Urban Street Retrofitting

An Application Study on Bottom-Up Design

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Urban streets will have to be retrofitted to improve walkability and to provide space for a diversity of transport modes. This paper introduces a framework which combines space syntax and shape grammars in a design support method for generating scenarios for urban street retrofitting. A procedure to hierarchize streets and select priority locations for urban street retrofitting is presented. Four different angular choice analyses with decreasing radii are used to derive the hierarchical structure of target urban areas with the aim of triggering shape grammar rules and generating bottom-up intervention designs. The same measure using a local radius to represent walking modal is then used to determine which streets should be retrofitted to improve pedestrian safety and walkability for the largest number of people. An application study using this procedure is presented and results are compared to street hierarchies from two different sources. This study is the first step towards automating the generation of design scenarios for urban street retrofitting.

Keywords: *Space Syntax, Street Hierarchy, Parametric Urbanism, Scenario Modeling, Travel Behavior*

1. INTRODUCTION

This research is based on the premise that urban expansion is limited by the amount of land needed for food and energy production, as well as other environmental services. With the urban growth expected in the following decades, strategies of spatial containment and urban densification will have to be adopted to limit urban sprawl (Carlow, 2016). Densification creates a challenge for urban mobility by concentrating origins and destinations. Cities will have to promote the use of mass and active modes of transportation, in order to decrease the use of private cars, so that more people can be transported without the need of expanding the road network. Urban design has been shown to influence travel behavior by encouraging people to be less car-dependent (Ewing and Cervero, 2010). Thus, streets must be retrofitted to enable cities to become denser.

Bottom-up processes and the idea that the designer can trigger self-organization through local, small-scale, interventions has been a recurrent topic in the field of urban design. Some researchers have approached this problem by suggesting that experimentation through temporary low-cost interventions, which can be made permanent, when successful, is a method to tackle urban complexity and propose bottom-up interventions (Wohl, 2017). Because the city is a complex adaptive system, these types of interventions have little effect if they are applied in isolation and should be planned as interacting networks. This raises the question of predicting design outcomes, which is a difficult task, because the information related to urbanism is complex and dynamic. Formulation of possible future scenarios through the observation of existing phenomena and extrapolation of empirical data can be used to better inform these networks of interventions, and reduce the uncertainty (Verebes, 2013).

The main approach to urban street retrofitting is usually the creation of guides and manuals which provide countless case-specific geometric rules, urban policies, design patterns, and guidelines for urban equipment, lighting and materials. Combining these rules in a project is a complex task, with potentially conflicting responses. In addition, estimating the impact that street design can have on modal choice is not supported by these methods. Parametric design and simulation can be used to provide a framework for virtual experimentation, allowing the generation of multiple scenarios in viable time. These scenarios can then be assessed and objectively compared, based on empirical data, to guide the design process.

This paper is part of a larger ongoing research into methods and computational tools that can be used to generate three-dimensional scenarios to support the retrofitting of urban street design in the context of urban densification. Four modules are proposed as part of the framework used in this research: formulation, design brief, generation and evaluation. The formulation and design brief modules, which are the focus of this article, use graph-based network analysis, i.e. space syntax (Hillier and Iida, 2005), to choose the most appropriate locations for this type of intervention and to hierarchize streets. This street hierarchy is the design brief and is used in the generation module to trigger the application of the prescriptive grammar, which is based on the shape grammar formalism (Stiny and Gips, 1972) to generate design proposals for retrofitting a given set of streets. It encodes design patterns extracted from guides and manuals for street design, with the aim of improving pedestrian safety and accessibility, to promote the use of active transportation, i.e. walking. It is a deterministic parametric grammar, because for each street description one design solution is generated. For further information on the generation module, refer to Sousa and Celani (2019). The evaluation module is a modal share calculator for estimating how each design proposal can affect each mode of transportation and will be the object of future research. This module is based on the concept of D-variables (i.e. density, diversity and design) and their measurable influence on travel behavior (Ewing and Cervero, 2010). It compares input from the initial and final states of the model to calculate the increase or decrease in the use of different travel modals (e.g. private vehicles, public transit, walking) by using elasticities, which are nondimensional empirically based relations between variables. They link a 1% increase in a D-variable to the percentage increase or decrease in vehicle miles traveled, walking or transit use.

The proposed division into four modules is based on the work of Duarte et al. (2012) for the City Induction Project. The main difference being that the formulation module proposed in this work is based on configurational analyses using space syntax to formulate the design brief, represented by the street hierarchy and choice of areas to retrofit. The design brief triggers the generation module. This is done to articulate top-down planning with bottom-up implementation approaches to propose changes based on existing urban characteristics. The initial input for generating different scenarios is the area to retrofit, which can be a town, a neighborhood or a set of urban blocks. The initial state and position of a street in a given network configuration can be the trigger for design generation, as opposed to the description of a final desired state as often found in design interventions, meaning design proposals are developed bottom-up, with no a-priori assumptions from the stakeholders other than the goal to promote densification through the improvement of pedestrian mobility. This framework was conceived for areas in which the street infrastructure was designed for lower urban densities than those currently in place or expected in the future. It allows interventions to be added incrementally to the model, enabling projects to be phased, or to generate different scenarios, which can then be compared to aid the design process.

The next section presents a literature review on the use of space syntax as a methodology to study street hierarchy and assess the potential of a street for attracting pedestrian movement. Based on this review, the third section presents the research procedures for using angular segment choice analysis to hierarchize and select streets for design intervention. The following section presents an application study using data from an existing city. The fifth and final section presents a discussion of the results and conclusions on the potentialities and limits of this research, as well as identifies issues for and further study.

2. METHODOLOGIES

An important part of this research was to identify methods that can be used for understanding different aspects of vehicular and pedestrian movement. Design interventions should be implemented in places where land uses that rely on pedestrian movement, e.g. retail and services, will be more likely to emerge and be sustained. They should also occur in areas where they can improve urban quality for the maximum number of people. Thus, assessing which places in a street network have a configuration with the potential to attract pedestrian movement is of crucial importance when planning urban interventions (Hillier and Penn, 2004; Nourian et al., 2018). In this section we discuss one of these methods, space syntax, with the following purposes in mind: a) hierarchizing streets in terms of their potential to attract vehicular traffic, in order to serve as triggers for the generation module; and b) identifying which places in the urban grid have the potential to attract and sustain pedestrian movement. This would permit to choose the locations where design interventions aiming at improving pedestrian safety and walkability should be implemented.

Space syntax is a method for graph-based network analysis which statistically relates network configuration to movement. It has been widely applied to study pedestrian and vehicular movement in urban networks (Hillier and Iida, 2005; Nourian et al., 2018). The theory behind applying space syntax to model pedestrian and vehicular movement is that movement in cities is a result of how people perceive their environment. Thus, some streets are naturally more attractive to users, either because of their legibility or because they are on the simplest route to other streets. In turn, this natural attractiveness to movement also makes these streets attractive to social and economic activities, which leads to denser occupation patterns (Hillier, 1997).

In the past two decades, several works have shown a significant correlation between measures of integration and choice with the distribution of pedestrian and vehicular movement (Sharmin and Kamruzzaman, 2018; Shatu et al., 2019). These measures have been used for determining the places in an urban network which are more likely to generate human movement (Kirkley et al., 2018; Nourian et al., 2018). Integration, called closeness centrality in graph theory, measures to-movement (i.e. how far a street is from all others), while choice, or betweenness centrality, imeasures through-movement movement (i.e. shortest paths between all pairs of streets). These measures can be calculated using topological, angular or metric distances. They can also be calculated globally or for different radii, which can be interpreted as the transport modal in an analysis. Global measures refer to the distance (topological, angular or metric) from each street in the network to all other streets while local measures are calculated within a certain limit, such as the number of turns, the sum of the angles or the metric distance. For example, global integration measures the mean distance, topological, angular or metric, from each line in an axial map to all other lines in the map, while the local integration measure uses a predefined number of lines, angular change or metric distance. Local integration and local choice have been shown to be strong predictors of pedestrian densities (Hillier, 1997; Hillier and Iida, 2005). Angular integration and angular choice have been shown to explain approximately half of pedestrian movement based on network configuration alone, with least angular change considerably more likely to explain pedestrian and vehicular movement than shortest metric or topological distances (Omer et al., 2017; Sharmin and Kamruzzaman, 2018; Shatu et al., 2019).

Cooper (Cooper, 2017) suggests that the measure of choice coupled with routing criteria can be used as a substitute to more complex models, such as the four-step travel demand model of trip generation, distribution, mode and route choices. This is possible because it generates "indiscriminate trips from everywhere to everywhere" (p.159) outputting the number of shortest paths that go through each link in a network, within a predetermined radius, which can be interpreted as flows. Because of this, choice serves as a proxy for density measures, i.e. trip generation and distribution, because the denser the network in the area of a given link, the higher the number of shortest paths that will go through the area. Mode choice is intrinsic to the radius chosen for an analysis, as each mode is only used up to a certain distance (Cooper, 2017). The use of routing criteria is only necessary for the aim of predicting absolute vehicular and pedestrian flows. For the purpose of deriving a street hierarchy the spatial distribution of choice is enough because it can be used to estimate which locations are more likely to attract higher levels of natural movement (Cooper, 2017; Kirkley et al., 2018, p. 10; Omer et al., 2017). Even if land-use and population density have a multiplicative influence on natural movement, configurational aspects have been demonstrated to account for significant differences in natural movement on their own (Nourian et al., 2018; Sharmin and Kamruzzaman, 2018). The location of attractors can be seen, to a certain extent, as a consequence of configuration (Hillier, 1997). These findings point towards using the measure of angular segment choice as an analytical tool for planning urban design interventions focused on promoting active modes of transportation. This contrasts with four stage models which focus on metric distances between origins and destinations (Hillier and Iida, 2005; Shatu et al., 2019). It is this capacity coupled with its comparatively small data input needs (Penn, 2003) that explain why space syntax has many supporters in the fields of architecture and urban design.

Thus, angular segment choice is used in this research, both for street hierarchization and intervention site location and, because it has been shown to be highly correlated to pedestrian and vehicular flows, depending on the radius used for the analysis, but also because it works as a proxy for urban density, because the denser the network the higher the number of shortest paths running through the links with highest centrality (Cooper, 2017; Sharmin and Kamruzzaman, 2018). The objective of an analysis must be considered when making modelling choices regarding: a) network representation (e.g. axial lines or road center lines); b) edge representation, scale and boundary of the analysis, and c) weights (Gil, 2017; Marshall et al., 2018).

There are different methods of representing a street network. The choice of representation used in a model influences the results obtained in an analysis (Marshall et al., 2018). For the purpose of this research we will focus on the axial representation and on Road Center Lines (RCL). An axial map represents urban space, using the minimum number of straight lines which can cover the entirety of a grid and its open spaces, while making all the existing connections. It is based on cognitive assumptions about route choice to represent how pedestrians and vehicles move through the network, using their perception of space (Penn, 2003). The advantage of using the axial representation to model pedestrian behavior is that it intrinsically represents how people move through a network. Using the axial representation adds a layer of significance to the model which would otherwise be lost with other methods (Penn, 2003). From the axial representation it is possible to derive a segment representation, by dividing the axial lines at intersections. The segment representation can be used to measure angular and metric distances (Sharmin and Kamruzzaman, 2018). RCL is an increasingly popular method of representation because of its accessibility, removing the step of drawing axial maps for large networks. However, when calculating angular centralities, because of the large number of street segments in RCL representations, these maps should be simplified to reduce angular changes, in order to approximate to the results obtained with axial maps. For smaller radii, used for analyzing pedestrian movement, results obtained using RCL are usually considerably different, and less sensitive, when compared to results obtained with axial maps, even after simplification (Kolovou et al., 2017). Thus, the choice of network representation is largely dependent on the choices of centrality measure, distance and radii being used. For measuring angular centralities, the segment representation is used. It can be derived from breaking axial lines or RCL at junctions. The first has better results for smaller radii, while the second has the advantage of being easily acquired (Kolovou et al., 2017; Omer et al., 2017; Sharmin and Kamruzzaman, 2018).

Another important factor when using centrality measures to analyze networks is the edge-effect caused by the boundary chosen for an analysis. Every network model has an artificial boundary, defined by the area being studied. Depending on how this boundary is defined, centrality measures can be affected. Thus, the boundary for the model must be a deliberate and justified decision at the beginning of the modelling process. There are different approaches to boundary definition, such as using existing barriers in the network, e.g. topography or the edge between rural and urban areas. This definition affects the calculation of global centrality measures. Nonetheless, Gil (2017) demonstrated that global measures of angular segment choice analysis are robust when calculated using buffer zones above 5km, specifically in the case of identifying street hierarchy. All results for the nodes within this buffer zone should be discarded from the analysis as their reliability will drop as they approach the edge. Furthermore, the area being studied should be centralized within the buffer zone (Gil, 2017).

Assigning weights to the links, based on distance, land-use, road-capacity, etc., has been shown to have a minor influence on the distribution of choice in street networks (Kirkley et al., 2018, pp. 3-4). Nourian et al. (2018) found that in the case of irregular grids, population density does little to improve the predictive power of the configurational model. Furthermore, the additional information needed to assign these weights complicates the use of spatial analysis as a design tool because more case-specific information is necessary at the beginning of the design process (Penn, 2003), while only marginally improving the overall precision in comparison to a model based on configuration alone (Nourian et al., 2018). While choice has been shown to be a valuable predictor of traffic and pedestrian movement, no set of weights has been shown to significantly improve its reliability. Because choice can be used as a proxy for density (Cooper, 2017), then the measure can be used to predict the potential of an area to attract traffic and pedestrian movement based on configuration alone.

3. RESEARCH PROCEDURES

For Marshall (2004, p. 160) hierarchizing streets is more than classifying them in terms of their size or cross section, traffic flow and speed. It also conveys the street's functionality in terms of their relationship within networks at different scales. Some streets connect cities within a country, others connect buildings within a neighborhood. A street hierarchy represents these different functional levels. Several different sets of named classifiers exist. Nonetheless, they refer to similar principles, and a level of correspondence between these different classification systems can easily be found (Beirao et al., 2009). In this study we approach the question of street hierarchization from the perspective of the different scales of through-movement, that can be found in cities. As seen in the previous section, different radii of analysis can be used to represent different modes of transportation, depending on how far a person can be expected to travel with the mode. Thus, street hierarchy can be interpreted as how far people can be expected to reach using a given road. By using the measure of angular segment choice, it is possible to find the shortest routes from everywhere to everywhere within a given radius. By combining analyses using different radii, it is possible to demonstrate which streets in a network have the biggest potential for through movement at different urban scales, e.g. region, city, neighborhood. The hierarchical levels used in the present study correspond to the ones used by Beirao (2009) for defining Transportation Network (TN). This was done for maintaining compatibility with the generation module (Sousa and Celani, 2019). They are: R1- ring road - high speed roads with regional functionality extending beyond neighboring cities, R2- structural street- urban functionally which extends into neighboring cities, S1-distribution street- urban functionality within cities limits, S2-local distribution street- urban functionality extending between neighborhoods, S3- local access street - functionality within neighborhoods. R1-Ring Roads are not used by the generation module, as their functionality is limited within urban centers and, therefore, will not be studied further.

With the above definitions it was determined that four angular choice analysis were needed. The first used a global radius (n) to determine streets which scored high on angular choice in a network extending beyond a city's neighboring cities; 10 km radius to determine streets that scored high on angular choice connecting the town to its neighbors; 5 km radius to determine streets that scored high on angular choice at the town scale; 3.2 km radius to determine streets that scored high on angular choice at the neighborhood scale. Streets which did not score high in angular choice in any of these radii were determined to have only local functionality. The results from each of these analyses were sorted into natural breaks. This statistical clustering algorithm groups angular choice values into a predetermined number of intervals by minimizing the difference between results within each interval while maximizing the difference between the results in different intervals (Jones et al., 2009). Three intervals were used for clustering the results from each analysis to represent the top, medium and lower scores for each radius. The procedure for interpreting the results from the four analyses is shown in Table 1.

Angular choice analysis		Interpretation	Hierarchy	
Global Radius	Score	Functionality extending into neighboring cities		
	Top	High	**R2**	structural street
	Medium	Medium	**S1**	distribution street
	Low	Undefined		
10km Radius	Score	Functionality within cities limits		
	Top	High	**S1**	distribution street
	Medium	Medium	**S1**	distribution street
	Low	Undefined		
5km Radius	Score	Functionality extending between neighborhoods		
	Top	High	**S2**	local distribution street
	Medium	Medium	**S2**	local distribution street
	Low	Undefined		
3.2km Radius	Score	Functionality within neighborhoods		
	Top	High	**S2**	local distribution street
	Medium	Medium	**S3**	local access street
	Low	Low	**S3**	local access street

Table 1
Interpretation of the results from the angular segment choice analyses as hierarchical categories.

Three different models were used for running the analyses at different scales. The first one used a road center line (RCL) representation to model the region where the town is located. To improve the results from this analysis the procedures described by Kolovou et al. (2017, p. 13) were followed: the RCL map was cleaned, its geometry was validated, segmented at level junctions and simplified using the Douglas-Peucker algorithm with a tolerance of

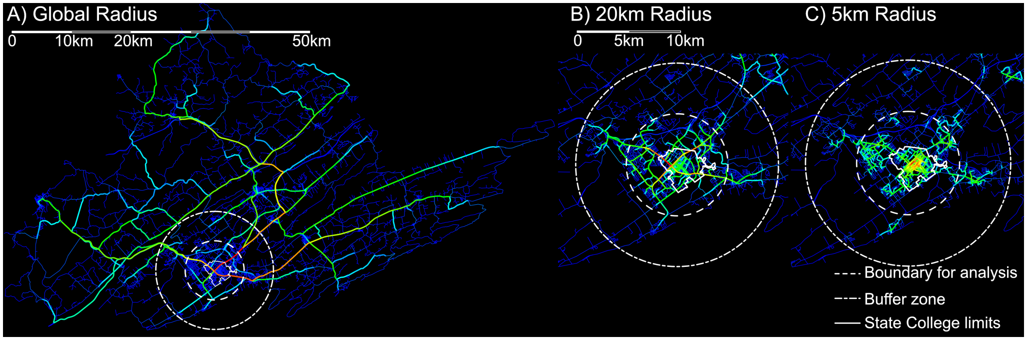

Figure 1
A) Global angular choice for Center County-RCL map; B) Angular choice 20km radius for Center County, detailing Stage College-RCL map; C) Angular choice 5km radius for Center County, detailing Stage College-RCL map.

20. This procedure reduced the number of segments and angular changes between nodes in the graph. This was done to approximate the results of the RCL map to those that could be obtained using an axial map. The RCL representation was used to run angular segment analyses with the following radii: n, 20km, 10km, 5km, 3.2km. These initial results were used to determine the center, the scale and the buffer zone for the second model, an axial map that was used to determine the street hierarchy using the radii discussed above. The third and final model is the axial map with the addition of axial lines representing the important pedestrian paths which are not adjoined to the streets previously modelled, to improve its reliability at smaller radii (Kolovou et al., 2017). This model was used to run a local angular choice analysis, using a 1km radius, to study which streets have the highest potential for attracting pedestrian movement. By using three natural breaks streets were categorized into high priority, medium priority and low priority streets for design retrofitting to improve pedestrian safety and walkability. This procedure resulted in two final maps: one representing the street hierarchy and the other the streets that should be retrofitted to improve pedestrian safety and walkability. The hierarchy obtained for the town being studied was compared to two hierarchical structures obtained from different sources, explained in the following section.

4. APPLICATION STUDY

The research procedure described in the previous section was applied to the town of State College, PA, located in the region of Centre County. GIS shapefiles used in this research were sourced from the town's borough database and from the Centre County open database [1]. Data from OpenStreetMap(OSM) [3] was used for comparison purposes. The analyses were run using QGIS [4], Space Syntax (SS) Toolbox for QGIS [2] and DepthmapX[net] [5]. SSToolbox was used because it integrates network analysis into QGIS, simplifying the workflow. It provides the functionality of using natural breaks to cluster the results of the analysis. Results of the analysis generate shapefiles which can be layered to generate a single hierarchical map.

The regional model using RCL was done for the region of Centre County, covering an area of over 2.880 km2. Angular segment choice analysis for the following radii were run: n, 20km, 10km, 5km, 3.2km. These radii were defined based on the size of the city used for the application study, which has approximately 5 km across. They showed a clear concentration of high angular choice across scales within 5 km of the junction of two main axes: Atherton Street and College Avenue (Figure 1). This junction was used as the center for the axial map, with a 10 km radius in total, of which 5 km correspond to the buffer zone. Every node belonging to the town's street network is over 7km from the edge of the axial map. This

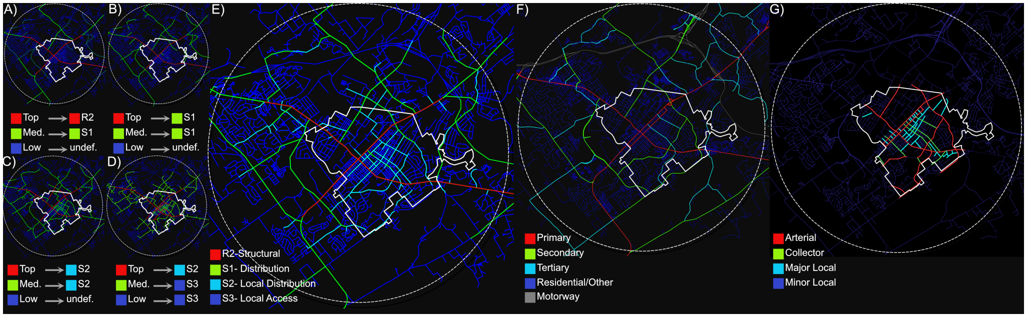

Figure 2
A,B,C,D) Angular choice analyses (Global, R10km, R5km and R3.2km respectively) using axial map, valid nodes; E) Hierarchization following the research procedure; F) Hierarchy obtained from OSM (2019); G) Hierarchy obtained from State College Borough.

map was used for determining the street hierarchy of the town through four analyses using the following radii: n, 10 km, 5 km and 3.2 km. Results were compared to existing hierarchical structures sourced from the State College Borough's database (SCB_Roads_-JLW) and from OSM [3]. The comparison between the three maps demonstrates that it is possible to identify the streets that are of importance in the network, i.e. belonging to the top three hierarchies, within the town's network. The hierarchies obtained from OSM for the State of Pennsylvania and from the town's official database, covering only the town of State College, have several differences between them (Figure 2). While the first only classifies streets of regional importance as Primary (Arterial/Structural), the latter uses the same classification for any street extending into neighboring towns, showing that there is a difference in how hierarchies are used depending on the scale of the network. This high level of variance between the two data sources reveals the importance of guaranteeing that the street hierarchy is objectively obtained, for triggering the shape grammar for retrofitting streets. Using the hierarchy obtained computationally, based on the street's

potentials to attract movement, it is possible to minimize variance in design generation due to different hierarchical structures extracted from GIS data obtained from different sources. The hierarchization that resulted from the research procedure has multiple similarities with the hierarchical structures obtained from both the data sources. This is particularly noticeable on the second and third hierarchical levels, i.e. S1-distribution and S2-local distribution. The hierarchy obtained computationally is better at describing S2 streets then OSM. Furthermore, it reduces the overestimation of R2 streets due to network scale, present in the State College Borough data. The computational hierarchy classifies S1 streets- which are functional at the city scale- similarly to OSM. It can be concluded that OSM is better at identifying R2 and S1 streets, because of its large scale, while State College Borough is better at identifying S2 streets, which function at the neighborhood scale. Thus, the computational results succeeded in merging knowledge present in the two other hierarchies.

The third and final model was prepared by adding axial lines representing the pedestrian paths that run through the Penn State Campus, located in the middle of the town, and has limited vehicle accessible routes. An angular segment choice analysis was run for 1km radius. Results were sorted in three natural breaks. The segments with the highest angular choice, when coinciding with streets, were interpreted as being the ones that should be prioritized for retrofitting interventions (Figure 3). The ones marked as medium priority could be considered for retrofitting in phased projects when they connect high priority segments.

5. DISCUSSION

The study presented in this paper is part of a larger undergoing research on methods and tools to develop a framework for generating and evaluating possible future scenarios for urban street retrofitting in the context of urban densification. The framework is comprised four modules: formulation, design brief, generation and evaluation. The formulation and design brief modules are described in this paper. The design brief is responsible for triggering the rules from the grammar-based generation module, through descriptions of the streets chosen for retrofitting, which are derived from their hierarchical classification and cross-section (Sousa and Celani, 2019). The evaluation module will be developed in the next phase of this research.

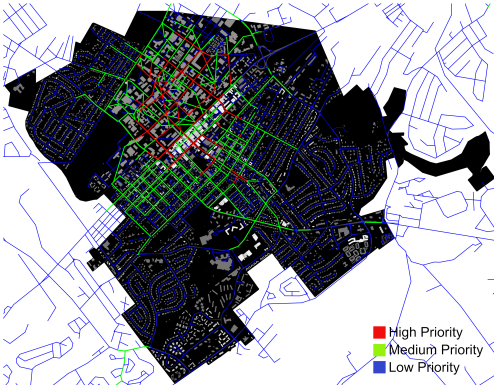

Figure 3
Angular Choice analysis-R1km using axial map with the addition of axial lines for pedestrian pathways through Penn State Campus.

The formulation module uses axial models of a street network as input to run five different radii of angular segment choice analyses. The pedestrian scale analysis is used to inform the choice of priority streets for retrofitting, while the four larger radii are layered following a rule-based procedure to produce a hierarchy for the streets in the network, which can then be used to trigger the generation module. As presented in the previous section, there are inconsistencies between hierarchizations obtained from different sources of urban data, depending on the context for which it is produced. Computationally deriving a street hierarchy to trigger design generation, which uses the same hierarchical structure as the shape grammar rules developed in the generation module, contribute towards the consistency and reproducibility of design results. The computationally derived hierarchy has significant similarities to existing data, demonstrating its potential to be used for the purpose of the proposed framework. Furthermore, because the same measure, i.e. angular segment choice, can be used both to hierarchize streets and to analyze the potential for pedestrian movement by using multiple radii, the procedure presented in this paper is concise and has minimal input needs to trigger design generation, making it more approachable for non-experienced users, who have not had previous contact with space syntax.

The modelling choices, such as the use of the axial representation, scaling boundary and choice to forgo weighing the segments, are based on the available studies to date. If new studies arise with conclusive findings on the advantages of using different techniques for predicting pedestrian and vehicular movement, these can be integrated into the model to improve its capabilities. Further studies are needed to understand if the procedures proposed in this research can be used is larger cities or metropolitan areas and, if so, if the radii for the angular segment choice analyses must be adjusted to the scale of the city or neighborhood.

The proposed modules are a framework for bottom-up urban design, where the initial design brief is to improve walkability to promote densification. The intervention area is the only necessary input and the urban context is responsible for triggering the generation of design scenarios based on network configuration and design knowledge encoded in the form of a deterministic parametric shape grammar. This framework allows interventions to be incrementally added to the model supporting the development of less ambitious designs which can, nonetheless, have significant impact on improving urban mobility. This research is a contribution towards bridging the gap between knowledge from the fields of transportation engineering and the practice of urban design, and it constitutes an alternative to approaches based on optimizing vehicular flow, which can lead to an increase in the road area, and thus to less sustainable urban environments.

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