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التحليل المكاني لشبكة الشوارع في الكويت

محمد العطار - مارك بيكروفت - جاسم البناي

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محمد أنور العطار
مارك بيكروفت
جاسم البناي

ملخص

الهدف: نظراً لعدم توفر معلومات كافية عن وضع شبكة الشوارع في الدول النامية في الوقت الراهن، فإن الهدف الشامل لهذه الدراسة هو التحليل المكاني لشبكة الشوارع في دولة الكويت من ناحية مدى مشابهتها للنمط الشبكي، وكفاءة النقل، والاتصال باستخدام عدة مؤشرات من بينها، على سبيل المثال، مؤشر ترتيب التوجه، ودوران الشوارع، ومتوسط طول الشوارع، ومتوسط درجة التقاطع، ونسبة الطرق المسدودة، ونسبة التقاطعات الرباعية. **المنهجية**: تستخدم هذه الدراسة حزمة البايثون OSMnx التي تعمل على تحصيل ونمذجة وتحليل مستودع البيانات مفتوحة المصدر OpenStreetMap لتحليل البيئة المبنية في الكويت. وقد تم استكمال هذا التحليل بالمعلومات النوعية. **النتائج**: (1) يتجلى أدنى توجيه لشبكة الشوارع في المناطق الساحلية، فيما يرتفع التوجيه في المناطق السكنية النموذجية؛ (2) مقارنةً بالمناطق السكنية، تتميز المناطق غير السكنية بشبكة شوارع ذات نسيج لا يتمتع بتفاصيل دقيقة، وباتصال أقل للتقاطعات، ودورانية أكثر للشوارع. **الخاتمة**: من خلال التعرف إلى هذه الخصائص، يمكن تطبيق تخطيط حضري أكثر استدامة في توسعة المنطقة المبنية في الكويت، بالإضافة إلى تقديم بيانات عن شبكة الشوارع لإجراء المزيد من الدراسات.

المصطلحات الرئيسة: تخطيط حضري، النقل، نظم المعلومات الجغرافية، شبكة الشوارع، نمذجة الشوارع.

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Spatial Analysis of Kuwait Street Networks

Mohammad Alattar*

Mark Beecroft**

Jasem A Albanai***

Abstract

Objective: Since only little is known about street networks (SNs) in developing countries, the overarching aim of this study is to spatially analyze Kuwait SN griddedness, transportation efficiency, and connectivity, using several indicators (i.e., orientation-order, street circuity, average street length, average node degree, proportion of dead-ends, and proportion of four-way intersections). **Methodology**: This work utilizes the python package OSMnx which obtains, models, and analyzes the open-sourced data repository OpenStreetMap to analyze the Kuwait built environment. This analysis has been complemented with qualitative information. **Results**: the key findings are: (I) orientation-order is lowest in some of the coastal areas and high in some modular residential areas; (II) Furthermore, compared to residential areas, non-residential areas have coarse-grained SNs, lower intersections connectivity and higher street circuity. **Conclusion**: Through acknowledging these features, more sustainable urban planning can be undertaken for expanding the built area in Kuwait. Further, the obtained data was made available for conducting further studies.

Keywords: Urban Planning, Transportation, Geographic Information System, Street Network, Street Modelling.

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* Assistant Professor, Department of Social Studies, College of Basic Education, PAAET.
Research interests: better understand the built environment by utilizing open geospatial data from various sources. email: ma.alattar2@paaet.edu.kw

** Senior Lecturer in Transport Studies, Center for Transport Research, School of Engineering, University of Aberdeen, UK. **Research interests**: personal security in travel; transport technologies and user needs; transport futurology; and intelligent transport systems.

*** DPhil. Candidate, School of Geography and the Environment, University of Oxford, Uk.
Research interests: machine learning, remotely sensed methods and spatial modelling in different sub-fields of geography in the Middle East and the State of Kuwait. email: albanay.com@gmail.com

1. Introduction

Street networks (SNs) are the backbone of any human settlements as they are determinants of many human activities. The way these networks are structured exerts an influence on travel behavior and travel mode choice (Marshall & Garrick, 2010), energy usage (Paradis et al., 1983), microclimate (Sanusi et al., 2016), and public health (Sarkar et al., 2013). These networks can expand either in a planned or self-organized manner due to terrains and other physical obstacles such as waterbodies (Boeing, 2019).

SNs are considerably resilient and can be capable of modification over time (Gudmundsson & Mohajeri, 2013). However, a better understanding of the performance of SNs, through various indicators will reveal the SN nuances and will help in informed decision making for future urban planning. Previous studies were conducted to understand the SNs performance in well-developed nations. For example, Gudmundsson and Mohajeri (2013) studied SNs in 41 British cities and Boeing (2019) examined SNs in 100 cities worldwide. Although there have been some attempts to study the various aspects of SN in the Gulf Cooperation Council (GCC), there is a geographical and temporal gap in the literature in countries like Kuwait, for example, where data are very scarce. The built area of Kuwait makes an interesting case study due to the following:

i) The country has undergone a series of master plans to support urban growth and accommodate the rapid population increase after the discovery of oil resources. Consequently, various challenges, such as housing shortage and traffic congestions, accompany this growth (Alghais & Pullar, 2018a).

ii) Kuwait is a car-dependent city, where SNs are a vital component of the urban fabric; trips made by private cars constitute 99% and 50% of trips made by citizens and non-citizens, respectively (Gomes, 2020).

This study aims to spatially analyze Kuwait SNs to understand their characteristics in terms of their griddedness and connectivity. The objectives of this study are: (1) Modeling Kuwait SNs and calculating the indicators of interests (shown in section 2); (2) Analyzing and qualitatively discussing the results of the findings; (3) openly providing a pythonic script to aid future researchers in conducting further studies on Kuwait

SN. Such an endeavor will advance the literature on urban morphology – the study of the built environment arrangement, spacing and other spatial characteristics - and help the transferability and comparability from other locations of the various urban fabric elements, such as public transportation and infrastructure (Leng et al., 2020). This study demonstrates the usability of the Python package OSMnx that utilizes OpenStreetNetwork – a crowdsourced data repository of SNs – to obtain and analyze SNs (Boeing, 2017). This approach is deemed to be valuable in view of the unavailability of an authoritative dataset.

1.1. Literature Review

1.1.1. Street Networks

SNs in quantitative studies are represented mathematically using graph theory, where streets are expressed as edges, connected with other streets using intersections expressed as nodes. Indicators of interest are presented in Table 1.

Table 1.

Indicators of Interest

Indicator	Description
Orientation-order	Measures the griddedness of a given SN through quantifying the streets' orientation internal consistency.
Average street length	Measures the average distance between each two ends of every street. This indicator is a proxy for network size.
Street circuity	Measures transportation efficiency by calculating the ratio to straight-line distances.
Average node degree	Measures the average number of edges (streets) each node (intersection) is connected to.
Proportion of dead-ends	Proportion of nodes (intersections) connected to one edge (street)
Proportion of four-way intersections	Proportion of nodes (intersections) connected to four edges (streets)

Orientation-order quantifies the extent to which streets point in four directions shaping a perfect grid. Gridded SN, is believed to maximize social equality and uniformity (Wingert-Playdon, 2014). Along with other spatial cues, such as landmarks, waterbodies, green spaces, the griddedness of a given SN plays an important role in wayfinding and navigation (Davies & Pederson, 2001). Historically, grid street patterns were adopted by the Roman Empire to facilitate the expansion of the empire seamlessly (Kaiser, 2011); in some medieval towns, grid streets with east-west orientation arrangement had been applied to maximize sunlight (Lilley, 2001). Grid pattern has an impact on route choice as Dalton (2001) claimed; people tend to conserve angular linearity while travelling; van Nes and Yamu (2017) stated that people prefer angles of 90 degrees or 180 degrees when changing directions, where 30 degrees or 60 degrees might make people lose their way.

However, little is known about these remaining indicators and their impact on urban form. As for street length, Mohajeri, Gudmundsson and French (2015) found a linear relation between fuel consumption and CO2 emission with total street length. Street circuity measures the transport efficiency of a given street, and it is also known as a detour index or a route factor. High values of street circuity usually indicate obstacles and underlying terrain (Costa et al., 2021). For example, in winter, ice impede shortcuts and thus increases the circuity of walking trips in Calgary (O'Sullivan & Morrall, 1996). Average node degree assesses the level of connectivity of the street network (Mottelson & Venerandi, 2020).

1.1.2. Kuwait and GCC Built Environment

GCC countries (the Kingdom of Bahrain, the United Arab Emirates, the Sultanate of Oman, the Kingdom of Saudi Arabia, Qatar, and Kuwait) exhibit similarities in urban externalities and challenges either because of or due to the SN. Countries in this region have always sought to improve their sustainability and livability. Most studies in this region discussed the walkability issue, such as Abu Dhabi (Alawadi et al., 2022) and Dubai (Mushtaha et al., 2018) in UAE; Qatar (Shaaban, 2019),; Khobar (AlQahtany et al., 2021) and Riyadh (Almahdy, 2020) in KSA. These studies indicated that certain infrastructure such as shading, and sidewalks might increase walkability. Most GCC countries, including Kuwait, are applying superblocks in which large tracts of area is connected by arterial roads. The superblock phenomenon has been studied numerously in Abu Dhabi, UAE (Kyriazis et al., 2002; Scoppa et al., 2018; Scoppa & Anabtawi, 2021). Yet, there are no studies that have been conducted on the SN of Kuwait.

Kuwait is facing many challenges due to the rapid urbanization, such as traffic congestions, safety, housing shortage and inadequacy of city vibrancy. Elmi and Al Rifai (2012) stated that the problem of traffic congestion is ubiquitous in Kuwait, and in virtue of the high standard of living, it is estimated that there is a car for every two persons. This is accompanied by pollutant emissions. Consequently, this has raised traffic safety issues; Al-Rukaibi, Ali and Aljassar (2006) claimed that on average one person dies every day because of road accidents. There is also scarcity of adequate open spaces (recreation areas and seafronts) and green spaces as they are not well-maintained or accessible (AlHammad, 2022). Better SN design might mitigate the accessibility issue. More recently, the rise in property prices in Kuwait have led house owners to build apartments within their houses. These apartments are seen as either investment opportunities or secured accommodation for their dependents in the future. This phenomenon is increasingly prevailing, causing overcrowded residential neighborhoods (Al-Haroun, 2019).

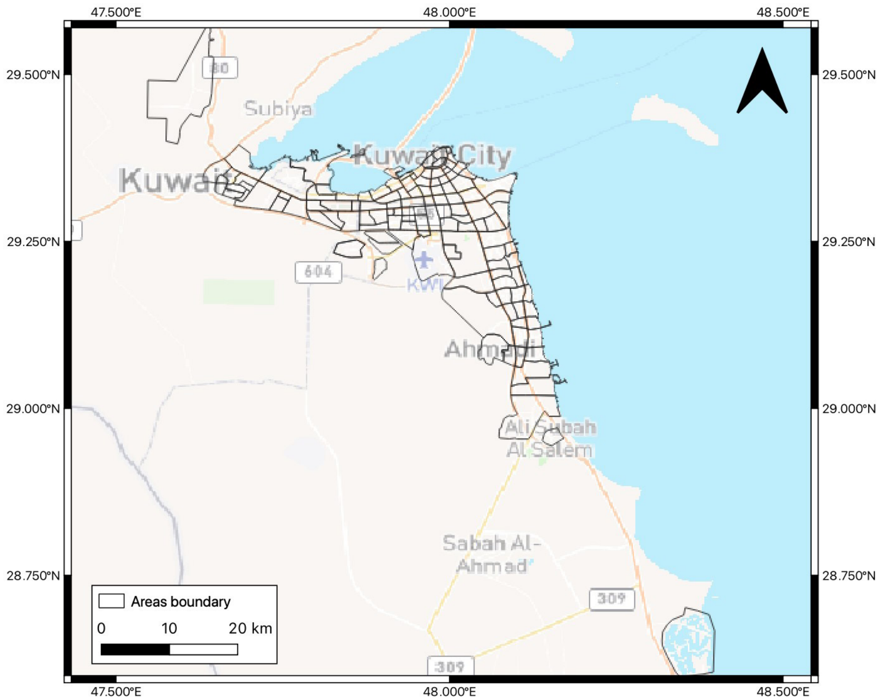
Some previous studies investigated urban form and planning in Kuwait. AL-Munais and AL-Otaibi (2008) analyzed two master plans and their water, population and urban growth projections. Algharib (2008) deployed remote sensing to detect urban growth in the city. Alghais and Pullar (2015) modelled the current urban form expansion patterns using agent-based model, where agents include government, developers and citizens. Alkhuzamy and Alghais (2021) analyzed the urban expansion of Kuwait cartographically. Koushki and Ali (1993) studied the promoting of walking in Kuwait City Center (the Capital) and found that walking in this area is similar to walking in the city of Riyadh in Saudi Arabia with average mean walking speed reaching 71 meters/minutes. As far as we know, no study exists that studied the SNs of the entire built area of Kuwait.

1.2. Study area

As seen in Figure 1, Kuwait is a coastal country overlooking the north-western Arabian Gulf and is located in the northwestern part of the Arabian Peninsula. Kuwait lies between latitudes 28° 30’ and 30° 05’ north, and between longitudes 47° 30’ and 48 ° 36’ east. The urban area (located in the southern part of the country) covers nearly 17,8 km^2. It is inhabited by around 4.4 million people. Nationality-wise, non-Kuwaitis (60%) constitute the majority of the population with gender composition that consists of 66% males. Whereas Kuwaitis form (40%) of the population, and gender is almost equally distributed between males (49%) and females (51%) (PACI, 2022). Unlike Kuwaitis who live in residential districts, most non-Kuwaitis reside in mixed-use neighborhoods (development, shopping and commercial) adjacent to their workplaces (Alghais & Pullar, 2018b).

Figure 1.

Map of the Study Area. [Source: Kuwait Municipality and Manual Digitization]



The urban area contains six governorates: the Capital, Hawalli, Mubarak Al-Kabeer, Al-Ahmadi, Al-Jahra, and Al-Farwaniyah. The urban structure of Kuwait consists of areas connected by seven ring roads that stretch to the Kuwait City (the Capital district). These ring roads are partitioned by express ways. However, in this paper, we are only considering SNs within the areas but not between the areas. It can be seen in Figure 1 that most areas are contiguous with two remote areas located in the far north and south. However, these areas are considered as an extension of the built environment as they are equipped with all needed facilities. Notably, the urban development is still closer to the coast from the inside because expansion is restricted by some factors; the most prominent factor is the presence of oilfields, the warming of the interior areas, and the concentration of economic and social activities at the heart of Kuwait City (Albanai, 2020 & 2022).

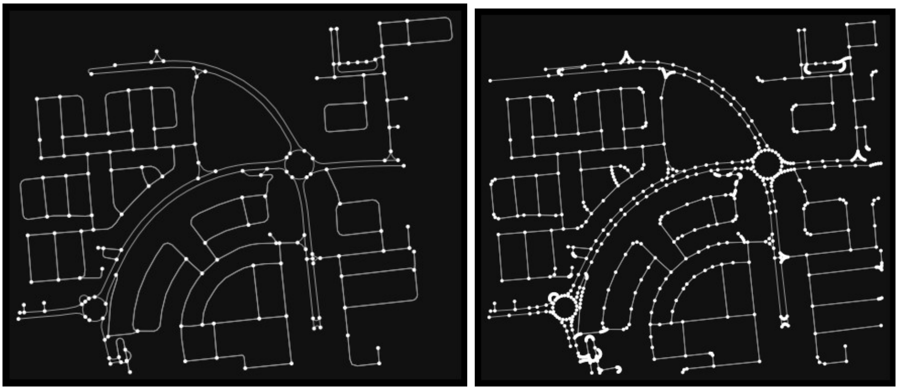
The reader is referred to Figure 1 in Al-Haroun (2019) for detailed Kuwait urban growth during the period from 1951 to 2012. There are areas dedicated for each specific activity that define each type of area (i.e., agricultural, industrial, educational, health, and residential). Kuwait Municipality (2021) distinguished between two main types of residential areas: modular residential areas and private residential areas. Both areas are characterized as low-density areas dedicated for single-family use, where no other usage is permitted. However, in the former, the government designed the areas by unifying the façade of the houses, whereas, in the latter, the areas were designed by either the house-owners or by companies from the private sector.

2. Methodology

A vector layer of Kuwait areas was obtained from Kuwait Municipality(1) in 2005. The data was validated against OpenStreetMap in November 2022, to ensure that all areas were included. Some missing areas have been digitized manually using QGIS, and resulting in 110 polygons. The produced shapefile containing these polygons has been inputted in the Python package OSMnx to fetch the street lines within the boundary of each shapefile. OSMnx is a Python package that uses OpenStreetMap to model, visualize and analyze street networks which consist of edges (street lines) and nodes (intersections) (Boeing, 2017). This package automatically simplifies the street lines. The difference between simplified and unsimplified SN is presented in Figure 2. Unlike unsimplified SN, simplified SN retains only intersections and dead-ends by removing interstitial nodes.

(1) baladia.gov.kw/sites/ar/Pages/main.aspx

Figure 2.
Demonstration of simplified and unsimplified SN.



For each area's SN we calculated the following indicators: orientation-order (φ), average street length ($\tilde{\imath}$), street circuity (ς), average node degree ($\bar{k}$), proportion of dead-ends (P_{de}), and proportion of four-way intersections (P_{4w}) (Table 1). These indicators have been adapted and explained extensively in Boeing (2019). Orientation-order returns the value where a given SN is on a spectrum ranging from 0 (depicting perfect disordered SN) to 1 (depicting perfect grid-like SN). Street circuity returns the ratio of a given SN distances to straight-line distances.

To examine the spatial dependence of the Φ, $\tilde{\imath}$, ς, and $\bar{k}$ indicators, univariate Moran's I tests was preformed using the open-source spatial analysis tool GeoDa. This test returns values ranging between -1 (indicating spatial dispersion) and 1 (indicating spatial clustering); where 0 indicates spatial randomness (Moran, 1950).

3. Findings and discussion

In this work we consider the built area of Kuwait and neglect military and agricultural areas. The result indicates that the built area constitutes nearly 5% of the total in land area of Kuwait. The indicators of interest in this work are orientation-order (φ), average street length ($\tilde{\imath}$), street circuity (ς), average node degree ($\bar{k}$), proportion of dead-ends (P_{de}), and proportion of four-way intersections (P_{4w}). The results are provided for further investigation and analysis in this work.

Riqqa has the highest orientation-order (φ = 0.78); whereas Sabah Al Ahmad Sea City has the lowest orientation-order with the value of (φ = 0.02). Interestingly, Kuwait City (the capital of Kuwait) is the second to last (φ = 0.06). As shown in Figure 3, the grid pattern SN is clear in Riqqa, thus, it has high φ value. The case of Sabah AlAhmad Sea City, the maximization of the shoreline resulted in disorder SN.

Figure 3.

Street Network of Two Selected Areas. Left: Riqqa (An area with high ϕ value). Right: Sabah AlAhmad Sea City (An area with low ϕ value)

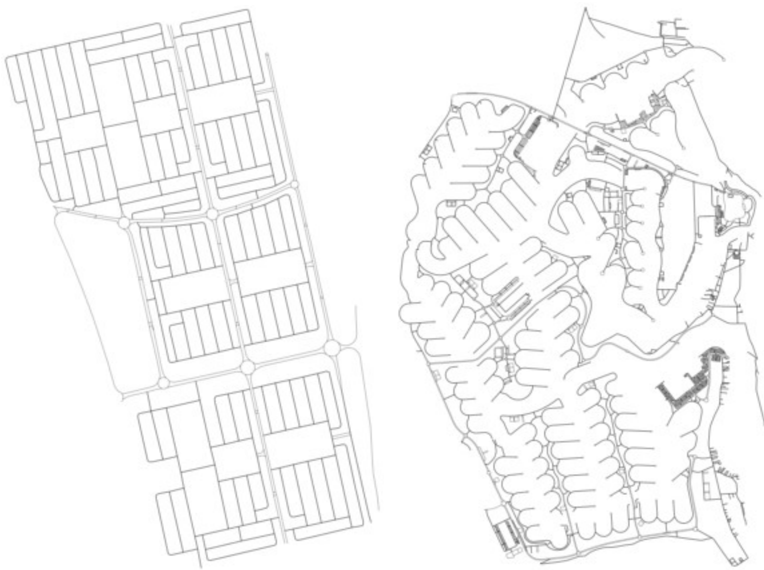
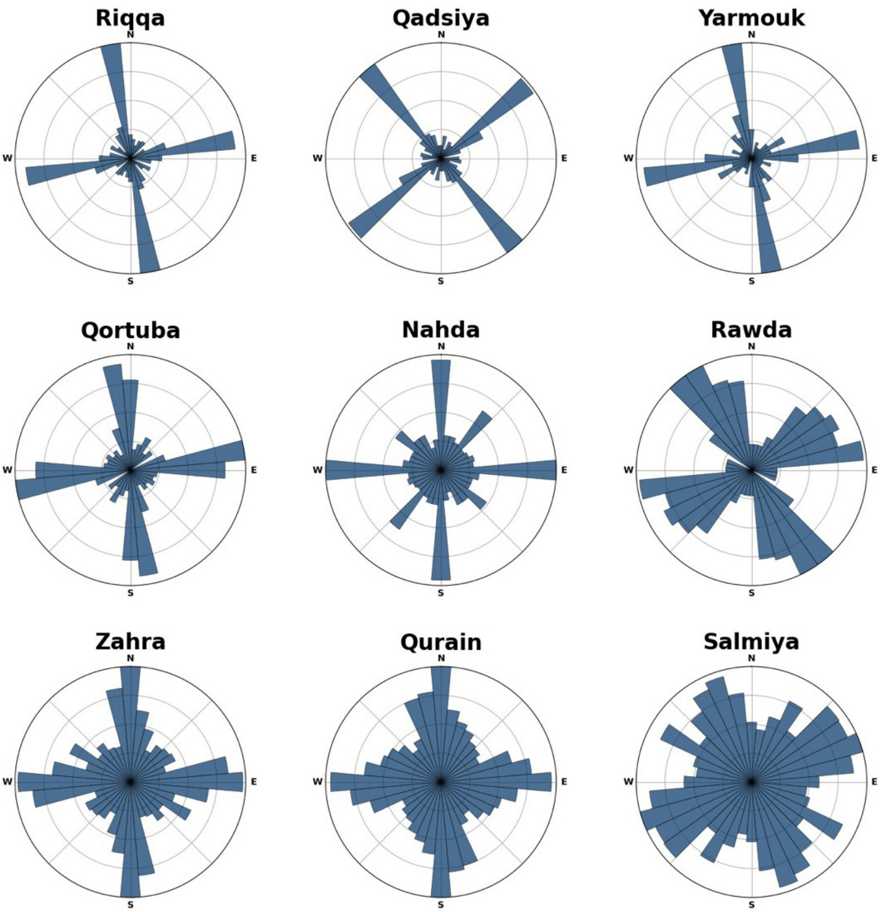


Figure 4 presents the orientation of SN for selected areas arranged in terms of their φ value to visualize φ indicator using polar histograms. These Polar histograms consist of 36 bins representing streets orientation and the heights corresponding to the frequency. Most streets of areas with high φ values exhibit near perfect north-south-east-west orientation trend, for example Riqqa, Qadsiya, Yarmouk. However, in areas with low φ values, streets are scattered in all directions representing disorder.

Figure 4.
Selected Areas Street Network Orientation



The granularity of the SN can be depicted from the average street lengths (ĩ). The top ten areas with coarse-grained street networks given their long median street lengths are non-residential (i.e., Jahra Campus, Magwa, Doha Port, South Sobahiya, South Wosta, Subahiya, Wosta, and Ardiya 6), except West Abdullah Al-Mubarak which is ranked the seventh. While in contrast, areas that feature fine-grained street networks are mostly residential (i.e., Jaber Alali, Kifan, Mubarak Al-Kabeer, Dahar, Rehab, Ashbeliah, Qadsiya, Oyown), except Kuwait City and Shuwaikh Educational ranked the 4^{th} and 5^{th} respectively. In virtue of the street griddedness in Qadsiya ($\varphi = 0.71$), Yarmouk ($\varphi = 0.62$) and Dasma ($\varphi = 0.41$), these areas has the least street circuity with 3.7%, 4.1% and 4.7% more circuitous than straight-line distances, respectively. In contrast, Naeem, Naseem and Ali Sabah Al-Salem – also residential areas – have high street circuity ranging from 43.8% to 24.5%. Average node degree was found to be highest in Egila, Ardiya 4 and Nahda with 3.08, 3.08 and 3.06 streets per node. Sulaibikat and Abduallh Port have the most dead ends. All areas within the Ahmadi Governorate have the highest proportion of four-way intersections.

The orientation-order (φ) was found to be not correlated with any of the indicators other than simplified and unsimplified street entropy, namely, average street length ($r(\varphi, \tilde{\imath}) = 0.021$, $p = 0.824$), average node degree ($r(\varphi, \bar{k}) = 0.088$, $p = 0.357$), dead-ends ($r(\varphi, P_{de}) = -0.020$, $p = 0.828$) four-way intersections ($r(\varphi, P_{4w}) = 0.116$, $p = 0.224$) or with street circuity ($r(\varphi, \varsigma) = -0.124$, $p = 0.194$).

Univariate Moran's I was preformed to identify whether the Φ, $\tilde{\imath}$, ς, and $\bar{k}$ are globally spatially autocorrelated using first order queen contiguity. This analysis was performed after omitting isolated areas that had no adjacent areas such as Al Mutla City and Sabah Alahmad Sea City. Moran's I coefficients were found to be ($\Phi_{\text{Moran's I}} = 0.103$, $\tilde{\imath}_{\text{Moran's I}} = 0.063$, $\varsigma_{\text{Moran's I}} = 0.027$, $\bar{k}_{\text{Moran's I}} = 0.27$) with pseudo p-value < 0.05 indicating spatial randomness of all indicators. This suggests that areas adjacent to each other do not exhibit similar φ, $\tilde{\imath}$, ς, and $\bar{k}$ values.

This work attempts to fill the geographical gap in the literature about analyzing the SN of Kuwait through the lens of urban spatial order. By doing so, this work also contributes to the urban geography literature by performing spatial analysis on urban spatial order indicators. Unlike previous studies, where developed countries have been investigated, Kuwait makes an interesting case study as: (i) it is a small country, and (ii) it consists of heterogeneous areas, each of which, has a unique SN pattern. The built area covers only 5% of the entire inland area, which means that such studies are needed to examine the efficacy of the current SN patterns to either replicate or alter it for future development.

Koushki and Ali (1993) criticized the urban form of Kuwait as it had been developed in a piecemeal manner. This is supported by our finding where no spatial autocorrelation between (neither spatial clustering nor dispersion) were found between the indicators of interest. This resulted in inconsistent SN patterns.

Unlike previous findings, Boeing (2019) found that φ was correlated with ς, $\tilde{\imath}$, $\bar{k}$, P_{de}, and P_{4w}, in 100 cities around the world, but only Dubai was considered in his work. In this study, no such significant correlation was found, suggesting that previous findings are not applicable to Kuwait. This implies that generalized findings should be taken with caution. In Kuwait, Riqqa, Alqadisa, Omariya, and Yarmouk have the highest φ, in this order. As can be seen from Figure 4, this area consists of gridded blocks connected with roundabouts. These areas are considered modular residential areas (explained in subsection 1.1). Whereas the areas with low φ value, namely, Sabah AlAhmad Sea City, Kuwait City, Salmiya and Jahra Campus, are all coastal areas. This implies that the topological factor interferes with the areas order along with the organic development of the Kuwait City. This finding is consistent with Boeing (2019) and (Boeing, 2021). However, this is not the case for all coastal areas; for instance, Sulaibikhat has φ of 0.58.

Areas with coarse-grained SN are non-residential (high $\tilde{\imath}$ value), such as Magwa, Doha Port, and South Sobahiya). Such a configuration might have undesirable societal implications as these areas are expected to be used by non-citizens who are inclined to walk, where walking becomes extremely physically taxing, given the long streets and the prevailing climate in Kuwait. Similar finding was described by Koushki and Ali (1993). The authors noticed that commercial areas have large blocks, which discourage walking.

Conversely, areas with low $\tilde{\imath}$ value are usually residential areas, with Kuwait City ranking the 4^{th}. In virtue of the fine SN granularity, many people – particularly expats – might be able to incorporate walking with other transportation methods within this area. Residential areas have been found in both ends of street circuity (ς) – a proxy for routing efficiency – spectrum. Naeem ($\varsigma = 1.43$) which means that this area has 43% excess over the optimal route; Whereas Qadsiya, which is more grid-like and has less circuity ($\varsigma = 1.03$) is only 3% more circuitous than optimal route. It is anticipated that the greater the street circuity, the lower the mean speed (Rada Orellana, 2022).

Average node degree ($\bar{k}$) was found to be high in most residential areas (i.e, Egaila, Nahda, Qadsiya and Abdullah Alsalem). This indicator is believed to introduce more connectivity to the area. In contrast, areas such as Abdullah Port, Jahra Campus, Shaiba and Sabah Al-Ahmad Sea City require more detouring due to its low $\overline{k}$ value. Sulaibikhat has the highest proportion of Cul-de-Sac (P_{de} = 3) lowering the connectivity between neighborhoods. This value is far more than Abdullah Port which ranked the second in terms of dead-ends. Finally, four-way intersections are high in Ardiya 4) where several educational institutes are located as well as Jaber Al-Ahmad International Stadium) and Ardiya 6 (a commercial area).

As for the implications and future directions, there is a wide variety of SNs patterns in Kuwait and this reflects a lack of consistency in urban form and planning. The public involvement in city improvement and designing has been marginalized (Al-Nakib, 2014). Additionally, in many areas the current patterns of urban form favor automobile dependency. Thus, these indicators must be considered to catalyze transportation shift to walking and cycling. At the time of writing, there were a few areas within the built area that were nder development, which meant that modification of their SNs was possible. For example, providing walking alleys will increase the connectivity for pedestrians; this study is a precursor for further Kuwait SNs exploration.

The current study provides a data repository that can be obtained from executable python script of entire Kuwait SN prepared for GIS environment, allowing future researchers to analyze and deploy other analyses. Evidently, more work is needed to accumulate literature about Kuwait which is an understudied area. Future studies should delve deeper into the impact of these indicators on the livability of these areas. For example, it is anticipated that walking alleys and dead ends in residential areas will encourage ‘apartment house’ phenomenon in Kuwait as it is a desirable feature to tenants (described in section 1.1.2) as it allows for abundant parking spaces.

4. Conclusion

To understand the current Kuwait SNs characteristics, this work empirically investigated Kuwait SN coupled with descriptive analysis. This work utilized mainly data obtained from OSM for each area in Kuwait using the python package OSMnx. Areas were delineated using vector file from Kuwait Municipality updated by manually digitizing missing areas. Various indicators were calculated using OSMnx, namely, orientation-order (φ), average street length ($\tilde{\imath}$), street circuity (ς), average node degree

($\bar{k}$), proportion of dead-ends (P_{de}), and proportion of four-way intersections (P_{4w}). These indicators were interpreted by using a qualitative method and visually examining area location. Finally, GeoDa software was used to examine the spatial correlation of these indicators.

The discussion put the findings in the relevant context. For example, for several areas' orientation-order was found to be low for coastal areas since the shoreline dictates certain street orientation. The provided python script along with our discussion serve as a precursor for future work that might guide informed future SNs, as changing the current SNs is a cost-prohibitive process. Through the findings, more sustainable urban planning can be undertaken for expanding the built area in Kuwait and other countries with similar urban conditions. Future work can adopt the following directions:

1 - Deploy Google Maps or Kuwait Finder app street view for qualitative auditing of each SN characteristic; this approach was used by Kelly et al. (2013).

2 - Assessing walkability and bikeability in Kuwait, given that the country has various obesogenic environment component (Garduño-Diaz & Garduño-Diaz, 2014).

5. Appendix

Alattar, Mohammad; Beecroft, Mark; Albanai, Jasem, 2023, "Replication Data for: Spatial Analysis of Kuwait Street Networks", https://doi.org/10.7910/DVN/X6YL1V, Harvard Dataverse, V2

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