K02

Directions in Space Syntax. Space Syntax modelling of pedestrian flows for sustainable urban development

Keynote

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ABSTRACT

Modelling pedestrian flows has been one of the main directions of Space Syntax since its introduction, but what we see in the last years is that it has also become a central interdisciplinary objective within the Sustainable Development research agenda. The agenda calls for promotion of sustainable mobility (i.e. walking, cycling, public transport) and a clear shift from car-oriented development. There is an acknowledged need in the broader fields of urban development to model pedestrian flows: to explain and assess the functioning of existing built environments, to predict future situations and assist scenario analysis when planning new areas and infrastructural changes and support decision-making. The keynote argues that Space Syntax can claim expertise for this emerging interdisciplinary field of study, having built a relevant and comprehensive theoretical and methodological framework and having provided sufficient and solid empirical evidence that it is an appropriate methodology to model pedestrian flows. What is more, it is perfectly aligned with the main tenets of Sustainable Development. The keynote continues to lay out the opportunities created for Space Syntax research by the Sustainable Development research agenda, but also the needs for further development. Using recent and current projects from the Spatial Morphology Group (SMoG) at Chalmers University of Technology, three research priorities are identified and exemplified further.

KEYWORDS

Pedestrian flows, Sustainable urban development, Space Syntax modelling, Space Syntax representations, Design-support tools

1 PEDESTRIAN MOVEMENT. AN INTERDISCIPLINARY OBJECT OF STUDY IN THE SUSTAINABLE DEVELOPMENT RESEARCH AGENDA

Modelling pedestrian flows has been one of the main directions of Space Syntax, represented by a large share of theoretical, methodological, and empirical studies (Krenz et al. 2019). While pedestrian movement was always a deep concern of architecture, urban design and planning, it has more recently become an interdisciplinary objective within the Sustainable Development research agenda (UN Agenda 2030), especially related to Goal 11. 'Sustainable cities and communities' and Targets 11.2. 'Affordable and sustainable transport systems', 11.6. 'Reduce the environmental impact of cities', and 11.3 'Inclusive and sustainable urbanization'. The agenda clearly calls for promotion of sustainable mobility and transport (i.e. public transport, walking, cycling, micromobility) and a clear shift from car-oriented development.

Pedestrian movement is acknowledged as an important means of sustainable mobility and active travel and its benefits have been documented for environment and climate (e.g. Litman 2020), health and well-being (e.g. Roe et al. 2020, Bird et al. 2018); safety (e.g. Jacobsen 2003, Chu 2006); social inclusion and cohesion (e.g. Legeby et al. 2015, Legeby 2013). Pedestrian flows are recognized as an important driver of local economies (e.g. Hillier et al. 1993, Hillier 1996a, Litman 2020), while neighbourhood walkability is related to higher property values (e.g. Cortright 2009, Pivo and Fischer 2011), and perceived liveability (e.g. Stavroulaki and Berghauser Pont 2020a). Pedestrian movement is brought to the front of sustainable urban development and is becoming an interdisciplinary object of study extending far beyond urban design and planning, to transport planning, social and environmental sciences, cultural studies, and crowd and crisis management, to name a few. Due to its many implications, it has also become a central issue in policy making.

Within this framework, there is an acknowledged need in the broader fields of urban development in all scales (comprehensive, strategic, detailed - municipal, regional, national) to model pedestrian flows to: a. explain and assess the functioning of existing built environments, b. predict future situations and assist scenario analysis when planning new areas and infrastructural changes, and c. support decision-making. This need has highlighted a gap. Appropriate methods to model pedestrian flows (i.e. analyse, predict, simulate) are lacking in broader urban research and planning practices.

For example, transport and traffic modelling are still car-oriented. Pedestrians are largely excluded from the models (e.g. traffic flow models, route-choice models) and are mainly introduced as 'vulnerable users' in simulations of vehicle-pedestrian interactions aiming to improve safety (e.g. Rinke et al. 2016, Pascucci et al. 2015, Obeid et al. 2017). As traffic flow and route-choice models were never intended for pedestrian modelling, they are built on principles and assumptions that do not apply to pedestrian movement. They assume a highly regulated travel behaviour, movement within lanes and road limits, and route choices based primarily on Origin-Destination shortest paths, measured by travel distances or travel times. The road network representations follow a node-link principle, where the node is the intersection and the link is the road segment (Porta et al. 2006, Marshall et al. 2018). The intersections claim significance being the points of route choice, while the street is just the means to travel from A to B.

However, pedestrian movement is an informal, free-flow movement. Pedestrians jay-walk, take shortcuts, go in and out of buildings, use the whole street space, are guided and attracted by the built environment. Their behaviour is not regulated by traffic rules but is the result of spontaneous interaction, negotiating priority according to social rules, such as eye-contact or courtesy (Rinke et al. 2016). They rely heavily on perceptual overview to navigate and keep safe. They choose routes based on perceptual ease and minimising cognitive and perceived distance (e.g. Bongiorno et al. 2021, Shatu et al. 2019, Conroy-Dalton 2003, Montello and Sas 2006), along with travel time (e.g. Svetsuk and Basu 2022).

Space Syntax descriptions and analyses are primarily pedestrian-oriented and in accordance with the informal, unregulated, and free-flow nature of pedestrian movement. The representations used are based on a 'cognitive geometry' (Marcus 2018), taking the perspective of the moving perceiving subject. The route choices are assumed to be based on the shortest 'perceived distance' (e.g. angular deviations, number of turns), navigational ease and intelligibility, rather than the metric distance (Stavroulaki et al. 2017). The network representations are street-based, emphasizing the street as a place of importance rather than a transport link that connects locations. Hence, opposite from the transport network representations, in the node-link graph, the node is the street (Stavroulaki et al. 2017, Porta et al. 2004). Finally, Space Syntax models are traffic-flow and not route-choice models; they explain and predict aggregated pedestrian flows and not simulate individual traces. It is the social patterns, rather than the individual behaviours that are in focus.

Hence, while Space Syntax does not aim to describe pedestrian movement per se, but rather architectural and urban space and the potentials for movement created by their spatial configurations (e.g. street networks, building layouts), *or precisely because it is so*, it has nevertheless created a powerful model to explain and predict pedestrian flows. For the last decades it has built a comprehensive theoretical (Hillier et al. 1993, Hillier 1996b, Hillier and Hanson 1984) and methodological framework (e.g. Turner 2007, Hillier and Iida 2005, Peponis et al. 2008, Hillier et al. 2012) and has provided solid empirical evidence that it is an appropriate methodology to model, explain and predict pedestrian flows (e.g. Stavroulaki et al. 2019, Hillier and Iida 2005, Osbil et al. 2011, 2015, Netto et al. 2012, Peponis et al. 1997, 2008, Hillier et al.1993, Penn et al. 1998).

The pedestrian focus of Space Syntax modelling, though, is not the only reason why it is fundamentally in line with the Sustainable urban development rational. What distinguishes Space Syntax models is that they are based only on street network measures. So, they can be used for early assessments of new area plans or infrastructural changes, in the very beginning of a design and planning process when local and global structures, such as the street networks, are being designed and when the structural decisions are being made. It is largely acknowledged that the ability to impact cost and performance of a development plan is higher in the early phases of the project and greatly decreases as the planning and design proceeds. Showing the opposite trend, the costs of design changes are lowest in the early phases of the process and then largely increase (Figure 1).

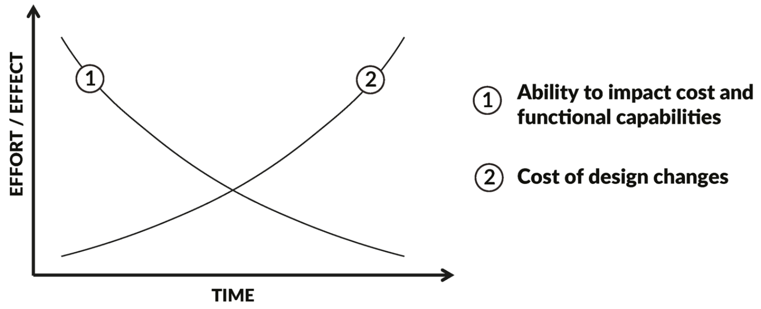

Figure 1: The MacLeamy curve (CURT 2004)

While there are many studies outside the field of Space Syntax that have proposed different statistical models to assess the impact of built environment on walking, and give guidelines for walkable environments, they are very complex and rely on many variables, some of which are too detailed to include in the early stages of a design (e.g. sidewalk width, street lighting, exact land-use mix), or include socioeconomic variables that are not predefined in development plans (e.g. income, age, gender) (e.g. Sealens et al. 2003, Moudon et al. 2019, 2007).

Both these unique qualities - the pedestrian-oriented nature and the ability to be used in the early stages of a design and planning process - make Space Syntax modelling a most useful and appropriate methodology to support sustainable urban development. As argued in the beginning, there is a fast-growing interdisciplinary field of study within the Sustainable Development research agenda relying on pedestrian flow models, for which Space Syntax can and should claim expertise.

2 FUTURE RESEARCH PRIORITIES FOR SPACE SYNTAX

There is a demand for Space Syntax expertise on modelling pedestrian flows within the Sustainable Development agenda, creating new research opportunities, but also needs for further development in certain areas. Using recent and current projects from the Spatial Morphology Group[1] (SMoG) at Chalmers University of Technology, three relevant research priorities are identified and will be further exemplified in the following sections:

1. Increase the general predictive power of statistical models and aim for empirical findings that generalise across different environments.
2. Invest in explorative work on the descriptive models, the representations, the measures.
3. Create design-support tools targeting urban designers and planners to include space syntax analysis in everyday design and planning.

[1] Besides the author the SMoG includes Lars Marcus, Meta Berghauser Pont, Jorge Gil, doctoral and post-doctoral researchers.

2.1 Priority 1: Increase the general predictive power of statistical models

There have been many studies that prove the high significance of different space syntax centrality measures in explaining pedestrian flows (e.g. Hillier and Iida 2005, Peponis et al., 1997, 2008; Penn et al. 1998; Read 1999; Ozbil et al. 2011, 2015; Netto et al. 2012) but are often case-specific, testing one area, one type of areas, one city. In addition, previous studies show that the explanations are better for regular than highly irregular street patterns and that they vary depending on the built density of the area (e.g. Berghauser Pont and Marcus 2015, Ståhle et al. 2005). Read (1999) also highlighted variations between local and super-grids.

However, to argue for the validity of Space Syntax measures as good predictors of pedestrian flows and advocate for the inclusion of Space Syntax modelling in the toolkit of urban development and scenario-analysis, there needs to be a more robust answer; a model that does not depend on specific cases and generalises across different urban environments. From this perspective, the significance no longer lies on getting the highest correlations for each specific case; it lies on testing and improving the general explanatory power of the models. After numerous empirical studies, it is time to shift focus from explanatory to predictive modelling.

3.1.1. Explanatory models and empirical findings that generalize across urban environments.

With these objectives in mind, we conducted three large empirical studies from 2017 to 2020 (Stavroulaki et al. 2019, Berghauser Pont et al. 2019a, Bolin et al. 2020), using the same empirical dataset including Stockholm, Amsterdam and London. We systematically selected[2] 53 neighbourhoods of different density type (from high-dense urban grids to low-dense suburban areas) with varied street types (from high streets to side streets and small alleys) in areas of diverse land use mix and socioeconomic profile (from business districts and mixed-use neighbourhoods to villa areas) (Figures 2, 3). We collected original data, measuring pedestrian counts during one day from 7 pm to 10 am, on 669 street segments distributed in the 53 neighbourhoods. The method used was capturing anonymised wifi-signals from mobile phones and the survey was conducted on weekdays in October-November 2017 (see Stavroulaki et al. 2018, 2019).

[2] For the method of selection, see Berghauser Pont et al.2019a. For the detailed methodology of the generation of density and street types, see Berghauser Pont et al. 2019b.

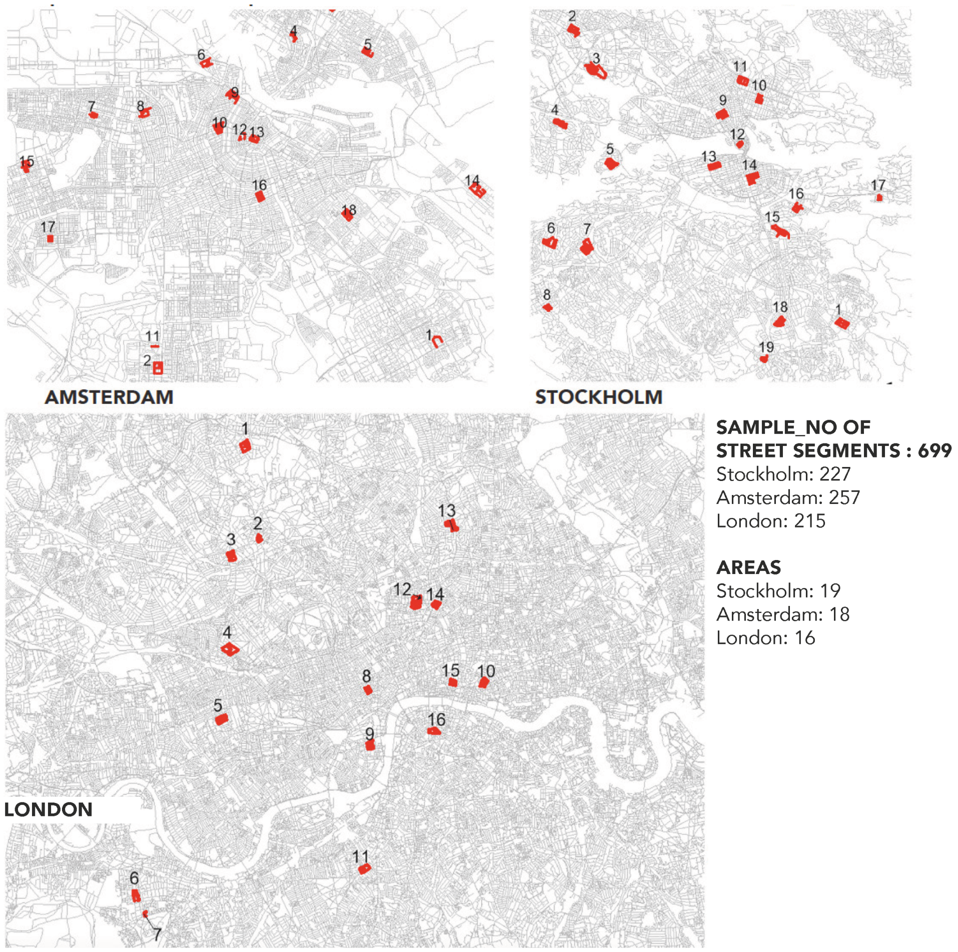

Figure 2: Neighbourhoods included in the empirical studies (Stavroulaki et al. 2019, Berghauser Pont et al. 2019a, Bolin et al. 2020)

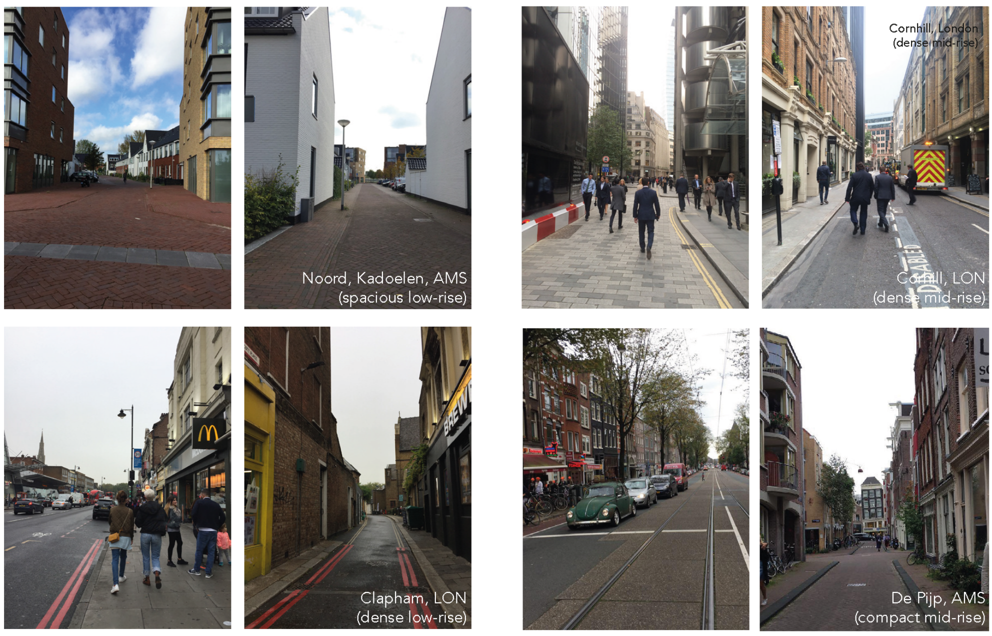

Figure 3: Examples of selected neighborhoods in London, Amsterdam, Stockholm

The explanatory variables included were angular betweenness and angular integration in 10 radii (from 500 to 5000m), accessible built density[3], accessibility to different attractions (e.g. local markets, public transport stops, schools[4]) and land division. We also tested multiscalar street types, based on each street's angular betweenness profile in 10 radii (from 500 to 5000m). The dependent variables were the full-day pedestrian counts and the daily fluctuations (based on the hourly counts from 7pm to 10 am)[5].

Summarising the findings, the studies confirmed that space syntax angular centrality measures could explain the distribution of pedestrians within each neighbourhood (i.e full-day pedestrian counts) in a high degree. Stavroulaki et al. (2019) showed that 65% of the variation was explained by continuous centrality measures, while Berghauser Pont et al. (2019a) showed that 55% of the variation was explained by the multiscalar centrality street types. However, the centrality measures and street types could not explain the volume of pedestrians within each neighbourhood (i.e. how many pedestrians there were in absolute numbers) or, the variation between neighbourhoods (i.e. which neighbourhoods had more pedestrians).

The latter could be much better explained by the built density of the area (Bolin et al. 2020, Berghauser et al. 2019a) [6]. That means that the high-density neighbourhoods consistently had more pedestrians than the low-density ones, although within each neighbourhood the streets with the highest centrality consistently had the most pedestrians. In other words, a side street in a high-dense area consistently had more pedestrians than the main street in a low-dense villa area.

Berghauser Pont et al. (2019a) showed that in combination, built density and street centrality types explained 45 to 55% of the pedestrian volume. Given the diversity of the sample, these are high numbers. The high explanatory power of the interaction between street centrality and built density was confirmed by Bolin et al. (2020). The authors also showed that in explaining the hourly fluctuation of pedestrian counts only the built density profile of the area was significant.

3.1.2. From explanatory to predictive modelling. Macroscale simulations of pedestrian flows.

Statistical modelling can have different objectives. First, explanatory models help us understand the absolute or relative impact of spatial variables, for instance centrality, on pedestrian flows. Second, predictive models help us estimate the expected pedestrian flows in areas with no empirical data, or in future urban plans and unbuilt situations. In the three published empirical studies summarized previously, we focused on the first type, aiming to produce empirical results that generalize across

[3] Accessible Floor Space Index and Ground Space Index in 500m walking distance
[4] In 500m walking distance and on the street segment
[5] For the details of the empirical studies concerning the calculation of the explanatory and dependent variables (e.g. GIS datasets, measures), and the statistical models used, please refer to the original papers.
[6] For the detailed tables of results please refer to the original papers.

very different urban environments. For this reason, the models were tested in a very diverse empirical dataset. As a next step, the running research project ‘Crowd movement’[7] shifts focus entirely on macroscale simulations and predictive modelling, putting the statistical models to an even harder test. The working questions is: Can a model ‘trained’ in one city be used to predict pedestrian flows in another? We exemplify the question using the empirical data from Stockholm to train the statistical model, and then try to predict pedestrian flows in central Gothenburg.

To validate the model, empirical data collected in Gothenburg centre are used (Trafikkontoret 2019), making sure that the training and validating data were collected and processed using the same methods and principles[8]. The training data from Stockholm include 19 neighbourhoods with 227 street segments, while the validation data from Gothenburg include 76 street segments in the city centre (Figure 4).

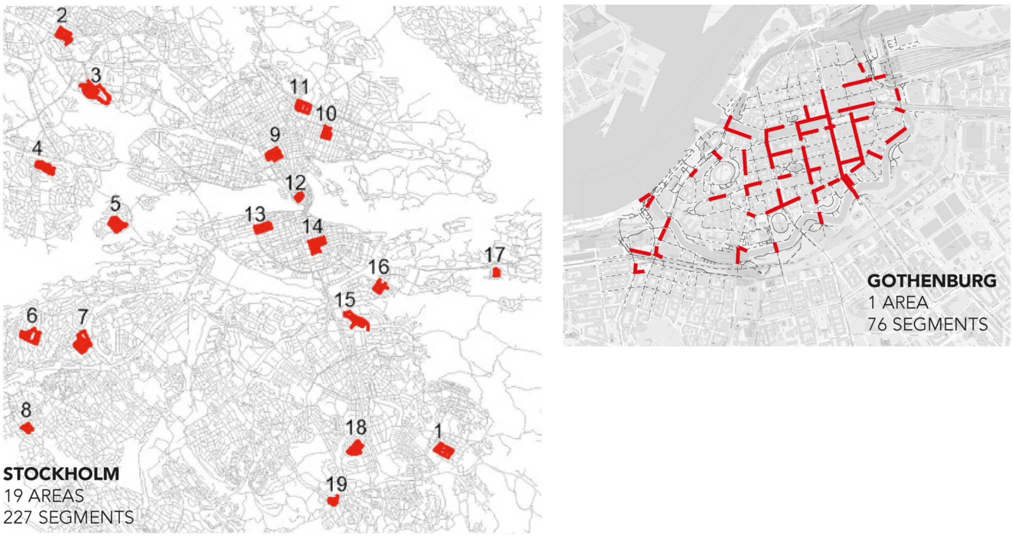

Figure 4: Neighborhoods included in the training (Stockholm) and validation (Gothenburg) empirical data

The predictive model is still in the explorative phase, both regarding the variables included and the choice of statistical modelling method (e.g. elastic net regularization, lasso variable selection, variable interactions). Added to the Space Syntax centrality measures (angular betweenness and integration in 10 radii from 500m to 5000m), the general spatial (built density, land division) and accessibility variables (accessibility to public transport, local markets, schools) are two new variables of attraction betweenness centrality for local markets and built density[9], several street characteristics (i.e. sidewalk width, street segment width and length, number of lanes, street greenery, speed limits) and socioeconomic variables (e.g. working and residential population density). Also, in addition to the density types and multiscalar street centrality types developed by the SMoG (Berghauser Pont et al.

[7] Project of the Digital Twin City Gothenburg (https://www.chalmers.se/en/projects/Pages/Crowd-MovementQ-Predicting-pedestrian-movement-in-public-spaceQ.aspx). The author leads the ‘Macrosimulation of pedestrian flows’ work package. Data analysts are V.Verendel, O.Ivarsson. The project is led by M.Berghauser Pont.
[8] The same company and method was used (Bumbee labs, Stockholm). The empirical data from Gothenburg were collected in November 2018 by Gothenburg municipality.
[9] Angular betweenness centrality weighted with attractions. Attraction betweenness is calculated with PST (Place Syntax Tool, https://www.smog.chalmers.se/pst)

2019a), transport road classifications used by the Swedish Transport Administration are included in the model (i.e. functional class, road type[10]).

Although the statistical model is still under construction some interesting observations can already be made. The best predictions so far are:

1. When only the central neighbourhoods of Stockholm are included in the training data (neighbourhoods 9 to 14). Given that we try to predict central Gothenburg, this means that the predictive power of the model improves when we control for the density or, better yet, the area type. This observation is in line with our previous findings that the built density of an area is the key factor in defining the general volumes of pedestrian flows.

2. When some validation empirical data from Gothenburg are included in the training data of Stockholm; for example, when we include data collected from 10 random streets[11] in central Gothenburg in the training data. This means that some area-specific empirics are needed to fine-tune the general predictive model.

   This preliminary finding is worth exploring further. It suggests building a robust general predictive model, that can be customized and fine-tuned on a case-by-case scenario, by adding a limited set of collected empirical data from the area of interest or its context. It could prove to be a feasible methodology when trying to predict pedestrian flows in future situations when planning new areas and infrastructural changes, or in existing areas with no empirical data. Given the high costs and challenges of collecting original data on pedestrian movement (e.g. GDPR, national regulations for monitoring public) this could offer a more pragmatic solution.

3. When pairwise interactions between variables are included in the model. A variable might not be significant but, in combination with another, can make a significant pair. For example, speed limit is not a significant variable, but its interaction with the street centrality type is[12]. Confirming previous studies (Berghauser Pont at al. 2019a) the interaction of street centrality and accessible built density is more significant than the two variables separately.

Another interesting preliminary finding is that the statistical model consistently underpredicts streets with extremely high pedestrian volumes, for example high shopping streets or transport hubs. These streets, where the ’multiplier effect’ has taken place so to speak (Hillier 1996a), appear as the statistical outliers in the general predictions.

[10] ‘Funktionell väg- klass’ and ‘VagTyp’ included in the National Swedish Road database (NVDB).
[11] Pedestrian counts from 10 random streets out of the 76 streets included in the validation data. Experiments are also made with 5, 20, 30 and 40 random streets, using 40 random sets of streets in each iteration. So far, 10 streets are enough to reduce the Mean Average Prediction error from 25% to 50%.
[12] Higher order interactions are also tested, but so far pairwise interactions perform better.

Besides the practical predictive objective of this project as part of the DTCC Gothenburg, it is a fruitful experiment with broader methodological implications. As argued in the introduction, developing robust predictive models for pedestrian flows is central in claiming expertise for this field of study and in advocating for including Space Syntax modelling in the sustainable urban development toolkit, for scenario-analysis, crowd movement simulations and impact assessments of new area plans and infrastructure changes.

2.2 Priority 2: Invest in explorative work on the descriptive models.

The second priority direction outlined in the Introduction is tightly related to the first. In Space Syntax research, the statistical models are built around selected centrality measures, that are based on a specific descriptive-analytic model; they have been calculated based on specific formulas and analytical settings and a particular geometric representation of the street network. This series of underlying choices is not trivial. It can affect the calculation of the centrality measures and potentially impact their performance in predicting pedestrian flows when included in the statistical models.

A case in point is the choice of the street network representation that is used in Space Syntax analysis. Although other fields and disciplines use street-based representations (Marshall et al. 2018, Gil et al. 2018) Space Syntax representations are distinct for being geometrically defined, where the representation of streets is based on their geometry and not on other attributes, such as capacity or functional types. Many alternatives of street network representations have been put forth in Space Syntax methodology (Stavroulaki et al. 2017, Figueredo 2015). Recurrent and implicitly embedded in all of them, although differently addressed, is the representational principle of ‘angularity’. Especially after the introduction of segment maps in Space Syntax analysis, the angularity of the streets became a key issue of representation, one that has both a practical and a principal side.

The principal side is that in Space Syntax the significant change of direction represents a significant perceptual change for the moving subject and is the basis of the perceived distance calculated in the analysis, either this is the step depth, the angular distance or the directional distance (Hillier and Hanson 1984, Hillier and Iida 2005, Peponis et al. 2008, Figueredo and Amorim 2005). There is always an underlying assumption of which angular changes and deviations count as significant changes of direction, and which not and are disregarded as trivial, either in the drawing and editing of the map or in the analysis (Stavroulaki et al. 2017). Different angular thresholds have been used with different representational models[13]. There are even proposals (Peponis et al. 2008, Stavroulaki et al. 2017) and tools[14] for a parametric definition of the angular threshold to allow researchers to modify

[13] For example, Peponis et al. (2008) use a 5° threshold to demonstrate their concept of ‘directional distance’, and a 10° for their pilot empirical study. Ozbil et al. (2011) follow Peponis et al., while Ozbil et al. (2015, 2016) increased the threshold to 20°. Figueredo and Amorim (2005) when introducing the ‘Continuity maps’ as an alternative representation to the Axial maps, argued that the moving subjects perceive curvilinear streets as one perceptual entity when their sinuosity does not exceed the 35° threshold.
[14] For example, the ‘Segment grouping’ and ‘Segment group integration’ functions included in the Place Syntax Tool (PST). For documentation see Stavroulaki et al. (2017, 2022)

their choice following the latest theoretical insights on human cognition or adapting to the underlying geometry of a particular network. Angular Segment Analysis (ASA) includes all angular deviations but weights them accordingly, so that small deviations count for less. Axial maps also disregarded low angular deviations already in the drawing of the axial lines, although not using a precise angular threshold.

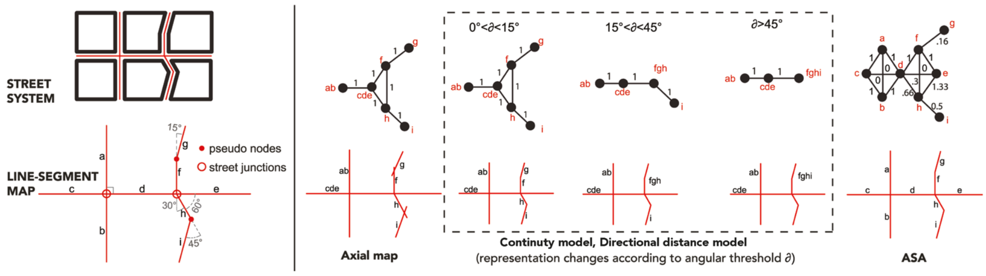

Figure 5: Alternative space syntax representations of the same street network (dual graphs).

The practical side of the angularity issue is that in Road-Centre-Line maps, extensively used in Space Syntax, the street segments are usually too detailed and too disaggregated in small line segments with low or zero angular deviations. As part of the editing process researchers tend to simplify the map, where very low angular deviations are disregarded and colinear contiguous segments are merged, before analysing the network. So even when the choice is ASA, not all angular deviations are counted as some are lost in the simplification process[15].

The question arising is how significant is the threshold that defines the angular deviations included in the representation and analysis? How much does this choice impact the analysis results and the performance of the calculated centrality measures in explaining and predicting pedestrian flows?

To investigate that, we did an explorative comparative study[16] of alternative street network representations using the 'Segment group integration' function in PST[17]. The same line-segment map of Stockholm[18] was processed using 18 different angular thresholds from 5° to 85°, where contiguous segments with angular deviations below each threshold were merged on-the-fly. The 18 on-the-fly networks were calculated for closeness centrality in different radii. We compared the results both for the whole Stockholm, and for selected areas, characterized by regular (Area1) and irregular street patterns (Area 2), to get a more complete account (Figure 6).

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[15] For a thorough study on the impact of angular thresholds in the simplification processes, see Kolovou et al. 2017.
[16] Stavroulaki G., Berghauser Pont M., Marcus L., 'Comparative study of alternative approaches to street network analysis; from representation to performance', unpublished
[17] See Footnote 14
[18] Stockholm non-motorised network (Stavroulaki et al. 2020)

Figure 6: Selected areas (light grey: Area 1, dark grey: Area 2)

The main findings are these:

Concerning the representations, the choice of the exact threshold used to define the insignificant angular deviations was very important up to the 30°-35°. Above that, the choice became trivial both for the graph (the node count) (Figure 7) and for the centrality calculations (Figure 8). The analysis results produced by the representations using thresholds higher than 40° correlate more than 90-95%. The findings were confirmed for the whole Stockholm, and for the selected areas (1 and 2) with slight variations.

30 degrees

	THRESHOLDS	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
AREA 1: City centre, Rectilinear street pattern	Segment no	171	113	92	77	70	59	58	56	55	53	53	52	52	51	50	49	49	49	47
	% of affected segments	*0*	*46%*	*63%*	*75%*	*80%*	*89%*	*90%*	*91%*	*92%*	*94%*	*94%*	*94%*	*94%*	*95%*	*96%*	*97%*	*97%*	*97%*	*98%*
AREA 1: Suburban, Curvilinear street pattern	Segment no	344	216	151	118	92	79	62	57	51	51	50	48	48	48	48	47	46	44	44
	% of affected segments	*0*	*43%*	*64%*	*75%*	*83%*	*88%*	*94%*	*95%*	*97%*	*97%*	*97%*	*98%*	*98%*	*98%*	*98%*	*98%*	*99%*	*99%*	*99%*
STOCKHOLM	Segment no	358415	253100	171096	119446	88405	68862	56926	49229	44212	40218	37563	36002	34944	34202	33605	33031	32472	31754	30433
	% of affected segments	*0*	*32%*	*57%*	*73%*	*82%*	*88%*	*91%*	*94%*	*95%*	*96%*	*97%*	*98%*	*98%*	*98%*	*99%*	*99%*	*99%*	*99%*	*99%*

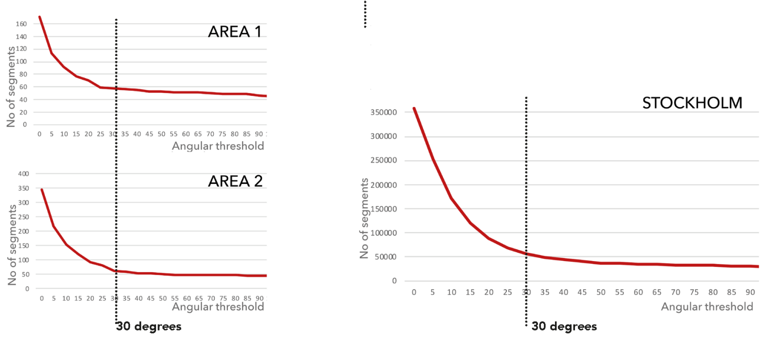

Figure 7: Reduction of node count for every angular threshold used to merge contiguous line segments

RECTILINEAR STREET PATTERNS

CT_5	0,947	0,945	0,824	0,752	0,393	0,382	0,310	0,199	0,289	0,290	0,265	0,276	0,296	0,278	0,301	0,423	0,417
0,882	CT_10	0,896	0,696	0,594	ins.	ins.	ins.	ins.	ins.	ins.	ins.	ins.	ins.	ins.	ins.	0,299	0,286
0,538	0,814	CT_15	0,912	0,853	0,553	0,543	0,505	0,402	0,484	0,484	0,468	0,477	0,493	0,478	0,493	0,596	0,595
0,565	0,743	0,794	CT_20	0,955	0,782	0,767	0,740	0,668	0,719	0,698	0,684	0,680	0,701	0,689	0,695	0,776	0,775
0,729	0,800	0,738	0,903	CT_25	0,837	0,820	0,815	0,762	0,784	0,777	0,768	0,767	0,782	0,772	0,781	0,838	0,842
0,503	0,671	0,775	0,637	0,666	CT_30	0,986	0,923	0,907	0,886	0,843	0,852	0,827	0,837	0,838	0,834	0,842	0,866
0,573	0,711	0,752	0,604	0,662	0,974	CT_35	0,896	0,878	0,849	0,804	0,813	0,786	0,798	0,799	0,793	0,796	0,820
0,566	0,701	0,719	0,596	0,638	0,951	0,951	CT_40	0,988	0,977	0,967	0,971	0,962	0,965	0,967	0,961	0,953	0,958
0,573	0,696	0,694	0,571	0,620	0,934	0,936	0,998	CT_45	0,967	0,956	0,965	0,954	0,955	0,959	0,950	0,924	0,931
0,582	0,674	0,622	0,492	0,564	0,897	0,904	0,976	0,984	CT_50	0,990	0,991	0,979	0,982	0,983	0,976	0,970	0,976
0,584	0,686	0,630	0,487	0,538	0,874	0,882	0,957	0,967	0,987	CT_55	0,998	0,997	0,998	0,998	0,995	0,985	0,982
0,644	0,739	0,632	0,487	0,548	0,845	0,886	0,926	0,935	0,952	0,970	CT_60	0,996	0,996	0,997	0,994	0,978	0,979
0,653	0,743	0,629	0,481	0,548	0,841	0,886	0,921	0,929	0,947	0,965	1,000	CT_65	0,999	1,000	0,996	0,982	0,976
0,655	0,748	0,634	0,481	0,546	0,840	0,885	0,920	0,928	0,946	0,966	0,999	1,000	CT_70	1,000	0,995	0,985	0,978
0,662	0,748	0,626	0,479	0,547	0,834	0,879	0,918	0,927	0,947	0,967	0,999	0,999	0,999	CT_75	0,995	0,982	0,976
0,671	0,743	0,630	0,480	0,575	0,836	0,902	0,874	0,874	0,886	0,900	0,966	0,971	0,970	0,968	CT_80	0,987	0,984
0,661	0,744	0,631	0,474	0,560	0,824	0,892	0,852	0,850	0,855	0,872	0,949	0,955	0,954	0,952	0,989	CT_85	0,995
0,667	0,742	0,622	0,475	0,562	0,821	0,888	0,854	0,852	0,860	0,878	0,953	0,958	0,958	0,956	0,990	0,999	CT_90

CURVILINEAR STREET PATTERNS:

Figure 8: Pearson correlations (r) of centrality values calculated using the 18 representations

To investigate further, the closeness centrality results produced by the 18 different geometric representations were correlated to full-day pedestrian counts from four selected neighbourhoods (Östermalm, Norrmalm from Area 1, Mälarhöjden, Västertorp from Area 2), using the empirical dataset of Stockholm, described in section 3.1.1. (Figure 6). The main finding is that centrality values from representations using lower angular thresholds –10° to 20°– correlated more to pedestrian flows than higher ones, both for the regular and the irregular street patterns areas (Figure 9). The important finding is not the actual numbers, but that these lower thresholds reconstituted the long linear or quasi-linear streets continuing through street junctions, that were broken in the creation of the line-segment map. This improved the explanatory power of the calculated centrality measures. When higher thresholds were used, reconstituting even greater continuities of highly curvilinear streets, the explanatory power dropped significantly.

a)

RECTILINEAR STREET PATTERNS Östermalm, Norrmalm

	CT_5	CT_10	CT_15	CT_20	CT_25	CT_30	CT35	CT_40	CT_45	CT_50	CT_55	CT_60	CT_65	CT_70	CT_75	CT_80	CT_85	CT_90
Correlation to Pedestrian counts (R)	,645	,532	,735	**,802**	,713	,654	,667	,561	,495	,534	,478	,474	,453	,469	,464	,467	,526	,551

CURVILINEAR STREET PATTERNS Mälarhöjden, Västertorp

	CT_5	CT_10	CT_15	CT_20	CT_25	CT_30	CT35	CT_40	CT_45	CT_50	CT_55	CT_60	CT_65	CT_70	CT_75	CT_80	CT_85	CT_90
Correlation to Pedestrian counts (R)	,548	**,575**	,357	,534	,496	,242	,277	,248	,241	,224	,261	,363	,367	,368	,372	,402	,425	,431

Figure 9: Pearson correlations (r) of centrality values to pedestrian full-day counts

The preliminary findings of this limited empirical study suggest that the representation should respect the long continuities of the linear or quasi-linear streets. This idea was embedded in the Axial map drawing, is respected in the ASA, and is confirmed again by this focused investigation on the impact of angularity on the representation and analysis. What is also highlighted by this study is the potential created by the line-segment map, being the least aggregated and most flexible representation of the street network, facilitating similar explorations and new methodological developments within the theoretical tenets of Space Syntax.

2.3 Priority 3: Create design-support tools

As argued in the introduction, Sustainable urban development calls for informed decisions and early assessments in the design and planning process in all scales (municipal to regional, strategic to detailed). The potentials for pedestrian flows created by a new plan or an infrastructural change should be correctly and timely identified. No matter how much the descriptive, explanatory, and predictive models are improved, they cannot effectively support the design of sustainable environments unless Space Syntax analysis is used in the early stages of the design process, when the structural decisions are made, and the main street structures are designed. To facilitate this, we need to provide urban designers and planners with design-support tools that could potentially integrate space syntax analysis in the creative design process.

With this objective in mind, we developed Urban Design Calculator (UDC, https://urbancalculator.se) [19] a user-friendly standalone software based on the Place Syntax Tool (PST)[20]. Focus groups and surveys with urban designers and planners from municipal and regional planning administrations as well as private offices in Gothenburg, Sweden, were organized during 2018 to identify needs, potentials, and challenges in integrating spatial analysis in the design and planning process (Berghauser Pont et al. 2020). A pilot for Gothenburg was tested by practitioners and architectural students and the software was officially launched in 2022.

In a nutshell, with UDC designers and planners can easily test the structural changes of their plans in a preloaded street network of the whole city; they can modify the existing streets, design - or redesign - a given area, and very quickly see the effects of their changes in the centrality and accessibility of the area, the urban context, and the city. Based on the results they can describe the potentials for pedestrian flows created by their designs and make informed estimations about the expected distribution of pedestrian flows in the future.

Developing the software, the central objective was to target the reasons why urban designers and planners do not use analytic software in the creative design process, as identified in the focus groups:

- *User friendliness, easy-to-learn*
  No prior knowledge of GIS is required, and one can learn UDC within 30min.
- *Saving time*

[19] The UDC is developed by M.Berghauser Pont, G.Stavroulaki, E.Bobkova and L.Marcus. It is based on a research project called Urban Calculator (https://www.researchgate.net/project/UDC-UrbanDesignCalculator), Chalmers University of Technology.
[20] PST is an open-source QGIS plugin for spatial analyses developed by Chalmers University of Technology, KTH School of Architecture and Spacescape AB (https://www.smog.chalmers.se/pst)

No time is lost with finding and preparing data, since customized datasets are integrated in the tool (e.g. non-motorised and motorized street networks, buildings, green and blue areas).

- *Analysis is part of the design loop*
  Early-stage sketches can be done within the tool, where users can immediately analyse design alternatives (e.g different street structures) and where analysis can guide their design iterations from the start.
- *Confidence in the analysis results*
  Given that urban designers and planners are not necessarily familiar with spatial analyses, and Space Syntax in particular, there is low confidence in the analysis results. To tackle this and control the accuracy of results, we include only a limited set of informative centrality analyses, (e.g. angular betweenness in 2km) with predefined analytical settings (i.e. radii, normalization, weighting).
- *Guided interpretations of results*
  The users get easy-to-read, before-and-after visualizations of the analysis results, with simple explanations of the visualized measure and what it means in practice. This way, the interpretations are guided to facilitate understanding and avoid misinterpretations and miscommunications by novice users.

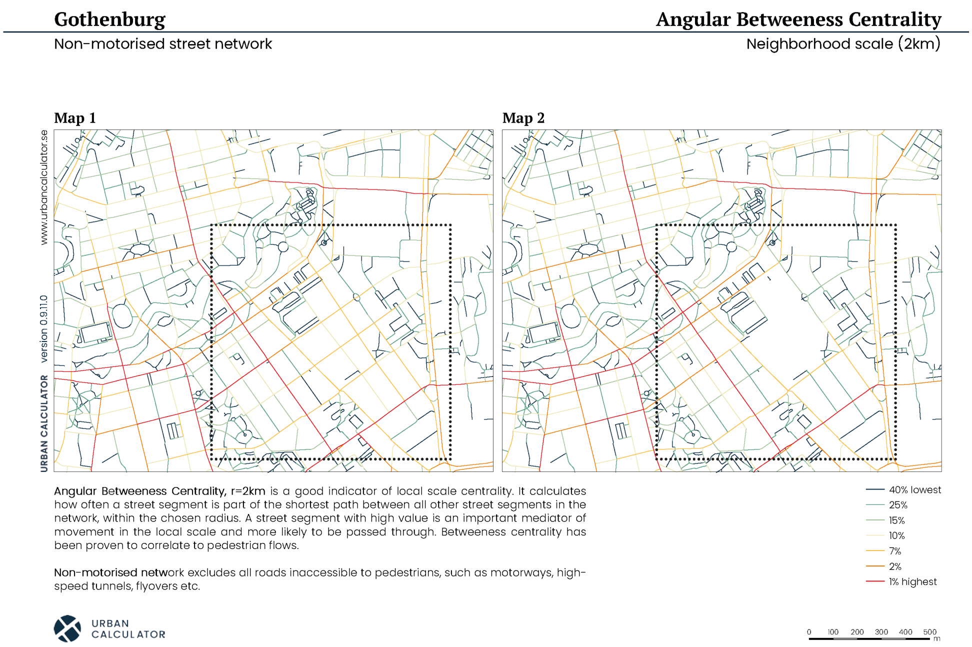

Figure 10: Example from before-and-after visualisation exports

4. CLOSING ARGUMENT

The Sustainable Development research agenda, by bringing pedestrian movement in the forefront of mobility and transport and by making it an interdisciplinary object of study, has created newfound opportunities for Space Syntax research. Sustainable urban development relies heavily on sustainable mobility and designing areas that promote pedestrian movement is key. Modelling pedestrian flows, one of the solid directions of Space Syntax research for almost four decades, is acknowledged as central for the successful design of sustainable urban environments. Within this context Space Syntax gains a broader societal relevance and it can be brought to the front of the methodologies included in the sustainable urban development toolkit, for scenario-analysis, crowd movement simulations and impact assessments of new area plans and infrastructure changes. It has built an empirically grounded theoretical and methodological framework with premises aligned with the central tenets of the sustainability agenda. This keynote aimed to reframe and remotivate Space Syntax modelling of pedestrians flows within the contemporary context, identifying research needs and opportunities and outlining research priorities to keep up the momentum gained by the Sustainable Development research agenda.

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