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ORIGIN-DESTINATION WEIGHTED CHOICE MODEL AS A NEW TOOL FOR ASSESSING THE IMPACT OF NEW URBAN DEVELOPMENTS

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Abstract

Different measures of pace syntax analysis have consistently produced efficient representations of urban phenomena, such as movement, which could be used in urban design, urban planning and decision making processes. All these measures, however, are based on pure spatial configurations and are not directly influenced by other attributes of the urban network, such as land use and density. In the absence of data on these attributes, or when the main focus of the study is the spatial layout, the pure spatial analysis remains a very powerful tool, but in cases that we need to study and model the non-spatial attributes of urban areas, it is important to develop methods that could link those attributes intrinsically with the spatial analysis. One of the cases that demands for such methods is the assessment of the impact that large-scale developments create in the city. In this assessment issues such as the different types of uses and their distributions become as important as the spatial layout itself.

This paper proposes and tests a methodology to create a space syntax model that could takes into account urban attributes such as land use and density inside the process of spatial analysis. In this approach the syntactic measure of 'choice', or 'betweeness centrality' as it is usually called in network science, is calculated by imposing weightings on the origins and destinations of the shortest path in the urban network. The weightings are obtained from the special conditions of each segment and are used for calculating the choice value of all segments located on the shortest routes between all origins and destinations. The model has been tested in the city of Jeddah, Saudi Arabia, to measure the impact of major urban development on the vehicular traffic demands in the centre of the city. Furthermore, the analysis is used to identify the vulnerabilities of the network in Jeddah after the implementation of the new developments. The paper focuses mainly on the methodological aspects of this approach, which will need further research to generate a consolidated impact assessment methodology for cities.

Keywords: *space syntax, impact assessment, betweeness centrality, weighted choice*
Theme: *Modelling and Methodological development*

1. Introduction: the need for weighted syntactic measures

The major virtue of using space syntax analysis in urban design and planning is in its simplicity, speed and clarity, enabling the designer, planner or decision maker to understand clearly how a complex system works or could be modified (Karimi 2012). Most of other available analytical methods and models have a major difficulty: they cannot easily become an integral part of the design, or planning process. There are several reasons for this, but perhaps prime amongst them is the lack of an urban theory that could link physical aspects of the urban system with its functional, social and behavioural aspects, directly and seamlessly (Hillier 2008; Penn 2008; Sailer et al. 2008). Furthermore, analytical models that could deal with large urban systems, such as transport models, are usually time-consuming, data-intensive and rather expensive to be built (Weber and Landis 2012). The large amount of data, time and resources that is required to create and run those models, make their applications difficult and impractical in dynamic planning and design. Space syntax methodology provides a fast and efficient solution by using the spatial network as a proxy for the aggregate impact of different layers of issues such as movement, human activities, land use and density (Hillier and Stonor 2010; Penn and Turner 2004; Hillier and Stutz).

Space syntax analysis is based on representing the geometry of the spatial layout by a network of lines which correspond with inter-visibility and movement desire lines of an urban system. This network of lines is then turned into a graph, in which each line is a node and the connections to the other lines are vertices of this graph (Hillier and Iida 2005). By translating the network of lines into a graph that represents the topological relationships between lines, a quantitative analysis of the system is performed by calculating how each space is connected with the other spaces in the system. Space syntax analysis uses graph computation to derive a series of network measures, which are then attributed to the lines using a colour scale. When seen together, the original layout and the graph analysis of the lines provide a thorough understanding of how the network works.

The lines in the spatial network could be treated as continuous entities, or they can be de-composed into segments. The relationship between each segment and all other segments is calculated by analytical computer software,[1] using various methods, such as metric distances (how far to travel), topological distances (how many changes of direction) and angular distances (what degree of angular shift). The first type of analysis is similar to the methods that are used by transport models. The second type of analysis is called an 'axial analysis' and the third, which has been developed more recently, is called 'segmental angular analysis' (Hillier and Iida 2005).

The analysis can be based on the relative depth (or shallowness) of spaces from each other, which is a measure of 'proximity' or 'to-movement', or based on the possibility of being used in journeys throughout the system, which is a measure of 'betweenness' or 'through movement'. The former measure of analysis in space syntax terminology is usually called *integration* and the latter is called *Choice* (Hillier and Iida, 2005). Each of these measures explains certain aspects of the urban structure and is used in connection with specific questions that have to be answered in an urban study.

Space syntax analyses of different urban systems show a remarkable degree of consistency in results. In most cities, the spatial structure is normally a "foreground network of linked centres at all scales, set into a network of largely residential space (Hillier and Vaughan, 2000)". These

[1] One of the main software for this kind of analysis is called Depthmap, which was developed by the Space Group at Bartlett, UCL (Alasdair Turner 2001). Depthmap has become an open source software since 2011 and a major re-write of the software, called DepthmapX, was released in 2012 (https://github.com/SpaceGroupUCL/Depthmap).

centres range from very local centres, where you find very local functions, to major centres of large cities, where a specialised system of high permeability routes and smaller urban blocks facilitate a more complex urban system (Hillier 1999). The research also shows that the structure of the grid correlates consistently with pattern of pedestrian and vehicular movement (Penn et al., 1998) and other issues such as the distribution of land uses (Penn and Turner, 2004) and social behaviours (Hillier and Shu, 2000). Such correlations with multiple planning variables make space syntax analysis a great method for evidence-informed and analytical urban design or planning.

Despite the obvious efficiency and clarity that space syntax analysis provides, we have to bear in mind that the model is a pure spatial model. As long as the changes to an urban system are spatial, the model accounts for them, but if the other urban attributes, such as land use, density and attractors are changed, the pure spatial model cannot demonstrate their impacts. Moreover, the space syntax model is a more powerful model to reveal distributions, but it cannot directly provide a means to forecast real measures (such as the volume of activities, or land uses). This means that in order to use the analysis in urban design and planning, we need to link other layers of information with the base model. This can be done by overlaying any mappable layers of information onto a GIS platform to see how the spatial analysis is compared with the other issues. We could even go further and build composite models by linking spatial analysis with other types of analysis, but these models do not change the way each layer of analysis is done.

The main issue here is that space syntax analysis treats all lines or segments of an urban grid similarly: they all become 'one' node in the graph. This makes a lot of sense in the systems that are evenly distributed or evenly loaded, but in unevenly distributed systems the analysis cannot capture directly how the spatial network is influenced with attractors, densities or land uses. In naturally evolved systems, this is not a big problem, since most of these issues have become compatible with the spatial structure to maintain the efficiency of the grid (Hanson 1989; Hanson 1989; Hillier 1996), but in urban systems that have not evolved, you normally find discrepancies between the spatial layout and how the other issues are embedded (Karimi 2009). Furthermore, for assessing new designs or plans, it is essential that we could assess the impact of our decisions on other important factors, as well as the spatial layout.

This paper proposes a method of analysis that enables the pure spatial model to be linked directly with other factors when the analysis is carried out. The main proposition here is that if we could define an appropriate method of 'weighting' for the spatial elements of the network, we could give a proportional role to each node in the graph and analyse the graph as a weighted system. This is not really an unprecedented proposition for space syntax analysis since the angular analysis itself is a weighted model ((Dalton 2001; Hillier and Iida 2005; Alastair Turner 2001), in which the shortest routes between the nodes are calculated by weighting the angular distances between the segments. The difference here is that each segment receives an extra weightings obtained from the specific urban attributes of that segment. In this way the analysis becomes responsive to spatial and non-spatial changes.

2. Origin-destination weighted choice model

Theoretically a weighted measure could be applied to any network measure. However, the 'choice' measure, which is normally called 'betweeness centrality' in network analysis ((Freeman 1977; Brandes 2001), in particular seems to lend itself more to this type of weighting. Previous studies found choice measure as a good measure for describing long-distance movement in the city (Hillier and Iida 2005) and all major transport models use origin-destination matrices to build the traffic demand for the network. For the sake of clarity in this paper, we focus mainly on the calculation and applications of the weighted ‘choice’ measure. The method of weighting in this approach is based on the weight of ‘origins’ and ‘destinations’ when the choice value is calculated for each segment of the segment model.

Non-weighted angular choice (or angular betweenness centrality) is calculated by obtaining the shortest angular trips between all segments, and then counting the number of shortest trips that go through each segments. The choice value of each segment is therefore a more or less large integer value.

The formula for betweenness of segment x is:

$B_\theta(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} \sigma(i,x,j)$, such that $i \neq x \neq j$;

where the function $\sigma(i,x,j)$ equals 1 if the shortest path from i to j passes through x, and 0 otherwise.

Choice, or angular betweenness can naturally be weighted by some value, by letting the function σ depend on the weight if the shortest path passes through x, rather than being equal to 1.

For this study we use a weighted betweenness formula σ'',

$$B''_\theta(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} \sigma''(i,x,j), \text{ such that } i \neq j;$$

where the properties of the origin as well as of the destination contribute to the weight. Here, the weight of the origin ω_o (the number of residential trips emitted from this segment); and the weight of the destination ω_d (the number of trips attracted by a segment). The total weighted function σ'' equals

- $\omega_o * \omega_d$ if the shortest path from i to j passes through x and $i \neq x \neq j$
- $\omega_o/2 * \omega_d$ if the shortest path from i to j passes through x and $i = x$
- $\omega_o * \omega_d/2$ if the shortest path from i to j passes through x and $x \neq j$
- 0 if is not on the shortest path between i and j

This weighting is implemented by a DLL module that works with Depthmap software. What the DLL does is that it creates two columns for origin and destination weights based on predefined assumptions. These weights have to be determined from the particular attributes of each segment such as land use, density, or attraction. After this, the weighted choice value of each segment is calculated by the above mentioned algorithm.

So far this sounds relatively simple, but the main complexity is to determine the appropriate weighting for origins and destinations. The method of weighting that we use will depend on what parameters we want to use and for what purpose we create a weighed model. In the next sections we describe an implementation of this method for creating a vehicular demand model to assess the impact of adding high density development in the centre of a major city.

3. The applications of a weighted choice model in assessing the traffic impact of proposed mega projects in central Jeddah

This model was developed as an impact assessment tool to understand the consequent impact on traffic flows and congestion, brought about by the mega project developments in the city centre of Jeddah. The city is currently undergoing massive transformations and there are several proposals for mega projects in the centre of the city, but the planners and decision makers are not clear about the impact of these projects as individual developments, or as a collective city centre transformation. A major question here is the impact on vehicular traffic, which is already a problem in this part of the city (Municipality of Jeddah 2009).

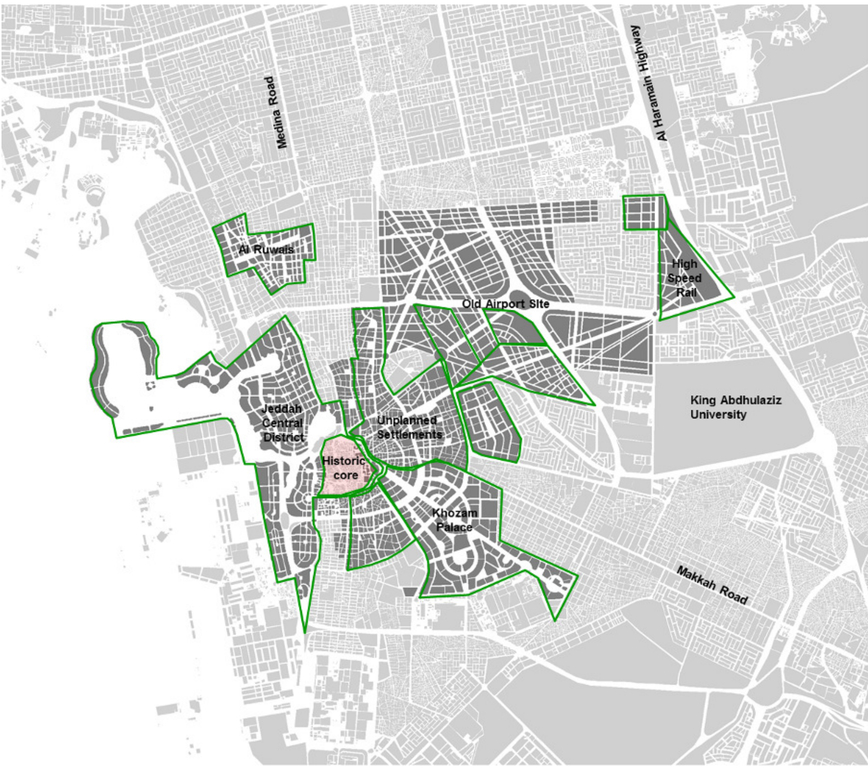

Figure 1: The plans for new mega projects in the centre of Jeddah, Saudi Arabia. The dark grey areas represent all development proposals and the green boundaries mark the most likely developments to be implemented.

Clearly a change in land use distribution or densities will affect the preferred routes for travel within the city and if a large quantity of mixed used developments is placed somewhere, we will have an increase for vehicular demand at certain parts of the network. In the absence of a full transport model, a weighted choice model was developed to do this assessment. The reason for choosing choice as the base measure was due to the fact that it uses the origin-destination concept and can produce a more realistic number of journeys between two segments through the shortest path between them.

At the first step, a spatial model was developed as a proxy for travel behaviour within the city. This model was then tested against available data on the existing flows within the city to ensure that it is an accurate representation of traffic behaviour (Figure 2). Once established and revised, the spatial model was updated according to the new set of origins, destinations and route layouts associated with the mega project. A resulting change in traffic flows throughout the city is then forecast using the spatial model as a predictor of future flow distributions.

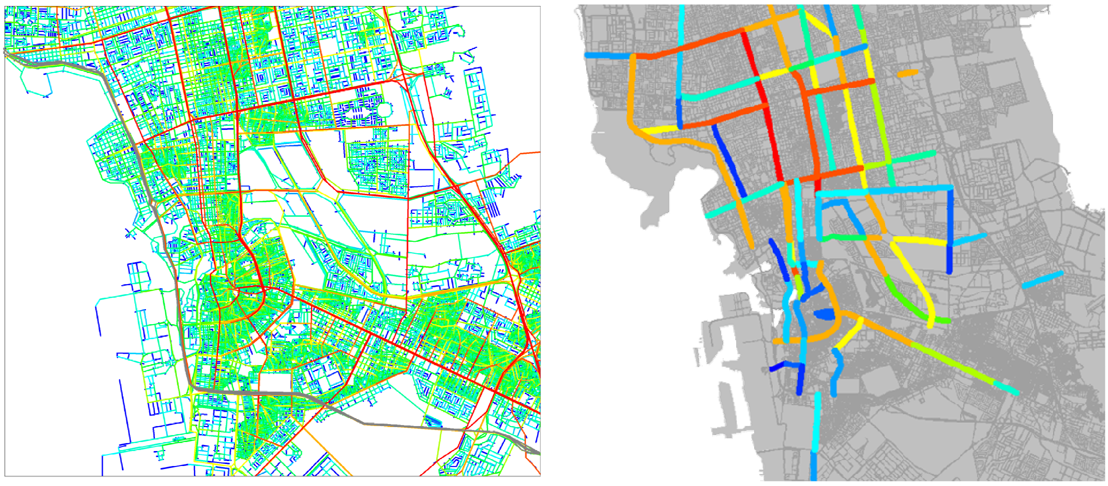

Figure 2: The base model for the study is a space syntax choice model (left). This model has been compared and revised against vehicular data available at the time of the study (right).

For the city centre traffic impact assessment, the models were built on a range of datasets, assigned to different virtual objects within the GIS tables available. These include street connectivity values assigned to street segments, land use and development density at the building and plot level and street capacity derived from underlying base maps of street dimensions. These various datasets have been integrated into the final models by linking data from different objects together (Figure 2).

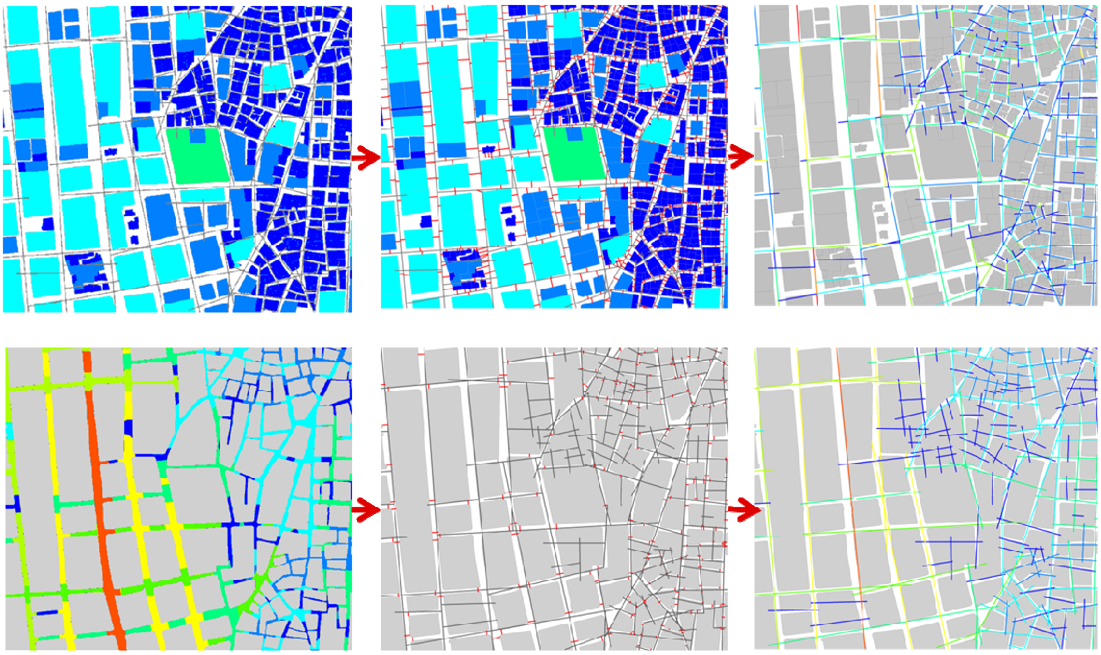

Figure 3: The images above show how plot level data has been linked to street segments (1st row) and similarly street level data has also been linked to street segments (2nd row). Having all the various datasets in the same form has enabled the models to incorporate data from different morphological typologies.

The basic approach to the model is to use spatial proxies as indicators of route convenience and trip probability. The first part of the model is a calculation of likely origin and destination pairs that affect the probability that a particular route is chosen on a vehicular trip. By calculating the number of potential trip origins and destinations throughout the city, the probability of any one origin destination pair can be calculated.

This weighting is then integrated with the spatial model to influence the value of street connectivity – a highly connected and continuous route in a quiet residential area will gain less importance than an equivalent route I a busy residential and commercial mixed use zone. The second part of the model helps determine the value of those particular routes and is based on the traditional route choice algorithm. The combination of these two parts of the model leads to a combined forecast model.

3.1 Input assumptions

The first step in producing such a model is to collate data on essential information relating to the generation of vehicular trips within the city. For this, the most crucial data is the total amount and distribution of population and employment across the city. This provides the gross fundamentals behind trip generation. Table 1 shows the basic input assumptions derived from a number of sources that have been used to construct the model. This has come primarily from the Jeddah Strategic Plan, the balanced scorecard of indicators and the City Growth Strategy produced by the Municipality (Municipality of Jeddah 2009). The table shows the breakdown of existing population and employment across the broad categories of land use within Jeddah. When intersected with the GIS dataset available from the municipality on the distribution of land use, a picture of the density of origin and destinations for all modal trips can be produced.

		Population (Happold)		Population (scaled)	Population (scaled & summed)	Landtake (Happold)	Landtake(624U_LU_Density)
Residential							
Appartments		2126382		2453563.211		4346	3584.1
Villas		311268		359162.0478		3706	4490.6
House		508962		587274.7413		3469	2528.4
							255.5
		2946612	1.2	3400000		11521	10858.6
Employment							
Manufacturing	industrial	65848		75,980	165,691	526	3535
Transport & Storage		77748		89,711		600	
Retail	Commercial_Retail	168241		194,128	216,922	155	441
Retail		19755		22,795		13	
Tourism	Hotel	226235		261,045	261,045	216	213.6
Education & Training	Educational	148699		171,579	171,579	411	869.1
Health	Health	129580		149,518	149,518	320	115.3
Government	Government government	71797		82,844	82,844	45	470.9
R & D		32289		37,257		42	
Banking & Finance		109613		126,479		62	
Consulting & Business	Commercial_Offices	109679		126,555	290,291	54	284.1
		1159484		1,337,891			

Table 1: The table shows the breakdown of existing population and employment across the broad categories of land use within Jeddah. When intersected with the GIS dataset available from the municipality on the distribution of land use, a picture of the density of origin and destinations for all modal trips can be produced. (note: in the third column 'Happold' refers to the origin of data)

3.2 Vehicular trip generation

The actual distribution of all origins and destinations does not have a one-to-one relationship with the generation of vehicular trips within the city. The actual generation of vehicular trips will be affected by the income of residents and as such their ability to own, maintain and service a car. It will also be affected by the need to use private transport rather than walking, cycling or using public transport.

Strong correlations are consistently found between an individual's mobility and their income and as such there is likely to be a significant correlation between property price, land value and the length and number of vehicular trips undertaken. As the actual trips undertaken per income category was unknown in Jeddah, the gross floor area per head of population was used as a proxy for income and as such the number of trips associated with a particular area is a factor of both population density and the propensity for each head of population to generate a vehicular trip.

Figure 4 (left) shows the resulting number of vehicular trips generated from each plot. A similar process has been applied to the location of trip destinations, namely all non-residential categories (Figure 4, right). Whereas residential area per head of population was used as a proxy for income and hence vehicular trip generation from resident locations, the density of commercial or industrial employment space would not directly relate to propensity for vehicular trips; rather the total amount of space or plot area would be a better proxy.

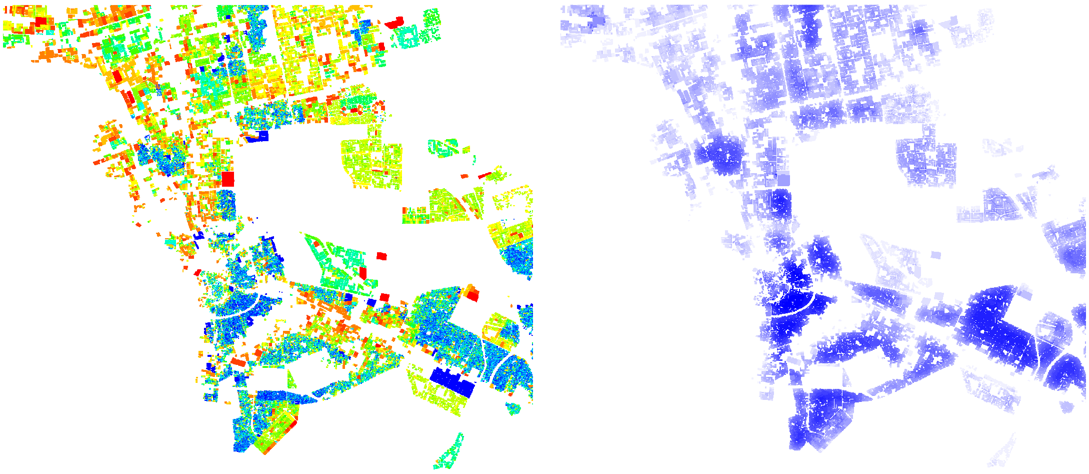

Figure 4: Vehicular trip generation (left) and destinations (right) in the city of Jeddah.

3.3 The weighted model

We can now run the forecast (in this case for the morning peak period), using number of people coming from residential places as ω_o and number of workers as ω_d. This will give us a probabilistic picture of all the trips taken from residential places to work places, under the assumption that the attraction of all work places is the same for all residents. To obtain the actual number of trips it is necessary to divide the weighted choice value by the number of work places, so that we end up with a total number of trips that is equal to travelling population. Alternatively, the destination column (the work place column) can be normalized to values between 0 and 1 before the analysis, to represent relative attraction rather than number of work places.

The outcome of the model is a description of the main vehicular routes in the city with major routes shown in red through to rarely used roads in blue (Figure 5). The output of the weighted model emphasises clearly the main vehicular corridors. These roads have a combination of high capacity, route convenience and connect a large number of origins and destinations across the city and between Jeddah and Makkah.

Within this network there appear to be 'hotspots of traffic on King Fahd Street and at the intersection of Madinah and Falastine Roads which are known locations of vehicular congestion throughout the city. Where the Madinah Road changes in character and integrates with the street network, the vehicular model shows gradually decreasing flows, which is reflected in observed levels of traffic (Figure 5, right).

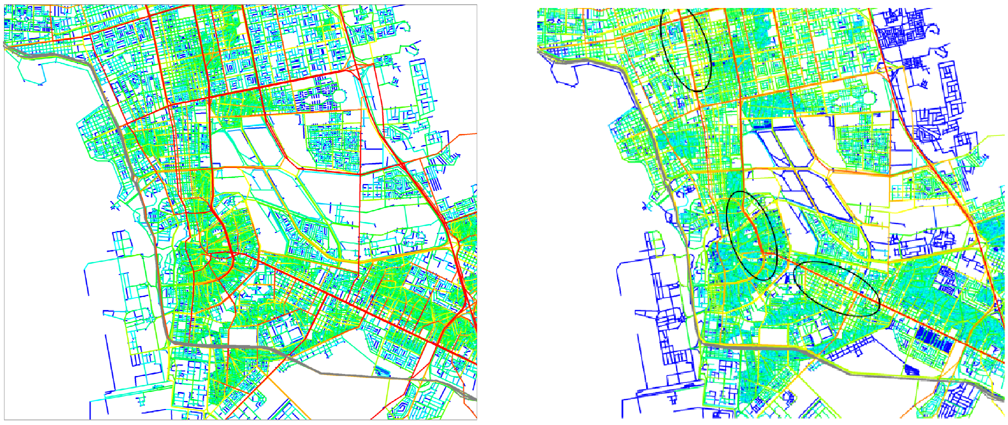

Figure 5: The syntactic 'choice' model of the city (left) compared to the choice model weighed by origins and destinations (right). The outcome gives a much more realistic picture of movement patterns in the city and identifies the potential bottle necks in the system.

3.4 Impact assessment

Now that we have the weighted model for the city as it is now, we could add any new developments to it and re-run the model to assess the impact on the traffic. Under each scenario for development of the city centre, a new weighted model can be constructed which not only adds to the model the layout of the new development, but builds a new weighting system that takes into account the land use composition, work and residential densities and public transport hubs of the new development. The assessment model shows the change of the traffic demand for each segment in the city. To avoid a lengthy discussion, here we review only the results for the most likely scenario for development is shown in Figure 6.

The model shows the output of the vehicular movement demand model when modelling the most likely development scenario for the mega projects (figure 6). The major changes include: an overall uplift in vehicular demand across all primary, secondary and tertiary roads within the city centre; a continued concentration of the majority of vehicular demand on the primary road network; continued heavy demand on the north-south arteries such as Madinah Road and King Fahd Road, as well the route from the city centre to the south-east (Makkah Road); a greater inter-connection between the primary road network and surrounding secondary roads; the emergence of important new connections such as Khosam Boulevard and Jeddah Boulevard (two new roads radiating from the historic centre), and higher demand to the north and east of the city centre than to the west or south.

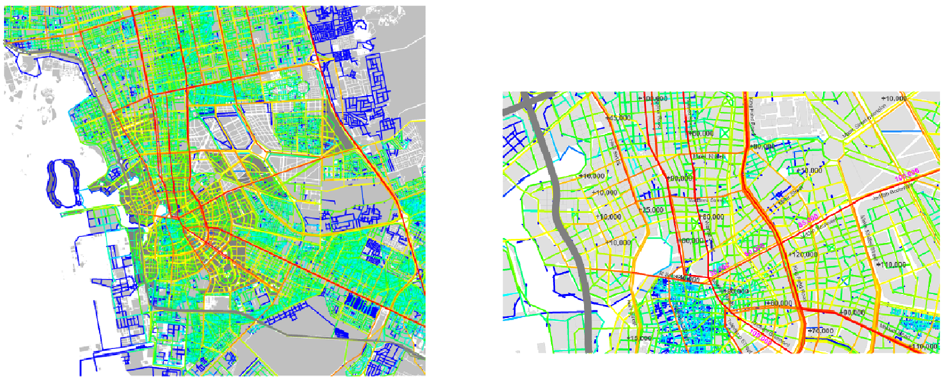

Figure 5: The origin-destination weighted choice model of Jeddah (left) and the changes in the volume of traffic that go through the main streets (right).

By using the current volumes of traffic on each segment, the changes in the value of weighted choice could be translated into the increase or decrease in the volumes of traffic (Figure 5, right). These volumes, which are normally used by traffic engineers, are useful to show the extent of the impact, but they could also be used to assess the capacity of the roads and the vulnerable parts of the network.

3.5 Congestions vulnerability

To understand how vulnerable the city centre may be to traffic congestion it is necessary to see the forecast demand in the light of the proposed street width. In order to do that analysis we need to rank the individual segments of the city's primary road network according to street width as a proxy for capacity (Figure 6, left). On the main characteristics of Jeddah's street capacity is that the street widths are not consistent within the city centre and neither along individual roads. Many roads reduce in width toward the city centre and many reduce but then widen again. This exacerbates congestion as traffic backs up as cars slow down to cope with a reduction in capacity. Furthermore, street width reduces quickly toward the historic core with. This reflects the growth of vehicular transport as the city grew from the historic core and more and more space was needed on streets to cope with demand for car transportation.

After determining the widths, the added traffic volumes calculated by the weighted choice model are added to the existing volumes and the total is divided by the street width to see how the extra demand meets the capacity of the road (Figure 6, right). This provides an indication of where the greatest risks of congestion may lie and where vehicular infrastructure is potentially underused.

This analysis identifies three categories of the roads. The first (shown in red) is the roads that will have a huge increase in vehicular demand, but don't have enough capacity. For these roads, we need to either increase the capacity, or reduce the traffic by other means (such as providing public transport or re-redirecting the traffic). The second group of the roads (shown in yellow) are the ones that will have major increases in vehicular demand, but have sufficient capacity to deal with the increases. For these streets we need to make sure that the design of the public realm and distribution of land uses are coordinated with the anticipated increase for the vehicular traffic. Finally, the third category of the streets is the ones that will have limited increase in demand and currently have sufficient capacity. For these streets our design and planning focus will be shifted to other issues, such as improvement of public realm for pedestrians and improvement of street life.

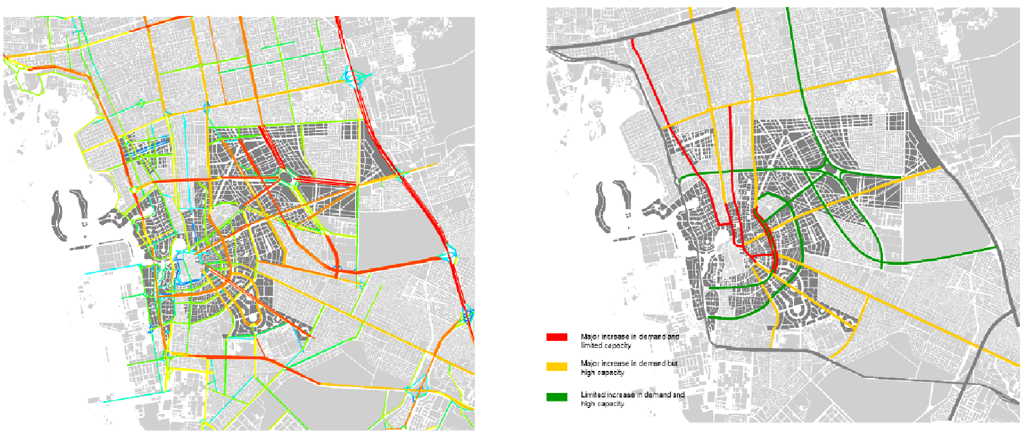

Figure 6: the analysis of street widths (left) and network vulnerabilities (right)

4. The potential for further studies

The same methodology explained in this paper for creating an assessment tool for the impact of new development on the traffic flows could be used to look at other issues such as future pedestrian movement flows in a designed new development or town. What we need to do in these cases is to determine the weightings for all origins and destinations of the pedestrian network based on land uses, densities, total population and the behaviour profiles of people in terms of age, gender, employment and so on. When the appropriate weightings are obtained, the weighed choice model could be used to analyse the system. The analysis will not only show the distribution of the pedestrian activities, but it will give the volumes of the flows based on the above-mentioned assumptions.

One of these examples is the development of a fully weighted pedestrian movement model for the City of Masdar in Abu-Dhabi. Masdar project, which initially started as an urban design competition, has been widely recognised as a sustainable, zero-carbon development (Heap 2010a; Droege 2012). In a review of the masterplan in 2009, space syntax methods were used to make an assessment of the masterplan and assist the design team with further development of the design. To improve the strength of the forecast model, a weighted choice model was created, using employment densities, residential densities, internal and external transport systems, and the profile of users to create an accurate weighting for origins and destinations. These weightings were then applied to the weighted choice algorithm, which was explained before.

The details of this study are beyond the remit of this paper and will be discussed in other publications, but it is important to know that the method described in this paper is applicable to a much wider range of studies and projects.

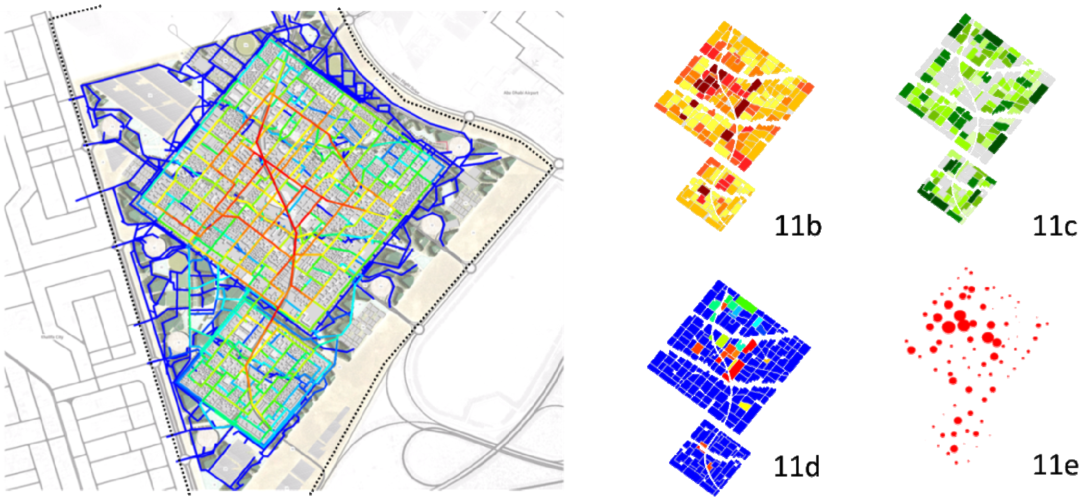

Figure 7: The City of Masdar, Abu Dhabi. A spatial configuration model was used to help optimise the spatial structure of the city. Furthermore, the spatial model was linked with land use distribution, residential densities, employment centres and transport nodes to create a weighted choice model for urban evaluation. The model was used to optimise the design further. The model also generated an accurate Pedestrian Movement Model which could be used to forecast the volumes of pedestrian flows.

5. Conclusions

This paper discussed that the pure spatial analysis models are powerful tools that could be used by designers, planners, decision makers and stake holders to optimise the process of design and planning. It was argued, however, that these models need further enhancements, if they are to be used in projects that non-spatial attributes of the urban system are as important as the spatial layout. An obvious example of these cases is the impact of new 'mega projects' or massive new developments in cities, where the new land uses and densities play a major role in changing the structure of the city, but there are a large number of other cases that could benefit from an enhanced tool as well.

The paper introduced a 'weighted angular choice' model which uses the main concept of calculating choice (or betweeness centrality) applied by space syntax methodology, but it adds weightings to the origins and destinations of the shortest paths between the segments according to the number of trips generated by each segment in the city. This model was implemented as an impact assessment tool in the city of Jeddah to measure the likely increase or decrease of the vehicular traffic flows generated by major developments in the centre of the city. The results where then used to identify the vulnerabilities of the network and possible solutions that could resolve those problems.

The Jeddah study is only one example of the applications of this method, but there are many other cases that could benefit from this type of analysis. One of these examples, the Pedestrian Movement Model for the City of Masdar, was briefly introduced at the end of the paper, but further work has to be undertaken to explore the potentials of the method. It is also essential to verify the results of the analysis with real databases to improve the methods of weighting, or the measures that are most suitable to be used for this type of analysis.

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