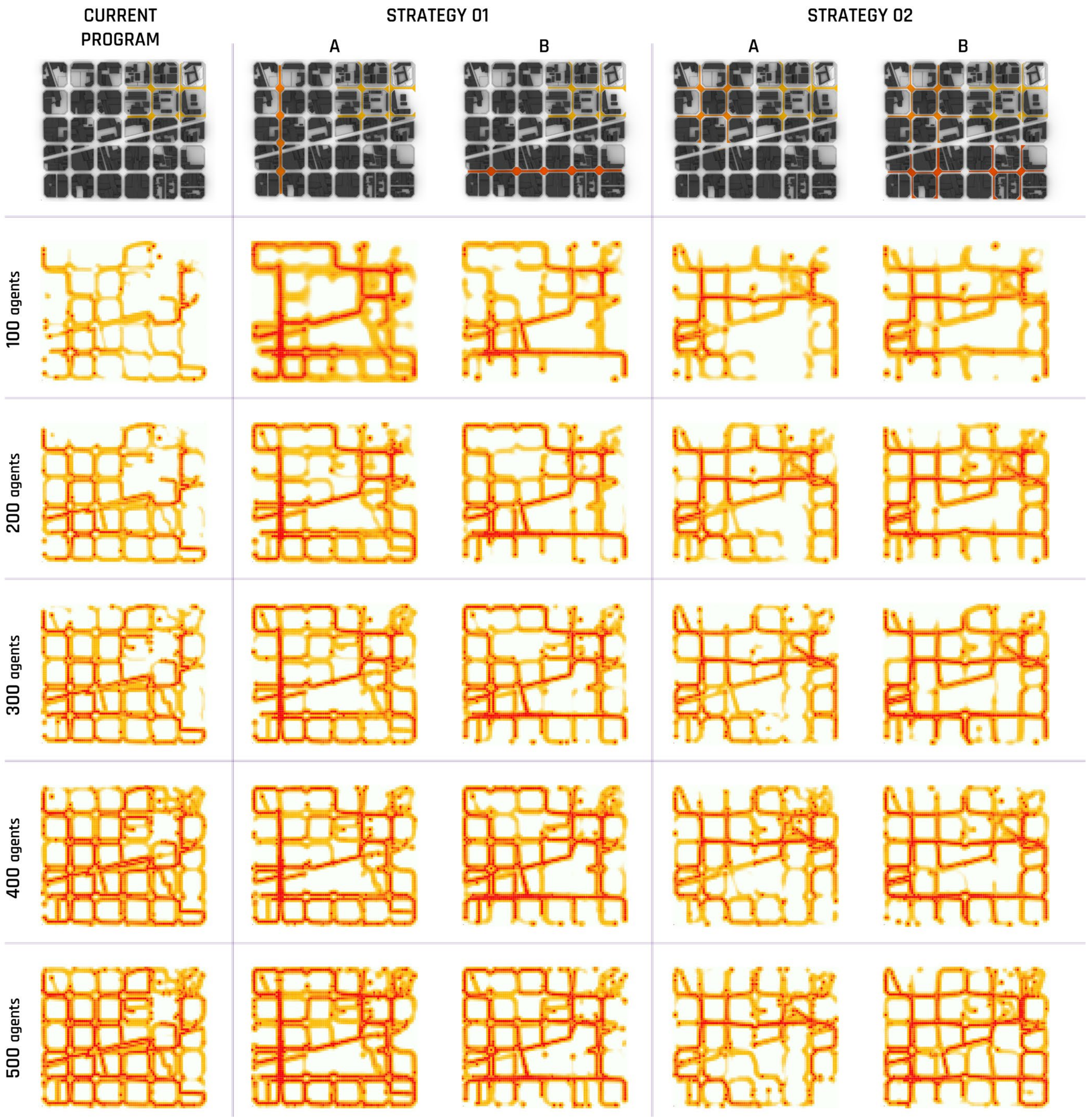

Figure 6. Testing strategies

Looking at the effects of the two strategies on pedestrian activity, it was evident that changes in the mobility plan have a significant impact on the pedestrian movement and dynamics within the area. By creating a long continuous axis, higher density is generated on this axis. This strategy can be used to improve the economic and social activity in the new pedestrian areas. It is noticed that some internal streets stop being used and the activity on the periphery is decreased. Compared to the simulation of the current mobility plan where a more evenly distributed use of the space is observed, in the pedestrianization strategies higher density is generated in the wider areas where no vehicular traffic is permitted. Going into more detail and looking at the pedestrian activity in different times of the day, patterns and correlations are observed.

3.6 Prediction and Implications

Pedestrianization strategies can create the appropriate conditions for meaningful public interaction and improve general health by decreasing traffic pollution and increasing pedestrian activity. However, these strategies have implementations on various aspects and must be studied,

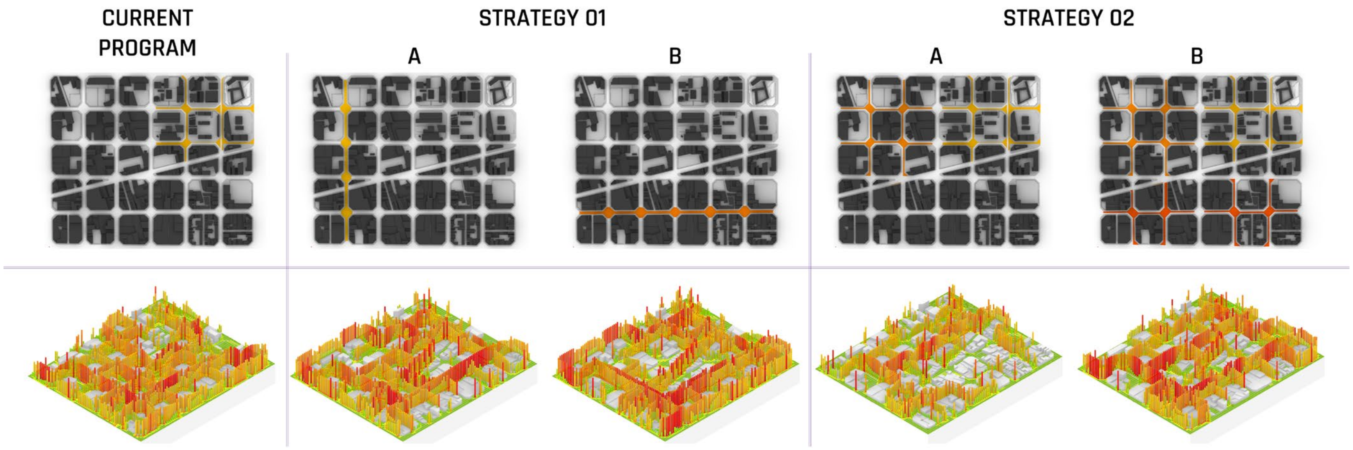

Figure 7. Identifying highly populated areas in for each strategy for a workday 12h period (7h – 19h)

analysed, and communicated thoroughly. The developed workflow allows us to test various aspects of the urban environment and mobility program. Recognizing links between spatial factors and pedestrian activity provides stakeholders, planners, and designers with a framework for more informed and citizen-based decision making. Successful implementation of human-centric regeneration policies requires better understanding of their impact on spatial occupation and pedestrian behaviour.

The case study used in this paper, provides evidence that by changing the available walkable space, social activity can be boosted and accommodated based on the new pedestrian flows. The incentive is to maintain lower density on the sidewalks, used mainly for reaching from one place to another, and to promote higher but distributed density in public plazas and parks. The increase of pedestrian area (gained from the street area) alone might not be a sufficient solution to increase walkability and pedestrian activity. It may be required to couple the pedestrianization strategy with other urban regeneration strategies such as redesign of services or recreational places (eg. parks). However, the comparative analysis of strategy A and B (Figure 6) showed correlation between pedestrian movement and walkable area. Wider streets and paths with more available walking area are more likely to be used by agents (pedestrians). During the pedestrianization strategies more space was provided along some streets and the narrower or internal streets were selected less. It can be argued that this tendency is caused by the limited number of agents. To challenge this notion, a study of the effect of the number of agents on the occupational patterns was conducted (Figure 7). Similar results were observed in each test regardless of the number of agents. Furthermore, more agents (500) within the area generated more homogenous spatial use. The differences in the occupational patterns were more distinctly recognized when less agents are generated.

The developed tool can be used to diverge pedestrian traffic from industrial areas or to increase pedestrian flow by creating more walkable areas and promoting services. The urban program (land use) has the highest effect on the pedestrian activity within the developed simulation. Understanding the tendencies that occur from functional elements such as office areas, bars and restaurants, recreational areas, and public transport stops it is possible to anticipate the pedestrian traffic. One of the limitations is that spaces that act repulsively and are avoided have not been considered in the current simulation model. A new relation between the vehicular and pedestrian traffic can be, therefore, further studied. The research highlights the importance of a more profound understanding of correlations and dependencies of area and urban mobility plan for the optimum re planning of urban space with respect to its walkability, diversity, and pedestrian use.

4 CONCLUSION

Pedestrianization policies can contribute to the quality of the built environment by creating increased safety and visual attractiveness as well as increased environmental health. The paper looks at the link between the pedestrian activity and the spatial configuration that affects such activity. Specifically, it studies the relation between pedestrian flow and pedestrian mobility plan. The research provides quantitative insights into the effects of the Superblock strategy when applied in the entire zone, rather than a part of it. Two strategies are tested and compared to the current mobility program. The method is mainly used for identifying the impact of pedestrianizing certain areas, but it can also identify optimum locations for urban interventions or assist in coordinating temporary events. However, there is still room for more rigorous validation against a mobility inclusive framework. The research showcases the first step of a bigger simulation engine that will eventually include more urban data on mobility, such as public transport, and more urban data specific to each area or city (such as density, contamination levels, land use).

Pedestrian simulations can be a powerful tool for urban development and sustainability when planning pedestrian mobility. This paper presents a computational method, developed with Unity and Rhino's Grasshopper, that can be used by architects, designers, and urban planners to verify strategies. As demonstrated, Unity is a reliable environment for agent-based simulation and can be used for pedestrian motion data collection. The simulation software can be used as a tool for effective visualization and communication. With the advancements in computer graphics and high-resolution displays, the tools for communication of strategies and policies have become engaging and even tailored to the audience. The simulation can be visualized in real-time with HDPR and communicated in form of renderings or videos. Furthermore, with Unity it is possible to jump from traditional means of visualization and communication to more immersive and interactive technologies such as Augmented Reality (AR) or Virtual Reality (VR).

Finally, pedestrian simulation is merely a tool and it is meant to complement, not replace, existing wisdom, experience field studies, and analytical computations. This additional tool facilitates design iteration and visualization; and might help highlight previously unforeseen problems or opportunities that warrant further investigation.

5 FUTURE WORK

One of the limitations of this study is that only two pedestrianization strategies are examined. More case studies must be investigated to gain a better understanding of the relations between the variety of urban and pedestrian parameters. Additionally, more thorough analysis of the pedestrian activity with hourly rather than daily resolution must be conducted. The visualization strategies can also be improved. For instance, generating maps of normalized distribution of pedestrian's densities along routes could help the comparative analysis. Even though the simulated activity indicated that pedestrianization of streets leads to increased density and usage of the pedestrian areas, further studies must be conducted to provide more conclusive results.

Another limitation of the developed simulation method is its stochastic nature. In future iterations of the research an attempt at more mixed method between stochastic and deterministic approach can improve the rigor of the simulation tool. Although, the current method has limitations in terms of realism of the generated data it can be revised at another iteration of the simulation by incorporating calibration of the goal assignment strategy combined with memory of the past goals of each function assigned to each agent. Nevertheless, the current framework still provides valid insights into the relation between space program and pedestrian flow.

The main drawback of the simulation's current version is the lack of either real or simulated data of other mobility agents. Overlapping additional urban data such as existing vehicular traffic or public transport routes and schedule, will enrich the gained information. The effects pedestrianization has on traffic and congestion have not been considered in this study. To further develop the tool, it is important to assimilate available datasets of the ground floor program, traffic lights, public transport routes and schedule, and mobility data. Without further development of the simulation, the information gained can be misinterpreted as valuable knowledge is missing. Nevertheless, by removing all other mobility agents, the tool provides fast and easily comprehensible assessment of pedestrian temporospatial changes occurring during pedestrianization.

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