Reading Urban Spaces through Agent-Based Simulation in Light of Mobile ICT

Aminreza Iranmanesh[1*], Resmiye A. Atun[2]
[1]Department of architecture, Eastern Mediterranean University, Famagusta, North Cyprus, Turkey
[2]Department of architecture, Eastern Mediterranean University, Famagusta, North Cyprus, Turkey
*Email: aminreza.iranmanesh@emu.edu.tr

Abstract

This study aims to provide an empirical way for the utilization of geotagged social media into urban pedestrian movement simulation as a way to improve the design, planning, and development. During the past decade, the advent of Information and Communication Technologies (ICT) into the everyday life of people has restructured some of the fundamental interactive aspects of cities. People's perception of cities is being reconfigured by the constant interactions that pass through connected mobile devices. This paper aims to explore new possibilities for the integration of social media into a visibility based pedestrian agent simulation. Four staged of data collection and analysis is proposed: First, the paper establishes a baseline by conducting a thorough systematic observation of the case study, the number of pedestrians were counted for 72 segments of an organic urban pattern. Second, a visibility-based agent simulation for predicting pedestrian movement patterns is conducted. This phase uses the morphological dimensions of space as the input and predicts the potential points of interest based on the agent's field of view. Third, the geographically tagged social media interactions from a limited timeframe were collected and analysed. Twitter has been used for reading volunteer pedestrian documentation of urban spaces. Fourth, the agent-based model output and tweet count were used in a regression model exploring the predictability of the actual pedestrian count (first phase). Finally, the results of different regression analysis were compared, and the outcome shows improvement in the simulation when Twitter data was included in the model, indicating that 69% of all pedestrian movements can be explained by the improved model. The outcome provides a reading into urban areas of interest for the pedestrian that is being formed by both visual accessibility and people's interaction through social media.

Keywords: Visual graph analysis, agent-based pedestrian simulation, ICT, Urban design, social media, mixed methods

1. Introduction

Mobile ICT has transformed the role of people to the recorders and broadcasters of the urban narrative. The active choice of citizens to take part in urban spaces are being influenced by others' activities on social media. Since the socio-economical aspects of urban network and land-use are dependent on the flow of people, it could be argued that mobile ICT plays a critical role in the resilience and socio-economic sustainability of urban spaces. Although the simulation of people's movement has been a significant part of the urban studies in the past decade, few have paid attention to the integration of social media data into those simulations. Accordingly, the power of the active interaction between people and city could be harvested for providing a more comprehensive perspective on design, planning, and development of contemporary cities. The process of reading, diagnostics, and proposal for city spaces must be mindful of the emerging layers of data. In the past century, urban-related research has shifted toward analytical approaches trying to address the increasing complexity of cities. The increase in computational power and accessibility to new sources of data has revolutionised the research on cities. In this paper, we address one of the emerging methods for exploring socio-spatial structures of cities: the visibility based agent simulation. Understanding the flow of pedestrian movement is a critical aspect of urban design and planning as it is closely related to the Microeconomics and vitality of public spaces. The paper uses the suggested algorithm by Turner and Penn (2002) and tries to explore new methodological possibilities by introducing a new layer of ICT data into the model.

2. Agent-based Model

An agent-based simulation is a powerful method for assessing and understanding complex spatial structures according to the human perceptual process of decision making while moving. The method was established by Turner and Penn (2002) and it is grounded on the theory of ecological perception set forth by Gibson (1979). Gibson (1979) established the theory of ecological perception in which he suggested a bottom-up approach toward the visual and information processes of the environment by animals and humans. He creates the concept of "affordance" as a set of potential opportunities that environment offers; he fundamentally describes it as the walkable/visible plane or a surface that affords the movement (Gibson, 2014). In other words, the affordance is the potential actions, or the availability of movement that space creates for the actors (Norman, 1999). This framework provides new possibilities in exploring complex spatial systems because the bottom-up processing of environment enables analytical models which are less bounded by the complex contextual parameters of human cognition.

Accordingly, Turner and Penn (2002) proposed an agent-based model that incorporates the visibility affordance of the space as the major factor in movement. The agent-based model follows a very simple rule that seeks to understand the complex nature of human movement; people tend to travel toward the further accessible space base on their current position (Koutsolampros & Varoudis, 2017). the method is called "Exosomatic Visual Architecture: EVA" (Turner & Penn, 2002) and it explains the process of decision making and movements by the virtual agents. EVA is comprised of the following steps:

- The spaces that support unrestricted movements (and visible) are broken down into a basic mosaic of cells (gates). The dimension of these cells is often considered 0.75 x 0.75m because it is the average length of steps while walking (Turner, Doxa, O'sullivan, & Penn, 2001) (Figure 1: a&b).
- The visual graph analysis (VGA) is conducted, VGA explores the degree of visibility for each part of the space from all other parts. VGA represents the "intensity of intervisibility" among all cells in the plane of sight/movement (Karimi, 2012). Here we take into account that a cell must be both visible and accessible, this is following Gibson's theory of affordance (Figure 1:c).
- Aa agent is randomly placed in the field; each agent is assigned a field of view that can be adjusted according to the parameters of the study. In order to enable the random movement of agents, the field of view is further broken down to 32 possible bins each covering approximately 11 degrees (Koutsolampros & Varoudis, 2017) (Figure 1:d). The most efficient applied field of view is considered 170 degrees or 15 bins (Turner & Penn, 2002).
- The agent chooses a destination from the available field of view (Figure 1: e).
- The agent moves n number of steps toward the selected destination, n can be defined by the research, n=0 means the agent picks a new destination every single step, and a higher n means that the agent does not change the target before reaching the initially selected target. According to Turner and Penn (2002), n=3 gives shows the best outcome when compared to the actual movement of people in the space, meaning that the agent takes 3 steps and then chooses a new destination. During this process If at any point the agent faces an obstacle (wall, corner, other agents) it randomly turns 90 degrees, if the movement is still not possible, the agent chooses a new destination.
- The agent repeats the cycle of steeping toward randomly selected destinations from the field of view for a given number before being removed. The number of steps could be defined by the

parameters of the study, for instance, how much people are willing to walk in a given context? or How large is the area of the study.

- The same procedure is repeated for a given number of agents. And the number of encounter with each cell is presented on the map (the random next step map, Figure 1:f&g).
- Turner and Penn (2007) proposed an alternative process for selecting destinations in which the decision is weighted by the longest available line of sight arguing that it resembles more similarities with how people pick a destination (Figure 1:h).

The initial studies show that the EVA agent base simulation can explain 50% to 75% of natural pedestrian movement (Penn & Turner, 2002; Turner & Penn, 2002), Jiang and Jia (2011) report a correlation coefficient between 60-90%. These studies imply that high cognitive functions of human observation are not necessary for explaining the collective pedestrian movement. The critical question here is why the random movement of agents based on the visible layout of the environment can represent the natural flow of pedestrian movement? Why the method works where at first glance, it seems to be counter-intuitive and irrational? To address these question the following section elaborates on the "social logic of space" (Hillier & Hanson, 1984), and the configurational theory of socio-spatial space.

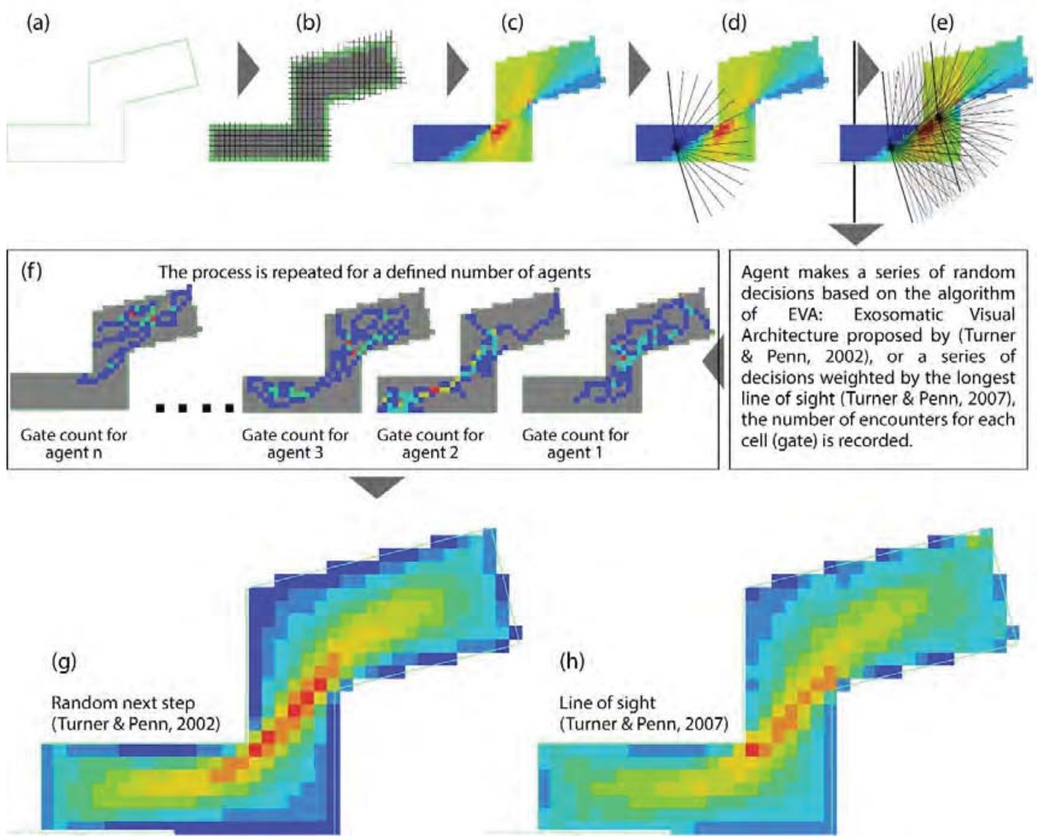

Figure 1. The process of agent-based simulation according to the available visual field of view, based on (Turner & Penn, 2002)

3. Space Syntax and Natural Movement

Urban design is a process of decision making that forms connections between people and places. Accordingly, the methodological approach for designing spaces must make a link between the spatial dimension of society and the social properties of physical forms (Karimi, 2012). This fundamental connection is the bases of space syntax method that tries to prove a tangible analytical reading of the complex socio-spatial forms of human life on the surface of the earth. Space syntax a way of looking, reading, understanding the city (or architecture) as a whole (Netto, 2016).

Space syntax is a configurational theory of socio-spatial behaviours that explores the possibilities in peoples' movements through the elemental spatial network. The spatial network is formed with an inherent "social logic" (Hillier & Hanson, 1984). Peoples' movements and spatial properties of space are connected (Hillier, 1996; Hillier, 2012). The possibility of people's presence in urban spaces is closely related with how those spaces were formed, simultaneously, the flow of people shapes the spatial grid and the spatial grid shows how people move within it. Therefore, in line with the aim of this study, space syntax offers a rich framework for evaluating socio-spatial interactions because it argues that there is a mutual relationship between how those interactions and urban spaces form and reform together.

At its core, space syntax advocates two fundamental propositions. First, space is not a mere background to human activities, it is rather a semi-social entity that co-evolves with those activities. Hence, the logic of human movement is an intrinsic aspect of the built environment (Hillier & Vaughan, 2007). The configurational geometry of the built environment is based on how people pensive and move through and to different spaces. According to Hillier (1999), people choose their paths to either minimize the necessary effort for their commute or to maximize the efficiency of it. Second, manmade spaces work in relation to each other and cannot be understood in isolation. The intricate connections among all spaces in a network are critical in how they function individually and as a whole. The most basic spaces of a house or the complex structure of a city can be represented as a network of potential movements, connections, and choices. Each component of the network has a certain function and simultaneously works with all other components of the network, this approach provides a configurational reading of city network as a whole (Karimi, 2012).

The space syntax analysis shows the effectiveness of destinations and in-between spaces of a network. This paper does not go deep into why space syntax works in predicting the collective movement of people as it is well represented throughout the space syntax literature (see Karimi, 2012). However, it is important in addressing the logic of agent-based modelling. An overall review of the literature shows the high predictability of human movement via space syntax centrality measures (Sharmin & Kamruzzaman, 2018). A study by Jiang (2009) shows that almost 60% of all movements in urban spaces can be explained by the structure of the network through space syntax measurements. Accordingly, the visibility base agent simulation makes the proposition that if the network possesses an inherent social quality then randomly moving agents in the field of visual affordance would eventually travel more through the most integrated paths.

3.1 Addressing the Land-use through Space Syntax

The relationship between land-use and space syntax has been the centre of two debates. Ratti (2004) argued that the absence of land-use in the analysis is one of the main inconsistencies of the space syntax method. Although only the changes in configurational geometry of space affect the results of the analysis, the definition and evolution process of those configurational elements bares critical significant. Hillier and Penn (2004) argue that the intrinsic social qualities that form urban spaces shape the distribution of land-use. In line with many other studies (Namely: Hillier, 2012; Kim & Sohn, 2002; Penn & Turner, 2004). We consider the land-use as a built-in function of evolving accessibility throughout the urban network. This paper implements the land-use into the analysis by providing access into the building at the ground floor of the network when movement is possible. Hillier (1999) suggests this technique the adding destinations into the analysis would weigh the analysis by the active land-use. Accordingly, all the active shops, cafes, restaurants were accessible by the agents during the simulation. The size of doors and the possibility of moving into the shops were carefully implemented into the model. This action makes a significant change in agents' patterns of movements by introducing the active ground floor plains of affordance as active players in the analysis processes (Figure 2). It seems that including more destinations provides the possibility of detours and sideways movements for the agents similar to how it affects the actual pedestrian movement. Furthermore, the implementation of geo-tagged Twitter data in this study explores the possibility of increasing the impact of active land-use (points of interest) through the perspective of social media. García-Palomares, Salas-Olmedo, Moya-Gómez, Condeço-Melhorado, and Gutiérrez (2018) show the applicability of Twitter data in reading urban land-use dynamic.

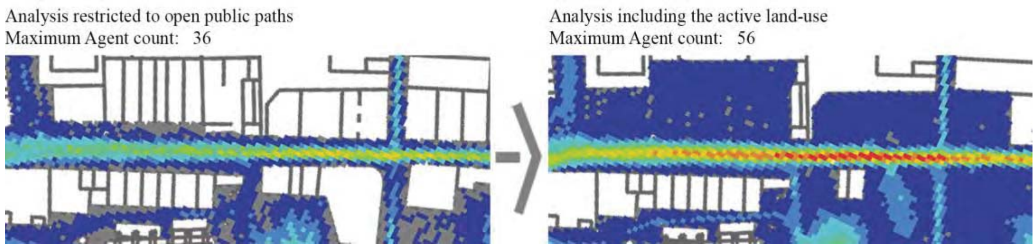

Figure 2. Improving the agent-based analysis by integration of the ground floor active land-use

4. The Emergence of Social Media into the Everyday Life of the City

One of the main contributions of this study to the main body of literature is to explore the possibility of improving the outcome of agent-based modelling with social media data that represents the new type of interaction between people and city spaces. This new form of data is the side product of the integration of social media into the everyday life of the city. The new sources of data are becoming mainstream in contemporary research, mobile devices with their convenient internal camera and connection to the internet are now a part of the framework of human life. Furthermore, mobile devices' built-in Global Positioning System (GPS) provides an unprecedented opportunity that connects the content produced by people to an actual point in urban space. Accordingly, it could be argued that the implementation of this new data is essential in understanding contemporary cities and how they function. On the other hand, the sheer volume of the data when compared to traditional surveys could potentially increase the validity of analytical urban approaches. Lazer et al. (2009) argue that our increasing capacity to collect and analyse this data is providing insight with unprecedented depth and detail in all the sciences.

This paper uses Twitter as the source of geographically tagged data as a testament to peoples interaction with the spatial network of the city. Twitter is a public social media platform with short content and additional information (if allowed by the user) to be extracted. Similar to the agent-based approach, the random tweets might seem unrelated as individual points in space, but the accumulation of these points tell a story about urban hotspots, and the intensity of active interaction. Implementation of geo-tagged Twitter data into urban research might unfold hidden socio-spatial dimensions in cities (Arribas-Bel, 2014; Shelton, Poorthuis, & Zook, 2015). Analytical methods using any type of big data (geo-tagged tweets here) must clearly address the biases, varying degrees of accuracy, and the noise that the data brings to the research (Shaw, Tsou, & Ye, 2016). Clearly, the users of Twitter do not represent the entire society and this target group might be subject to social, economic, or age biases (Lloyd & Cheshire, 2017). Currently, the users of Twitter are not a homogenous sample of the population, and the over/under presentation of certain groups must be addressed according to the objective of the research (Steiger, Westerholt, Resch, & Zipf, 2015). Many studies have shown the inherent sampling bias of the Twitter data sets, for instance, García-Palomares et al. (2018) show that people without university education are under-represented in the data. Other studies indicate the existence of biases related to age, gender, ethnicity, and geographical location (Hecht & Stephens, 2014; Mislove, Lehmann, Ahn, Onnela, & Rosenquist, 2011). Furthermore, only a small fraction of all tweets (1-3%) include geo-tag information (Kumar, Morstatter, & Liu, 2014). It could be argued that even the geo-tagged tweets which are often used for spatial analysis might not be an unbiased representation of all Twitter users. Nevertheless, Mislove et al. (2011) argue that these biases are slowly fading over time. As mobile technology is becoming a part of everyday life and as new generations are being born and raised within these frameworks, the biases are becoming less dominant. The current study acknowledges these shortcomings, but many studies support the idea that Twitter is a valuable source for understanding urban dynamics, collective human motilities, land-use, and patterns of behaviour in urban contexts (Arribas-Bel, 2014; García-Palomares et al., 2018; Shelton et al., 2015; Steiger et al., 2015).

5. Case Study: The Walled City of Famagusta

The study was conducted in the walled city of Famagusta located at the eastern coast of Cyprus. The walled city has a compelling history and its urban tissue has been formed to support a strong internal structure that can be protected by a walls-moat system. Due to its fortifications, the walled city has limited access to the surrounding urban network and it is home to numerous historic landmarks and cultural spaces. The area of the study was limited to the central part of the walled city which is home to a variety of public activities. This area includes the most dominant urban public space in front of the "Cathedral of Saint Nicholas": currently known as "Lala Mustafa Pasha Mosque" (Figure 3). The movement of cars in the selected area is limited and it offers a mostly pedestrian-friendly environment that matches the parameters of the agent-based modelling. Having the entire historic city in a small contained border helped for conducting a through agent-based analysis which is often restricted by area; it enabled the study to see the entire city as a whole, and simultaneously, the possibility for a closer detailed survey.

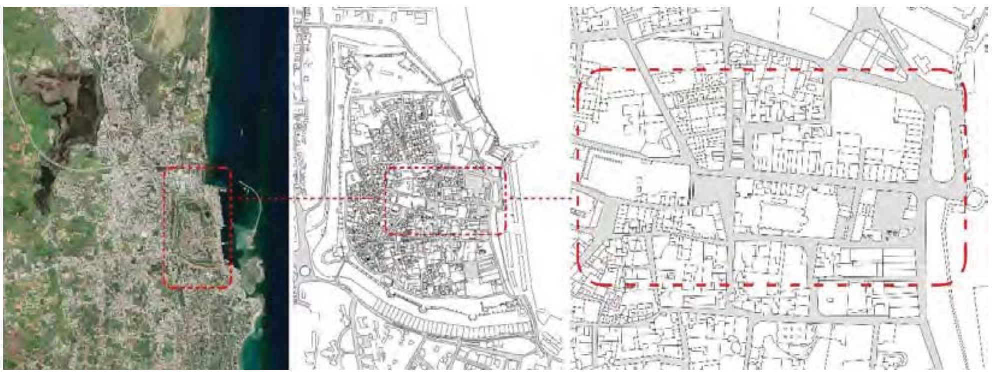

Figure 3. Left: The city of Famagusta (Google, 2019), middle: the walled city, right: the limits of the study.

The data was collected in 3 phases: first within the selected boundary of the case study, the number of pedestrians was counted for each segment. For this, the map was broken down to 72 segments (affordances). The number of people passing by each segment was counted for a 10minute window during a weekday. All segments were observed between 3-5 O'clock. The observation was repeated the following day to control for anomalies and outliers. The rounded-up average of the pedestrian count for each segment was recorded for each segment (Figure 4).

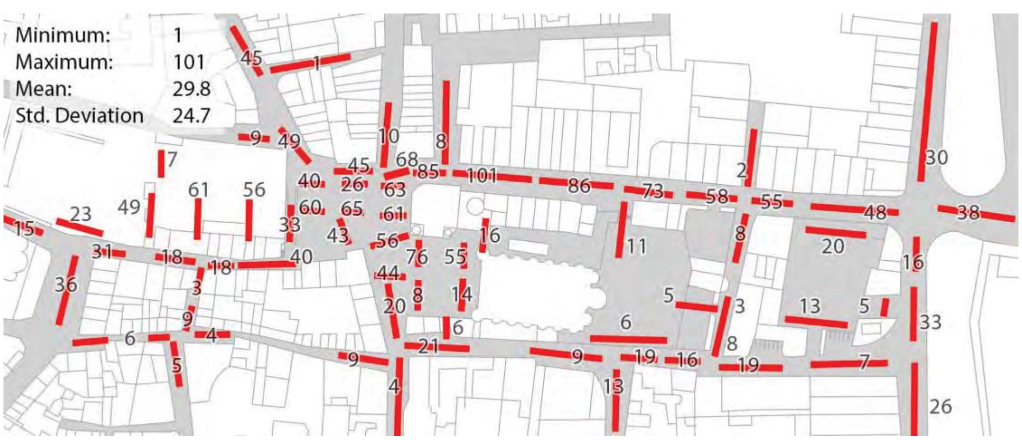

Figure 4.The result of the pedestrian count for 72 segments within the border of the case study.

Second, the agent-based analysis was performed. The analysis was done using DepthmapX developed at UCL university for space syntax analysis (Varoudis, 2012). Depthmap is a "multi-platform spatial network analysis software"[1] capable of performing a variety of spatial analysis supported by the configurational theories of space syntax. Initially, the VGA map was produced for the entire boundary of the walled city. It must be mentioned that although the boundary of the case-study is limited, both VGA and agent-based were performed for the extent of the entire area to provide a smooth and realistic representation of how people move within the network of spaces. The limitation was also set due to the software limitation for producing VGA map; the definable number of cells is limited. Accordingly, the dimension of cells was increased to 1.5m so that the entire area can be considered. All visual obstacles such as trees, thick bushes, fences were carefully taken into account. The VGA connectivity map illustrates the central public plaza as the most visually integrated section of the walled city, but a quick comparison with the number of observed pedestrian suggests that it does not have the highest pedestrian traffic. This is often caused by the distribution of active land-use which is denser around move-through streets. The agent-based simulation was conducted (Figure 5), the parameters of the simulation include:100 agents according to the maximum number of the observed pedestrian count, 5000 random steps, and the field of view was set to 170 degrees (15 bins). The obvious difference between VGA and agent base here is the shift of intensity toward the connecting streets because the agents are not looking for a final destination. The large volume of space in the main plaza leads to the dispersion of virtual agents. This is similar to the observation count of the pedestrian. The highest count of agents was assigned to each segment.

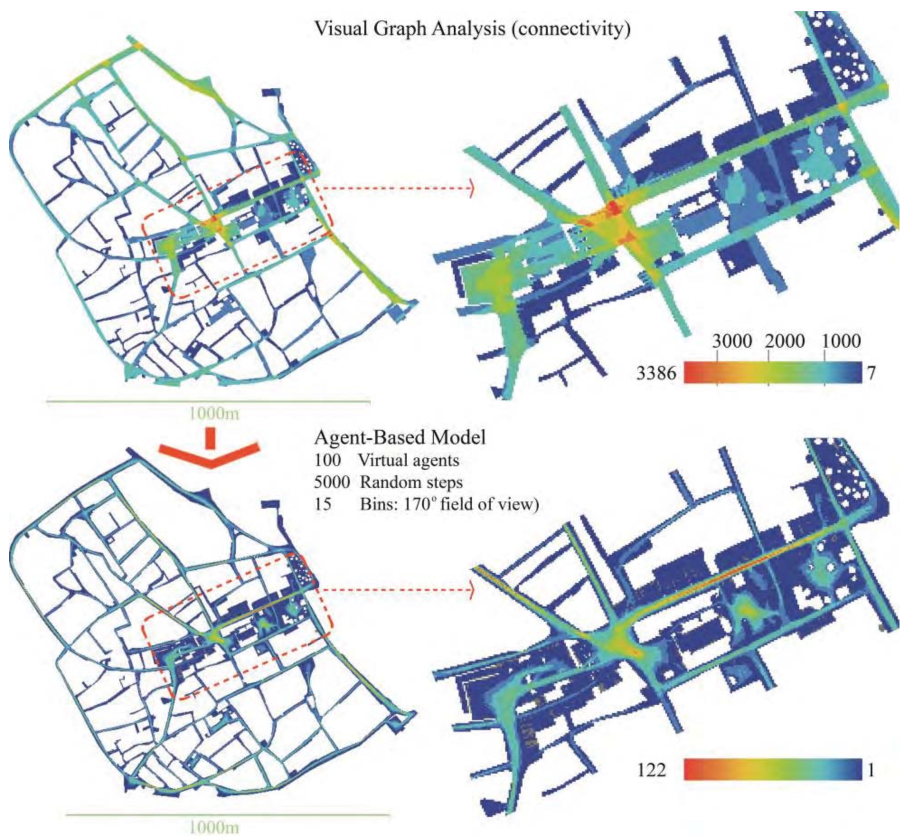

Figure 5. Top: Visual graph analysis of the walled city and limits of the case study, Bottom: the agent-based simulation.

Third, the Twitter data was collected using NodeXL application (Hansen, Shneiderman, & Smith, 2010). The tweets were collected using the inclusion of relevant metadata such as "Famagusta", "walled

[1] https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax/depthmapx

city", "Cathedral of Saint Nicholas", "Lala Mustafa Pasha Mosque", "sea gate", and "Namik Kemal square". Twitter data must be used with caution, the nature of data s accidental and includes instances of irrelevant information, for instance, commercial tweets, tweets from people working at a certain place. Therefore, the processes of filtering, cleaning and sorting are necessary to make sense of the data (Iranmanesh & Atun, 2018; Lansley & Longley, 2016). Furthermore, only around 2% of all tweets include volunteer geo-tag metadata. In this case, more than 20000 tweets were collected initially, the majority of them were outside the limits of the study, among these tweets only 1683 tweets were located inside the limits of the study, included intact geo-tagged data, and met the filtering requirements set for this study. The majority of the final tweets are linked with cafes, restaurants, the main public plaza, and historic checkpoints. Figure 6 shows an interesting phenomenon, in the public plaza the majority of tweets are located in distance with the main façade of the cathedral, this zone is the best place to observe and to take pictures of the building.

Figure 6. The filtered geo-tagged Twitter data superimposed on the map.

Conducting a simple regression using the observation data as the independent variable shows that 59% of all movements can be explained by the agent simulation (

Table *1*). The results confirm the findings of the previews studies (Aknar & Atun, 2017; Jiang & Jia, 2011; Koutsolampros & Varoudis, 2017; Penn & Turner, 2002; Turner & Penn, 2002). It could be argued that the bottom-up approach of constructing models based on the configurational aspects of space can provide a reliable illustration of pedestrian behaviour. This finding also indicates that increasing the cell size to 1.5m is applicable in predicting pedestrian movements. Furthermore, using geo-tagged Twitter data shows a slightly different picture. The Twitter data cannot be predicted by the agent model at the same level (R^2=0.20), this dissimilarity could be explained by the nature of Twitter data which is more closely related to land-use and does not work well with constantly moving agents. The majority of tweets, in this case, are coming from destinations, not move-through spaces, this can be shown by the correlation coefficient between tweet count and pedestrian count (R^2=0.31). although the correlation between the two variable is significant, it is not as strong as the predictability of pedestrian count via agent count. Building upon this idea, conducting a multiple regression using both agent count and tweet count shows 10% improvement over the simple regression (R^2=0.69). This outcome confirms that the spatial nature of two data types is different.

Furthermore, Inclusion of Visual connectivity does not improve the statistical model because the agent count is built upon the VGA and it is superior for predicting pedestrian movement. The results were further controlled by the alternative model suggested by Turner and Penn (2007) based on the longest line of sight. The statistical model shows a slightly lower correlation coefficient (Figure 7: R^2=0.45).

Table 1. Regression model for exploring the predictability of pedestrian movement vis agent-based and Twitter data.

	Regression	**Independent variable**	**R^2**	**Sig.**	**Collinearity Diagnostics VIF**
Dependent Variable: Pedestrian Count	Simple linear regression	Agent Count	0.59	0.000	-
		Twitter Count	0.31	0.000	-
		Visual connectivity	0.36	0.000	-
	multiple regression (enter)	Agent Count Twitter Count	0.69	0.000	1.21
		Agent Count Visual connectivity	0.60	0.000	1.52
		Agent Count Visual connectivity Twitter Count	0.70	0.000	1.61 1.66 1.31

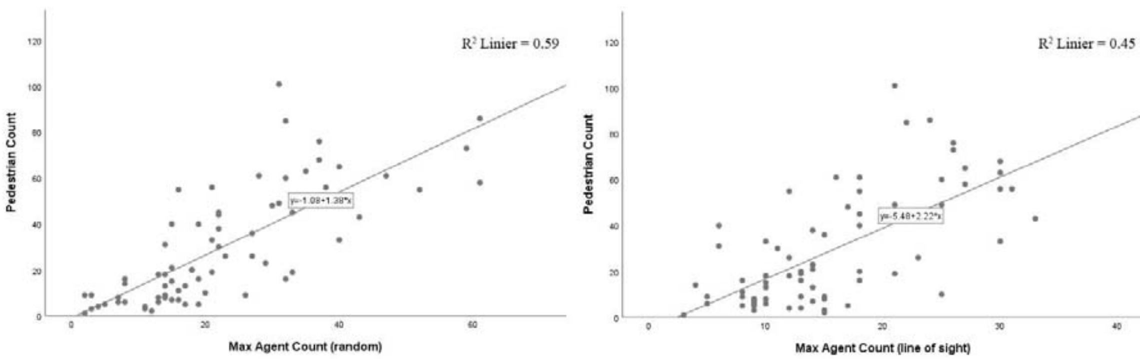

Figure 7. Left: the scatter plot of random next step agent-base against the pedestrian count, right: the line of sight agent-based model against pedestrian count.

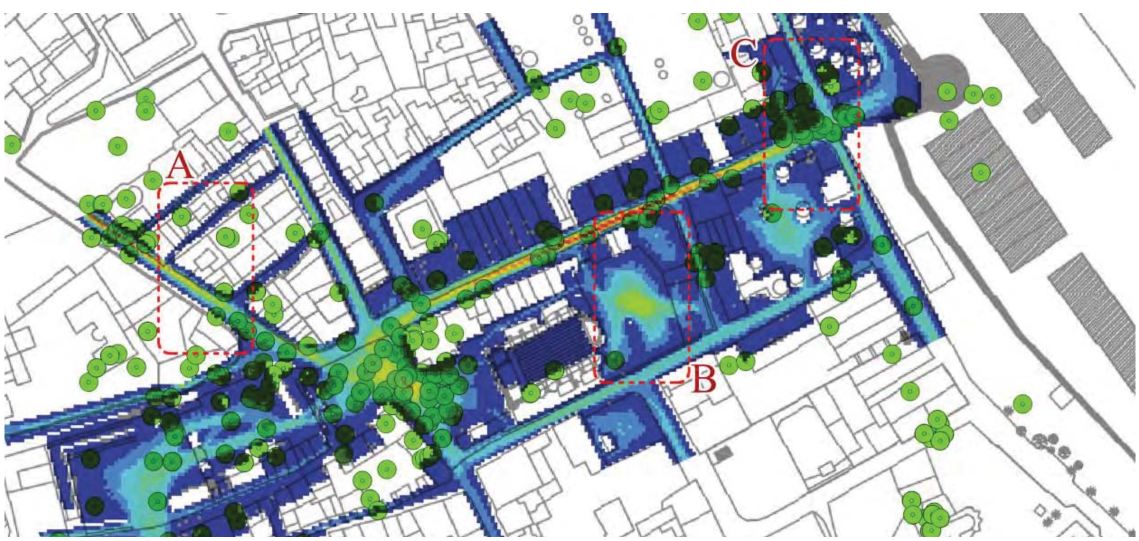

Figure 8. Spatial anomalies

Going back to the two basic propositions of space syntax, it is clear that the central spaces of the grid are also most visited by virtual and real agents! Tourists randomly around find themselves in these spaces. The land-use can affect the movement but it is the movement that eventually defines the land-use. This method can be implemented in problem diagnostics/solving phases of urban design. There are spaces that show potential in terms of affordance but fail to show significant pedestrian movement, the potentials of these spaces must be utilised in urban land-use development (Figure 8: A). Figure 8:B shows the space behind the cathedral, the agents seem to find it easily but the pedestrian count is low, this might be caused by the limited points of access to the space, it seems that some agents are being trapped inside and since it is a large space they survive and leave a mark; this space can be used for exactly such activities!, exhibitions, workshops, and NGOs. Figure 8:C shows a space with the highest number of tweets, it is connected to a famous pastry shop and also one of the best places to look back and snap a photo, however, the car traffic that cuts through space undermines its potential for pedestrian movement.

6. Conclusion

This paper undertakes the predictability of pedestrian movement through visibility base agent simulation and tries to improve the result by integrating new sources of geotagged social media data representing emerging ICT. The agent-based modelling is built on the bottom up idea that geometrical layout of the field of vision/movement is the most influential in how people move through space. Accordingly, virtual agents are making random steps on bases of available ground, and the accumulation of encounters with segments of space creates an intensity map that shows a strong correlation with pedestrian behaviour. Our findings confirm and improve upon the existing literature on the field by the addition of geo-tagged tweets into the regression model. The result shows 10% improvements over the agent-based model. The geo-tagged tweets bring some aspects of the active land-use into the equation, they represent urban hotspots and points of interests. It could be argued that the improvement is caused by introducing destination motivated movements upon the existing random through-movements. Twitter was used in this study as a representation of people’s digital footprint. The mobile devices and social media are becoming inseparable features of everyday life on contemporary urban spaces, so the research must take the emerging field of communication into account. The results are interpreted through space syntax configurational theories, and answers the question that why random movements can make sense of built environment? cities have been, and are being constantly formed by people through a collective logic that is fabricated into the essence of space. Furthermore, future studies could focus on the effects of biases in the Twitter user profile by providing more detailed content and user classifications.

References

Aknar, M., & Atun, R. A. (2017). Predicting movement in architectural space. *Architectural Science Review, 60*(1), 78-95.

Arribas-Bel, D. (2014). Accidental, open and everywhere: Emerging data sources for the understanding of cities. *Applied Geography, 49*, 45-53.

depthmapX: visual and spatial network analysis software. Retrieved from https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax/depthmapx

García-Palomares, J. C., Salas-Olmedo, M. H., Moya-Gómez, B., Condeço-Melhorado, A., & Gutiérrez, J. (2018). City dynamics through Twitter: Relationships between land use and spatiotemporal demographics. *Cities, 72*, 310-319.

Gibson, J. J. (1979). The ecological approach to visual perception.

Gibson, J. J. (2014). *The ecological approach to visual perception: classic edition*: Psychology Press.

Hansen, D., Shneiderman, B., & Smith, M. A. (2010). *Analyzing social media networks with NodeXL: Insights from a connected world*: Morgan Kaufmann.

Hecht, B., & Stephens, M. (2014). *A tale of cities: Urban biases in volunteered geographic information.* Paper presented at the Eighth International AAAI Conference on Weblogs and Social Media.

Hillier, B. (1996). *Space is the Machine: A Configurational Theory of Architecture*. Cambridge: Press Syndicate.

Hillier, B. (1999). The hidden geometry of deformed grids: or, why space syntax works, when it looks as though it shouldn't. *Environment and planning B: Planning and Design, 26*(2), 169-191.

Hillier, B. (2012). Studying Cities to Learn about Minds: Some Possible Implications of Space Syntax for Spatial Cognition. *Environment and planning B: Planning and Design, 39*(1), 12-32. doi:doi:10.1068/b34047t

Hillier, B., & Hanson, J. (1984). *The Social Logic of Space*. Cambridge Cambridge University Press.

Hillier, B., & Penn, A. (2004). Rejoinder to carlo ratti. *Environment and planning B: Planning and Design, 31*(4), 501-511.

Hillier, B., & Vaughan, L. (2007). The city as one thing. *Progress in Planning, 67*(3), 205-230.

Iranmanesh, A., & Atun, R. A. (2018). Exploring the spatial distribution of geo-tagged Twitter feeds via street-centrality measures. *Urban Design International*. doi:10.1057/s41289-018-0073-0

Jiang, B. (2009). Ranking spaces for predicting human movement in an urban environment. *International Journal of Geographical Information Science, 23*(7), 823-837.

Jiang, B., & Jia, T. (2011). Agent-based simulation of human movement shaped by the underlying street structure. *International Journal of Geographical Information Science, 25*(1), 51-64.

Karimi, K. (2012). A configurational approach to analytical urban design:‘Space syntax’methodology. *Urban Design International, 17*(4), 297-318.

Kim, H.-K., & Sohn, D. W. (2002). An analysis of the relationship between land use density of office buildings and urban street configuration: Case studies of two areas in Seoul by space syntax analysis. *Cities, 19*(6), 409-418.

Koutsolampros, P., & Varoudis, T. (2017). *Assisted agent-based simulations: fusing non-player character movement with space syntax.* Paper presented at the Proceedings of the 11th International Space Syntax Symposium.

Kumar, S., Morstatter, F., & Liu, H. (2014). *Twitter data analytics*: Springer.

Lansley, G., & Longley, P. A. (2016). The geography of Twitter topics in London. *Computers, Environment and Urban Systems, 58*, 85-96.

Lazer, D., Pentland, A. S., Adamic, L., Aral, S., Barabasi, A. L., Brewer, D., . . . Gutmann, M. (2009). Life in the network: the coming age of computational social science. *Science (New York, NY), 323*(5915), 721.

Lloyd, A., & Cheshire, J. (2017). Deriving retail centre locations and catchments from geo-tagged Twitter data. *Computers, Environment and Urban Systems, 61*, 108-118.

Mislove, A., Lehmann, S., Ahn, Y.-Y., Onnela, J.-P., & Rosenquist, J. N. (2011). *Understanding the demographics of twitter users.* Paper presented at the Fifth international AAAI conference on weblogs and social media.

Netto, V. M. (2016). ‘What is space syntax not?’Reflections on space syntax as sociospatial theory. *Urban Design International, 21*(1), 25-40.

Norman, D. A. (1999). Affordance, conventions, and design. *interactions, 6*(3), 38-43.

Penn, A., & Turner, A. (2002). Space syntax based agent simulation: Springer-Verlag.

Penn, A., & Turner, A. (2004). Movement-generated land-use agglomeration: simulation experiments on the drivers of fine-scale land-use patterning. *Urban Design International, 9*(2), 81-96.

Ratti, C. (2004). Space syntax: some inconsistencies. *Environment and planning B: Planning and Design, 31*(4), 487-499.

Sharmin, S., & Kamruzzaman, M. (2018). Meta-analysis of the relationships between space syntax measures and pedestrian movement. *Transport Reviews, 38*(4), 524-550.

Shaw, S.-L., Tsou, M.-H., & Ye, X. (2016). Human dynamics in the mobile and big data era. *International Journal of Geographical Information Science, 30*(9), 1687-1693.

Shelton, T., Poorthuis, A., & Zook, M. (2015). Social media and the city: Rethinking urban socio-spatial inequality using user-generated geographic information. *Landscape and urban planning, 142*, 198-211.

Steiger, E., Westerholt, R., Resch, B., & Zipf, A. (2015). Twitter as an indicator for whereabouts of people? Correlating Twitter with UK census data. *Computers, Environment and Urban Systems, 54*, 255-265.

Turner, A., Doxa, M., O'sullivan, D., & Penn, A. (2001). From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and planning B: Planning and Design, 28*(1), 103-121.

Turner, A., & Penn, A. (2002). Encoding natural movement as an agent-based system: an investigation into human pedestrian behaviour in the built environment. *Environment and planning B: Planning and Design, 29*(4), 473-490.

Turner, A., & Penn, A. (2007). Evolving direct perception models of human behavior in building systems *Pedestrian and Evacuation Dynamics 2005* (pp. 411-422): Springer.

Varoudis, T. (2012). DepthmapX multi-platform spatial network analysis software. *Version 0.30 OpenSource, http://varoudis. github. io/depthmapX.*