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RESEARCH ARTICLE

The building blocks of walkability: Pedestrian activity in Abu Dhabi city center

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Abstract This study develops an empirical approach that underlines the effect of land use mix and development grain on pedestrian movement in the streets and public spaces of urban neighborhoods. The study begins with the end in mind; it compares two urban sectors in Abu Dhabi city with broadly recognized contrasting levels of pedestrian movement. The research works backward to identify the combination of built environment attributes that result in differing levels of pedestrian activity between the eastern and western sectors of Abu Dhabi city center. Using Geographic Information Systems maps/data files, direct observations, and field metrics, the study computes various indices related to land use mix, density, and street connectivity for Abu Dhabi central business district. The findings of this study highlight the land use, spatial and street network configurations that enhance pedestrian activity in urban centers. From a local perspective, the research outcome would inform future visions aimed at transforming the city of Abu Dhabi into a global metropolis that provides its citizens and visitors with unique and vibrant urban settings conducive to intra- and inter-neighborhood walkability.

1. Introduction

Design and planning studies generally associate pedestrian activity and urban vitality with built environment attributes such as mixed uses, fine-grained urban blocks, connected streets, and enhanced building/street interfaces (Jacobs, 1961; Alexander, 1977; Trancik, 1986; Kashef, 2009b, 2011; Barnett, 2016). Studies note that certain configurational and spatial dynamics are correlated with increased pedestrian activity in urban areas. They often cite mixed-use traditional city streets as models for urban vitality and pedestrian-friendly built environments. These environments manage to provide economic opportunities for small businesses, support communal practices, and

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integrate streetscape aesthetics with well-articulated relationships between buildings, sidewalks, and streets (Rossi, 1984; Cullen, 1995; Krier, 1998; Rapoport, 2013; Kashef, 2017; Bramiana et al., 2017). A host of morphological studies characterize good urban forms as having flexible movement networks with rich visual dynamics that enhance sense of orientation, wayfinding, and spatial permeability (Lang, 2017; Canter 2016; Lynch, 1960, 1981; Newman, 1973; Rapoport, 1990; Kashef 2007, 2018).

This study focuses on two measurable urban design criteria: land use mix and street network design and connectivity. The objective is to articulate relevant and potentially quantifiable design parameters to incorporate in subsequent field study procedures. The field study identifies two urban sectors: the eastern and western sections of Abu Dhabi city center with similar building configurations and spatial patterns yet exhibiting varying levels of pedestrian activity. The two selected sectors share common features such as land area, morphology, and land use mix. The eastern section of the central business district (CBD) exhibits higher levels of pedestrian activity and overall street vitality despite the similarity in land use mix, street network design, and overall configuration of the built environment. These findings were confirmed by a dual process of structured observations over an extended period and a public survey. The researcher conducted systematic visits to Abu Dhabi city center at different times of the day and recorded the levels of pedestrian volumes in the major streets of both CBD sectors. The results of direct observations coupled with 600 survey responses pointed to 30 percent higher levels of pedestrian flows in the eastern sector thoroughfares as compared to their counterparts of the western sector. Owing to such marked differences in pedestrian activity between the eastern and western sections of Abu Dhabi CBD, this study compares a group of blocks and streets from both areas of the CBD. The study aims to move beyond the seemingly observable differences and examine the subtle built environment features that contribute to the enhanced pedestrian activity of the eastern section. It focuses on the effect of land use interaction, density, connectivity, and street network on pedestrian activity. The ultimate objective of this research is to find associations between certain combinations of physical/spatial development patterns and pedestrian activity. Fig. 1 delineates the theoretical context and methodological framework of the entire research.

2. Research methodology

This research examines the planning and urban design literature that underlines the configurational and spatial dynamics that contribute to urban vitality and pedestrian flows in city streets. The structured direct observations and public exploratory surveys that preceded this research have been critical to confirm the visible and broadly recognized difference in pedestrian activity levels between the eastern and western sectors of Abu Dhabi CBD. Although some survey respondents favored the glitzy buildings of the western sector, most respondents referred to living and walking in the eastern sector as providing more accessibility in terms of the number of retail shops, cafes, restaurants, convenience stores, and services, as well as a wide range of affordable entertainment venues. Given that both Abu Dhabi CBD sectors exhibit similar physical and morphological characteristics, this research seeks to identify the subtle land use differences and street network attributes that lead to differing levels of pedestrian flows between them. The study makes intensive use of Geographic Information Systems (GIS), direct observations, and field metrics to quantify built environment features that aid in calculating walkability indices (entropy and LUM) for each sector. Up-to-date GIS maps and data files have been obtained from the Urban Planning Council (UPC 2020) and Abu Dhabi Municipality (ADM 2020). This work was undertaken using ESRI ArcMAP version 10.4.1 for Desktop. Owing to the complexity and intensity of mixed uses in the CBD, the study consolidated land uses into five instead of seven to facilitate the computing of walkability indices. The crux of the fieldwork is to juxtapose direct observations of pedestrian activity levels and measured built environment features using GIS and area metrics of the two urban sectors. Although not planned as part of the methodological approach of this research, a considerable number of flash public surveys were conducted to determine the purpose of walking in selected urban blocks. The ultimate objective of this research is to find associations between certain combinations of physical/spatial development patterns and pedestrian activity. Fig. 2 provides a detailed research methodology diagram and adds further details regarding the methodological strategies and data collection tools.

3. Theoretical context

This research examines a broad array of theoretical and empirical literature sources that generally correlate built environment features with pedestrian activity in city streets. Various studies point out that some physical and spatial configurations are conducive to communal behaviors and a heightened sense of safety and security in the public realm (Kashef 2009a). Land use mix and street network design figure prominently in the planning and urban design literature as significant contributors to pedestrian flows in urban neighborhoods (Jacobs, 1961; Kashef, 2008; Kashef and El Shafie, 2020). The following literature review highlights the land use mix, street network configurations, and measurement tools of potential implementation in the research field study (Abu Dhabi City Center).

3.1. Land use mix

Jacobs (1961) refers to primary and secondary levels of land use functions that enhance urban vitality and bring more people to city streets. Primary uses include dwellings, offices, and other compatible facilities for retail, manufacturing, education, and employment facilities. Secondary functions provide a wide range of services such as restaurants, cafes, and entertainment venues that generate pedestrian activity at different times of the day and generate revenue not only from nearby residents but also from visitors from other areas of the city. The combination of primary and secondary land uses creates functional diversity and brings a critical mass of people to the

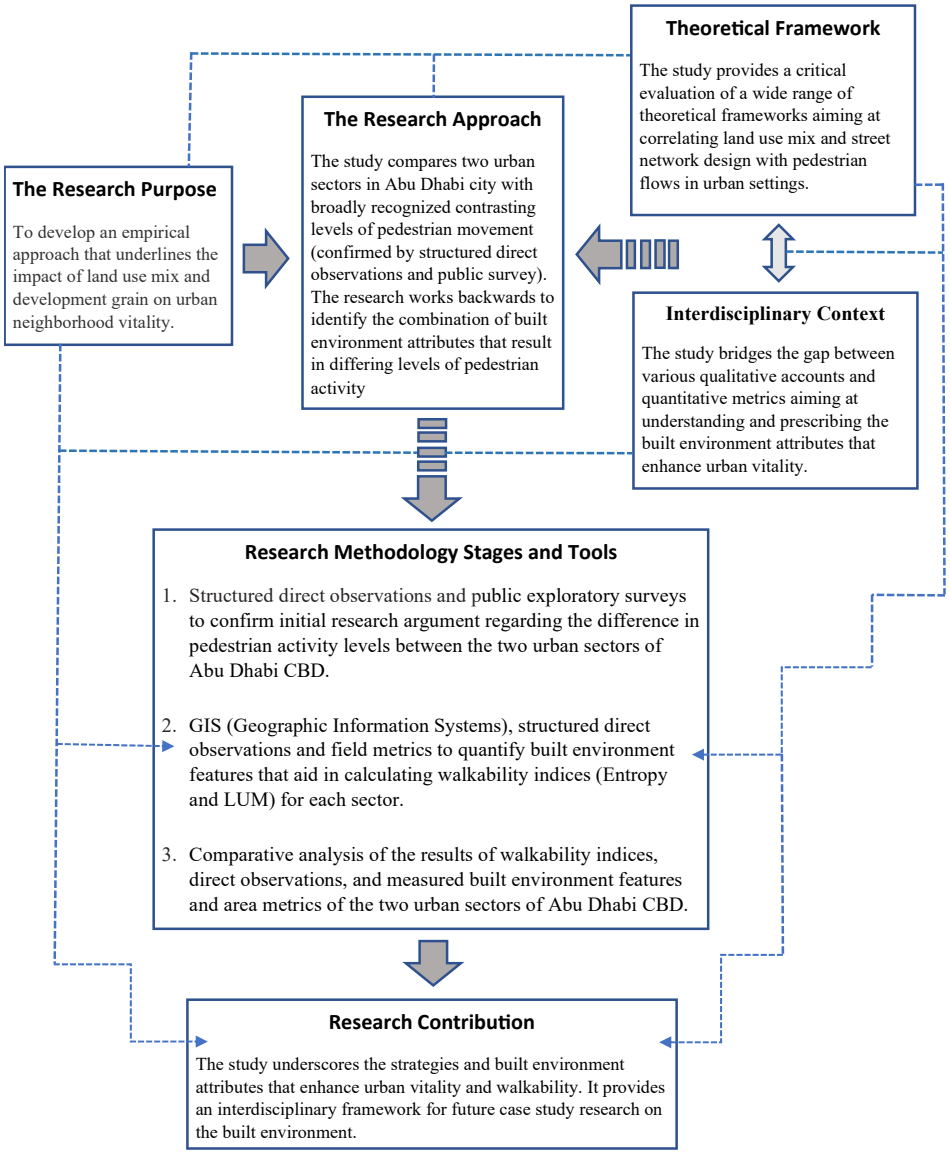

Fig. 1 Research model and process diagram.

streets at different times of the day and for different purposes. Various studies also emphasize the need for physical integration, geographic proximity, concentration, and locational fit that allows pedestrians to occupy streets and public spaces as part of their daily work/live/play routine (Grant, 2002; Schwanke, 2003; Ewing, 2004; Kashef, 2016). Empirical investigations found that mixed-use developments (residential, employment, and retail) generated almost twice the walking activity of conventional suburbs (Saelens et al., 2003; Handy, 2004; Handy et al., 2004, 2008; Kashef and El Shafie, 2020). The New Urbanism also champions mixed-use as an essential strategy in designing new developments aiming to enhance pedestrian activity and neighborhood vitality (Duany and Plater-Zyberk, 1991; Calthorpe, 1993; Calthorpe and Richmond, 1992; Katz, 1994; Kelbaugh, 1997, 2002; Dutton, 2000; Duany and Plater-Zyberk, 2000; Kashef, 2009a). Thus, a broad agreement has been reached in the design and planning literature on the merits of diverse mixed-use developments in enhancing urban vitality and pedestrian activity. The most widely accepted statistical measures that operationalize required levels of land use mix/diversity are entropy and LUM. (Handy et al., 2002; Saelens et al., 2003; Cervero et al., 2004; Ewing and Cervero, 2010, Gehrke and Clifton, 2016). Both measures use the same logic in the way land use percentages are factored in the index calculations.

This study uses entropy to compute land use percentages in Abu Dhabi CBD sectors as commonly identified in official land use maps and building permit registries. By contrast, LUM is used to measure gross floor areas of uses in as-occupied properties, which have been subject to various modifications over the past few decades. The bulk of such modifications were not permitted and/or documented in building permit registries. Thus, the results of entropy and LUM calculations in this study are expected to provide different percentages for specific land use types, hence different index values. On the basis of statistical analysis of

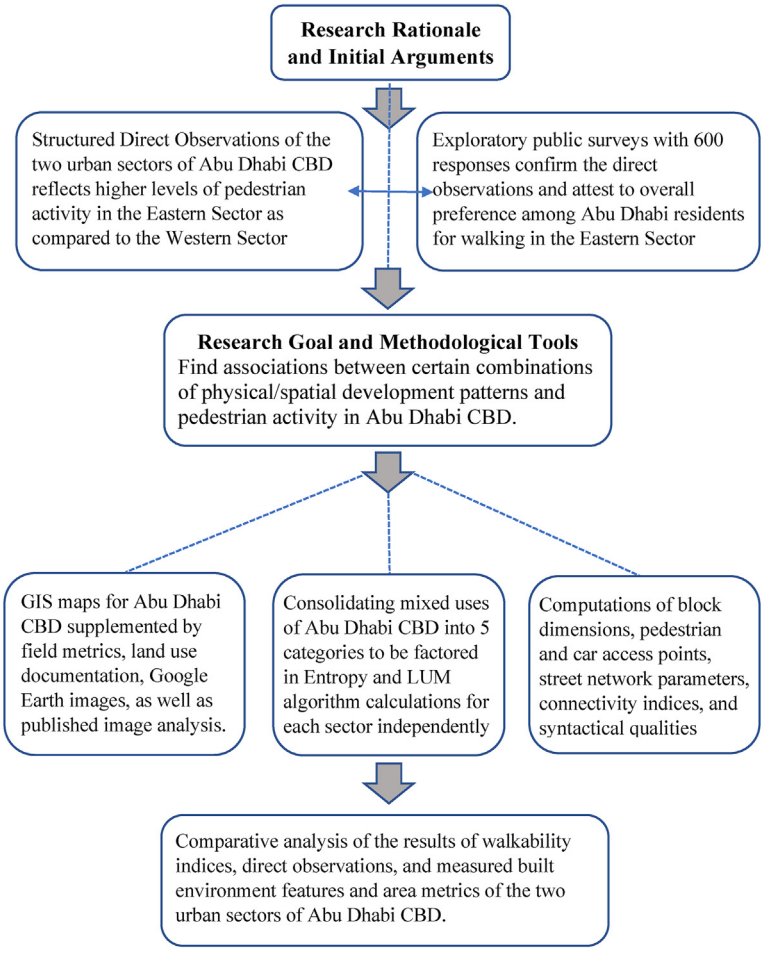

Fig. 2 Research methodology diagram.

different mixed-use developments with seven land use categories, Frank and Pivo (1994) expressed the results as normalized values between zero and one. The higher value indicated more mix and diversity in land use types and was positively correlated with higher pedestrian activity.

Manaugh and Kreider (2013) expressed the entropy index as:

$$\text{Entropy} = \frac{-\sum A_{ij} \ln A_{ij}}{\ln N_j}$$

where A_{ij} = Percent of land use i in census tract j; N_j = Number of represented land uses in census tract j.

Sung et al. (2015) expressed the LUM, which considers gross floor area of uses rather than land areas. The index results also range from zero to one. A perfect evenness or equal distribution between functional use categories in the area would score one.

$$\text{LUM} = \sum_{i=1}^{n} \frac{P_i * \ln P_i}{\ln(n)}$$

where P_i = the proportion of building square footage of land use i; n = the number of land uses.

Entropy measures are often criticized in the way they seek an even balance in the mixed-use configuration of urban areas. Though providing a measure of use heterogeneity, even distribution does not consider the level of complementarity between the different land uses in an urban tract. The latter is a crucial factor in predicting travel behavior and walking patterns (Hess et al., 2001, Ewing and Cervero, 2010; Gehrke and Clifton, 2016). Mavoa (2018) point out that entropy assesses the relative proportion of different land uses rather than distinguishing between the types of land uses. However, the entropy and LUM indices in the present study are not used to predict travel patterns or transportation mode of choice. As indicated earlier, the starting point of this study is the field direct observations of pedestrian activity in selected urban tracts. Based on the observed patterns of walkability and the public survey in Abu Dhabi CBD, the research found 30% higher pedestrian flows in the eastern tract compared with the western tract. The research uses entropy and LUM indices to compare the two selected tracts and in a sense examines the validity of evenness or equal distribution of heterogeneous land uses in Abu Dhabi neighborhoods. Developers in Abu Dhabi city can integrate retail, office, and residential uses in the same property. Several properties may be consolidated to create large-scale developments. Various housing tenures and income groups may also be integrated into a single development. The mixed-use categories in such consolidated properties do not necessarily comply with existing codes but often get approved through variances that provide developers with opportunities to

maximize their profits and respond to market needs. In some cases, the mix of commercial and office with residential uses in a block or several consolidated properties generate a richer diversity and synergy, but in other cases may internalize pedestrian activity across a limited number of city blocks.

3.2. Urban Development grain and street network

Some empirical studies differentiated street layouts as gridded, partially gridded (mix) or not (cul-de-sac) (Boarnet, 2011). The grain of urban settlements is invariably noted in the literature as a marker for pedestrian activity and street vitality. The key features of urban grain are block size and street geometry and connectivity (Rowley, 1996). On the basis of the results of various empirical studies, some communities have adopted maximum block length standards ranging from 300 to 600 feet (100—300 m). Another variation of limiting block dimensions is the use of block size in acres without specifying maximum length or width to provide more flexibility with existing zoning regulations (Handy et al., 2003; Dill 2004). Jacobs (1961) estimated a density level of 100 dwellings per acre as necessary for creating vibrant city life. A mix of six-story walk-up apartment complexes and 12- to 14- story buildings with elevators figured in Jacobs's accounts as appropriate to achieve this density. Upon studying three neighborhoods in Stockholm, Choi and Sara Sardari, 2012 found positive correlations between higher population densities in mixed-use settings and pedestrian activity. The results from other empirical studies in Seoul indicated that higher residential and employment densities contributed to increased pedestrian activity (Sung et al., 2015). In these and other studies, the measured population densities have been in the approximate range of 100—200 dwelling units per acre, which approximates Jacobs's density formula (Berhie and Saif, 2017).

Street network connectivity indices include various measures such as block density, intersections density, street density, connected node percentage, and link-node ratio (Dill, 2004; Cervero and Kockelman, 1997). The block density index denotes the number of blocks per urban sector or census tract. The higher number of blocks and smaller geometries for a given tract indicates a finer grain with improved accessibility and connectivity (Ewing, 1996). Intersection density refers to the number of four-way street intersections per unit area of measurement. The higher number of four-way street intersections in a developed urban area, the higher likelihood of accessibility, connectivity, and street vitality. Street density is positively correlated with intersection density and is represented by the cumulative length of street sections per unit area of the urban development tract. Connected node percentage refers to the proportion of street intersections to the total of intersections plus dead ends; values above 50% indicate better network accessibility (Dill, 2004).

The link-node ratio, often termed connectivity index, is derived by dividing the number of street links by the number of street intersections and nodes (cul-de-sacs or dead ends included). A higher connectivity index signifies a well-connected street system with the perfect grid scoring a ratio of approximately 2.5 (Ewing, 2014). Empirical studies confirmed the positive correlation between increased levels of pedestrian activity and higher connectivity indices (FrankSchmidt et al., 2005).

Space syntax delineates a set of spatial concepts and principles that underlie human interaction in the built environment (Hillier and Hanson, 1984). It aims to find the most effective street network configurations that optimize land use allocations and facilitate movement through urban space. Space syntax logic is currently used in studying land use allocations and movement networks on the building, urban block, neighborhood, city, metropolitan regions, and countrywide levels (Salingaros, 1998; Hillier, 1996, 1999; Jiang and Claramunt, 2002; Bafna, 2003; Raford and Ragland, 2003; Nophaket and Fujii, 2004, Peponis et al., 2007; Baran et al., 2008; Kashef, 2011; Berhie and Saif, 2017). A neighborhood syntax analysis generally starts with an axial representation of streets and visibility lines creating a series of intersecting lines and nodes. Each line on the street syntax map represents a pathway, and the intersection of two lines corresponds to a network node (Fig. 3). The lines on the map with the highest number of nodes and the shortest path between network nodes hold higher connectivity values. The axial representation aids in quantifying the topological distance between spaces of a given network. Depth integration is a key topological measure used in conjunction with space syntax analyses (Jiang and Claramunt, 2002; Marshall et al., 2018; Jeong and Ban, 2020). The most integrated streets are depicted graphically with thicker or heavier lines denoting their importance in the network and potential of performing as catalysts for economic activity and urban vitality. They represent the physical and visual skeleton of the city and are often the most familiar and highest navigable elements of the urban network. Lines on the legibility syntax map represent a hierarchy from the longest to the shortest visual axes intersected by critical viewing points, from which maximum visibility fields are determined (Hillier et al., 2010).

4. Field study: a comparison between two urban tracts in the city of Abu Dhabi

The City of Abu Dhabi is the capital and the federal seat of the Government of the United Arab Emirates (UAE). Over the last five decades, the city has experienced tremendous urban development growth that transformed this small pearling base into a metropolitan region. The current population of Abu Dhabi City is 1.67 million, a quarter of which are Emirati citizens working in professional, managerial, and senior-level occupations in the private and public sectors. The rest of the population are expatriates working in a broad spectrum of professional, industrial, and labor occupations in the private and public sectors. The average annual household income of UAE residents is $58,000 (UAE Ministry of Economy). The economic growth rate of Abu Dhabi was 5.6% between 2010 and 2016, and most nationals and expatriates relatively enjoy prosperous living standards. The male population constitutes a majority of 65% and the rest are female; both have an average life expectancy above 75 years of age. This gender

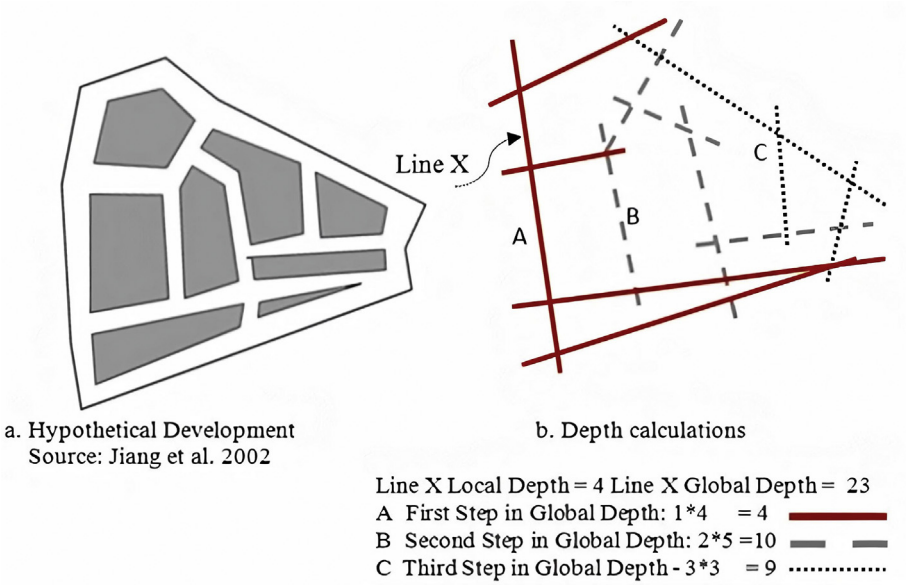

Fig. 3 Network Syntax for a Hypothetical Development (Sources: Jiang and Claramunt, 2002; Batty and Rana, 2002).

disparity is also reflected in the workforce, with men amassing more than 80% of Abu Dhabi jobs. Illiteracy rates in Abu Dhabi are among the lowest in the world, with only 6.4% of the population above the age of ten being recognized as illiterate. The private automobile is the main mode of transportation in the city, with limited public transportation services that cater to the low-income expatriate labor force (WPR, 2021; SCAD, 2020). With the introduction of limited foreign business ownership, Abu Dhabi has become a magnet for global corporate presence and is poised to become a regional financial capital and a global metropolis. The city has a thriving and expansive CBD that currently covers an area of more than 12 square kilometers. Abu Dhabi CBD is characterized by a rich land use mix with primary functions such as residential, retail, office, hotels, healthcare, government, educational, and commercial, as well as a broad range of secondary functions that incorporate cultural, entertainment, and service facilities. The area combines highly contrasting urban forms that are within walking distance of each other. A few skyscrapers (50 stories or higher) penetrate the CBD skyline that is mostly dominated by 20- to 30-story buildings. The adjoining areas of the CBD juxtapose mid-scale and fine-grain mixed residential and office buildings (6- to 12-story) with retail outlets on the ground floor. Low-rise areas border the CBD and encompass different residential typologies including three-to four-story walkups, duplexes (semi-detached units), and single-family homes. The fine-grain fabric of the CBD shares a grid street network with adjoining areas that eventually fade away into a rapidly evolving urban edge with various building forms and density structures. The expansion outside the city center has catalyzed the development of lower-tier cores or urban sub-centers such as the Grand Mosque and Al Maqtaa, Khalifa, Mohammed Bin Zayed, and the planned industrial areas in Mussafah. The edge city centers primarily encompass auto-oriented commercial, hotel, and office establishments with commensurate residential apartment buildings. Despite the vast metropolitan growth of Abu Dhabi that exceeds 900 square kilometers, public transit service is limited; the private automobile is the dominant mode of transportation. Abu Dhabi CBD is one of the most dynamic and diversified business centers in the UAE and second only to Dubai in the Gulf region. It is home to global engineering, financial and commercial operations. The city is renowned for having a reliable telecommunications network, smart public service utility infrastructure, as well as high-tech security and traffic systems. These attributes combined with various patterns of development and building typologies make the CBD of Abu Dhabi a representative urban form of particular significance to this study. The city has embarked on an ambitious 2030 plan, aimed at encouraging further growth within and outside the current metropolitan boundaries. Fig. 4 presents a series of progressive scale maps from the metropolitan level down to the CBD level with highlights of the field study areas. Fig. 5 juxtaposes some current images of Abu Dhabi CBD.

4.1. Field study areas

Owing to the marked difference in pedestrian activity between the eastern and western sections of Abu Dhabi CBD, this study compares a group of blocks and streets from the eastern and western areas of the CBD. The eastern section of the CBD (Fig. 6) exhibits a higher level of pedestrian activity and overall street vitality despite the similarity in land use mix, street network design, and overall configuration of the built environment. The visible difference is manifested in the additional number of high-rise buildings and density concentrations in the eastern section, which is

also characterized by a relative variety of building age. The density according to the city official plan for both sections ranges from 100 to 150+ units per gross hectare (UPC 2020). This study aims to move beyond the seemingly observable differences and examine the built environment characteristics that contribute to the enhanced pedestrian activity of the eastern section. It focuses on the effect of land use interaction, density, connectivity, and street network on pedestrian activity. The ultimate objective of this research is to find associations between certain combinations of physical/spatial development patterns and pedestrian activity.

4.1.1. Eastern sector of Abu Dhabi CBD

The CBD eastern sector incorporates a number of city blocks with an area of approximately four square kilometers. The sector blocks are amongst the original CBD developments that started in the late 1970s and continued to expand in all directions including the reclaimed waterfront of the Gulf. Although most buildings in this sector were constructed more than 30 years ago, a few of them have been added more recently over the last decade. The twelve blocks forming the eastern CBD sector vary in size and offer a variety of building configurations and heights. They are primarily demarcated by high-traffic arterial roads (Fig. 7). Almost half of these blocks are dominated by high-rise mixed-use buildings. The other group of blocks features low-to-midrise residential uses in their cores and high-rise mixed-use buildings along arterial roads. The sector is defined by a well-connected street grid that boasts a link-node ratio (connectivity index) of 2.23. The 49 links forming the sector are connected via 17 four-way and 5 three-way intersections, with a perfect connected node percentage, and all are provided with proper pedestrian crossings.

Despite the varying block sizes, pedestrian movement across all the blocks at different times of the day and for different purposes was documented through direct observations and flash public surveys. During the day, the great majority of surveyed pedestrians reasoned their walking activity throughout the eastern sector as moving from home to work or vice versa. Home/work travel was considerably reduced in the evening and the bulk of pedestrians expressed other purposes such as personal errands, shopping, socialization, and, to a lesser extent, for entertainment, leisure, or recreation. The percentage was halved between those living and working in the area and others coming from other areas throughout the city of Abu Dhabi. Unpredictably, almost 15% of respondents reasoned their

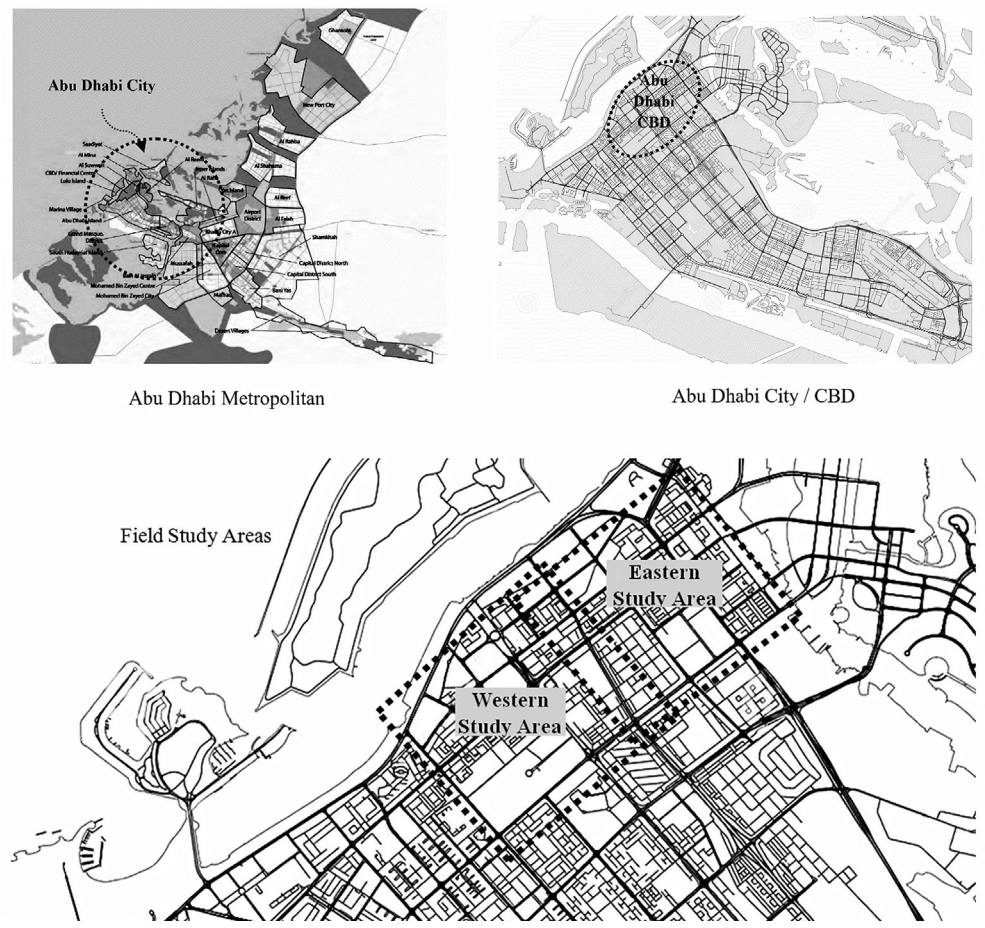

Fig. 4 Progressive scale maps for UAE, Abu Dhabi Emirate, City, CBD and Study Areas. Source: Urban Planning Council, The Department of Municipalities and Transport, https://www.dmt.gov.ae/.

Fig. 5 General images of Abu Dhabi CBD area.

walking by the lack of parking spots or free parking in the CBD; they used to drive more before the city applied a parking charge from 2011 onwards.

The block density index of 12 is not favorable in absolute terms because the number of blocks is considered low for the area of 4 square kilometers. The arterials demarcate supersize blocks, which are certainly larger in area and dimensions than those recommended by Jacobs and others for enhanced walkability. However, as shown in Table 1, these blocks are very well connected with the arterial grid network through numerous external access points, which cater to cars and pedestrians. According to land use regulations in the city, wall-to-wall buildings across property lines are not allowed. Developments are to leave setbacks from all directions including the sides for pedestrian alleyways in-between buildings. This renders these large blocks much smaller and more accessible with opportunities for pedestrians to shortcut walking journeys or change direction. These large blocks are subdivided by many pedestrian alleyways that make them smaller than recommended by Jacobs (120—190 m). The longest side of most buildings in the eastern tract does not exceed 100 m. Hence, lower index values of 12 for blocks and 23 for intersection density are not indicative of the sector accessibility. Syntax analysis generated lower depth values and shorter paths throughout the network; arterial roads in this sector are among the most integrated in Abu Dhabi and extend for several kilometers connecting the CBD with the City. Heavy pedestrian flows are often present along arterials and inside blocks.

Density and land use are critical to understanding the levels of pedestrian activity and overall vitality of the eastern study area (Fig. 8). According to the Abu Dhabi Official Plan, the overall density of the sector is approximately 150 units per hectare. This density is certainly higher than those recommended by Jacobs and others for achieving the critical mass required for intense pedestrian activity and street vitality. Heights vary from 2-story to 50-story buildings. The bulk of high-rise structures are located on the block perimeters with lower densities inside the blocks as shown in the building heights map (Fig. 8a). The dearth of recreational open space in this sector is striking. On the basis of GIS data, the percentage of green cover and recreational parks is less than 8% of the sector area. Flash public surveys and direct observations pointed to the lack of recreational walking in the area; some area residents drive and others walk to the nearby waterfront parks or boardwalk for recreation. Driving is very much encouraged by the availability of spacious parking lots by the waterfront recreational spaces. As shown in the land use map (Fig. 8b), the sector is largely dominated by mixed uses that include residential, commercial, office, schools, as well as a wide range of government, health and community facilities. The bottom two floors of mid-and-high rise buildings are occupied by retail uses of different categories such as groceries, bakeries, pastries, clothing, mobiles, accessories, home appliances, electrical, and sanitary fixtures, as well as some bank branches and financial investment companies. Retail outlets occupy approximately 70% of the gross linear length of arterial roads and most shops boast permeable glass facades. The upper floors of mid-and-high-rise buildings are occupied by a mix of residential and office uses. More floors are devoted to residential units of various sizes, and others include offices, clinics, and miscellaneous service providers. Community facilities in the area encompass public schools, mosques, government services, transportation terminals, and parking grounds. This study systematically tallied the gross floor areas of each use. GIS data pointed to land cover areas occupied by different uses. Mean building height for every use was calculated block by block and averaged over the entire sector area. Table 2 provides the final tally of land use areas, floor count, and gross areas of different uses, as well as the final calculations of entropy and LUM indices for the five use categories of the CBD eastern sector.

The most significant aspect of the field study data is that actual footprints and floor occupancies of every land use have been calculated through the triangulation process of

Fig. 6 Images in the streets of the CBD eastern study area.

GIS, building permit registries, and census data, as well as field-collected metrics from real estate development companies and direct observations. Therefore, Table 2 lists actual land use footprints, number of floors, and occupancy percentages for every land use in the 12 blocks that constitute the CBD eastern sector. Although entropy calculations considered area percentages of different land uses and LUM measured number of floors and gross use square footages (sq.m), the results have been strikingly similar, and both returned very high indices, of 0.894 and 0.887, respectively. The results corroborate the premises of entropy and LUM equations, validate the data collection strategies, and explain the intense pedestrian activity in the CBD eastern sector.

4.1.2. Western area of Abu Dhabi CBD

The CBD western sector incorporates a number of city blocks with an approximate area of four square kilometers (Fig. 9). Newer developments and a number of high-rise structures/skyscrapers form the bulk of this sector. Medium-to-high traffic arterials and collector roads demarcate the thirteen blocks of this sector. The block perimeters are lined up with high-rise buildings that are 20—30 stories, while the block cores are dominated by low-to-midrise developments that are 2—15 stories. The sector boasts a rich mix of uses that include residential, commercial, retail, office, government, community, and a wide range of recreational and entertainment venues. It includes two significant developments: Al Hosn Palace Fort and Al Manhal Presidential Palace. Al Hosn was originally constructed in 1761 and served as the seat of government and residence for the ruler of Abu Dhabi until 1966. The fort has endured various additions/modifications and is considered the most significant cultural and architectural heritage of pre-modern Abu Dhabi. It sits on 15-ha grounds that have undergone major development over the last several years.

Fig. 7 The Eastern Study Area street map, blocks and images.

The site currently serves as the center of the city with the fort turned into a museum surrounded by immaculately landscaped public plazas and recreational open spaces. By contrast, Al Manhal Presidential Palace spreads over an area of 58 ha and succeeded Al Hosn as the seat of government and presidential palace for Zayed Bin Sultan, the Late President of Abu Dhabi and founding ruler of the United Arab Emirates. With the completion of the newer Presidential Palace, the grounds of Al Manhal are slated for a major mixed-use development that will open up the current 4-km long boundary walls to the CBD. At present, residents use an external sidewalk that encircles the palace walls for leisure and exercise walking (Figs. 10 and 11). The street network is primarily analyzed at the sector level but attributes of the blocks' internal streets and pedestrian alleyways are also discussed. The western sector has proper pedestrian crossings and a well-connected street grid with a link-node ratio (connectivity index) of 2.0.

The western sector incorporates different block sizes with varying levels of pedestrian activity across its roads and alleyways. On the basis of direct observations over several days and at different times of the day, the bulk of pedestrian activity is concentrated inside the blocks rather than the commercial perimeters along the arterials. Pedestrian travel along the arterials tends to be spotty and primarily created by movement between car parking lots and adjacent retail or commercial outlets. Flash public surveys along the arterials identified a majority of pedestrians from outside the study area; more than 60% of respondents indicated that they reside many miles away from the CBD and come to this area for shopping from specialty stores, entertaining, dining, and exploring the new CBD developments. Some of the new developments offer spacious underground parking and internalize a good percentage of walking inside indoor commercial establishments, thereby depriving the CBD western area of

Table 1 Block geometry of the CBD eastern sector in Abu Dhabi.

Block Characteristics	1	2	3	4	5	6	7	8	9	10	11	12
Dimensions in Meters	340 −580	340 −620	700 −1040	340 −670	340 −670	340 −670	670 −670	340 −600	340 −600	340 −600	340 −600	340 −600
Area in Thousands of Square Meters	197	211	728	302	228	228	449	204	204	204	204	204
Car access pts. from arterial service lanes	7	6	15	9	9	9	8	8	7	7	8	6
Pedestrian access pts. from arterials	28	36	45	36	36	36	24	32	28	28	32	24

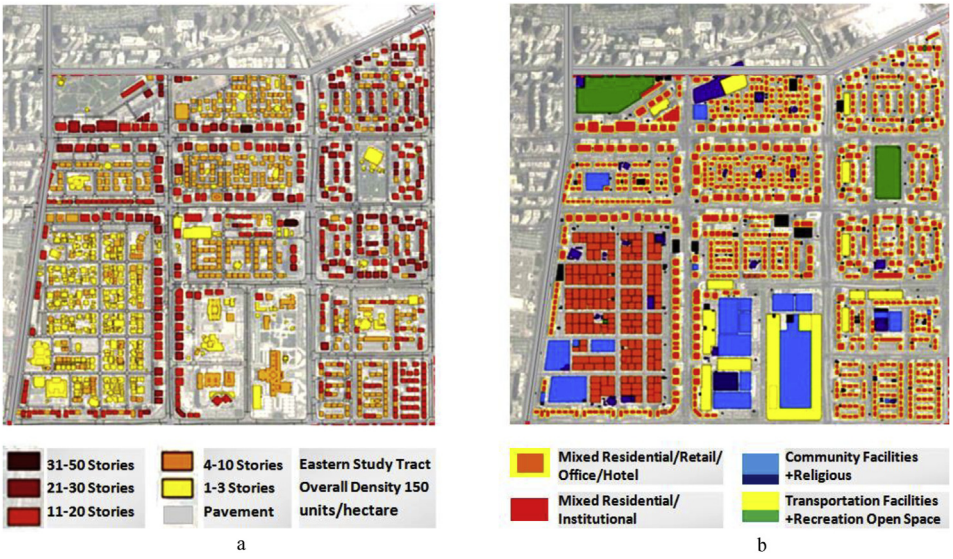

Fig. 8 CBD eastern sector building heights and land use maps. (a) Building Heights Map. (b) Land Use Map.

pedestrian movement facilitated by secondary/tertiary uses and related venues. Unlike the blocks of the eastern sector, which are uniform in land use distribution, density, and built form, the western sector manifests variegated configurations that render GIS map analysis less effective and warrant some description of each block in the sector. The following account moves beyond the GIS compiled data and provides a real-world overview of the eastern sector blocks to contextualize subsequent comparisons and analyses between the two sectors. Block measurements listed below are in linear meters.

Block 1: (143,000 sq.m)

This block is mostly occupied by green open spaces and public plazas equipped with fountains and one-floor service facilities for the park users. It is separated from the waterfront by the arterial road that runs parallel to the

Table 2 Abu Dhabi CBD eastern sector.

BLOCK LAND USE	BLOCK AREA (SQ. M.)	LAND USE ACTUAL FT.PRT %	LAND USE ACTUAL FT.PRT SQ. M	LAND USE MIX BREAKDOWN (AS BUILT)																							
				RESIDENTIAL USE APARTMENT BUILINDGS SINGLE -FAMILY SEMI-DETACHED MULTI-FAMILY				RETAIL + COMMERCIAL + ENTERTAINMENT + RESTAURANT				OFFICE + HOTEL + APARTMENT			HOTEL	COMMUNITY RELIGIOUS / CULTURAL / EDU HEALTH / RECREATIONAL				PUBLIC / GOV/ UTILITY TRANSPORTATION						
				%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA				
BLOCK 1	197000	80%	157600	16%	25216	6	151296	18%	28368	2	56736	11%	17336	8	138688	49%	77224	1	77224	6%	9456	2	18912				
BLOCK 2	211000	60%	126600	40%	50640	3	151920	27%	34182	2	68364	25%	31650	5	158250	8%	10128	2	20256	0%	0	0	0				
BLOCK 3	728000	72%	524160	29%	152006	4	608026	32%	167731	1	167731	25%	131040	6	786240	12%	62899.2	2	125798	2%	10483	1	10483				
BLOCK 4	302000	50%	151000	30%	45300	3	135900	31%	46810	2	93620	14%	21140	6	126840	12%	18120	1	18120	13%	19630	2	39260				
BLOCK 5	228000	60%	136800	25%	34200	6	205200	52%	71136	2	142272	17%	23256	6	139536	3%	4104	0	0%	3%	4104	1	4104				
BLOCK 6	228000	50%	114000	25%	28500	5	142500	33%	37620	2	75240	29%	33060	4	132240	3%	3420	1	3420	10%	11400	2	22800				
BLOCK 7	449000	30%	134700	11%	14817	8	118536	11%	14817	2	29634	0%	0	0	0%	43%	57921	6	347526	35%	47145	6	282870				
BLOCK 8	204000	50%	102000	34%	34680	6	208080	35%	35700	2	71400	25%	25500	8	204000	3%	3060	8	24480	3%	3060	8	24480				
BLOCK 9	204000	50%	102000	21%	21420	8	171360	29%	29580	2	59160	12%	12240	10	122400	33%	33660	2	67320	5%	5100	1	5100				
BLOCK 10	204000	50%	102000	32%	32640	10	326400	37%	37740	2	75480	24%	24480	15	367200	3%	3060	10	30600	4%	4080	10	40800				
BLOCK 11	204000	50%	102000	21%	21420	4	85680	31%	31620	2	63240	15%	15300	4	61200	21%	21420	2	42840	12%	12240	2	24480				
BLOCK 12	204000	50%	102000	41%	41820	6	250920	32%	32640	2	65280	20%	20400	6	122400	5%	5100	4	20400	2%	2040	5	10200				
USE SUM FT. PRT AND GROSS AREA	3363000	NA	1854860	NA	502659	NA	2555818		567944	NA	968157	NA	355402	NA	2358994	NA	300116	NA	777984	NA	128738	NA	483489				
USE PERCENTAGE FOR ENTROPY					0.271				0.306				0.192				0.1618				0.069						
USE LN PERCENT. FOR ENTROPY					1.30565		7144442		1.18354		7144442		1.65231		7144442		1.82139		7144442		2.6678		7144442				
LN 5 (NO. OF USES)					1.60944				1.60944				1.60944				1.60944				1.6094						
ENTROPY PER USE					0.21984				0.22517				0.19671				0.18311				0.0694						
PERCENTAGE FOR LUM							0.357735				0.13551				0.3301859				0.10889				0.067673				
USE LN PERCENT. FOR LUM							1.027963				1.9987				1.10809945				2.21738				2.693061				
LUM FOR USE							0.228489				0.16829				0.22733329				0.15003				0.113238				
ENTROPY TOTAL	0.894235714																										
LUM TOTAL	0.887373143																										

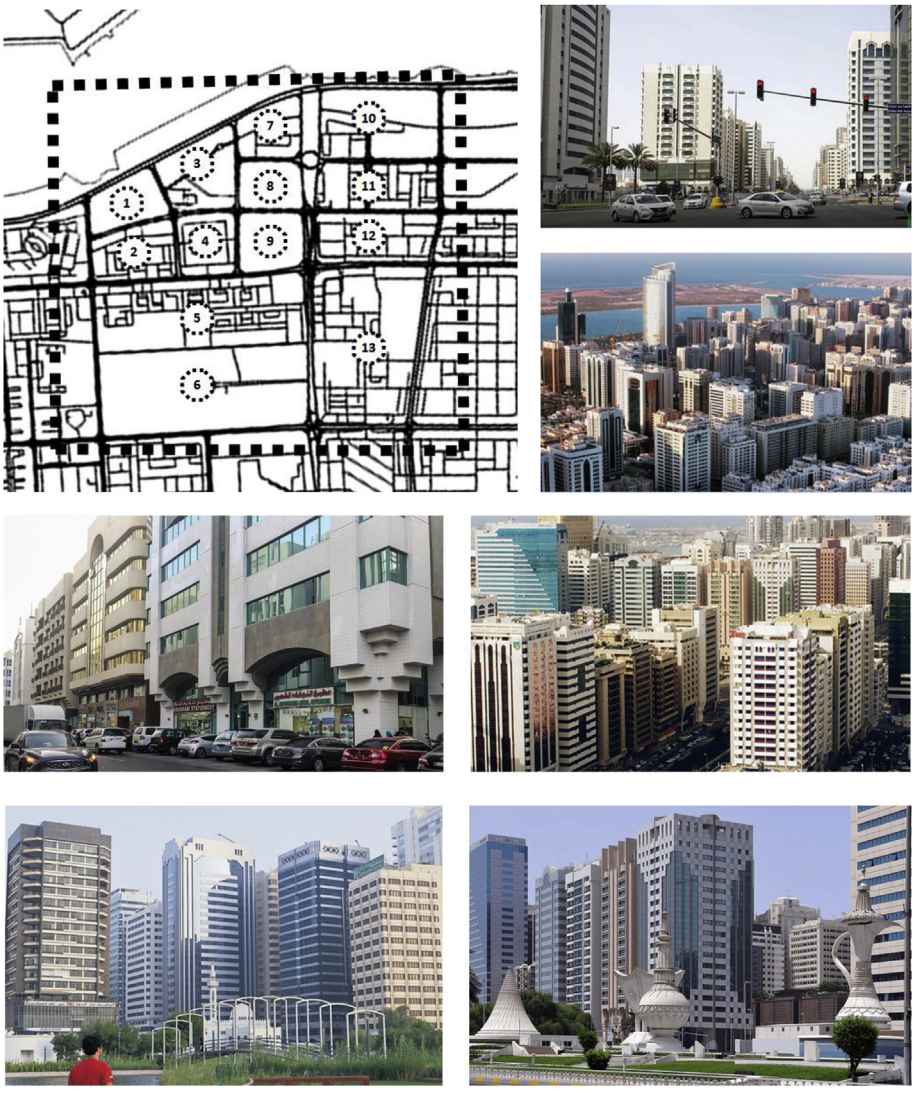

Fig. 9 Street map, blocks and images of the Western Study Area in Abu Dhabi CBD.

a b

Fig. 10 Blocks 5 & 6 views and Images. (a) Google Earth views for Blocks 5 & 6. (b) the walkway around Al Manhal Palace.

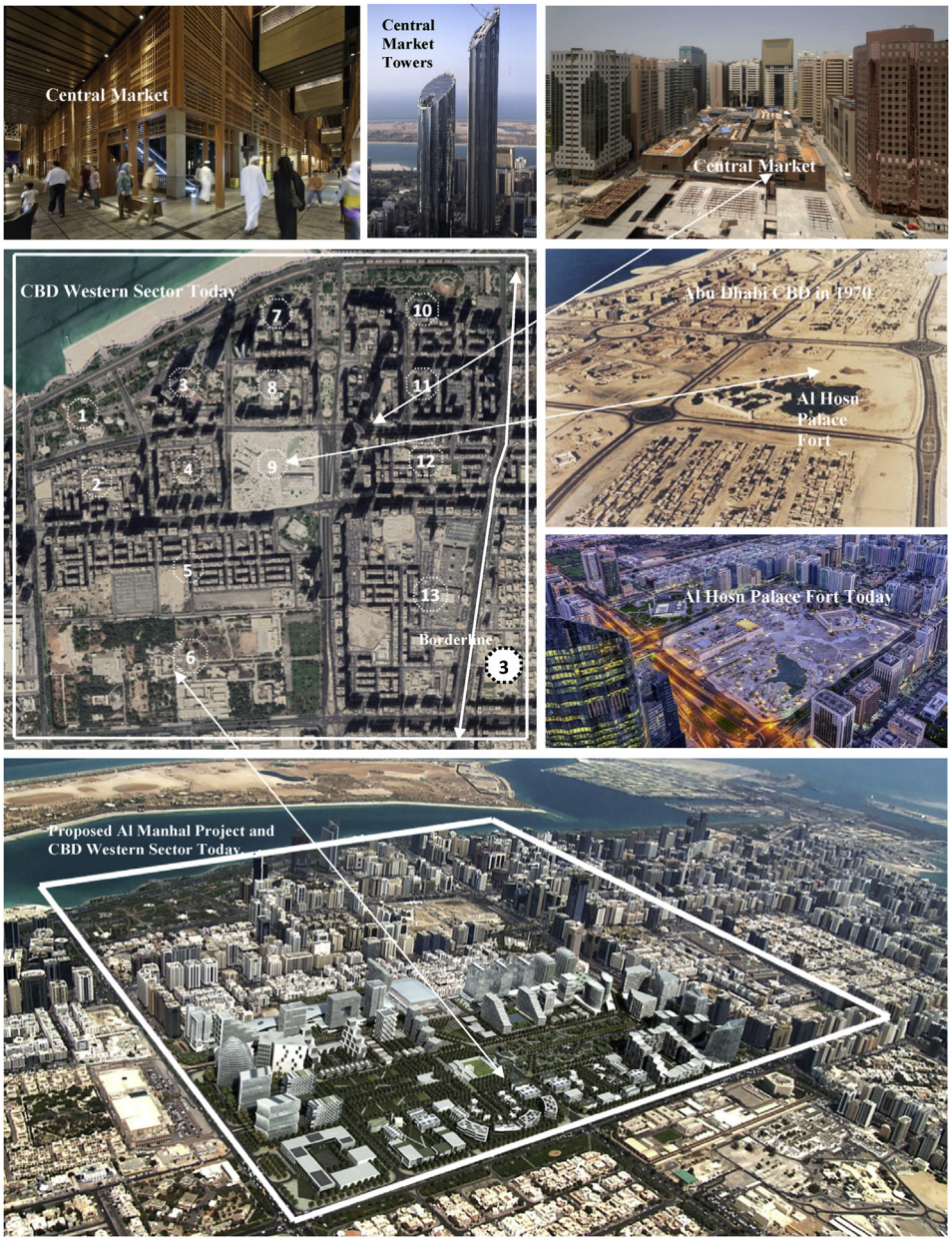

Fig. 11 Aerial views and blocks of the Western Study Area in Abu Dhabi CBD www.constructionweekonline.com — UPC 2020 - Urban Planning Council of Abu Dhabi Government.

Gulf shore throughout the entire city of Abu Dhabi. The block is provided with pedestrian tunnels that connect the CBD with the waterfront boardwalk. It serves as one of the major recreational resources for the entire city and is shaped like a trapezoid with a length of 520 m and an average width of 275 m.

Block 2: (162,000 sq.m)

A local access street subdivides block 2 into two sub-blocks. One is rectangular (285—315) and the other is trapezoidal with a length of 300 m and an average width of 240 m. Two-story residential villas occupy more than 50% of the block area, half of which switched use to a mix of company offices, restaurants, clinics, and general services. Another 20% of the block area is devoted to two-story schools and government buildings. As a rule for such urban blocks in Abu Dhabi, the block perimeters facing arterial roads are lined up with high-rise buildings, which in this case are capped at 20 stories (less than 30% of block area). The footprint of buildings is no more than 35% of the block total area.

Block 3: (190,000 sq.m)

This block is a unique block that incorporates three sky-scrapers of 50+ stories, notable among them is the Landmark Plaza Tower (72 stories, 325 m high), which was completed in 2013, and is one of the tallest buildings in Abu Dhabi. The tower includes hotel and office suites as well as high-end

retail stores in the bottom third and residential condominiums on the remaining floors. Two-story older residential villas occupy 10% of the block area behind the Plaza Tower. The block also accommodates 14 high-rise structures (20—25 stories) with mixed retail, office, and residential uses. Recreational green areas and facilities occupy almost 30% (62,000 sq.m) of the block area. The building footprints do not exceed 25% of the total block area.

Block 4: (137,000 sq.m)

The block perimeter is lined up with 29 mixed-use high-rise buildings (20- stories each), with a building footprint of 35,000 sq.m (25% of the total block area). The block is devoid of green spaces except for some scattered trees in-between buildings. Almost 50% of the block area is used as parking spaces, local access streets, pedestrian alleyways, and other hard surfaces, while building footprints cover the other 50%. The block interior is dominated by low-rise two-story villas and a mosque. A limited number of villas switched from residential to office use and few retail outlets. As per land use regulations in Abu Dhabi, wall-to-wall buildings on property lines are not permitted, thereby leaving pedestrian alleyways that provide turning points and shortcuts for walking around buildings.

Blocks 5 & 6: (575,000 & 650,000 sq.m)

A narrow collector street separates these two large blocks. Empty fields and huge parking lots (140,000 sq.m) comprise 25% of block 5's area (Fig. 13a). The useable area of block 5 is only 375,000 sq.m, a quarter of which consists of 15—20 story mixed-use towers located on the block perimeter. The interior part is occupied by seven-story mixed-use buildings with two commercial floors topped by residential units and company offices. As mentioned, the grounds of Al Manhal Palace (block 6) will be redeveloped as an iconic mixed-use development that serves the entire city (Fig. 10). At present, the fence walls are encircled by pedestrian walkways (Fig. 10b).

Block 7: (127,000 sq.m)

This block accommodates 20 high-rise office buildings (20-30 stories) and few iconic towers including the Abu Dhabi Investment Authority. Almost 1/3 of the block is devoted to public green space and separated from the other part by a collector street and office parking lot. Some of the buildings offer commercial gallery space on the lower floors.

Block 8: (127,000 sq.m)

High-rise office towers (20—25 stories) with two commercial/retail floors face the arterial roads. Almost 30,000 sq.m of the block area is occupied by a large mosque with service facilities, parking, and green space. The block interior (50% of the total block area) houses higher education and community facilities as well as local access streets and parking spaces.

Block 9: (150,000 sq.m)

This is the site of Al Hosn Fort Palace and the current geographic center of the city of Abu Dhabi. The 15-ha grounds of Al Hosn have been transformed into a world-class public space with a museum, cultural foundation, research center, and expansive landscaped plazas with water features and entertainment venues (Fig. 11).

Blocks 10, 11, & 12: (317,000, 230,000, & 220,000 sq.m)

Blocks 10 & 11 together host one of the most significant new developments in the city of Abu Dhabi, which include two of the tallest towers and the largest indoor shopping mall in the city center. The new Central Market and shopping mall development occupy the interior space of both blocks with a functional shopping bridge crossing over the road separating the two blocks. It was designed by Norman Foster as a new shopping experience replacing the old Abu Dhabi Bazaar. Block 10 is further subdivided into three zones by collector streets. The northern zone of block 10 (108,000 sq.m) includes a recreational park space that is connected with the waterfront boardwalk with underground tunnels. The other two zones host high-rise residential/office buildings (15—25 stories) with two-to-three commercial floors in the bottom. Similar building heights and mixed-use arrangements characterize Block 11 as well. The perimeter of Block 12 is lined up with 20-story mixed-use buildings but the interior is occupied by 7-story residential buildings as well as a two-story school and a mosque. The bottom two floors of many buildings contain commercial and retail establishments.

Block 13: (615,000 sq.m)

This block is one of the oldest and largest developed urban blocks in the city center. As typically found in most CBD blocks, the perimeters facing arterial roads are lined up with mixed-use residential/office high-rise buildings (20 stories) with two retail/commercial floors in the bottom. The interior of this large block is divided into different zones by collector streets and contains miscellaneous uses such as old cemeteries (50, 000 sq.m), post office and other government service buildings (40,000 sq.m), mosques (10,000 sq.m), school facilities (30,000 sq.m), vegetable market (15,000 sq.m), and one of the oldest indoor shopping malls in the city (130,000 sq.m). What remains of the block interior is occupied by seven-story buildings with retail in the ground and mostly residential on the upper floors.

As indicated in the block description, the western CBD area is relatively different from its eastern counterpart. The majority of its blocks contain not only newer but also unique developments that are considered major landmarks for the entire city of Abu Dhabi. The old buildings and developments in Block 13 might be the only exception. Block 13 borders Block 3 of the eastern sector and its use mix more or less complements the uses on the other side of the arterial road separating the two study areas (Fig. 11). Spillover effects in pedestrian activity between Block 3 and

Block 13 were evident in the flash public surveys conducted along the arterial corridor. Beyond this borderline, pedestrian activity on the west side starts to decline in comparison with the eastern side. Although a small percentage of pedestrians pointed that they live in the area and walk to work, the majority of respondents commute to their work; this trend increased substantially towards the western edges of the CBD. Flash public surveys during the evenings indicated that more than 50% of pedestrians in the western sector have driven from other areas to enjoy extensive upscale shopping, restaurants, and other entertainment venues. The western sector generally provides more parking opportunities for residents and commuters, fostering the reliance on the automobile for transportation much more than the eastern sector. As noted, a small percentage of pedestrians enjoyed the walkways around Al Manhal Palace (Block 6) and used them as part of their routine exercise and/or recreational walking. The majority of visitors to Al Hosn Fort Palace and public spaces (Block 9) have commuted to the city center from different corners of Abu Dhabi. Due to the recent completion of civil works, Al Hosn public spaces are not yet usual destinations of CBD visitors.

Given that the area demarcated for each of the CBD sectors is approximately the same (4 square kilometers), the block density index (13) and intersection density (25) of the western sector are higher than their eastern counterparts (12 & 23 respectively). In both CBD sectors, the block and intersection density indices are considered low as evaluated by Jacobs' block geometry descriptors. However, the land use regulations in Abu Dhabi mandate pedestrian alleyways in-between buildings, thereby rendering the width of the building as the effective block dimension with many opportunities for pedestrians to shortcut walking journeys and change direction. Table 3 summarizes the metrics of the western sector blocks and lists car and pedestrian access points from arterials. Twelve of the thirteen blocks of the western sector are well connected across the arterial grid, which is also favorably integrated with the road network across the entire city. However, local and global depth values (syntax metrics) are negatively affected by the walled-off block of the Presidential Palace (block 6). The frequency and intensity of traffic jams are generally less than in the eastern sector. Pedestrian flows are intense along the arterial road separating the eastern and western sectors, becoming spotty and declining further toward the westernmost edges of the CBD.

According to the Abu Dhabi Official Plan, the overall density of the CBD is 100–150+ units per hectare. The higher end of the range belongs more or less to the CBD eastern sector. On the basis of tallying the building footprints, distribution of residential, office, and commercial uses as well as building heights, this study assesses the density of the western sector at 115 units per hectare. Such a density and rich land use mix is sufficient to create the critical mass commensurate with high levels of pedestrian activity. The bulk of pedestrian activity, however, is concentrated on the borderline or the spillover area between the CBD eastern and western sectors; it declines rapidly westwards and does not reflect the intensity of development and/or availability of recreational and other service facilities in the western sector. This sector is generally infused with landmark structures and skyscrapers that have become part of the modern image of Abu Dhabi such as the World Trade Center towers, landmark plaza, and Investment Authority (Fig. 9). The percentage of recreational green open spaces exceeds 12% of the built-up area. Flash public surveys and direct observations pointed to moderate recreational walking activity around Al Manhal Palace walls. Most area residents drive and few walk to the nearby waterfront parks or boardwalks for recreation. Driving is very much encouraged by the availability of spacious parking lots by the waterfront recreational spaces. Table 4 summarizes the field study measurements, use footprints developed from GIS maps, and tallied gross floor areas, as well as entropy/LUM index values generated for the western sector.

As shown in the analysis table, the western sector accommodates mixed uses that include residential, commercial, office, and schools, as well as a wide range of government, health, and community facilities. The bottom two floors of mid-and-high rise buildings are often occupied by retail shops and commercial activities of different categories such as groceries, bakeries, pastries, clothing, mobiles, accessories, home appliances, and electrical and sanitary fixtures, as well as some bank branches, travel agencies, service, and financial investment companies. The latter uses occupy approximately 55% of the gross linear length of arterial roads and most boast permeable glass facades. The upper floors of mid-and-high rise buildings are occupied by a mix of residential and office uses. Generally, more floors are devoted to residential units of various sizes and a smaller percentage for offices, clinics, and miscellaneous service companies. Community facilities in the area encompass public schools, mosques, government

Table 3 Block geometry of the CBD western sector in Abu Dhabi.

Block Characteristics	1	2	3	4	5	6	7	8	9	10	11	12	13
Dimensions in Meters	250 –520	285 –315	425 –448	370 –370	418 –1375	473 –1375	314 –404	300 –383	355 –411	425 –746	290 –793	310 –710	650 –946
Area in Thousands of Square Meters	143	162	190	137	575	650	127	115	145	317	230	220	615
Car access pts. from arterial service lanes	6	8	6	8	12	0	6	6	0	6	6	6	8
Pedestrian access pts. from arterials	30+	32	15	30	48	0	18	18	30+	20	18	18	30

Table 4 Abu Dhabi CBD western sector.

BLOCK LAND USE	BLOCK AREA (SQ. M.)	LAND USE ACTUAL FT.PRT %	LAND USE ACTUAL FT.PRT SQ. M	LAND USE MIX BREAKDOWN (AS BUILT)																			
				RESIDENTIAL USE APARTMENT BUILINDGS SINGLE -FAMILY SEMI-DETACHED MULTI-FAMILY				RETAIL + COMMERCIAL + ENTERTAINMENT + RESTAURANT				OFFICE + HOTEL + HOTEL APARTMENT				COMMUNITY RELIGIOUS / CULTURAL / EDU/ HEALTH / RECREATIONAL				PUBLIC / GOV/ UTILITY TRANSPORTATION			
				%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA	%	BUILT FT.PRT	NO. OF FLOORS	GROSS AREA
BLOCK 1	130000	100%	130000	0%	0	0	0	2%	2600	1	2600	0%	0	0	0	80%	104000	1	104000	18%	23400	1	23400
BLOCK 2	160000	75%	120000	32%	38400	4	153600	22%	26400	2	52800	15%	18000	3	54000	23%	27600	2	55200	8%	9600	1	9600
BLOCK 3	190000	75%	142500	27%	38475	12	461700	12%	17100	2	34200	11%	15675	7	109725	36%	51300	1	51300	14%	19950	1	19950
BLOCK 4	137000	50%	68500	49%	33565	7	234955	29%	19865	2	39730	15%	10275	4	41100	7%	4795	1	4795	0%	0	0	0
BLOCK 5	575000	65%	373750	48%	179400	3	538200	26%	97175	2	194350	12%	44850	2	89700	2%	7475	1	7475	12%	44850	1	44850
BLOCK 6	650000	5%	32500	0%	0	0	0	0%	0	0	0	0%	0	0	0	100%	32500	1	32500	0%	0	0	0
BLOCK 7	127000	50%	63500	27%	17145	4	68580	15%	9525	2	19050	15%	9525	4	38100	40%	25400	1	25400	3%	1905	1	1905
BLOCK 8	115000	60%	69000	24%	16560	4	66240	8%	5520	2	11040	8%	5520	3	16560	57%	39330	1.5	58995	3%	2070	1	2070
BLOCK 9	145000	100%	145000	0%	0	0	0	0%	0	0	0	2%	2900	1	2900	96%	139200	1	139200	2%	2900	2	5800
BLOCK 10	317000	50%	158500	29%	45965	8	367720	27%	42795	2	85590	13%	20605	5	103025	26%	41210	1	41210	5%	7925	1	7925
BLOCK 11	230000	50%	115000	38%	43700	12	524400	36%	41400	2	82800	15%	17250	10	172500	6%	6900	1	6900	5%	5750	1	5750
BLOCK 12	220000	50%	110000	38%	41800	6	250800	20%	22000	2	44000	15%	16500	3	49500	20%	22000	2	44000	7%	7700	1	7700
BLOCK 13	615000	50%	307500	37%	113775	6	682650	31%	95325	2	190650	10%	30750	2	61500	12%	36900	2	73800	10%	30750	1	30750
USE SUM FT. PRT AND GROSS AREA	3611000	NA	1835750	NA	568785	NA	3348845		379705	NA	756810	NA	191850	NA	738610	NA	538610	NA	570975	NA	156800	NA	159700
USE PERCENTAGE FOR ENTROPY					0.30984				0.207				0.105				0.2934				0.085		
USE LN PERCENT. FOR ENTROPY					1.17171		5574940		1.57581		5574940		2.25849		5574940		1.22622		5574940		2.4602		5574940
LN 5 (NO. OF USES)					1.60944				1.60944				1.60944				1.60944				1.6094		
ENTROPY PER USE					0.22557				0.20252				0.14665				0.22354				0.0854		
PERCENTAGE FOR LUM							0.6006962				0.13575				0.132488				0.10242				0.028646
USE LN PERCENT. FOR LUM							0.509666				1.99692				2.021267				2.27869				3.55274
LUM FOR USE							0.1902244				0.16844				0.166389				0.14501				0.063234
ENTROPY TOTAL	0.883694376																						
LUM TOTAL	0.733290255																						

services, and parking grounds. The western sector is unique because of the percentage of newer iconic structures, skyscrapers, and large indoor shopping malls (World Trade Center & Zayed). The Al Hosn museum, cultural foundation, and the surrounding public spaces provide the western sector with a major advantage in its ability to attract local, national, and international visitors. However, the walled-off grounds of Al Manhal Presidential Palace interrupt the continuity of the mixed-use urban fabric and severs a large chunk of land from the CBD. Fortunately, the palace grounds will be redeveloped and integrated with the CBD over the next few years.

4.2. Summary of field study results

Using GIS maps/data files and real-estate records as well as field metrics and direct observations, the field study not only calculated different land use allocations in the CBD sectors but also actual footprints of buildings, number of floors, and occupancy percentages dedicated to each functional classification. Land use and functional variety have been consolidated under five categories instead of the seven conventionally used in previous studies. This strategy collated all residential uses (single-family-semi-detached-multifamily-apartment buildings) into one category. Retail, small and big, as well as commercial, entertainment, and cafés/restaurants, have been lumped under commercial use. The office use encompassed all areas dedicated to company offices and hotels and hotel apartments. Religious, cultural, educational, health, and recreational resources have been clustered under community use. The last category included government departments, utility facilities, and areas dedicated to public parking lots. The clustering of uses under these five categories was rationalized by their physical proximity and intense variety that did not allow splitting them into unique categories. Pedestrian activity patterns around clustered uses followed similar patterns and justified the inclusion of them under each of the five categories. Tables 1 and 3 listed the dimensions, areas, and access points (car and pedestrian) for each of the blocks forming the CBD eastern and western sectors, respectively. The heightened inter- and-intra-block pedestrian access possibilities through alleyways and roads undoubtedly contribute to the street vitality in Abu Dhabi CBD. However, it did not explain the marked difference in pedestrian activity between the two sectors. The eastern sector was characterized by a much more intense pedestrian activity compared with the western sector. Tables 2 and 4 incorporated the results of land use and functional density analyses, providing the key to understanding the reduced pedestrian activity in the western sector. As documented in Table 2 and Chart 1, entropy and LUM computations for the eastern sector resulted in index values of 0.894 and 0.887, respectively. Such high values characterize urban areas with intense land use variety and a rich mix of primary and secondary functions. The results corroborate the premises of entropy algorithms and validate the data collection strategies. The entropy index value of the western sector was close to its counterpart of the eastern sector and did not also explain the marked difference in pedestrian activity between the two sectors. The LUM index value (Chart 1), by contrast, reflected a

more accurate picture of land use mix, functional concentration, population density, and capacity to draw visitors from other areas of the city and beyond. The latter value downgraded the western sector by approximately 17%, which to a large extent rationalized the reduced pedestrian activity in the western sector. The fact that the eastern sector developments predate their counterparts in the western sector by a decade or slightly more does not provide a major advantage or justify the noted increase in its vitality. Jacobs's formula regarding the need for a mix of old and new buildings referred to different contexts where buildings continue to be used, maintained, and reused or adapted to different functions over several decades. The urban fabric of the eastern and western sectors of Abu Dhabi CBD is fairly new and may not be associated with the settings of continuously lived-in/reutilized new and older urban developments. Public surveys in both sectors revealed a paradoxical preference amongst CBD residents/visitors to be around the new/glitzy buildings of the western sector. Nevertheless, most respondents referred to living and walking in the eastern sector as providing more accessibility in terms of not only the number of retail shops, cafes, restaurants, convenience stores, and services but also the wide range of upper- and lower-scale venues. Such preferences can be justified by the intense variety and mix of land uses that provide both functional differentiation and wide-ranging services and retail price choice. Although both CBD sectors are defined by highly integrated grid street networks, the eastern sector holds a higher connectivity index and connected node percentage (Chart 1). The shorter paths throughout the street network as well as the higher density and accessibility (both car and pedestrian) of the eastern sector add further advantages that contribute to its increased pedestrian activity and vitality throughout the day and evening times (Chart 2).

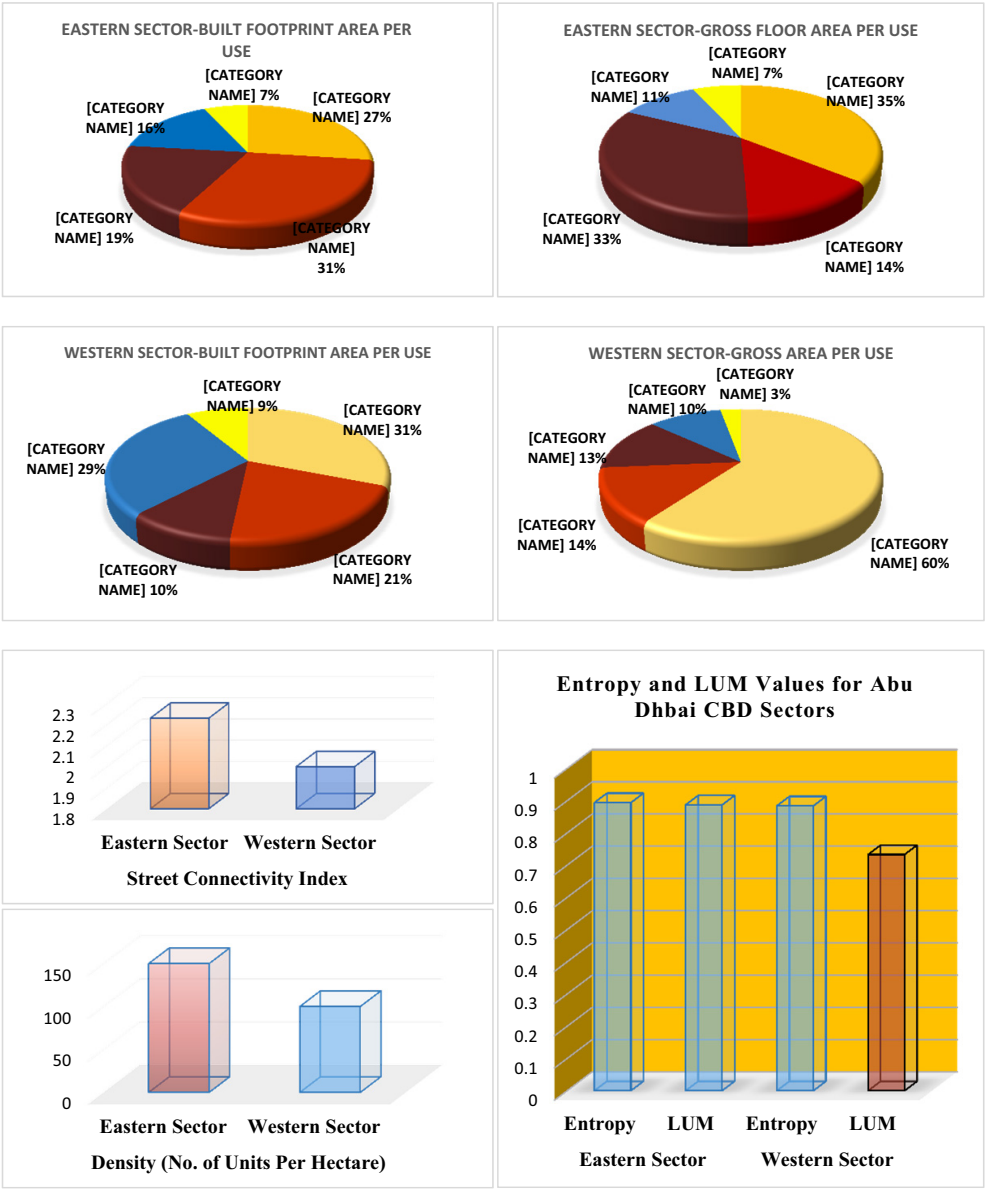

Chart 1 Abu Dhabi CBD Field Study Analysis of Results.

5. Discussion

On the basis of the analysis of land use, connectivity, and street network integration as well as direct observations and public surveys, the two sectors of Abu Dhabi CBD have spatial and functional configurations that are conducive to pedestrian activity and overall street vitality. These configurations are manifested in the grid street networks with few cul-de-sacs or partially blocked intersections. The ease of pedestrian movement and change of direction via alleyways left publicly open around all buildings transformed the CBD's oversized superblocks into small and highly accessible urban development units. The concentration of different but complementary uses and population density throughout the CBD is sufficient to create favorable levels of pedestrian movement during different times of the day and for different purposes. The two sectors host a variety of recreational resources and entertainment possibilities that seem to attract visitors not only from edge cities 30 miles away but also other cities in the region and beyond. The overall calculated values for entropy and LUM indices support the assessment of Abu Dhabi CBD and its ability to generate intense pedestrian activity and commensurable street vitality. Nevertheless, the breadth and depth at which the CBD was analyzed yielded significant and somewhat incongruous results.

The dual process of entropy and LUM computations for Abu Dhabi CBD sectors yielded results that may contradict the logic of land use evenness as a basis for predicting pedestrian flows and street vitality. The entropy index values of 0.894 and 0.884 for the eastern and western sectors respectively do not reflect an accurate picture of the documented difference in pedestrian flows between the eastern and westerns sectors in Abu Dhabi CBD. Structured direct observations and public surveys that preceded the research pointed to 30% higher pedestrian volumes in the eastern sector compared with its western counterpart. Entropy indices seek land use heterogeneity through balanced distribution or equal percentages of multiple functional categories. However, the concept of even land use distribution as a corollary for neighborhood vitality overlooks the functional diversity and complementarity of uses articulated in various studies as crucial for predicting travel behavior and pedestrian activity (Hess et al., 2001; Ewing and Cervero, 2010; Gehrke and Clifton, 2016; Mavoa, 2018). Land use variation amongst contiguous developments is emphasized as a critical aspect of vital urban spaces. Land use variation is measured through the dissimilarity index, which can be used in conjunction with entropy to predict travel patterns between complementary uses such as residential, retail, education, employment, and other support functions (Kockelman, 1997). Other studies referred to various possibilities of mixed uses in the same property or building with commercial and office spaces occupying lower floors and diverse residential uses in the upper floors (Hoppenbrouwer and Louw, 2005; Sung et al., 2015).

Abu Dhabi CBD manifests a very complex urban environment that has developed rather rapidly over the past few decades within relaxed regulatory frameworks. Developers in Abu Dhabi city were allowed to integrate retail, office, and residential uses in the same property. Some large-scale mixed-use developments were created by consolidating several properties that did not necessarily comply with existing codes and were often approved through variances. Others experienced successive use changes and adaptations that were not officially documented in building permit registries. Implementing the dissimilarity index on a massive scale in Abu Dhabi CBD proved to be forbidding. The study opted to use another entropy measure (LUM) and factor "as occupied" functions rather than documented land use categories in official city plans and building permit repositories. Although less daunting than implementing the dissimilarity index, calculating as occupied mixed-use functions in Abu Dhabi CBD has been a massive undertaking. Sources of information included onsite direct observations, field area measurements, and records of real estate development companies. As hypothesized at the beginning of this research, the entropy and LUM calculations culminated in different percentages for land use types, hence different index values. LUM index values for the eastern and western sectors of Abu Dhabi CBD were 0.887 and 0.733, respectively. LUM index values reflected a more accurate picture of land use mix variety, functional complementarity, and use concentration. These downgraded the western sector by approximately 17%, which to a large extent rationalized the reduced pedestrian activity in the western sector.

LUM computations in this research internalized entropy and dissimilarity indices and provided a more accurate procedure to assess the effect of mixed-use developments on pedestrian activity. The reduced LUM value for the

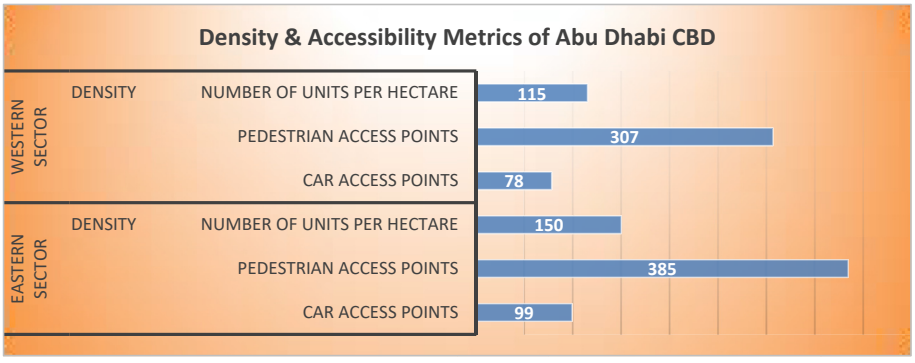

Chart 2 Abu Dhabi CBD Density and Accessibility Metrics.

western sector of Abu Dhabi CBD underlined other significant built environment features that decrease pedestrian street flows. This finding supports Kockelman's (1997) argument regarding the "island effect" phenomenon. The western sector has various use concentrations that include commercial establishments with indoor walking environments and government service facilities. Pedestrian activity becomes internalized in and around such use concentrations, also dictating the provision of massive parking lots that further the separation between complementary functions. Use concentrations such as these discourage walking across different city blocks and reduce the overall vitality of mixed-use centers.

Public surveys in both sectors revealed a paradoxical preference amongst CBD residents/visitors to be around the glitzy buildings of the western sector. Nevertheless, most respondents referred to living and walking in the eastern sector as providing more accessibility in terms of the number of retail shops, cafes, restaurants, convenience stores, services, and entertainment venues. The overwhelming respondents' preference for the eastern CBD sector is justified by its intense variety and mix of land uses that provide both functional differentiation and wide-ranging services and retail price choice. Although both CBD sectors are defined by highly integrated grid street networks, the eastern sector holds a higher connectivity index and connected node percentage. The shorter paths throughout the street network, as well as the higher density and accessibility (both car and pedestrian) of the eastern sector, add further advantages that contribute to its increased pedestrian activity and vitality throughout the day and evening times (Chart 2). Thus, the empirical approach of this study also captured the effect of enhanced street connectivity and pedestrian maneuverability around blocks and buildings as a corollary of intense mixed-use variety and functional complementarity.

This study, however, confirmed the validity of some of the basic entropy assumptions and their value for predicting pedestrian travel patterns. As a measure of the equal distribution or evenness of land use mix (Frank and Pivo, 1994; Manaugh and Kreider, 2013), the entropy index has offered an indication of pedestrian possibilities in the eastern and western sectors of Abu Dhabi CBD. LUM computations revealed the imbalance in land use categories in the western sector (60% residential against 40% for commercial, office, and community/government facilities combined). The reduced LUM value for the western sector (0.733) supports the entropy logic in terms of the need for somewhat balanced mixed-use distribution to enhance street pedestrian flows. Furthermore, the rich pedestrian activity in the eastern sector was reflected in the high LUM score of 0.883. The latter value underlined the complementarity between the different land uses and their potential for predicting travel behavior and walking patterns (Hess et al., 2001, Ewing and Cervero, 2010; Gehrke and Clifton, 2016). The substantial task of tallying as used properties, rather than land use classifications in building permit registries in ABU Dhabi CBD, produced more accurate walkability measures. As a result, this study advocates the need for extended visual, spatial, and contextual analyses to complement the application of statistical tools and justify variations in index values or results from one case study to another.

6. Conclusion

This study adopted a nuanced and critical approach to literature review and data gathering strategies. It critically reviewed and triangulated various strands of research from architecture, planning, transportation, and related urban studies. Design and environmental psychology literature emphasized that urban vitality is cultivated through a rich mix of land uses and appropriately configured streets, public spaces, and building facades. Pedestrian-friendly built environments integrate a rich mix of land uses, fine-grain street networks, spatially defined public spaces, visual stimuli, and well-articulated relationships between buildings, sidewalks, squares, and streets. By contrast, planning and transportation studies offered measurement tools for land use and street network attributes that potentially affect pedestrian activity. Owing to the limitation of mining land use metrics from GIS maps, the study embarked upon the empirical challenge of triangulating data from GIS maps, field measurements, and direct observations that were complemented by public surveys. The most significant aspect of the research has been manifested in the selection of Abu Dhabi CBD for the field study and the application of both entropy and LUM algorithms to assess the proportions of different uses that are positively associated with increased pedestrian activity. Abu Dhabi CBD generally offered a unique setting with a rich mix of uses and integrated grid street network, albeit with striking differences in the levels of pedestrian activity across its eastern and western sectors. The research opted for conducting quantitative analyses of two urban sectors with similar built form and functional mix to pinpoint intricate variations in their land use and street network configurations rather than tackling areas with obvious differences leading to a priori known results. As opposed to the close results of entropy values for the eastern and western CBD sectors (0.894 & 0.887), LUM computations underscored the nuanced divergence in land use concentrations and allotments that contributed to the decline of pedestrian activity in the western CBD sector (0.733). The entropy algorithm correctly considered different land uses and brought forth high index values for both sectors commensurate with considerable levels of pedestrian activity, which is generally factual about the totality of Abu Dhabi CBD. However, the intensity and complexity of use mix configurations, both horizontally and vertically, in some areas of the CBD exposed the relative imperfections of entropy calculations. The massive undertaking of tallying "as used" properties, rather than land use classifications in building permit registries in ABU Dhabi CBD produced more accurate walkability measures. The empirical results validated the methodological approach and data collection strategies of this research. The study contribution was manifested in the analytical review of various strands of related research and the development of a systematic empirical approach to investigate associations between land use mix and enhanced pedestrian activity. The issues raised in this study potentially enrich the debate on the concept of

evenness in land use mix, which is typically considered in walkability literature.

Declaration of competing interest

None.

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