Integrative Pedestrian Modelling Techniques based on Virtual Force Fields

Analysis, Generation and Evaluation in Public Open Spaces

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This paper demonstrates a preliminary research methodology towards an integrative digital design approach for the analysis, generation and evaluation of architectural proposals in public open spaces based on human movement behaviour performances. In order to achieve this, various computational mechanisms that involve the logic of pedestrian modelling are applied, aiming to be explored in different stages of design. The suggested models follow the idea of 'virtual force' fields, an approach initially introduced in previous work by author. Based on particle behaviour modelling, this approach examines the interaction and movement behaviour of individual entities within a system through virtual effects and specifically through attraction and repulsion forces, influencing pedestrians behaviour and hence their accelerated movement. Current paper argues that the idea of 'virtual force' fields can be used not only for pedestrian simulation but also for the analysis and generation of proposals, aiming on a holistic design development of public spaces.

Keywords: *Pedestrian modelling, Integrative techniques, Virtual force fields, Public open spaces*

INTRODUCTION

The meaning of human movement behaviour in public open spaces has been examined extensively, especially in relation bodily motion and perception of space. Regarding to Spinoza in [1] motion is a transition situation from one state of motion to another, or variation of motion/rest and therefore it is a human behaviour occurred by affordances of external environment, which is depended on the intentions, motivations and knowledge of individual (Lang 2005).

Within this frame, the human perception that leads to spatial experience is achieved through motion, going from one vista to another, that is natural vision as mentioned in (Gibson 1986) followed by the idea of 'intelligibility', which is defined as the degree of what we can see from the space that makes up the system indicating the integration of each space into the whole system (Hillier 2007). In addition, the concept of 'legibility' defines the visual quality, the apparent clarity of the city that has been introduced in

(Lynch 1960).

In parallel direction, 'field theory' introduced in Lewin (1951) described human behaviour based on force fields, an influential theory in the area of pedestrian modelling in micro level. Pioneer work in Helbing et al (2001) introduced a mathematical interpretation of this idea called social force modelling, which has been mainly used to investigate pedestrian interaction behaviour.

The complexity of human movement behaviour, especially in public spaces, demanded the application of simulation techniques and software particularly in regard to the evaluation of existing design solutions. Spatial analysis examples described the space utilization and prediction of movement in actual situations as well as vision based models that were applied to detect the degree of accessibility and visibility of space (Bada and Farhi 2009; Woloszyn and Leduc 2011).

Nevertheless, the movement as a constantly changing condition and the traces of flow as the morphological result might be considered as space generators followed by experimentations using agent-based and social collective intelligence models, which allow the generation of spatial diagrammatic results (Ireland 2008; Puusepp and Coates 2008).

Currently, software and computer models mainly focus their attention on the simulation of pedestrian movement and the evaluation of solutions after the design is specified. This paper puts forward the hypothesis that computational mechanisms, algorithmic logics and parameters applied for the evaluation of design solutions might also be part of an integrative process involving mechanisms for analysis and generation.

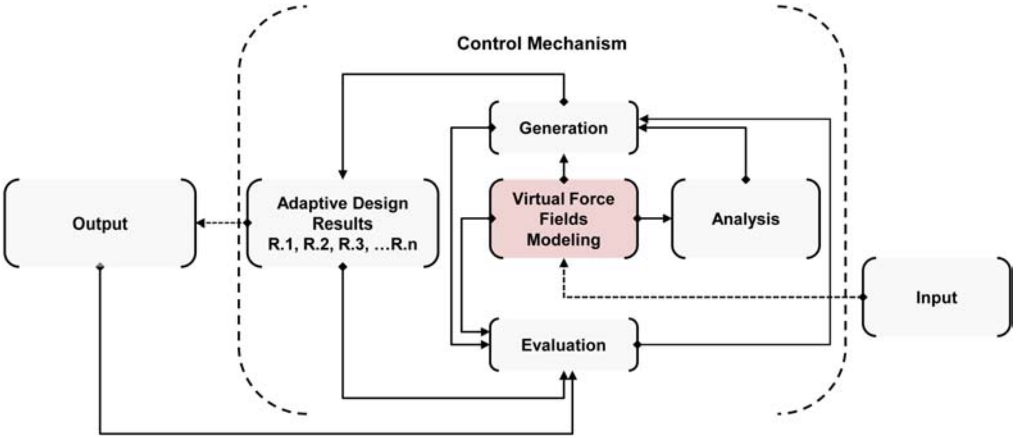
VIRTUAL FORCE FIELDS METHODOLOGY

This work aims to introduce an integrative strategy that is originated in a previous in-house pedestrian simulation program developed by the author under the name 'virtual force' model (Kontovourkis 2012). According to this, pedestrian movement simulation is based on the idea of particle behaviour modelling and particularly on the modelling of individual entities (individual entities might be described as pedestrians, obstacles, signs, etc), which are influenced by local rules that accelerate global behaviour. Specifically, the interaction and movement of pedestrians (a type of individual entity) is achieved by various behavioural rules that represent influences from the built environment generating a number of different effects. Those effects might be described as repulsive, attractive, obstacle avoidance effect, etc. For instance, in case of repulsive effect, individual pedestrians are subjected to virtual repulsive forces due to the tendency of pedestrians to keep a distance from others or from obstacles while their movement in space. As a result, the interaction and movement of pedestrians in discrete steps in space is achieved (Kontovourkis 2012).

Following the idea of particle behaviour modelling and its ability to generate a number of adaptive results due to the interaction occurred between different individual entities (including pedestrians) and the built environment, the current methodology suggests a conceptual design framework. This includes the idea of 'virtual force' as the basic factor for developing the three different stages of design investigation, i.e. analysis, generation and evaluation. The suggested framework describes the adaptive process as a continuous feedback loop between three basic parts: input, output and control mechanism. In control mechanism area, an iterative process between analysis, generation and evaluation stages is introduced based on the concept of 'virtual force' fields allowing the generation of numerous adaptive design outputs. Those results are fed back to the evaluation stage in a continuously repeated process until the desired objectives are achieved (Figure 1).

Analytically, in analysis stage, the different individual spatial entities and conditions are codified in order to transfer the physical behaviour into rules and parameters based on 'virtual force' concept and specifically into attraction and repulsion effects. In generation stage, the parametric logic and control of outcomes based on 'virtual force' fields are used to

Figure 1
Proposed conceptual design framework based on analysis, generation and evaluation stages incorporating the idea of 'virtual force' fields



develop movement flow systems in 2D and 3D environment allowing the formation of spatial morphologies. In evaluation stage, the generated outcomes are evaluated and the process is verified providing quantitative results in relation to the spatial utilization, maximum density, speed loss, and so on.

Preliminarily, the three stages of the control mechanism are developed separately using as common ground the 'virtual force' fields concept (Kontovourkis 2012). The proposed platform includes the FlowL plug-in [2] associated with parametric design software Grasshopper (a plug-in in Rhino) [3] and the commercial pedestrian modelling software SimWalk [4]. Then, in each stage, results in regard to the output data and findings are discussed together with theoretical suggestions on how the three different stages can be integrated and developed further.

CASE STUDY: A PUBLIC OPEN SPACE

The proposed conceptual framework is tested using the case study of an existing open public space, although the current methodology is expected to be introduced in other examples attempting to verify the validity of the idea. The area of design implementation is the small adjacent square next to the Eleftheria square, one of the main historical public spaces in Cyprus. It is located in the old city of Nicosia, at the beginning of Ledras Street and just after the Venetian walls. In the surrounding urban fabric there is a plethora of options for leisure, shopping and business activities as well as accommodation facilities and significant monuments. For this reason, the space under investigation is a transition point, highly accessible by a number of pedestrians. However, an interest in the appropriation of space from the majority of pedestrians or interaction among them is not obvious. In contrast, the current spatial configuration shows a separation in space utilization according to the type of pedestrians, preventing the creation of a lively space. The current methodology aims to detect the conditions and the degree of their affection as well as to recognize the spatial qualities in order to improve the living environment.

The process suggests a constant interaction between the proposed design stages (analysis, generation and evaluation) as well as researcher/architect interventions, whose decisions and observations are instrumental for the design configuration outcomes. Briefly, the procedure includes the analysis of the existing, the generation of 2D flow lines and 3D morphologies by visual algorithms and the evaluation of the results, all stages based on the 'virtual force' fields idea. Following sub-sections describe each stage.

Analysis

The investigation starts by analysing the existing area. In the process of pedestrian movement behaviour modelling, apart from the importance of origin and destination points that defines the goal of movement action, other innumerate factors, which play equal role in this process are visibility (an idea derived from Hillier 2007 and Gibson 1966) and pedestrians' collectiveness. Respectively, conditions related to visibility (advantageous viewing point) and elements that encourage collectiveness (sitting areas, shadow areas, etc) are integrated into the methodology.

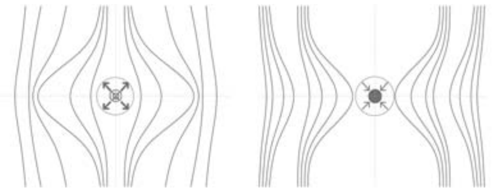


Figure 2
Diagrams of pedestrian flow displacements according to the intensity and distance of repulsion and attraction behaviour

Considering that the spatial entities influence pedestrian movement behaviour by attraction or repulsion, site analysis aims to codify such information in order to transfer the physical behaviour of pedestrians and their interaction with the built environment into rules and parameters. Spatial elements and physical conditions affect pedestrian movement, not only due to their spatial qualities, but also due to the specificities of individuals. Large impact values of spatial entities result large attraction or repulsion, and hence displacement of the initial pedestrians movement. The distance between a pedestrian and a spatial element, either attractive or repulsive, influences the displacement degree of pedestrians flow lines (Figure 2). In addition, the pedestrian movement intention (either pass through or stop) plays a crucial role in the simulation process and can define the type as well as the degree of local influences derived from the conditions of the environment.

Specifically, the proposed pedestrian movement scenario is analysed as follows: pedestrians move through the public square based on various needs and interests. The space is perceived differently according to pedestrian's destination and background. As a result, the type of influences and of conditions in regard to the spatial elements is differentiated in each case. The site analysis reveals that a pedestrian who is interested to stop is more attracted by the advantageous viewing and shadows areas and is less influenced by areas with great concentration of pedestrians. In contrast, a pedestrian who aims to pass through the public square, he/she is repulsed by concentration points while is less influenced by shadow. This is observed mostly when the pedestrian is familiar with the direction of movement that is based on destination goal. If the movement is exploratory, for instance tourist's walk, then advantageous viewing areas attracts the most.

Briefly, the site analysis indicates four types of pedestrians: group a: shoppers, group b: immigrants/elderly people, group c.: tourists, and group d: employees. The conditions that influence the attraction or the repulsion and hence the pedestrian movement are the obstacles, the advantageous viewing points, the shadows areas and the pedestrian concentration points. The movement behaviour is codified and analysed based on the four types of individual pedestrians and is examined by defining movement scenarios and by designing corresponding flow diagrams in each case.

The pedestrians move through the public square based on the configuration of the wider urban fabric. A pedestrian flow diagram within the existing public square consists of a starting and a destination point. Each group of pedestrians is related with flow lines of three possible routes, except the group c that is related with flow lines of four possible routes. The flow lines, which correspond to a particular pedestrian group, are determined by several points and a common destination point. For instance, based on the existing configuration, the initial flow lines that are set for pedestrians in group a (shoppers) are as follows: Start point [O2] - Destination point [D1], Start point [O3] - Destination point [D1] and Start point

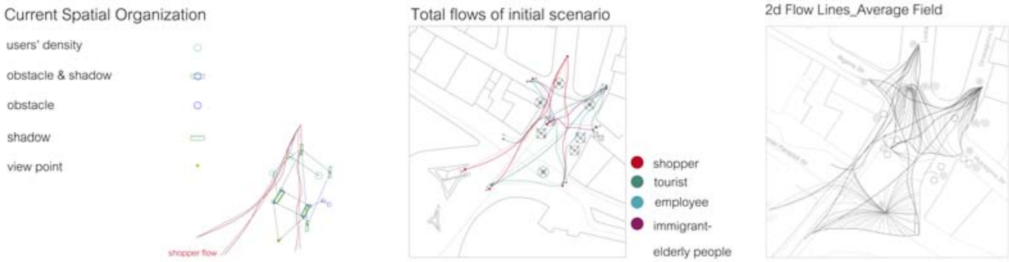


Figure 3
Existing spatial configuration, possible scenario of pedestrian modelling and generated 2D flow diagram

[O4] - Destination point [D1]. The starting points [O2, O3, and O4] refer to shoppers' access points, while the destination point leads to the main commercial road of the given area.

In the analysis stage, a preliminary codification of input data is demonstrated forming the background where generation and evaluation of solutions will be developed. In analytical level, the translation of pedestrian movement and the interaction behaviour based on repulsive and attractive effects provides the framework where the three stages will be integrated into a unified methodology under common input and output principles.

Generation of initial solution

Based on the 'virtual force' fields idea and using the parametric design software Grasshopper, this stage focuses on the spatial configuration and generation of movement flow systems and morphologies in 2D and 3D environment.

The procedure of morphological generation starts by digitising the input data, which are derived from the site analysis. Then, spatial elements are transformed into charging points of attraction and repulsion. According to the type of pedestrians, their behaviour as well as their distance from the point of influence, the attraction or repulsion effects can vary creating different displacements of the movement flow lines. For instance, based on the existing living environment, in the group a (shopper) the following effects are applied: Tree - repulsive effect, Bench - repulsive effect, Advantageous viewing point - none, Shadow area - none and Concentration point - repulsive effect.

In detail, the spatial entities named tree, bench and concentration points repulse the shoppers because these are perceived as obstacles in space. Since shoppers are familiar with the environment, aiming to reach their destination without aimless movements, they are not influenced by shadow areas or advantageous viewing points. The advantageous viewing point is detected in parametric environment by calculating the point with the largest viewable area ('isovist'- See Hillier 2007). This point of influence, and according to the movement scenario, can carry repulsive or attractive behaviour.

Initial results show that generated parametric flow lines that are influenced by the 'virtual force' fields. The displacement of initial flow lines is configured by the resultant force (or the average charge) related to the distance between the particular points of flow lines, the attractive and the repulsive points. Based on parametric flow lines, a 2D diagram, which indicates a field of flows related to the movement tendency, is generated (Figure 3).

Then, by using the parametric tool FlowL (a plug-in in Grasshopper) that is correlated with the generated pedestrian movement flow, a 2D diagram of flow lines according to the average field of charges is produced. The 3D generation of space is based on the 2D diagram of flow lines attempting to capture possible design solutions based on the given movement scenario.

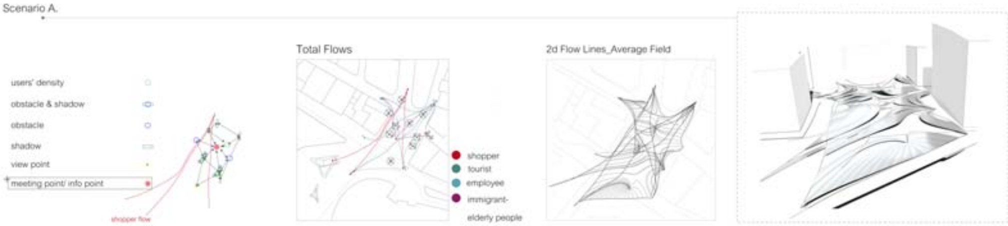


Figure 4
Scenario A: Proposed spatial configuration and pedestrian modelling scenario as well as generated 2D flow lines and 3D morphology

Figure 5
Scenario B: Proposed spatial configuration and pedestrian modelling scenario as well as generated 2D flow lines and 3D morphology

Preliminary evaluation and alternative solutions

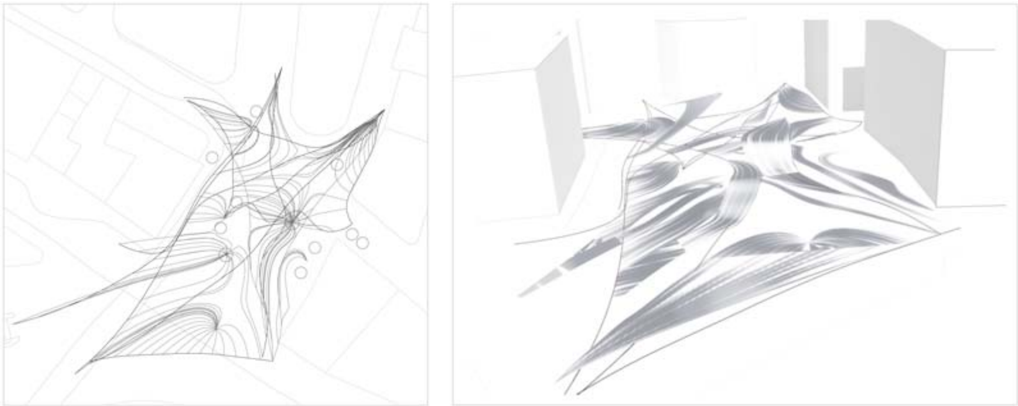
The 2D flow lines diagrams and 3D morphologies can be interpreted through the criteria of trend, intensity and free movement. Observations derived from the diagrams are correlated with the real situation and the digital results are evaluated preliminarily to define and organise alternative spatial configurations and movement scenarios.

In order to improve the living environment and to generate a lively space, the existing spatial elements are preserved and new conditions that attract more types of pedestrians are suggested. In the context of experimentation, considerable alternative solutions in a relatively short time period are implemented. The proposed experimentation consists of several charging points (function in real time) with different degrees of attraction or repulsion and positioning in the built environment. The following figures show diagrammatically different stages of generated procedure based on alternative scenarios A, B, and C. In the first stage, the conceptual development is shown, where intentions and movement scenarios are set. In the second stage, the generation of parametric flow lines are demonstrated, and in the third stage, the generation of the 2D diagrams of flow lines are shown. In the final stage, the process for generating 3D morphologies are presented, whereas charging points and flow lines diagrams are transformed into morphological and functional solutions (Figure 4, 5, 6).

Figure 6
Scenario C: Proposed spatial configuration and pedestrian modelling scenario as well as generated 2D flow lines and 3D morphology

Figure 7
Scenario D:
Selected spatial configuration and possible scenario of pedestrian modelling

Figure 8
Scenario D:
Selected diagram of parametrically generated 2D flow lines and 3D morphology



In the selected movement scenario D, the spatial configuration and the 3D generation correspond to the general aim of improving the existing on-site situation and is the result of a continuously evaluation procedure (Figure 7, 8). The current methodology attempts to attract more types of pedestrians by encouraging stops and spontaneous activities. Also, it intends to reduce pedestrian's acceleration movement and in parallel to increase the duration of stay in the public square. The classified functions that are found to be appropriate in this case are ramps of movement, shelters and seats/rest areas, which are formed by grouping the appropriate flow lines and transforming them into lanes/surfaces.

Through the suggested process of cyclical iteration between generation and evaluation stages a number of new movement flows are generated based on the alternative movement scenarios, simulating in parallel corresponding pedestrian movement behaviour. The configuration of lane/surface depends not only on the function but also on the range of charge (attractive or repulsive), which is defined in the analysis stage and used as the output data that are fed back to the generation stage. In this process, the user intervention is very important since he/she is able to determine the final desired morphology through the feedback loop process allowing the reformulation of analysis and evaluation scenarios based on the 'virtual force' fields logic.

Advanced evaluation of selected solution

In the next stage, the existing configuration and the selected solution D are evaluated based on the qualitative criteria of free movement, movement tendency and density of flow lines (indicating the intensity of movement) as well as on quantitative results related with the spatial utilization, maximum density and speed loss. In order to achieve this, the pedestrian simulation software SimWalk is used for evaluating the proposed outcome including the 3D morphological results.

The evaluation process starts by examining the existing configuration. The aim is to compare the digital results (diagrams of parametrically generated 2D flow lines) with the real situation based on the qualitative criteria mentioned above. Analytically, it is detected that the configured digital environment reflects the existing spatial utilization and its characteristics. In real time, the space is characterized by free movement while the main movement of pedestrians happens through the centre of space demonstrated by vectors (using relevant components in Grasshopper). Since the 2D flow lines indicate the intensity of movement, is revealed that there are areas where the movement flow is nonexistent. Similarly, based on site analysis, the same areas are used less frequently. It is clear, although, that space is experienced and appropriated not only because of spatial organization but also because of social economic circumstances. Nevertheless, the final outcome reflects the real situation providing a verification of the whole process consisting of spatial elements' codification and pedestrians' movement scenarios.

Then, results derived from the simulation of the existing and proposed configuration (selected solution D) are evaluated through a comparative process taking into account the movement scenarios, the spatial configuration as well as the generated 2D flow lines and 3D morphology. Quantitative results related to spatial utilization, maximum density and speed loss are derived. The spatial utilization graph shows the number of pedestrians passing through a specific spatial cell in each time step (P/min), while density graph shows the number of pedestrians in the same spatial cell (P/m2). The final graph is related to the speed loss and it presents the degree of pedestrians' speed reduction in each cell (rate of speed reduction in %). A pedestrians' trails diagram is also available, where each colour of trails corresponds to the destination point of pedestrians.

The simulation is set in three phases of a day (a. 9:00, b. 13:00, c. 20:00) with duration of 45 minutes. Also, initial pedestrian settings that include the time of appearance, attendance, and intentions are defined. Then, different movement scenarios are organized and the appropriate start, mid and destination points are specified (Figure 10).

Movement scenarios are organized based on the same four types of pedestrians (shoppers, immigrants/elderly people, tourists, employees). First simulation is set at 9:00 am and consists of 401 pedestrians (shoppers: 83, immigrants/elderly people: 62, tourists: 190, employees: 62). Second simulation corresponds to 13:00 pm and consists of 327 pedestrians (shoppers: 74, immigrants/elderly people: 41, tourists: 150, employees: 62). The third simulation corresponds to 20:00 pm and consists of 181 pedestrians (shoppers: 59, immigrants/elderly people: 52, tourists: 60, employees: 10). Alternative simulations can be set by modifying the number of pedestrians and the movement scenarios of pedestrians.

The results of simulation are compared with the initial intentions/initial goals of spatial organization scenarios and with the qualitative criteria of trend, intensity and free movement. Observations of the spatial utilization graph in the existing proposal shows that there is a free movement with large intensity through the center of space. Figure 10 shows the simulation set at 13:00 pm. In contrast, results of simulation related to the selected proposal show that

Figure 9
Existing and proposed diagrams of pedestrian simulation scenarios (Origin and Destination points)

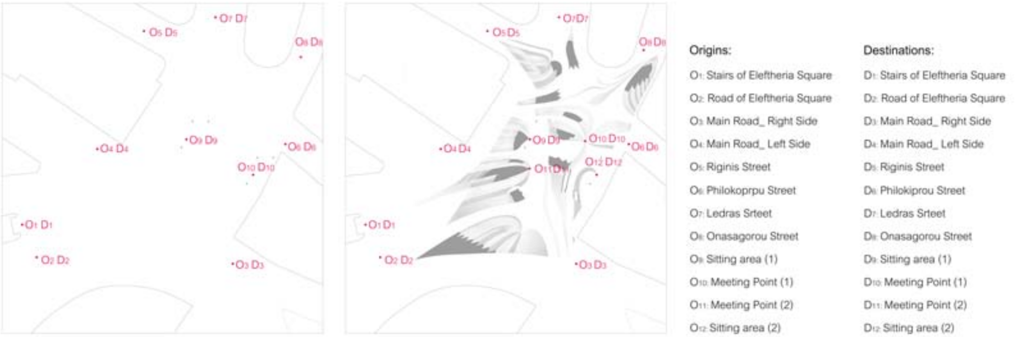
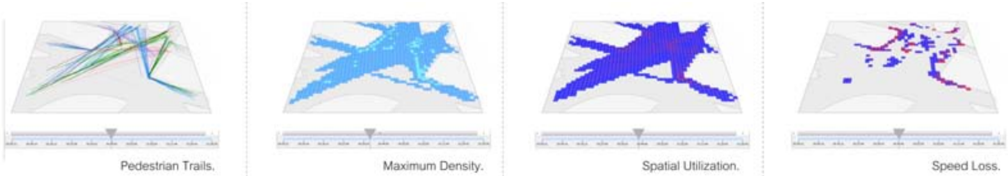


Figure 10
Existing configuration and results of simulation set at 13:00 pm



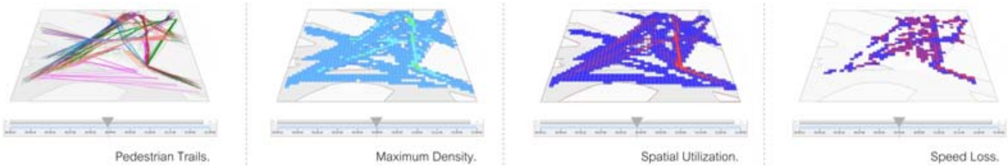
the spatial utilization is uniformly distributed in the whole area. Figure 11, 12 and 13 show the simulations set at 9:00 am, 13:00 pm and 20:00 pm respectively.

In relation to the density graph, is observed that the selected proposal is characterized by high density through the whole area (Figure 11, 12 and 13). The possibility for large number of interactions between the pedestrians is provided, showing that pedestrians' collectivity is encouraged. However, due to the limited free space and high density, the phenomenon of collision is more probably to be occurred in real time.

Observations in regard to the speed loss of selected proposal show that there is a high reduction of movement acceleration through the whole space (Figure 11, 12 and 13) compared with the results observed in the existing proposal where an uninterrupted and relatively fast movement is occurred (Figure 10). By encouraging stops and by increasing seats/rest time in selected positions, the speed loss target is also satisfied.

The preliminary conceptual methodology that integrates the three different stages in a proposed conceptual framework initially aims to find correlations between different computational techniques based on 'virtual force' fields. It is obvious that the application of such modeling techniques, which accelerate pedestrian movement behaviour within a continuously interactive built environment, can be the starting point for computational interoperability. In a preliminary stage, this is achieved by the applica-

Figure 11
Proposed configuration and results of simulation set at 9:00 am



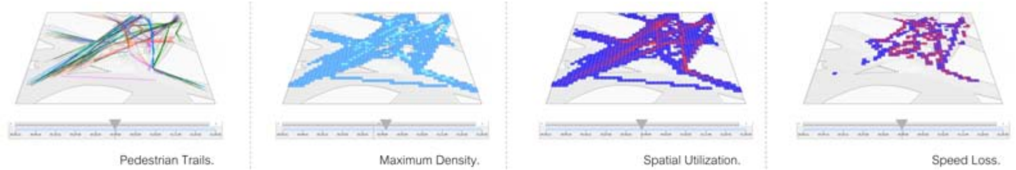


Figure 12
Proposed configuration and results of simulation set at 13:00 pm

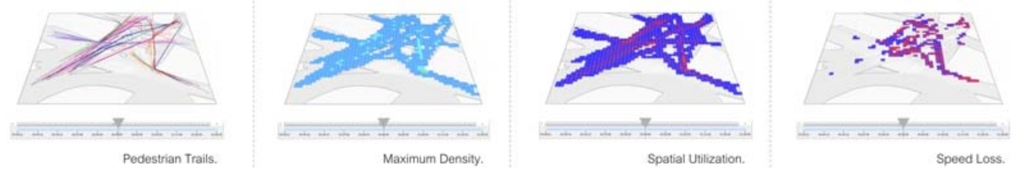


Figure 13
Proposed configuration and results of simulation set at 20:00 pm

tion of feedback loop logic linking the output results of the analysis with the input data of generation and evaluation stages. Also, by using output data derived from the evaluation as the input information in the generation stage.

CONCLUSION

This paper attempts to analyse, generate and evaluate a public space through a suggested preliminary integrative pedestrian modelling methodology based on 'virtual force' fields. The configuration of alternative spatial scenarios provides the possibility for morphological generation and evaluation of results in a continuous iterated feedback loop process. Nevertheless, it is obvious that the way space is experienced and appropriated by pedestrians in not only a result of spatial organization but also a result of other social-economic conditions. However, the analysis derived from this methodology might reflect real situations and the generated outcomes as well as the evaluation process might offer useful ground for digital reorganization and examination of spatial outcomes.

In conclusion, the current study proposes the integration of various models based on the idea of 'virtual force' fields aiming on the continuous regeneration of space with multiple spatial results. The involvement of different techniques based on the particle behaviour modelling as the programmatic framework towards analysis, generation and evaluation allow a holistic computational approach to be generated investigating results in all stages of design process towards common objectives but different decrees of complexity.

Future work will continue towards an in depth examination of the three different stages, i.e. analysis, generation and evaluation, aiming on input and output data specification and algorithmic control of the proposed methodology towards the interoperability of techniques. This will allow the generation and investigation of solutions within a holistic design perspective driven by pedestrian movement performances.

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