

# Macro- and Micro-scale Modeling of Multi-modal Transportation Spatial Networks in the City-State of Doha, Qatar

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## Abstract

*Researchers and practitioners have been modeling the street networks of metropolitan and geographical regions using space syntax or configurational analysis since the late 1990s and early 2000s. Some models even extend to a national scale. A few examples include the island of Great Britain, within the national boundaries of England, over half of the Combined Statistical Area of Metropolitan Chicago and the entirety of Chatham County, Georgia and the City of Savannah in the USA, and the Chiang-rai Special Economic Zone in northern Thailand bordering Myanmar and Laos. Researchers at Qatar University constructed a space syntax model of Metropolitan Doha in 2018. It covered a land area of 650 km<sup>2</sup>, encompassing over 24,000 streets, and approximately eighty-five percent (~85%) of the total population (~2.8 million) in Qatar. In a short time, this model led to a deeper understanding of spatial structure at the metropolitan and neighborhood level in Doha compared to other cities of the world, especially in the Gulf Cooperation Council region. The paper presents the initial results of expanding this model to the State of Qatar, which provides ideal conditions for this type of large-scale modeling using space syntax. It occupies the Qatari Peninsula on the Arabian Peninsula adjacent to the Arabian/Persian Gulf, offering natural boundaries on three sides. Qatar also shares only a single border with another country to the southwest, which Saudi Arabia closed due to the current diplomatic blockade. The expanded model includes all settlements and outlying regions such as Al Ruwais and Fuwayrit in the far north, Al Khor and the Industrial City of Ras Laffan in the northeast, and Durkan and Zekreet in the west. Space syntax is serving as the analytical basis for research into the effect of the newly opened rail transportation systems on Doha's urban street network. Researchers are also utilizing space syntax to study micro-scale spatial networks for pedestrians in Souq Waqif, Souq Wakra, and other Doha neighborhoods. The paper gives a brief overview of this research's current state with an emphasis on urban studies.*

## Keywords

*Geography, Model, National, Space Syntax, Transportation*

## 1. Introduction

Over the last 80 years, the computer science revolution and progressive evolution of digital technology have enabled models and simulations on a before-unimagined scale and complexity about our world's different aspects. The genesis of this revolution began – now famously – during World War II. It included British mathematician Alan Turing and the electro-mechanical bombe device's construction to assist decryption at Bletchley Park in the United Kingdom. It also involved American theoretical physicist Robert Oppenheimer and modeling the process of nuclear denotation in the collaborative Manhattan Project between Canada, the United Kingdom, and the United States.

Today, there are computer models and simulations in a cornucopia of fields dealing with natural systems like physics, chemistry, climatology, biology, and human systems such as economics, health care, social science, and engineering. A computer model is the digital representation of a system, which is similar to but simpler than the system it represents, offering a thoughtful balance between realism and simplicity (Whitt & Maria, 1997). Modeling is the act of building a model, i.e., “to produce a representation or simulation” from the Latin *modus* meaning small measure.<sup>1</sup> A computer simulation is a process of using the model to study the behavior and performance of an actual or theoretical system (Whitt & Maria, 1997). Simulating is the act of using a model for simulation, i.e., “to make a simulation of something” from the Latin *simulatus* meaning to copy or represent.<sup>2</sup> The keywords or phrases in these definitions of computer model and simulation as a thing (noun) and its act (verb) are *representation* (to represent), *simpler than*, and a *system* with ‘offering a thoughtful balance between realism and simplicity’ being an important but ancillary consideration, i.e., ‘providing necessary support to the primary activities or operation.’<sup>3</sup>

The emphasis on the *representation of a system* means the built environment was ideally-suited for the computer science revolution. Working with representations is an everyday occurrence in the architect, urban designer, and town planner's professional career. They work with plan and elevation drawings and two-dimensional representations of three-dimensional realities such as one- and two-point perspective drawings. Built environment professionals also work with two-dimensional representations of three-dimensional 'hyperrealities.' A hyperreality arises due to human consciousness's inability to distinguish reality from a simulation of reality, seemingly bending the real and the fictional together, so there is little distinction between where one begins and the other ends (Tiffin & Terashima, 2001; Baofu, 2009). Architectural representations of this type include section, architectural detail, three-point perspective, and axonometric drawings. In some ways, they are like reality, but we rarely, if ever, see the built environment in such same precise manner. Finally, some of the most iconic architectural and urban proposals were only ever representations, such as Le Corbusier's Ville Radieuse and Frank Lloyd Wright's Broadacre City. We never constructed these proposals, but cannot deny their subsequent influence as mere representations (Major, 2018).

The fields of the built environment, often in concert with civil engineering, enthusiastically embraced the computer science revolution's challenges. There are software programs to construct traffic models simulating vehicular movement flows based on the gross amount and relative intensity of origins and destinations available in an urban environment.<sup>4</sup> Many software programs enable the design of built environments, creation of architectural drawings, and the final product modeling entirely within a digital realm, such as SketchUp, Revit, AutoCAD, and many more. Software packages like Rhino and Grasshopper

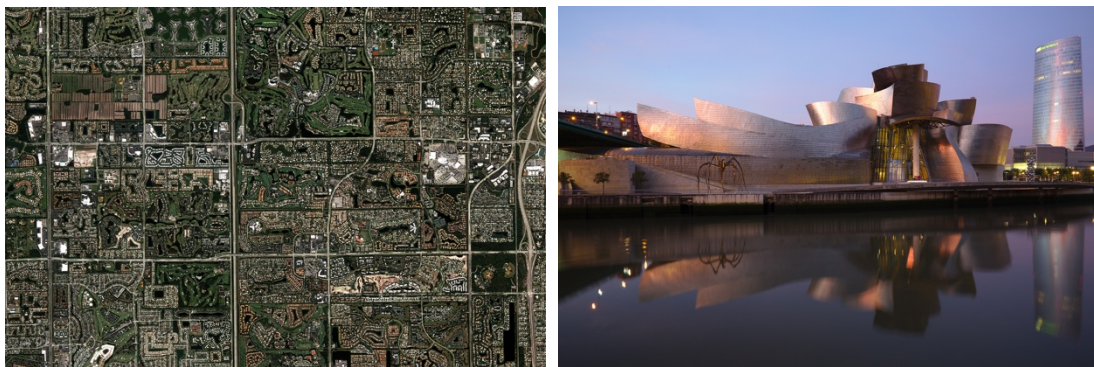
<sup>1</sup> Transitive verb of ‘model’ per Merriam-Webster Dictionary. Retrieved: 7 August 2020 at <https://www.merriam-webster.com/dictionary/modeling>.

<sup>2</sup> Transitive verb of ‘simulate’ per Merriam-Webster Dictionary. Retrieved: 7 August 2020 at <https://www.merriam-webster.com/dictionary/simulating>.

<sup>3</sup> Adjective per Lexico in collaboration with Oxford English Dictionary. Retrieved: 7 August 2020 at <https://www.lexico.com/en/definition/ancillary>.

<sup>4</sup> Also known as gravity modeling since their mathematical foundation is Newton's Law of Universal Gravitation.

fed the widespread adoption of parametric design principles in architecture over the last 30 years. Parametric design explores the technical limits of architectural planes, such as the building envelope. It utilizes an algorithmic process based on the grid subdivision of a plane into a coordinate system, which can be manipulated by the designer. Parametric design principles strongly relate to the traditional assessment of built forms' stability using structural grids in architecture and civil engineering. Parametric design software transitions a previous static, usually plan-based representation into a dynamic one, whereby the design intent of the architect leads to a design response in the architectural object (Woodbury, 2010; Jabi, 2013). Geographical Information Systems (GIS) software enables the modeling of the urban environment simultaneously with the storing of massive amounts of socio-economic data using shapefiles, which researchers and practitioners analyze in various ways, including conventional Cartesian measurements. These are only a few examples of the software available for modeling of the built environment. There are far too many to summarize here.



**Figure 1: Examples of the outputs for the computer science revolution in the field of the built environment over the last half-century including (left) suburban sprawl at the urban-level in Boca Raton, Florida USA in 2019 and (right) Frank Gehry's 1997 parametric design of the Guggenheim Museum Bilbao in Spain in 2015 (Source: Google Earth/Wikipedia Commons).**

Many computer software packages tailor their programming for the modeling of the built environment for particular purposes. Unsurprisingly, financial and technical considerations tended to feed digital evolution in the fields of architecture, urban design, and town planning over the last half-century. Typically, the former associates with cost-saving in some manner, usually reducing labor and increasing output for tasks. However, it also includes fiscal impact analyses of various kinds, especially at the urban-level. The latter is often consistent with exploring the technical limits and new meanings of architecture form, a theoretical preoccupation in the field since the late 19<sup>th</sup> century. Generally, the impact on the built environment has been positive. However, the results are not universal. For example, the institutional and professional spread of origin-and destination modeling to assess the fiscal impact of vehicle trips on roads in urban development coincides with the proliferation of suburban sprawl across the urban landscape, especially in the United States (Speck, 2010; Schmitt, 2014; Ball, 2015; Major, 2018) (Figure 1).

A small part of this story over the last 40 years is space syntax, which began to gain prominence during the 1990s. Space syntax is an international research program of academics and practitioners scientifically investigating spatial networks from the single building to entire metropolitan regions. Founded in the late 1970s and early 1980s by Bill Hillier, Julianne Hanson, John Peponis, Alan Penn, and many others in The Bartlett at University College London, space syntax researchers developed a set of techniques for the simple representation and mathematical measurement of architectural and urban space (Hillier and Hanson, 1984; Hillier, 1996; Hanson, 1998; Major, 2018). Their goal is to understand the role of built space in society. Computer models and simulation have been a fundamental part of space syntax from

the very beginning (Figure 2). Today, the international space syntax community composes hundreds of researchers and practitioners in more than forty countries worldwide with academic centers of excellence in Europe, South America, and the USA.

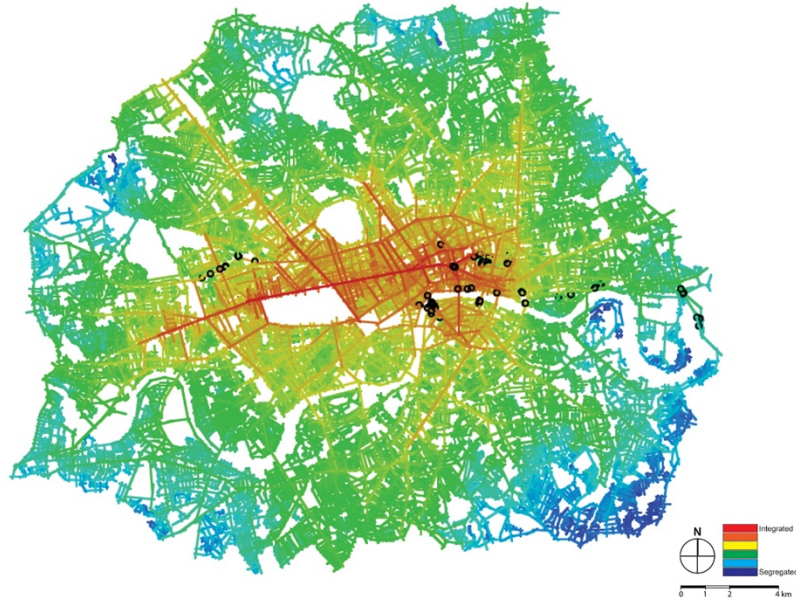


Figure 2: Space syntax model of global integration (radius= $n$ ) in Greater London within the North and South Circular Roads in 1999 where relativized mean depth of all streets (represented as lines of sight and movement) is in a range from red (most integrated or least depth) through orange, yellow, green, and light blue to dark blue (most segregated or most depth) (Source: originally by Hua Yoo, 1991 based on a color version in Major, 2000 and courtesy of Space Syntax Limited).

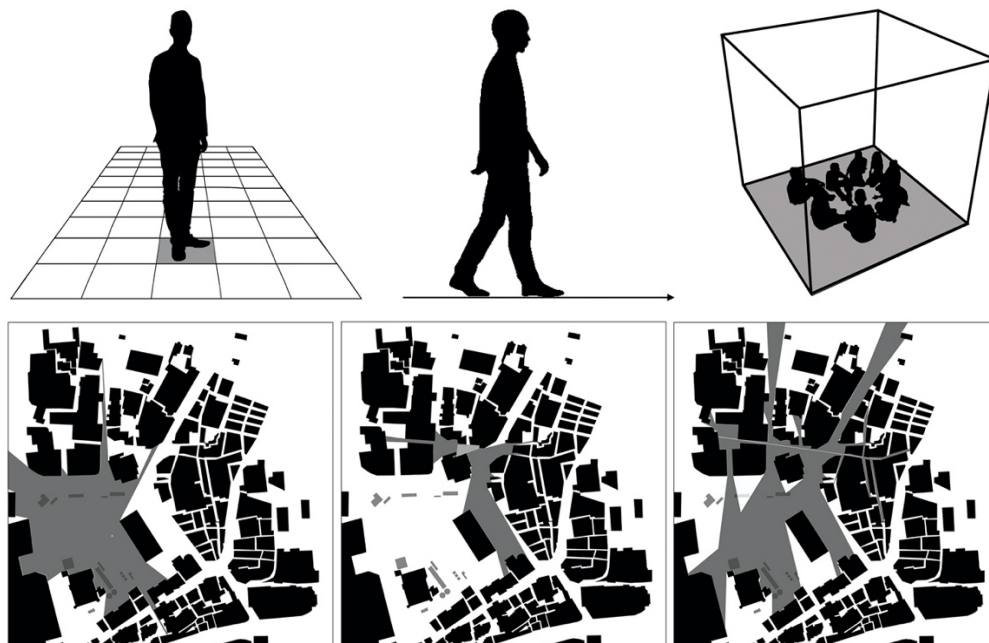
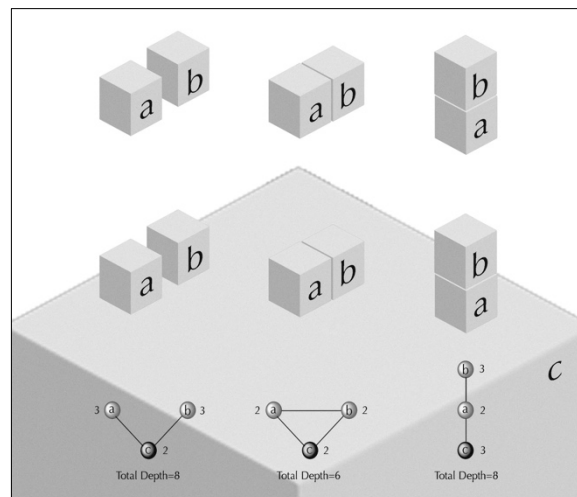


Figure 3: Representing (top, left to right) a *point*, *line*, and *convexity* ('the quality or state of being convex') in space syntax and (bottom, left to right) a *visual field* (in dark grey) from a point, line, and convex space (in light grey) in the plan of Souq Waqif in Doha, Qatar. NOTE: Plan elements in the large open plaza towards the lower left represents impediments to movement but not visibility, i.e., a normal human being can see over the top of these elements (Source: Authors).



## 2. About Space Syntax

A foundational principle of space syntax is that the built environment is both a product of society *and* an influence on society. Space syntax representations are usually plan-based. They utilize objective, easily understood constraints of the built environment for the most generic human uses such as movement, occupation, and visibility (Hillier, 1996) (**Figure 3**). A *point* in space is the simplest notion to build a geometry with no size, only position. The number of points in any space will be infinite without a resolution – defining the bounds of a space and a size for the points – such as the average standing area of a normal human being ( $0.28\text{m}^2$ ) (Turner et al., 2001; Major, 2018). Movement tends to be linear because we are bipedal, forward-facing creatures usually bound by gravity. The axis or *line of sight and movement* (e.g., axial line) represents an idealization because a line is a set of points having a length but no width or depth. The matrix of longest and fewest (i.e., most strategic) lines of sight and access completely covering all spaces of a built environment as defined by its built surfaces (walls or facades) is the axial map (Hillier and Hanson, 1984). The axial map is the most common reference to a space syntax model in forecasting for pedestrian and vehicular movement in the urban environment, typically within a range of 60%-80% accuracy (Hillier et al., 1993; Penn et al., 1998).

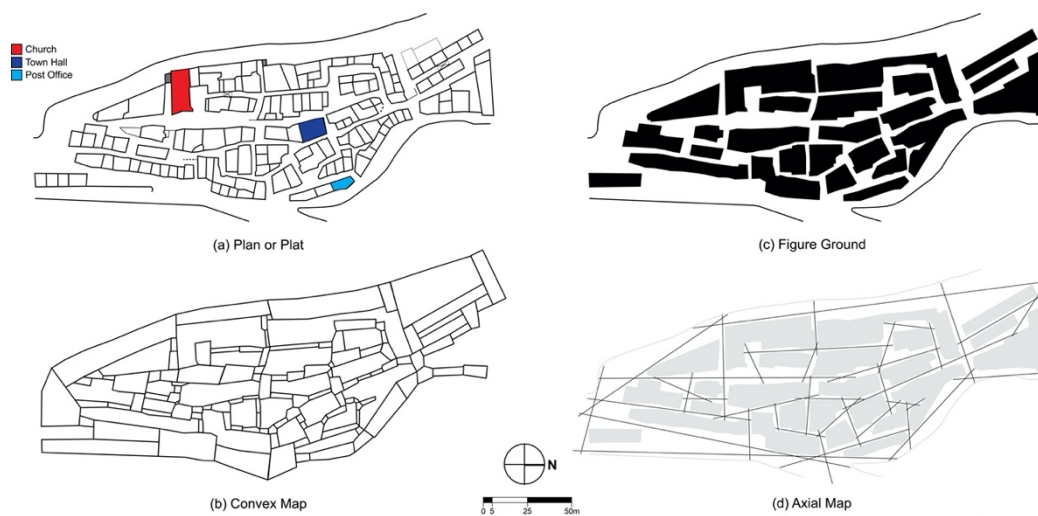


**Figure 4: The basics of configurational measurements using topological graph theory where (top row) two objects labelled A and B are similarly-related until (middle row) the introduction of a third object labelled C (such as the surface of the Earth). All three objects now have different configurational relationships based on connection or permeability, as represented (bottom row) in the justified graphs where the object is represented as a node and their relation as a line (Source: Major, 2018 after Hillier, 1996).**

The occupation of space tends to be convex where everyone can see *and* be seen by everyone else, such as a group of people gathered in a circle or a room. All points are visible to all others in a *convex space*. The collection of all convex spaces composing a built environment is the convex map, which tends to be more useful for building analysis (Hillier et al., 1987a-b; Hillier, 1996; Hanson, 1998). The potential for seeing and moving is a *visual field*, which is all visible and accessible space from which we might see or move as defined from a point or set of points such as a line of sight and movement or convex space (Benedikt, 1979). The matrix of all visual fields from a gridded set of points to all others in a built environment is a visibility map (Turner et al., 2001). Space syntax uses combinations of these simple descriptions — point, line, space, field — to create layered representations of the built environment.

We can measure the matrices of these representations using topological graph theory. It enables us to mathematically quantify the configurational relationship of all spaces to all others within a set range.

Configuration is a relational system where any *local* change in a system can have *global* effects across that system to varying degrees, dependent on the size of the system relative to the significance of the change itself *within* it (Hillier, 1996) (**Figure 4**). Configurational measures offer a scientific basis to *implicate or dismiss* the designed spatial network as a factor in higher-level social, functional, and cultural outputs. Space syntax software also incorporates metric parameters such as the length of streets/street segments and the plan area/perimeter surface area of visual fields. Over four decades, researchers have developed a large and diverse set of configurational and metric measures using space syntax. Some are more useful than others, and sometimes it can take years of testing to confirm or refute their usefulness. Space syntax software measures the configurational relationship of all spaces to all others across the entire network and automatically colors each space in a range from most integrated or shallow to most segregated or deep; for color, red through orange, yellow, green, to blue and purple (refer back to Figure 2).

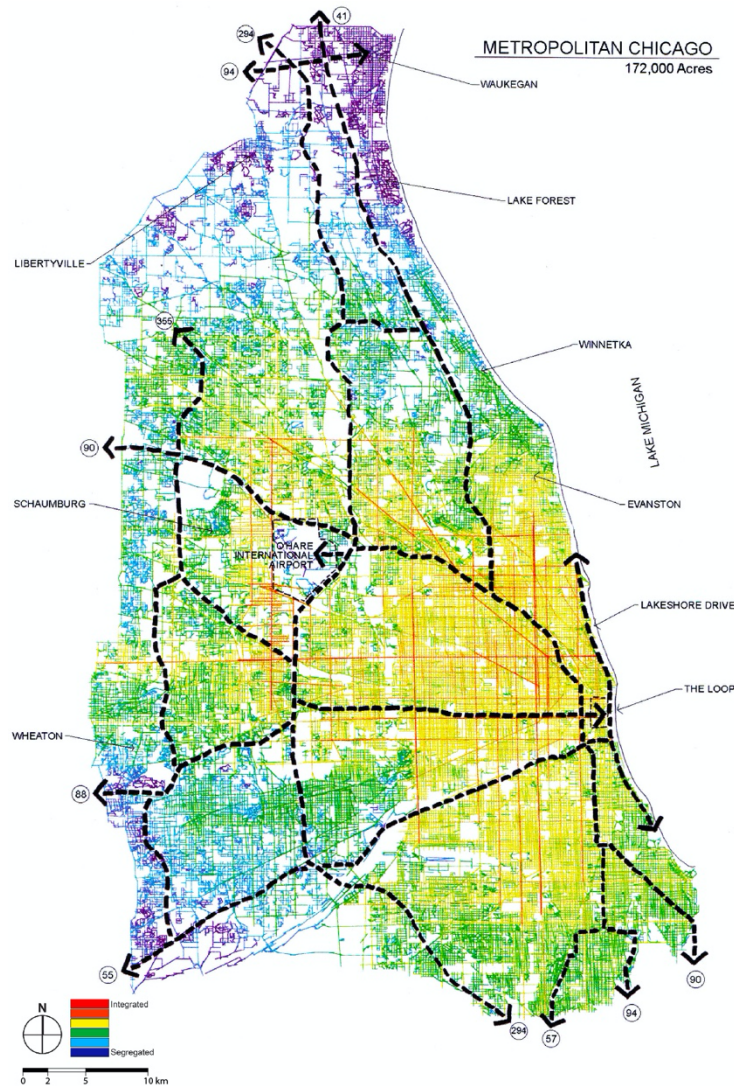


**Figure 5. The procedure for modeling settlements based on the (a) plan/plat, (b) convex map, (c) figure-ground, and (d) axial map for the layout of Gassin in the Var region of France circa 1980 (Source: Authors after Hillier and Hanson, 1984).**

Urban analysis in space syntax primarily relies on drawing an axial map of the open space structure based on a plan of a settlement (Hillier and Hanson, 1984; Hillier, 1989) (**Figure 5**). For the best results, this usually requires a plan or plat that accurately depicts all building footprints in the settlement. We can also divide the open spaces into the fewest and fattest set of convex spaces as defined by built forms necessary to encompass the entire settlement. We might do this if we wish to double-check that one-dimensional mapping of the longest and fewest strategic lines of sight and movement connects all the two-dimensional representations of space in the convex map. Most people forgo this stage unless they are researching the design or use of specific spaces in a settlement such as a public plaza or square. Instead, they tend to proceed to immediately draw the longest and fewest lines of sight and movement based on the plan/plat to create the axial map of the settlement. Best practice usually suggests beginning with drawing the longest lines, then the shortest lines, and concluding with the lines of intermediate length connecting between the two extremes. The use of a figure-ground representation with all built forms in black often assists this process. Once the axial map is complete, then we can process the model using computer software to analyze the system of relations between the lines.

Hillier and Hanson (1984) argue some basic properties tend to characterize all axial lines based on their degree of 'symmetry-asymmetry' and 'distributedness-nondistributedness' within the system. It means the degree to which space is composed of shallowness/rings of circulation or deepness/sequences that

form trees in the underlying topological graph. A space syntax model of the urban environment based on axial mapping can offer a very realistic picture of spatial networks based on a purely mathematical representation. We can layer in additional data about other urban functions such as land use, building heights, population density, and other socio-economic data to develop more sophisticated models.



**Figure 6: Space Syntax model of global integration (radius=n) in the urban spatial network of Metropolitan Chicago, Illinois in the USA in 2002 (Source: Major, 2018).**

Since the late 1990s and early 2000s, space syntax researchers and practitioners have been modeling street networks across metropolitan and geographical regions, even on a national scale. These models range in size and scale. A few examples include the island of Great Britain (land area of  $\sim 209,000 \text{ km}^2$ ), within the national boundaries of England ( $\sim 130,000 \text{ km}^2$ ), over half of the Combined Statistical Area of Metropolitan Chicago ( $\sim 10,900 \text{ km}^2$ ) (**Figure 6**), the entirety of Chatham County, Georgia and the City of Savannah ( $\sim 1,640 \text{ km}^2$ ) in the USA and the Chiang-rai Special Economic Zone ( $\sim 1,521 \text{ km}^2$ ) in northern Thailand bordering Myanmar and Laos (Hanson, 2009; Turner, 2009; Major, 2018; Kasemsook et al., 2019; Major, 2020).<sup>5, 6</sup>

<sup>5</sup> Space Syntax Limited, London, UK. Accessed 12 April 2020 at <https://spacesyntax-openmapping.netlify.com/#6/55.603/-3.252>. This modeling including the national boundaries of England uses auto-generation modeling based on road centerlines (Turner, 2007). The cited American

The first task for launching the burgeoning space syntax research program at QU in 2017 was constructing the axial map of Metropolitan Doha as part of "The Doha Syntax: A Configurational Model of Vehicular and Pedestrian Networks in Qatar's Capital" research grant.<sup>7</sup> It covered a land area of 650 km<sup>2</sup>, encompassing over 24,000 streets and approximately eighty-five percent (~85%) of the total population (~2.8 million) in the State of Qatar at the time. The researchers later expanded this space syntax model to the entire State of Qatar on the Qatari Peninsula as part of the Master of Urban Design and Planning (MUPD) program and "The Doha Syntax, Phase 2: Urban Movement Network Validation of Space Syntax Model of Metropolitan Doha, State of Qatar" research grant currently in progress until the end of 2021.<sup>8</sup> The expanded model includes all settlements and outlying regions such as Al Ruwais and Fuwayrit in the far north, Al Khor and the Industrial City of Ras Laffan in the northeast, and Durkan and Zekreet in the west. Space syntax is serving as the analytical basis for research into the effect of the newly opened rail transportation systems on Doha's urban street network. Researchers are also utilizing space syntax to study micro-scale spatial networks for pedestrians in Souq Waqif, Souq Wakra, and other Doha neighborhoods (Major et al., 2019; Khan et al., 2020; Major & Tannous, 2020; Tannous, 2020; Tannous & Major, 2020). In the next section, we provide a brief background about urban development and land use in the City of Doha and the State of Qatar over the last 50 years before reviewing some initial findings of our ongoing urban studies at the metropolitan and national scale.

### 3. About the City-State of Doha

The State of Qatar is a peninsular nation on the east coast of the Arabian Peninsula in Western Asia. It lies adjacent to the Arabian/Persian Gulf in the Middle East. Qatar encompasses a land area of 11,581 km<sup>2</sup>, sharing a common border with only Saudi Arabia to the south. However, the western border of the United Arab Emirates (UAE) is only 80 kilometers (km) to the southeast (**Figure 7**). Under normal circumstances, the UAE border is only a one-hour drive away from the border of Qatar. However, the border has been closed since the initiation *in June 2017* of the Qatar Diplomatic Crisis, which is an economic blockade of the State of Qatar involving Saudi Arabia, UAE, Bahrain, and Egypt.

There is archaeological evidence of Qatar's human habitation dating back to 50,000 years ago, including Stone Age settlements and tools. However, large-scale settlements are a relatively recent phenomenon on the Qatari Peninsula beginning in the late 19<sup>th</sup> and early 20<sup>th</sup> centuries. Initial urbanization gathered pace after the exportation of oil under British rule during the mid-20<sup>th</sup> century. Development in the country later transformed into rapid urbanization and globalization after independence in 1971 due to the exportation of natural gas, especially since the 1990s. The land in Qatar is generally flat along the coastline of the Arabian/Persian Gulf. It also tends to be extremely dry, with very few inlets (Major & Tannous, 2020). Qatar's official religion is Islam, although it is not the only religion practiced in the country. There is a significant minority of Christians, Hindu, and Buddhists (~31%) due to a large expatriate population.<sup>9</sup> Only about 12% of the population are Qataris. Arabic is the official language, though people extensively use English as a second language.

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examples and State of Qatar model in this paper relies on long-established, traditional axial mapping methods of space syntax (Hillier and Hanson, 1984; Hillier, 1996).

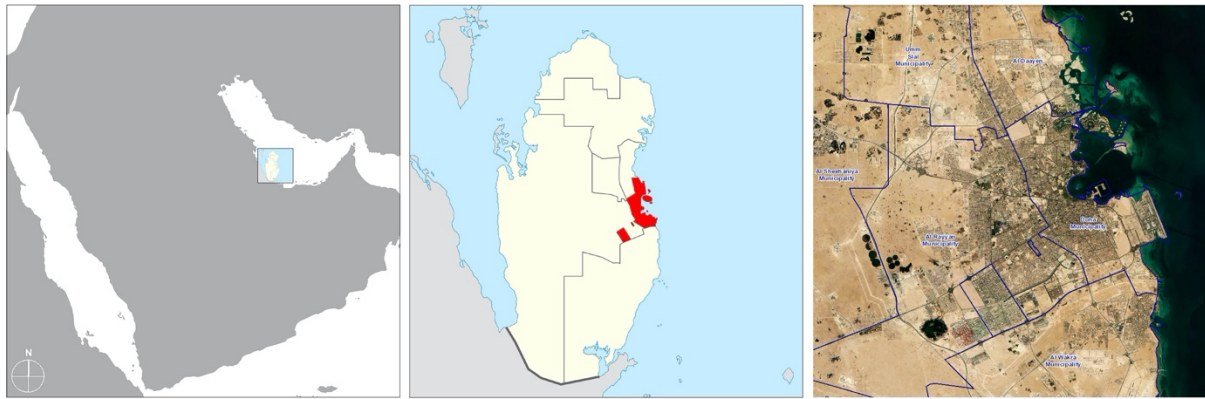
<sup>6</sup> A Combined Statistical Area (CSA) is a United States Office of Management and Budget term for a combination of adjacent metropolitan and micropolitan statistical areas (statistical areas with an urban cluster or area with a population of at least 10,000 but fewer than 50,000 people) in the United States and Puerto Rico that can demonstrate economic or social linkage (Source: US Office of Management and Budget).

<sup>7</sup> Grant ID: QUSD-CENG-2018/2019-4.

<sup>8</sup> Grant ID: QUCC-CENG-20/21-1.

<sup>9</sup> Source: Pew Forum.





**Figure 7: The location of the: (left) State of the Qatar on the Qatari Peninsula attached to the larger Arabian Peninsula adjacent to the Arabian/Persian Gulf; (center) municipal boundaries of the State of Qatar highlighting Doha Municipality (in red) and (right) satellite view of Metropolitan Doha with municipal boundaries (Source: Authors/MME).**

Seven municipalities divide the State of Qatar as administrated by the Ministry of Municipality and Environment (MME), which serves as the main regulatory body for urban planning and development in the country. The smallest in terms of metric area (203 km<sup>2</sup>) and densest for population (956,457 people) and urban development (4,711 people/km<sup>2</sup>) is Doha itself.<sup>10</sup> However, urban growth and expansion have spread to the adjacent municipalities – Al Daayan to the north, Umm Salal to the northeast, Al Wakrah to the south, and Al Rayyan to the west – during the last 20 years. The effective urban functioning and national impact of the Doha Metropolitan Region is significantly more expansive. Doha occupies up to ~5.6% of the land area in the State of Qatar. Still, it accommodates as much as ~85% of the country's total population, depending on the delineation of metropolitan boundaries and the accuracy of various population estimates.

Globalization and rapid urbanization have been distinctive characteristics of Qatar over the last 50 years, especially since the 1990s. As a result, the country witnessed a remarkable economic transformation from a small fishing and pearling nation into a prosperous, diverse economy based on natural gas and oil production and exportation. Today, the State of Qatar *"is, by far, the richest country in the world, with a GNI per capita of \$116,799 - more than \$20,000 higher than any other nation"* with more natural gas reserves (13% of total global supply) than all but two other countries (Russia and Iran) in the world (Suneson, 2019; CIA, 2020).<sup>11</sup> Revenues from natural gas and oil reserves fed rapid economic growth in the country and the hosting of mega-events such as the Asian Games 2006 and the upcoming Fédération Internationale de Football Association (FIFA) World Cup 2022. Most of this growth focused on Doha. Economic development included not only urban expansion. It also included the creation of Industrial areas in Doha and on the east coast and the inland conversion of desert wasteland tracts into irrigated agricultural land to promote food security, especially after the initialization of the diplomatic blockade in 2017 (**Figure 8**). Rapid urban growth and expansion impacted several different aspects of Doha, not only its physical size. It led to a massive population increase over the last 20 years, from an estimated metropolitan population of 492,000 in 2000 to over 2.4 million people in 2020. Over 80% of the national population lives in Doha and its suburbs of the metropolitan region.<sup>12</sup> As a result, the Qatari government faced significant issues for managing growth, transportation, infrastructure, housing, and protecting the natural environment.

<sup>10</sup> Source: Qatar Ministry of Development Planning and Statistics, 2015.

<sup>11</sup> GNI is Gross National Income.

<sup>12</sup> Approximate estimates based on various sources, but principally the Qatar Ministry of Development Planning and Statistics (MDPS).

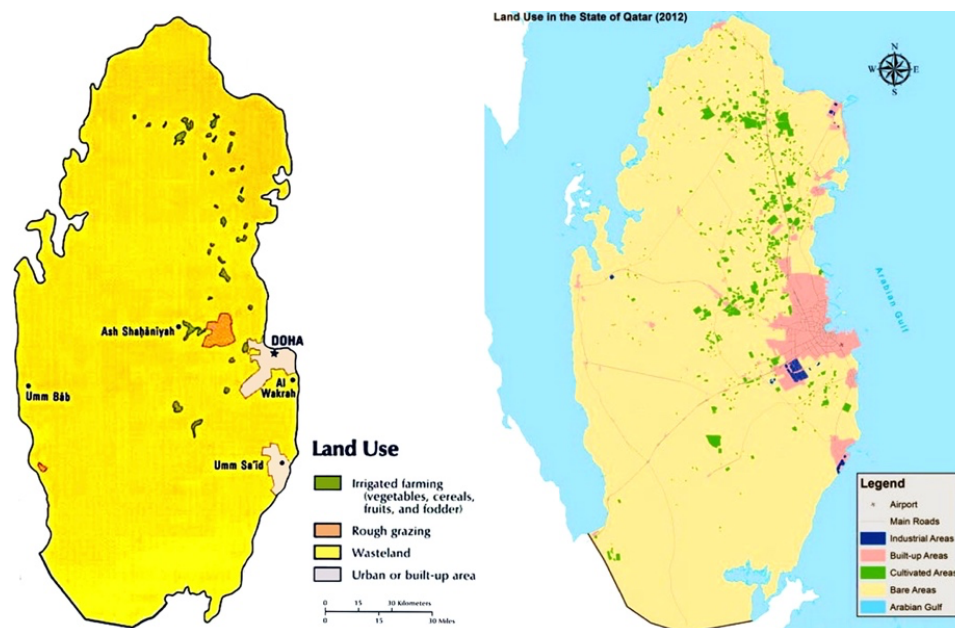


Figure 8: Land use maps of the State of Qatar in (left) 1993 and (right) 2012 (Source: Perry Casteñeda Library Map Collection, University of Texas).

Meeting these challenges led to investment in – and a radical transformation of Doha's urban environment (Salama and Wiedmann, 2013; Furlan et al., 2018). This transformation included constructing an extensive road network based on widening and a ring-road/expressway system. There was an almost complete abandonment of traditional low-rise courtyard housing in favor of contemporary (usually three-story) residential villas and high-rise apartment living (Al-Mohannadi et al., 2019). A proliferation of modern, climate-controlled shopping malls and new housing developments appeared in Doha's suburban peripheries. The planning, design, and construction of new, satellite business districts composed of iconic skyscrapers on reclaimed lands, such as the West Bay area in the 1990s and Lusail City today, changed the popular image of Doha into a city on the rise (Salama and Wiedmann, 2013; Furlan et al., 2018).

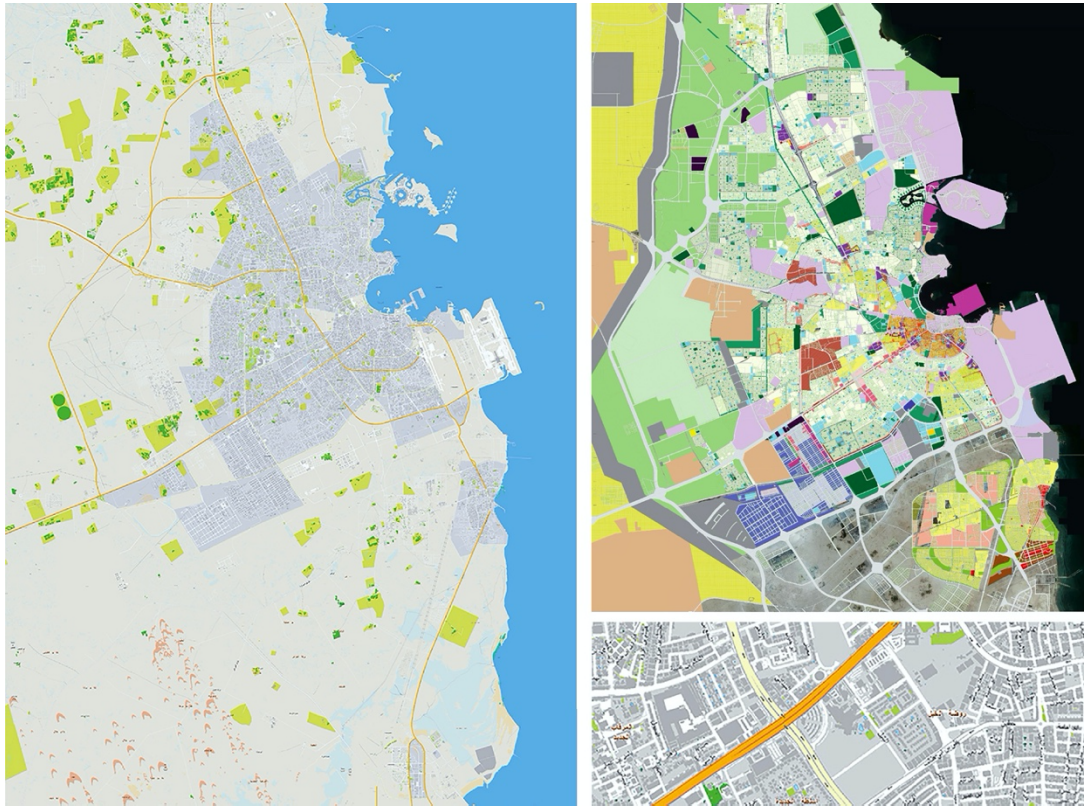
#### 4. Modeling Metropolitan Doha for Pedestrians and Vehicles

The key deliverable of a research grant in 2018-19 was a fully constructed space syntax model of the Doha metropolitan region accounting for variations between pedestrian and vehicular networks such as limited access highways, overpasses, underpasses, pedestrianized zones, etc.<sup>13</sup> Once constructed, researchers could regularly update the model to incorporate the most recent development changes to the metropolitan region's urban fabric. Researchers initially created an 'all-inclusive' model based on an MME map showing all building footprints at a scale of 1:100,000 in 2013 (Figure 9). All-inclusive means incorporating both pedestrian and limited-access vehicular routes. We also compiled an MME Zoning and Land Use map in 2008 as an additional reference.<sup>14</sup> Researchers double-checked and revised the initial iteration of the model based on the 2013 Google Earth satellite imagery. Once researchers were satisfied with the 2013 space syntax model's accuracy, they updated based on the 2018 Google Earth satellite

<sup>13</sup> Grant ID: QUSD-CENG-2018/2019-4.

<sup>14</sup> A Zoning Map of Doha Municipality using GIS shapefiles dated 31 March 2019 is now available from MME. Accessed: 25 August 2020 at [http://www.mme.gov.qa/QatarMasterPlan/Downloads/MSDP/msdp-new/English/Doha\\_Zoning\\_Arb\\_31stMarch2019.pdf](http://www.mme.gov.qa/QatarMasterPlan/Downloads/MSDP/msdp-new/English/Doha_Zoning_Arb_31stMarch2019.pdf). However, it was unavailable to the public at the start of initial mapping for the space syntax model of Metropolitan Doha during the QUSD-CENG-2018/2019-4 research grant.

imagery. Researchers double-checked this updated model against the most recent information available in Google Maps and several on-site visual surveys to ensure accuracy further.



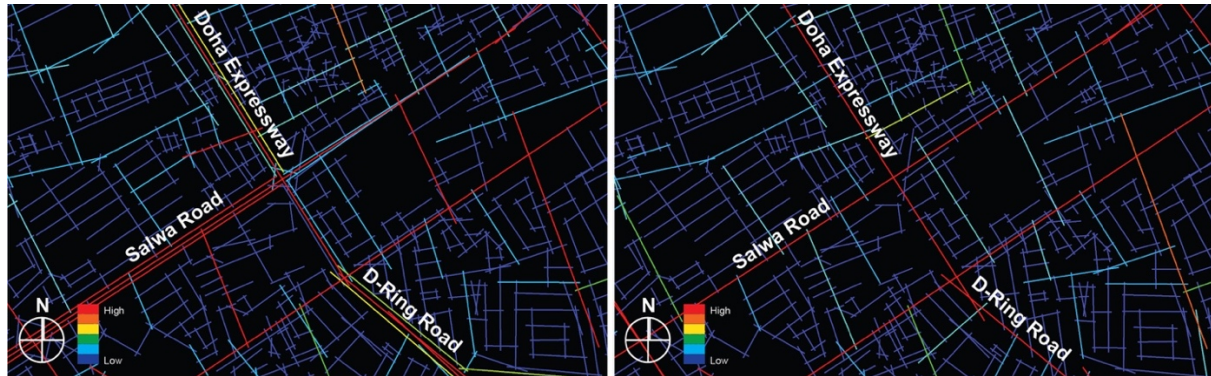
**Figure 9: The Qatar Ministry of Municipality and Environment (MME) maps showing (left) all building footprints in 2013, which served as the initial starting point for construction of the space syntax model of Metropolitan Doha, (upper right) the compiled MME Land Use and Zoning Map in 2008, and (bottom right) a close-up view of the 2013 MME map showing the building footprints near the Salwa Road/Doha Expressway interchange (Source: MME).**

During the space syntax model construction, researchers processed, revised, and updated more than 30 draft models in 2013 and ten draft models in 2018, constituting hundreds of revisions/corrections for each year. Researchers also constructed six different versions of the space syntax model for Doha at various scales by paring down the initial model using the ring road system as a successive series of smaller boundaries. Finally, once researchers were satisfied with the all-inclusive 2018 model's accuracy, it only took a single iteration to update and revise for turning movements/lanes, overpasses/underpasses, frontage roads, and the elimination of pedestrianized areas in generating the vehicular model of Doha. We double-checked this vehicular model again using Google Earth satellite imagery in 2018 and on-site visual surveys.

The primary difference between the pedestrian and vehicular model of Metropolitan Doha lies in the representation of vehicular turning movements such as the measurement of Global Choice at the interchange between Salwa Road and Doha Expressway/D-Ring Road (**Figure 10**). Global choice is a space syntax measure of 'through-movement' in the urban spatial network. The choice measurement gives every street (represented as a line of sight) an initial value of 1, which then proportionally shares that value among all immediate connections. The computer then adds up all the proportionate values shared for each street to measure the degree of importance of that street within the urban spatial network. Even this modeling technique for vehicular turning movements is relatively simplified based on cardinal



directions, i.e., left or right turns, and route continuation based on disconnection of crossing routes. However, the pedestrian model is much simpler, relying on a straightforward reading of the urban spatial network as defined by building facades. For example, the pedestrian movement model treats Salwa Road and Doha Expressway/D-Ring Road as singular spaces as read by pedestrians, incorporating simple left-right direction changes. The vehicular movement model treats Salwa Road and Doha Expressway/D-Ring Road as multiple spaces, as defined by frontage roads incorporating 45° turns to account for off-ramps in vehicular turning movements. It requires a disconnection (overpass/underpass) between the continuing route in the north-south (Doha Expressway/D-Ring Road) and east-west (Salwa Road) directions.



**Figure 10: Detail of the interchange between Salwa Road and Doha Expressway/D-Ring Road showing different modeling techniques for (left) vehicular and (right) pedestrian movement in the space syntax model for the pattern of global choice in the urban spatial network of Metropolitan Doha, Qatar in 2018 (Source: QUSD-CENG-2018/2019-4).**

The vehicular model of the urban spatial network in Metropolitan Doha incorporates this type of modeling technique for vehicular turning movements, overpasses and underpasses, and roundabouts (Figure 11). In contrast, the pedestrian network model of Metropolitan Doha incorporates a simplified reading of urban space as defined by the building facades and 90° changes of direction (left, right, straight, backward) at such significant interchanges. A key takeaway from the comparison of the pedestrian ('ped model') and vehicular ('vec model') models is that the pattern of the spatial configuration remains mostly consistent (Table 1). The model's axial size increases by 975 axial lines (+4%) due to the modeling of vehicular turning movements. Doha's most integrated street does shift from a long north-south segment of the Doha Expressway/D-Ring Road (global integration=1.86) approximately 4,000 m in length, intersecting with the most extended, straightest segment of Salwa Road (global integration=1.82) in the pedestrian model. The processing of mean depth from the most integrated street (7.43) rounds down to seven.

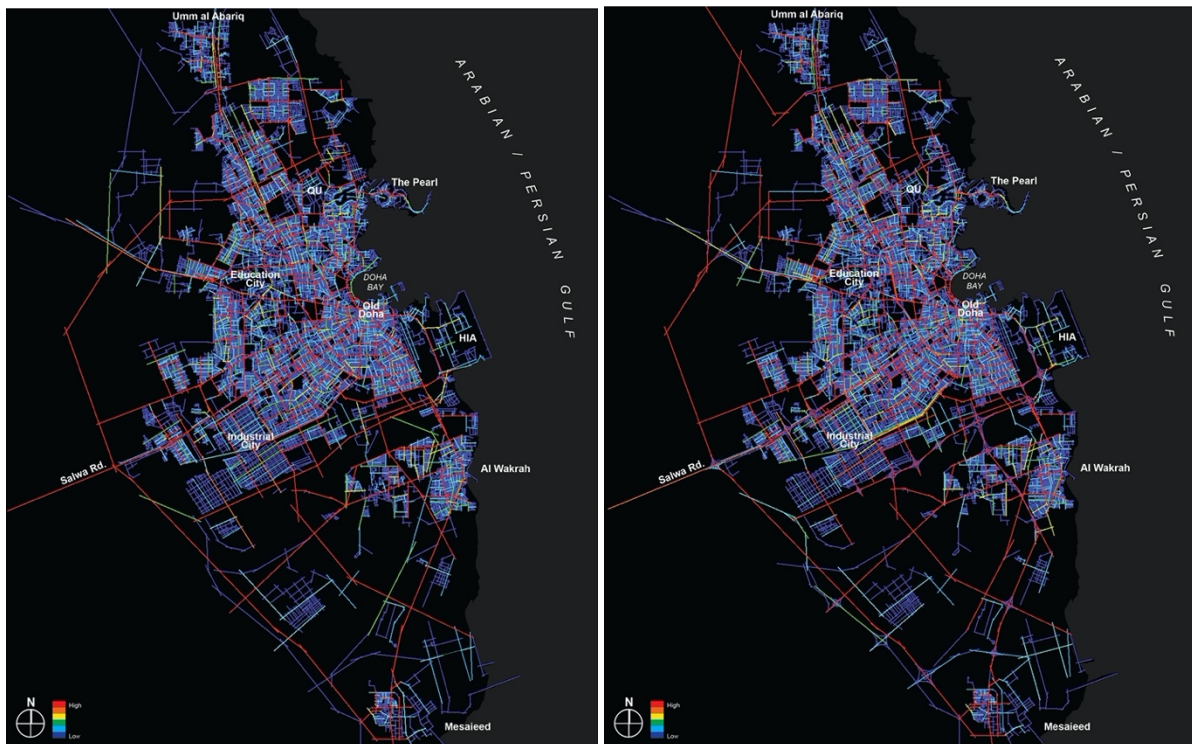
**Table 1: Comparison of axial size, mean depth from the most integrated street, intelligibility, and synergy in the pedestrian and vehicular models of Metropolitan Doha in 2018 (Source: QUSD-CENG-2018/2019-4).**

Metropolitan Doha 2018	Axial Size (Total # of Axial Lines)	Mean Depth (Most Integrated Street)	Intelligibility (R <sup>2</sup> of Global Integration v. Connectivity)	Synergy (R <sup>2</sup> of Global Integration v. Local Integration)
Pedestrian	23,800	7.43*	0.108	0.391
Vehicular	24,775	8.69**	0.097	0.376

\* Doha Expressway/D-Ring Road segment (~4,000 meters in length) interacting with longest, straightest segment of Salwa Road.

\*\* Haloul Street (~5,000 meters in length) running parallel about 590 meters south of Salwa Road.





**Figure 11: Space syntax model of global choice for (left) pedestrian and (right) vehicular movement in the urban spatial network of Metropolitan Doha in 2018 (Source: QUSD-CENG-2018/2019-4).**

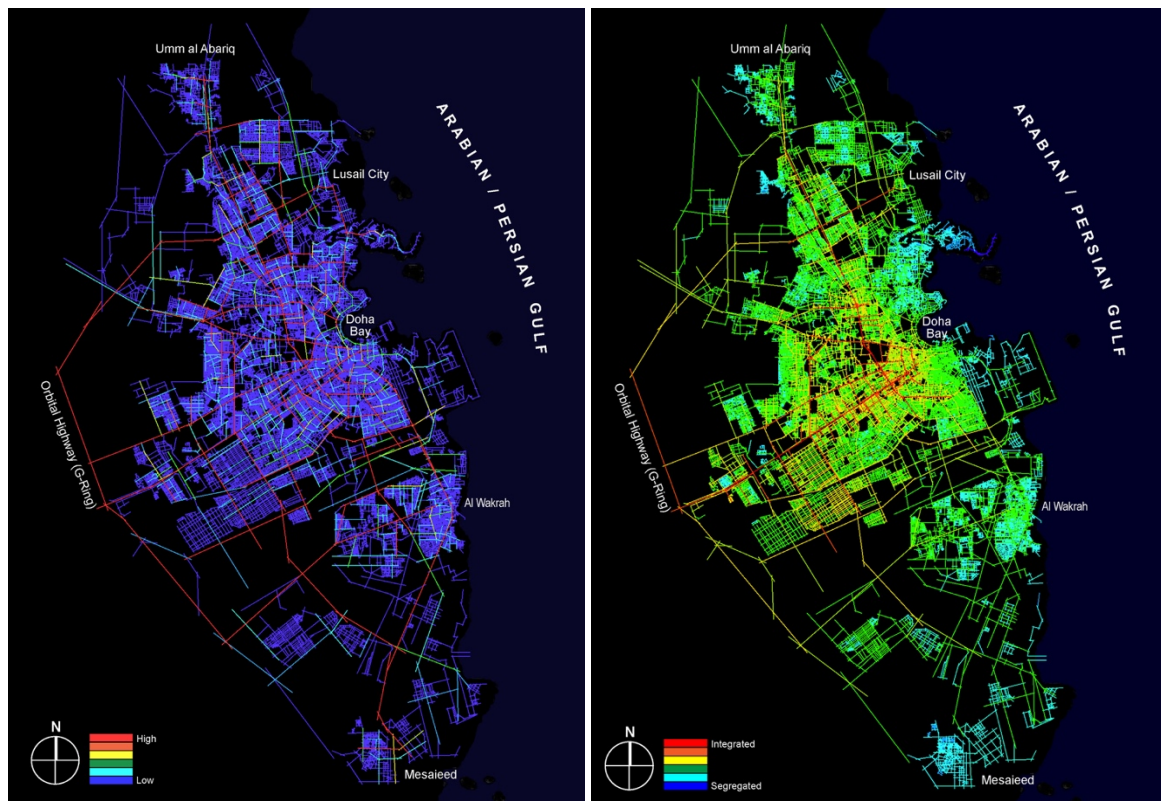
The most integrated street becomes Haloul Street (global integration=1.56) in the vehicular model. This segment of Haloul Street is approximately 5,000 m in length, running parallel to Salwa Road, about 590 meters to the south. The modeling of separate frontage roads and the limited access highway on this segment of Salwa Road drops its global integration value to 1.43 (-22%) in the vehicular model. Overall, the mean depth from the most integrated street in Doha increases 1.26 (+17%) due to the additional complexity in managing vehicular turning movements. There are other minor differences at the fine grain of the urban spatial network, most obviously in east-west frontage roads along Industrial Area Road and access roads within Hamad International Airport. The changes in Intelligibility (a second-order measure based on the  $R^2$  value of global integration vs. connectivity) and Synergy (a second-order measure based on  $R^2$  value of global integration vs. local integration, radius=3) are marginal: -10% for Intelligibility and -3.8% for Synergy in the vehicular model. Except for such detailed changes in the fine grain of the urban spatial network, the overall visual pattern for global choice, global integration, local integration, and integration based on mean depth from the most integrated street remains strongly consistent. At the large scale of the urban structure of Metropolitan Doha, these changes are minor. However, they will play a more important role when investigating specific regions and neighborhoods served by these streets.

Based on past results of space syntax research, there is an unsurprising argument that the traditional least-line axial mapping – based on a simple reading of urban space – of Metropolitan Doha offers a more realistic picture of the city as a whole than incorporating the management of vehicular turning movements and road separations, i.e., frontage roads, in the model (Penn et al., 1998; Hillier & Vaughan, 2007). After all, people drive vehicles, and they appear to ‘read’ urban space in the same manner, either way. All that changes is the speed of movement and decision-making for navigation purposes during that movement. It indicates that the ‘all-inclusive’ or pedestrian model (‘all-inclusive’ because it includes simplified modeling of major vehicular routes) should be sufficient in future research about the urban

spatial network in Metropolitan Doha. The vehicular model serves better to research transportation planning management outcomes in specific urban areas of the metropolitan region.

## 5. Metropolitan Doha 2020 and the Public Rail Transportation Network

Researchers implemented a 2020 update of the all-inclusive space syntax model of Metropolitan Doha as part of the QUCG-CENG-20/21-1 research grant. The grant also includes on-going fieldwork compiling direct counts of pedestrian and vehicular movement flows in three neighborhoods: Old Al Ghanim, northern Al Sadd, and the eastern Al Souq/Qatar National Museum area. The research team is adding pedestrian and vehicular counts for a fourth area (Souq Waqif) to the sample size based on research work arising from the "Space, Time And Natural movement in old Doha (STAND): The morphological case of Souq Waqif" grant (UREP25-002-5-001) provided by the Qatar National Research Foundation (QNRF). The direct counts of vehicular flows will be tested against automated traffic counts on segments of perimeter roads and flow projections on these areas' internal streets, all of which are being made available to the Qatar Transportation and Traffic Safety Center (QTTSC) at QU.

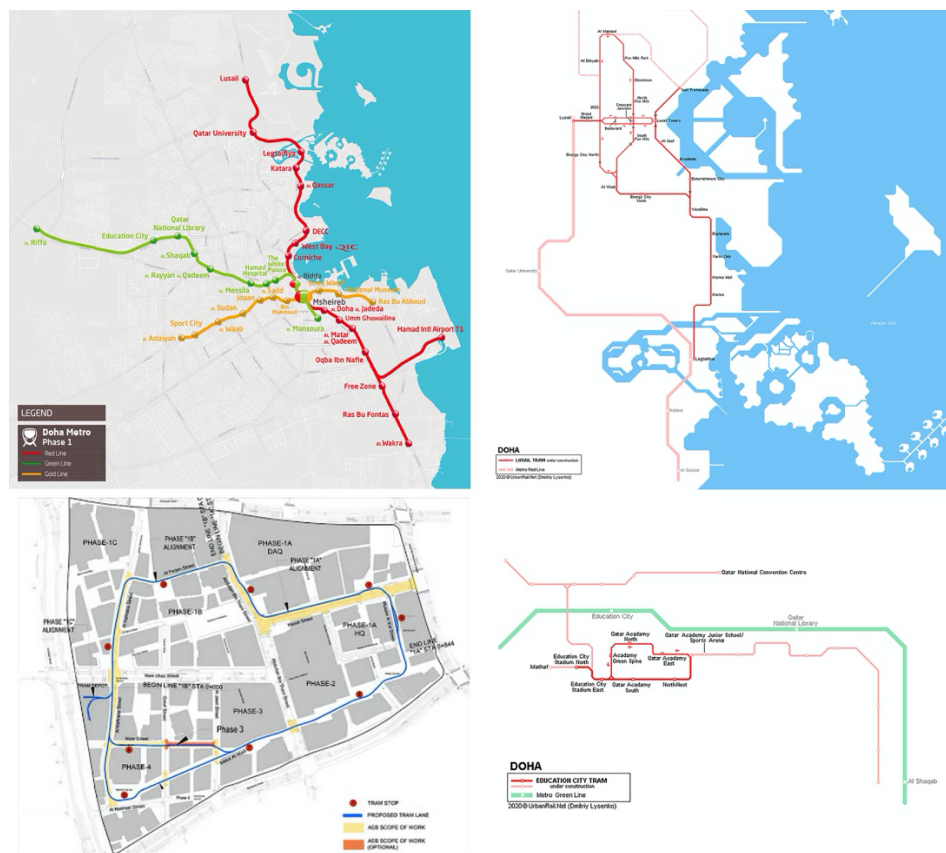


**Figure 12: Space syntax model of (left) global choice and (right) global integration (radius=n) in the urban spatial network of Metropolitan Doha, Qatar in 2020 (Source: QUCG-CENG-20/21-1).**

The primary updates to the space syntax model of Metropolitan Doha involve the inclusion of large sections of the recently-completed street network in Lusail City to the north, finalization of recently-open connections on the Orbital Highway/G-Ring to the west and north, a more detailed modeling of the Qatar University campus in north Doha, and various updates and revisions at the fine grain of the urban grid in several areas throughout Doha. Axial size increases to 24,335 in the 2020 model compared to the 2018 model (23,800 axial lines), representing an increase of 535 streets (+2.2%) modeled as axial lines in only two years. Researchers noted some changes in the value of configurational measures such as global choice and global integration at the fine grain of the urban spatial network, most clearly due to new

additions to the urban pattern in Lusail City (**Figure 12**). The most notable difference is the northward shifting of the most integrated axial line in the city from the ~4,000m segment of the Doha Expressway/D-Ring Road segment intersecting with Salwa Road to the next northerly part of Doha Expressway. It is a ~3,700m segment intersecting with major cross-streets of Khalifa Street to the north and Al Rayyan Road to the south between Zones 34-36 to the west and Zone 52 to the west. However, overall, the ortho-radial structure of the urban spatial network in Metropolitan Doha remains strongly consistent when comparing 2018 to 2020. It appears mainly due to the northward trajectory of urban development (such as Lusail City) and transportation planning efforts to redistribute and relieve, in relative terms, the degree of traffic congestion in the southern areas of the city, especially along Salwa Road.

During these updates, researchers also took the opportunity to incorporate the modeling of the new public rail transportation networks in Metropolitan Doha, including the Doha Metro (Red, Gold, and Green lines), opened portions of the Lusail City, Msheireb Downtown Doha, and Education City tram networks (**Figure 13**). There is a long history in space syntax research of simulating the connective effects of public rail transportation on the urban spatial structure, beginning with Shinichi Iida and the combined modeling of the Tokyo street network with the rapid transit system of the Tokyo Metro in the late 1990s at University College London. It includes studies modeling rapid transit public rail networks of the London Underground in London, UK (Gil, 2008; Law et al., 2008). There have also been additional studies based on Tokyo and the Tokyo Metro (Fujitani & Kishimoto, 2013), agent-based simulations of pedestrians using space syntax in Chinese rail stations (Tang & Hu, 2017), and combined modeling of the street network and rapid surface rail transit in Tel Aviv (Lebendiger & Lerman, 2019) to name but a few.



**Figure 13: Diagrammatic maps of the public rail network for the (top left) Doha Metro and the tram networks for (top right) Lusail City, (bottom left) Msheireb Downtown Doha, and (bottom right) Education City (Sources: Qatar Rail/Arab Engineering Bureau/UrbanRail.net/Dmitriy Lysenko).**



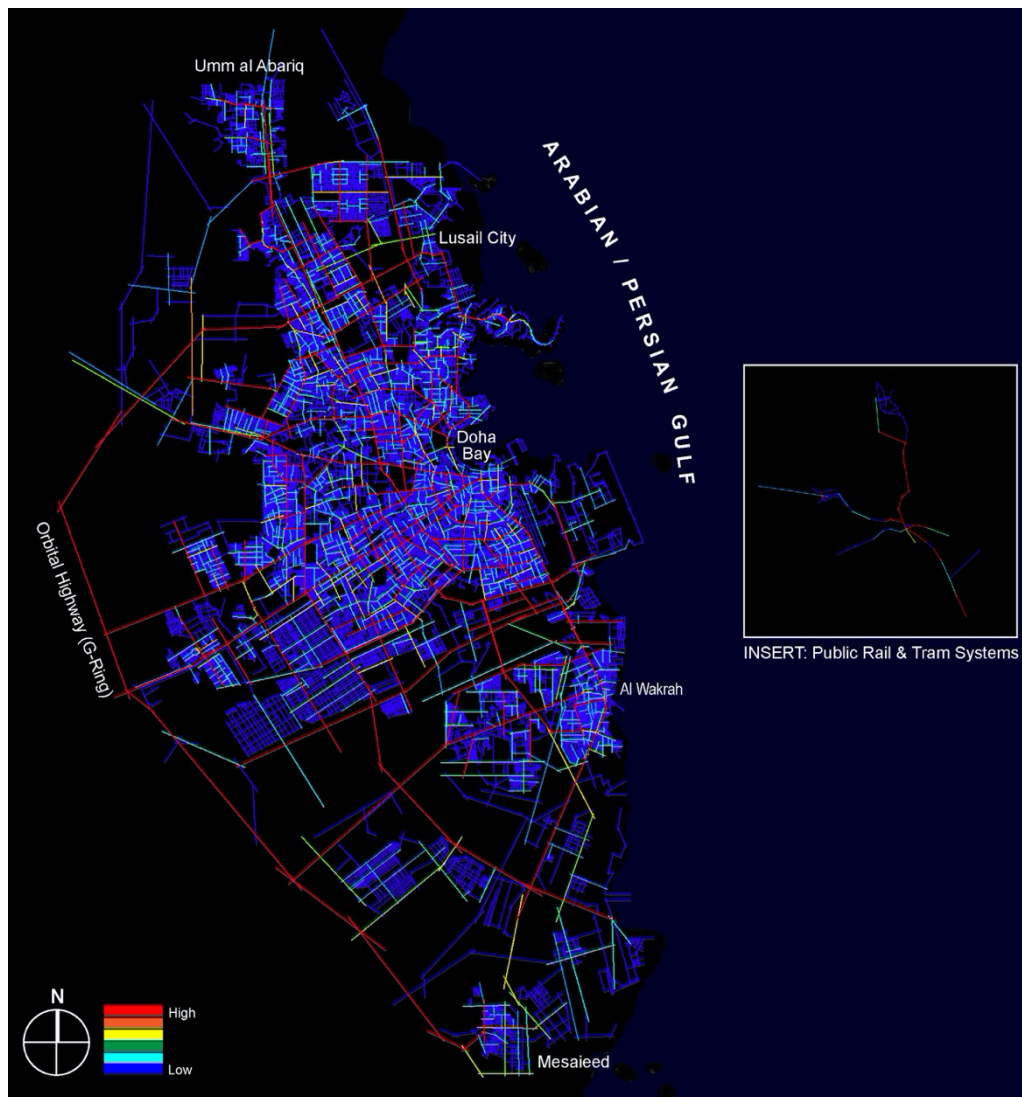
Typically, the methodology for simulating the effect of rapid transit rail transportation networks in a space syntax model of an urban spatial network involves drawing a single line of movement from station-to-station until accounting for the entire rail transportation network. Researchers need to ensure that all lines of movement connect at each station's location, including any overlap necessary to simulate the role of transportation interchanges between different rail lines. Akin to modeling and connecting with other floors of a single building using space syntax in building analysis, researchers incorporate this simplified model of the rail transportation network as a separate 'floor' of the urban spatial network. However, unlike building analysis, where researchers model the transition spaces (stairwells and elevators), this model of the rail transportation network is connected directly into the urban spatial network using a linking function in the space syntax software. The direct connection to the street network simulates the connective role of rail transportation on the urban spatial network at the macro-scale (**Figure 14**). If we were interested in the transition of passengers from the train platforms to the street level in a specific station, researchers would apply a more detailed modeling methodology to understand pedestrian movement at the micro-scale (Major et al., 1998; Tang & Hu, 2017).



**Figure 14: Demonstration of (right) close-up view of the modeling indicating key identifying rail lines and locations, and (left) linking methodology for incorporating the public rail/tram networks before computer processing of configurational measures in the space syntax model of Metropolitan Doha in 2020 (Source: QUCG-CENG-20/21-1).**

There is very little difference in terms of the visual pattern of the street network's urban structure for various space syntax measures, including Global Choice (**Figure 15**). Of course, this is unsurprising. Only 107 axial lines compose the Doha Metro's combined public rail transportation networks and various tram systems in a metropolitan region consisting of more than 24,000 streets represented as axial lines (**Table 2**). The bulk of the rail transportation network in terms of axial size (less than 1/10 of 1%) is insufficient to significantly adjust the visual pattern of the urban structure of the street network in the metropolitan region. The global choice pattern for the public rail transportation itself is interesting (see the insert image of Figure 15). It highlights the importance of the Red Line from the main terminal of Msheireb to the Qatar University Metro Station. It appears reflective of the northward trajectory of urban growth in the metropolitan region's street network as a whole in general. It also reflects the importance of the main terminal at Msheireb, including the immediate rail network connections from Msheireb on the Gold Line eastward to Souq Waqif, on the Green Line westward to The White Palace (eastern edge of Hamad Medical City), and on the Red Line southward to Al Doha al Jededa.





**Figure 15: Space syntax model of global choice in the urban spatial network of Metropolitan Doha, Qatar in 2020 with (insert) the public rail and tram systems (Source: QUCG-CENG-20/21-1). NOTE: Model of public rail and tram systems shown at half of actual scale in the insert.**

**Table 2: Comparison of axial size, mean depth from the most integrated street, intelligibility, and synergy in the space syntax model of the Metropolitan Doha with and without the public transportation rail network (Source: QUCG-CENG-20/21-1).**

Metropolitan Doha 2020	Axial Size (Total # of Axial Lines)	Mean Depth (Most Integrated Street)	Intelligibility (R <sup>2</sup> of Global Integration v. Connectivity)	Synergy (R <sup>2</sup> of Global Integration v. Local Integration)
Without public rail	24,335	7.43	0.109	0.388
With public rail	24,442	7.38	0.121	0.423

\* Northern segment of Doha Expressway ~3,700 meters in length with major cross-streets of Khalifa Street to the north and Al Rayyan Road to the south between Zones 34-36 to the west and Zone 52 to the west.

The clearest effect of modeling the rapid transit rail transportation network with the urban street network of Metropolitan Doha lies in the changes to several spatial measures (refer to Table 2). The mean depth from the most integrated street in Metropolitan Doha reduces from 7.43 to 7.38, and the degree of Intelligibility and Synergy both increase in the urban spatial network. Intelligibility increases 11% from 0.101 to 0.121 and Synergy increases 9% from 0.388 to 0.423. By definition, modeling the rail

transportation network means increasing the urban system's axial size, so it introduces more depth into the configurational model. Given these conditions, the logical interpretation is the reduction in mean depth from the most integrated street and increases in Intelligibility and Synergy represents a significant enhancement in the urban spatial network for accessibility and readability. In effect, this the explicit nature of connective rail transportation networks for cities. In this sense, the Doha Metro and more localized tram networks in Lusail City, Education City, and Msheireb Downtown Doha collectively appear to achieve their purpose at the macro-scale of the urban structure for Metropolitan Doha

## 6. Modeling the State of Qatar

As part of coursework on the MUPD Program in the DAUP-CENG at QU, graduate students prepared the initial modeling of different regions of the State of Qatar in expanding the space syntax model of Metropolitan Doha to the entire State of Qatar. In areas lacking built-up areas, graduate students and researchers merely modeled roads' alignment, erring on the side of simplicity and readability while ignoring minor changes in alignment. Researchers on the QUCG-CENG-20/21-1 then reviewed, revised, and verified this modeling to produce the final space syntax model of the State of Qatar in 2020. The expanded model includes all settlements and outlying regions such as Al Ruwais and Fuwayrit in the far north, Al Khor and the Industrial City of Ras Laffan in the northeast, and Durkan and Zekreet in the west.

The total size of the space syntax model of the State of Qatar without the rail transportation network in Doha is 28,700 streets represented as axial lines (**Table 3**). The effect of modeling the rail transportation network in Doha at the scale of the State of Qatar is minimal with only marginal differences for mean depth from the most integrated street in the State of Qatar (the same ~3,700m segment of Doha Expressway as the model of Metropolitan Doha), Intelligibility, and Synergy. It is unsurprising, given the connective focus of the rail transportation network in the capital city. The axial size of the space syntax model for the State of Qatar indicates that approximately 85% of all streets represented as axial lines composed the urban spatial network of Metropolitan Doha. It is almost the same as the proportion of the population living in Doha compared to the entire State of Qatar, i.e., ~85% of the total population of 2.8 million.

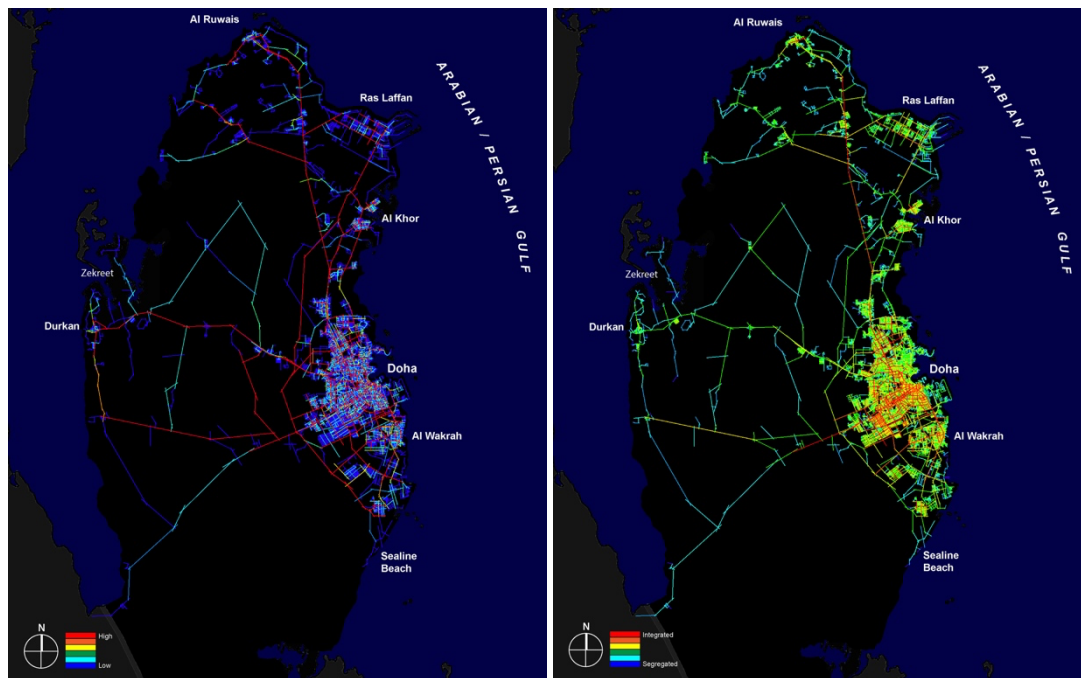
**Table 3: Comparison of axial size, mean depth from the most integrated street, intelligibility, and synergy in the space syntax model of the State of Qatar with and without the public transportation rail network (Source: QUCG-CENG-20/21-1).**

State of Qatar 2020	Axial Size (Total # of Axial Lines)	Mean Depth (Most Integrated Street)	Intelligibility (R <sup>2</sup> of Global Integration v. Connectivity)	Synergy (R <sup>2</sup> of Global Integration v. Local Intergration)
Without public rail	28,770	8.37*	0.082	0.298
With public rail	28,877	8.35*	0.086	0.309

\* Northern segment of Doha Expressway ~3,700 meters in length with major cross-streets of Khalifa Street to the north and Al Rayyan Road to the south between Zones 34-36 to the west and Zone 52 to the west.

The mean depth from the most integrated street in the State of Qatar is 8.37, representing a 12.7% increase compared to Metropolitan Doha (refer back to Table 2). It means that, on average, almost everywhere is only 8-9 changes of direction away from the Doha Expressway/D-Ring Road and Salwa Road in the State of Qatar. Intelligibility and Synergy at the scale of the country decreased to 0.082 and 0.298, respectively. This change represents a 23-25% decrease for these second-order measures, primarily due to the regional highway/road network connecting the hinterland settlements of Al Ruwais and Ras Laffan to the north, Durkan and the Zekreet peninsula to the west, and the overland road connection to Saudi Arabia. Interestingly, there is a still-noticeable effect of the rail transportation

network enhancing Intelligibility (+5%) and Synergy (+4%) in the State of Qatar as a whole. However, the effect is about half of that in Metropolitan Doha itself.



**Figure 16: Space syntax model of the State of Qatar for (left) global choice and (right) local integration (radius=3) in 2020 (Source: QUCG-CENG-20/21-1).**

Given the physical, social, and cultural importance of Doha's capital city in the State of Qatar, space syntax modeling of the entire country accurately reflects the functional dominance of the capital city in Qatari society. The visual pattern of all space syntax measures highlights the radial importance of Salwa Road, Al Waab Road, and Al Rayyan Road in Doha and the State of Qatar. They also highlight the role of the ring road system in the city, especially the importance of the new Orbital Highway/G-Ring Road, in mediating for urban expansion at the macro-scale of Metropolitan Doha. Global choice highlights not only the importance of these streets in Doha and Qatar but also the connective importance of the highways and roads in the hinterlands connecting Doha with the settlements of Al Ruwais and Ras Laffan in the north, and Durkan and the Zekreet peninsula to the west (Figure 16, left). A more localized view of the street network in the State of Qatar is also illuminating as local integration (radius=3, or only 3 change of direction away) highlights the importance of several streets associated with specific settlements. It includes Al Wakrah Road in a north-south direction and Al Wukair Street heading inland to the west on the east coast in Al Wakrah, south of Metropolitan Doha. Local integration also highlights the access road approximately 5.5 kilometers (km) in length connecting into Al Khawr Town Road at the center of Al Khor, the well-defined cross-axis to the west of Al Dhakira, and the two long roads parallel to each other and the coast in the geometric grid of Ras Laffan Industrial City in the in these northeastern areas of Qatar. Local integration also highlights the importance of the Madinat Al Shamal/Al Gharya Road running inland and parallel to the coast, and its intersection with the extension of Al Meena Road running perpendicular, in Al Ruwais in the far north of Qatar. Finally, Al Shamal Road/Highway 1 takes on critical importance for local integration values by connecting all of these northern settlements in the north part of the country.

## 7. Conclusion

Researchers and practitioners have been modeling the street networks of metropolitan and geographical regions using space syntax or configurational analysis since the late 1990s and early 2000s. Some models even extend to a national scale. Researchers at Qatar University constructed a space syntax model of Metropolitan Doha in 2018. It covered a land area of 650 km<sup>2</sup>, encompassing over 24,000 streets, and approximately 85%) of the 2.8 million people living in Qatar. In a short time, this model has led to a deeper understanding of spatial structure at the metropolitan and neighborhood level in Doha compared to other cities, especially in the GCC region. The paper presented the initial results of expanding the model to the entire State of Qatar, which provided ideal conditions on the Qatari Peninsula of the Arabian Peninsula for this type of large-scale modeling using space syntax. The expanded model includes all settlements and outlying regions. The results were a very realistic picture of the functioning of Metropolitan Doha and the State of Qatar for street-level and public rail transportation movement. The paper demonstrates how researchers can utilize space syntax to learn more and understand better about the spatial network of Metropolitan Doha and the entire State of Qatar. With this knowledge, researchers can help guide the future development of the built environment to the benefit of all citizens and residents.

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## 9. References

- Al-Mohannadi, A., Furlan R., Major, M.D. (2019). "Socio-Cultural Factors Shaping the Spatial Form of Traditional and Contemporary Housing in Qatar: A comparative analysis based on space syntax," *12th International Space Syntax Symposium Proceedings*. Beijing, China: Beijing Jiao Tong University, 8-13 July 2019, 285: 1-19.
- Baofu, P. (2009). *The Future of Post-Human Mass Media: A Preface to a New Theory of Communication*. Newcastle upon Tyne, United Kingdom: Cambridge Scholars Publishing. ISBN-13: 978-1-4438-0327-4, ISBN-10: 1-4438-0327-8.
- Benedikt, M.L. (1979). "To Take Hold of Space: Isovists and Isovists Fields," *Environment and Planning B: Planning and Design*, 6: 47–66.
- CIA. (2020). *The World Factbook 2020*. Washington, DC: Central Intelligence Agency.
- Fujitani, M., Kishimoto, T. (2013). Space syntax analysis integrating street and railway networks: A case study in Tokyo. *2013 International Space Syntax Symposium Proceedings*, Sejong University Press.
- Furlan, R., Petruccioli, A., Major, M.D., Zaina, S., Zaina, S., Al Saeed, M., Saleh, D. (2018) "The urban regeneration of west-bay, business district of Doha (State of Qatar): A transit-oriented development enhancing livability," *Journal of Urban Management*, Open Access, 16 November 2018, ISSN: 2226-5856.
- Gil, J. (2008). "Integrating Public Transport Networks in the Axial Model," *Eighth International Space Syntax Symposium Proceedings* (M. Greene, J. Reyes, A. Castro, Eds.). Santiago de Chile: Pontifical Catholic University of Chile, 8103: 1-21.
- Hanson, J. (2009) "The Economic 'Health' of Market Towns: A Configurational Approach to Accessibility," *Seventh International Space Syntax Symposium Proceedings* (Eds. D. Koch, L. Marcus, J. Steen), Stockholm: KTH, 2009: 014.1–014.28.
- Hanson, J. (1998). *Decoding Homes and Houses*. Cambridge: Cambridge University Press.



- Hillier, B. Vaughan, L. (2007). "The City as One Thing," *Progress in Planning*, **67**(3): 205–230.
- Hillier, B. (1996). *Space is the Machine: A Configurational Theory of Architecture*. Cambridge: Cambridge University Press.
- Hillier, B., Penn, A., Hanson, J., Grajewski, T., Xu, J. (1993). "Natural Movement: or, Configuration and Attraction in Urban Pedestrian Movement," *Environment and Planning B: Planning and Design*, **20**: 29–66.
- Hillier, B. (1989). "The Architecture of the Urban Object," *Ekistics*, **334/335**: 5–20.
- Hillier, B., Burdett, R., Peponis, J., Penn, A. (1987b). "Creating Life: Or, Does Architecture Determine Anything?" *Architecture et Comportement/Architecture and Behaviour*, **3**(3): 233–250.
- Hillier, B., Hanson, J., Graham, H. (1987a). "Ideas are in Things: An Application of Space Syntax Method to Discovering Housing Genotypes," *Environment and Planning D: Planning and Design*, **14**: 363–385.
- Hillier, B. Hanson, J. (1984) *The Social Logic of Space*. Cambridge: Cambridge University Press.
- Jabi, W. (2013). *Parametric Design for Architecture*. London: Laurence King. ISBN-13: 9781780673141.
- Kasemsook, A., Poon Porn, P., Chupradit, W., Boonyanusarn, S., Tanphalang, R., Srisalaui, B., Laithaviwat, M. (2019) "On the Borders: Reordering the Planning Landscape?" *12<sup>th</sup> International Space Syntax Symposium Proceedings*. Beijing, China: Beijing Jiao Tong University, 8-13 July 2019, 267: 1-15.
- Khan, A., Major, M.D., Tannous, H.O. (2020). "Tradition and Transformation in Two Marketplaces: Souk Al Wakrah and Souk Waqif, Qatar," *Urban Design International*, forthcoming.
- Law, S., Chiaradia, A., Schwander, C. (2008). "Towards a Multi-Modal Space Syntax Analysis: A Case Study of the London Street and Underground network," *Eighth International Space Syntax Symposium Proceedings* (M. Greene, J. Reyes, A. Castro, Eds.). Santiago de Chile: Pontifical Catholic University of Chile, 8021: 1-20.
- Lebendiger, Y. Lerman, Y. (2019). "Applying space syntax for surface rapid transit planning," *Transportation Research Part A: Policy and Practice*, Elsevier, 128(C), 59-72.
- Major, M.D., Tannous, H.O. (2020). "Form and Function in Two Traditional Markets of the Middle East: Souq Mutrah and Souq Waqif," Special Issue on Space Syntax Theory, Methods and Applications, *Sustainability*, **12**, forthcoming.
- Major, M.D. (2020) "The Good, the Bad, and the Ugly: Historic Design Lessons and Contemporary Planning Failures in Savannah, Georgia USA," *5<sup>th</sup> ISUF-Italia 2020 Conference*, Sapienza Università di Roma, 19-22 February 2020, Rome, Italy.
- Major, M.D., Tannous, H.O., Mirincheva, V. (2019) "Urban Transformations: From restricted random aggregation to designed cultural intent in Middle Eastern cities," *12<sup>th</sup> International Space Syntax Symposium Proceedings*. Beijing, China: Beijing Jiao Tong University, 8-13 July 2019, 282: 1-15.
- Major, M.D. (2018) *The Syntax of City Space: American Urban Grids*. New York/London: Routledge.
- Major, M.D. (2000). "Designing for Context: The Use of Space Syntax as an Interactive Design Tool in Urban Development," *Planning Forum*, Austin, Texas: University of Texas, **6**: 40–56.
- Major, M.D., Stonor, T., Penn, A. (1998). "Passengers, Pedestrians and Shoppers: Space Syntax in Design" *Passenger Terminal World*. London: April 1998, 38-42. ISSN: 1362-0770.
- Millard-Ball, A. (2015) "Phantom trips: Overestimating the traffic impacts of new development," *The Journal of Transport and Land Use*, **8**:1 (2015), 31-49. ISSN: 1938-7849, <http://dx.doi.org/10.5198/jtlu.2015.384>.
- Penn, A., Hillier, B., Banister, D., Xu, J. (1998). "Configurational Modeling of Urban Movement Networks," *Environment and Planning B: Planning and Design*, **25**: 59–84.
- Salama, A.M., Wiedmann, F. (2013). *Demystifying Doha: On Architecture and Urbanism in an Emerging City*. New York: Ashgate Publishing/Routledge.
- Schmitt, A. (2014). "Whoops! How Planners and Engineers Badly Overestimate Car Traffic," *Streetsblog USA*, 12 December 2014. Retrieved: 9 August 2020 at



- <https://usa.streetsblog.org/2014/12/12/whoops-how-planners-and-engineers-badly-overestimate-car-traffic/>.
- Speck, J. (2013). *Walkable City: How Downtown Can Save America, One Step at a Time*. New York: North Point Press.
- Suneson, G. (2019) "These are the 25 richest countries in the world," *USA Today*, 8 July 2019. Retrieved: 18 July 2020 at <https://www.usatoday.com/story/money/2019/07/07/richest-countries-in-the-world/39630693/>.
- Tang, M., Hu, Y. (2017). Pedestrian Simulation in Transit Stations Using Agent-Based Analysis. *Urban Rail Transit* **3**, 54–60, <https://doi.org/10.1007/s40864-017-0053-5>.
- Tannous, H.O., Major, M.D., Furlan, R. (2020) "Accessibility of Green Spaces in a Metropolitan Network: Using Space Syntax to Objectively Evaluate the Spatial Locations of Parks and Promenades in Doha, State of Qatar," *Urban Forestry and Urban Greening Journal*, forthcoming.
- Tannous, H.O., Major, M.D.; (2020) "The Spatial Logic of the Arabian Coastal City: The Case of Doha, State of Qatar and Muscat, Sultanate of Oman," *5<sup>th</sup> ISUF-Italia 2020 Conference*, Sapienza Università di Roma, 19-22 February 2020, Rome, Italy.
- Tannous, H.O. (2020) *Traditional Markets in Context: A Morphological Comparison of Souq Waqif in Doha, Qatar and Mutrah Souq in Muscat, Oman*. MUPD 760 Thesis Focus on Urban Design, Doha, Qatar, copies available from the authors and Qatar University Library.
- Tiffin, J., Terashima, N., Eds. (2001). *Hyperreality – Paradigm for the Third Millennium*. New York/London: Routledge. ISBN-13: 978-0415261043, ISBN-10: 041526104X
- Turner, A. (2009) "Stitching Together the Fabric of Space and Society: An Investigation into the Linkage of the Local to Regional Continuum," *Seventh International Space Syntax Symposium Proceedings* (Eds. D. Koch, L. Marcus, J. Steen), Stockholm: KTH, 2009: 116.1–116.1
- Turner, A. (2007) "From Axial to Road-centre Lines: A New Representation for Space Syntax and a New Model of Route Choice for Transport Network Analysis," *Environment and Planning B: Planning and Design*, **34**(3), 539–555.
- Turner, A., Doxa, M., O'Sullivan, D., Penn, A. (2001). "From Isovists to Visibility Graphs: A Methodology for the Analysis of Architectural Space," *Environment and Planning B: Planning and Design*, **28**(1): 103–121.
- Whitt, W., Maria, A. (1997). "Introduction to modeling and simulation," *Proceedings of the 1997 Winter Simulation Conference* (S. Andradóttir, K. J. Healy, D. H. Withers, and B. L. Nelson, Eds.). IEEE Computer Society, *Winter Simulation Conference*, Atlanta, Georgia USA, 7-10 December 1997, 7-13. ISBN: 0-7803-4278-X. Retrieved: 7 August 2020 at <http://acqnotes.com/Attachments/White%20Paper%20Introduction%20to%20Modeling%20and%20Simulation%20by%20Anu%20Maria.pdf>
- Woodbury, R. (2010). *Elements of Parametric Design*. New York/London: Routledge. ISBN 978-0415779876.

