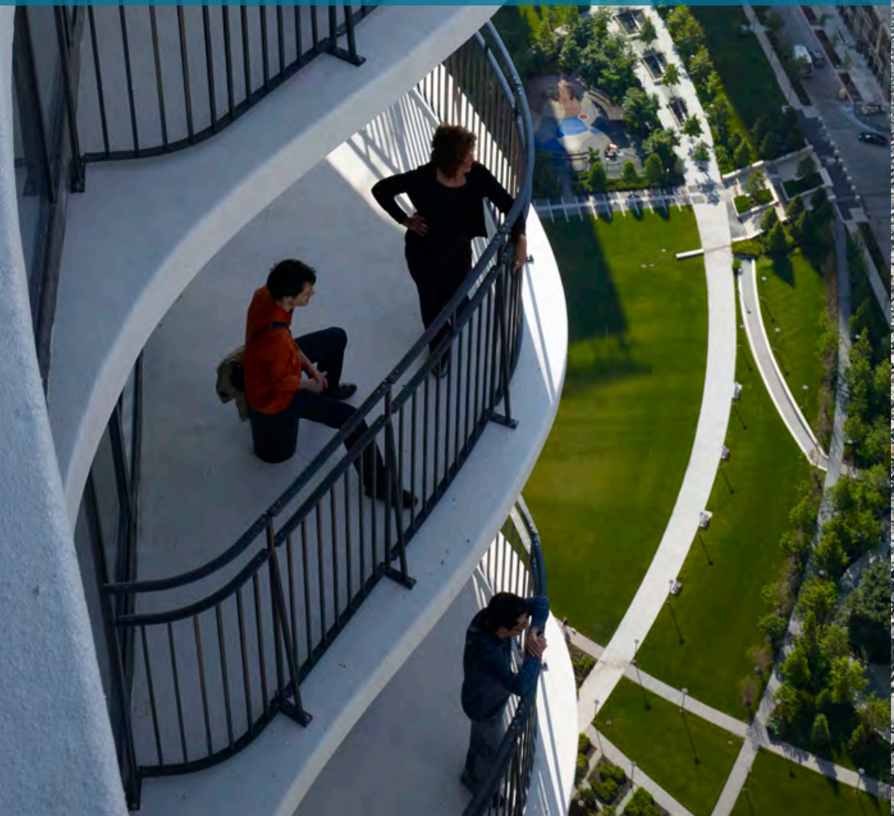
CTBUH Research Report

Downtown High-Rise vs. Suburban Low-Rise Living

A Pilot Study on Urban Sustainability

Peng Du & Antony Wood



Council on Tall Buildings and Urban Habitat

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0.0 Executive Summary

0.1 Introduction

There has been a long-standing debate on whether urban living is more or less sustainable than suburban living. Against the backdrop of more than one million people urbanizing on our planet every week (UN, 2014), it has become generally assumed that the "dense vertical" city is more sustainable than the "dispersed horizontal" city, which requires more land usage as well as a higher energy expenditure in infrastructure and mobility.

Studies to date have, however, been mostly generic, based on large data sets of generalized data regarding whole-urban energy consumption, or large-scale transport patterns. Crucially, there are very few studies that also take into account a 'quality of life' aspect to urban vs. suburban living, in addition to the energy equation.

The fundamental objective of this research project, then, is to investigate and compare the sustainability of people's lifestyles in multiple key areas from environmental and social perspectives, using Chicago based case studies. In doing this, though it draws reference to large-scale published studies, the emphasis is placed on obtaining real quality data wherever possible through, for example, the obtaining of actual home operational energy and water bills, tracking transport movements by all travel modes, or investigating residents' satisfaction with life and a sense of community. The theoretical framework for this study, including all the topics embraced, is shown in Figure 0.1.

The main vehicle for information collection became an online questionnaire which asked for information such as the uploading of energy bills, and took around 45-90 minutes to complete. The statistics on questionnaire response rate is shown in Figure 0.2.

0.2 Case Study Setting: Chicago

The research was undertaken based on two case study sets. Households in four residential towers spanning two "downtown" Chicago areas (The Loop and Lakeview) were selected as the downtown case studies, which resulted in 249 household responses in the high-rise realm. A similar sample size of 273 homes in Oak Park, comprising single-family detached homes and several duplex/townhouses, comprise the suburban case study. The geographic locations and connected transportation systems of the two case study sets are shown in Figure 0.3, whilst Figure 0.4 shows more detail on the selected case studies.

0.3 Demographics of Responding Residents

Figure 0.5 shows the summarized results of the resident and household demographics. As can be seen in the table, residents in both scenarios were roughly evenly split by gender. The majority of residents involved in this study were ethnically white/caucasian, at 88.6% of respondents in Downtown high-rises and 88.4% of respondents in Oak Park. The average age of residents in the Downtown high-rises was 51.1 years, significantly higher than Oak Park, at 31.8 years. The average household size of Downtown residential towers (1.9) is comparable to the US Census data (1.8 in the Loop and 1.9 in Lakeview), but the average household size of Oak Park low-rises was significantly higher (3.4) than the US Census data for Oak Park (2.4).

Respondents had a very high annual household income in both urban and suburban scenarios, at $220,541 per year Downtown to $175,343 per year in Oak Park, both significantly higher than median household income in the Chicago metropolitan area of $63,441 (CMAP, 2017).

Percentage of home ownership was high from survey respondents, with about 88% in both Downtown and Oak Park. These results are likely due to the survey targeting Downtown condominium owners rather than apartments, and mostly single-family homes in Oak Park (percentage of single family homes by Oak Park respondents was high, at 75%).

Oak Park had more private parking spaces per household, at 1.8, compared to 1.4 Downtown, but on a per-person basis, Downtown high-rises actually had more private parking spaces, at 0.6 spaces per person compared to 0.5 in Oak Park. Residences in Oak Park were larger on average on a per-household basis, with 226.4 m^2 in gross floor area compared to 147.1 m^2 Downtown. Interestingly, Downtown residents

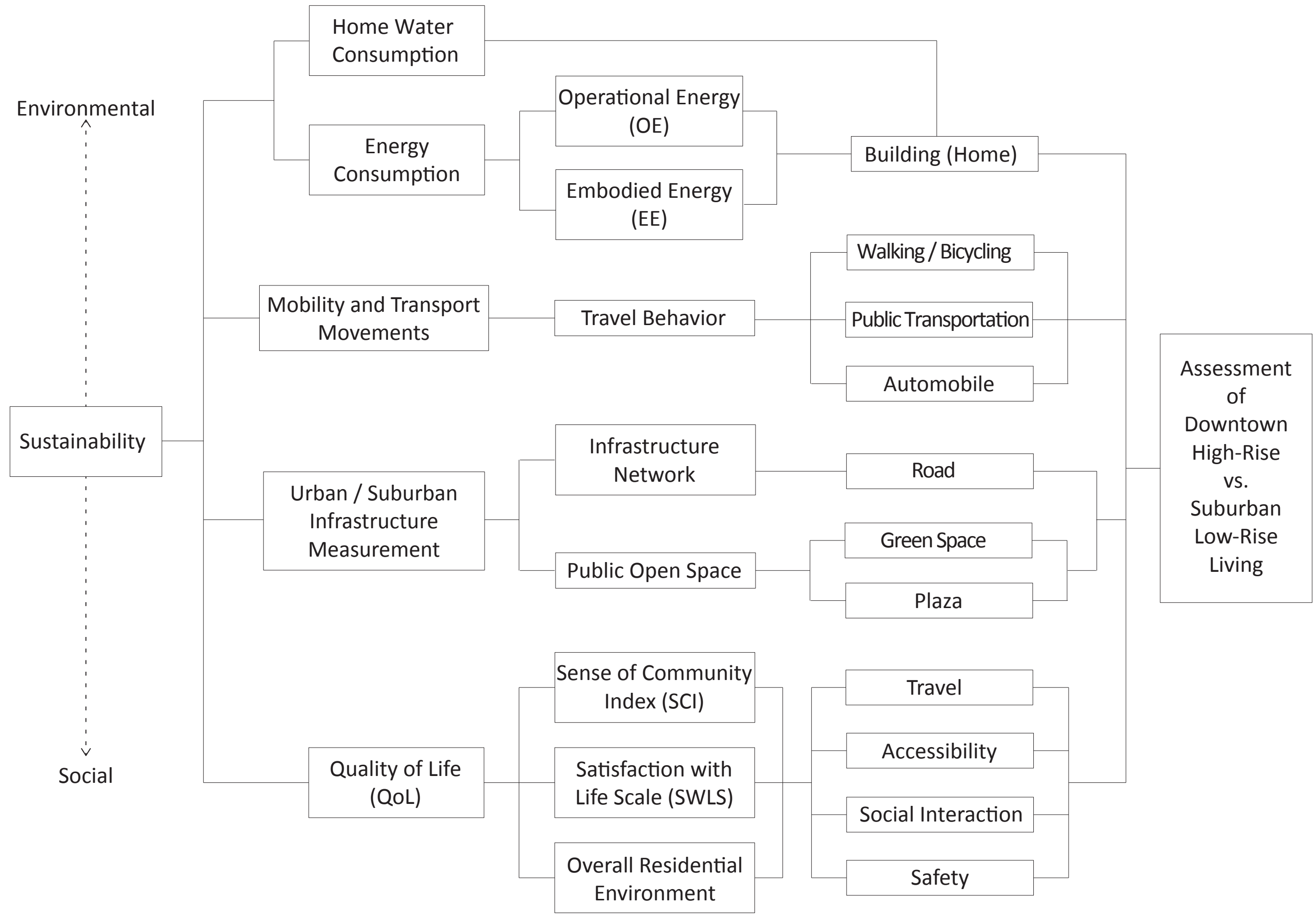

Figure 0.1. Analytical framework of the factors affecting sustainability that were embraced in this research project.

				Downtown High-Rise	Suburban Low-Rise
	Legacy	Aqua	Commonwealth Plaza (2 Towers)	All Four Towers	Oak Park
Total No. of completed[1] responses	41	40	31	112	123
Total No. of partially completed[2] responses	76	29	32	137	150
Total No. of responses	117	69	63	249	273
Total No. of households contacted directly[3]	357	264	375	996	565
Response rate	33%	26%	17%	25%	48%

Notes:
[1] Considering that not all questions were compulsory, a "Completed" questionnaire has been considered as one in which 60-100% of questions were answered.
[2] A "Partially Completed" questionnaire has been considered as one in which less than 60% of questions were answered.
[3] The total number of households contacted directly in Aqua includes condominium units only (Note: Aqua has 738 units in the entire building, which includes 474 apartment units, 264 condominium households, and 332 hotel units). Due to legal issues raised by the building owner and management, only condo residents (264) were able to participate in the survey. In Oak Park, this is the number of households the research team contacted personally and specifically, via direct mailing, local events, presentations, local government and school's assistance, personal connections, etc.

Figure 0.2. Questionnaire response summary.

1.0 Introduction

1.1 Urbanization: Driver for Density

The United Nations forecasts that 66% of the world's projected 9.6 billion inhabitants will live in urban areas by the year 2050, up from 54% of 7.2 billion urbanized inhabitants as of 2014 (UN, 2014). The enormity of this total figure of 2.4 billion people moving into cities over the next several decades is perhaps more clearly appreciated when converted into an annual rate of nearly 67 million people per year, or around 180,000 people per day. The human race will need to build a new or expanded city of more than one million people every week for the next 40 years to cope with this urban growth.

It is generally assumed that these one million new urban dwellers every week would be more sustainably accommodated through the densification of city centers, rather than through the spread of suburban low-rise "sprawl." However, very few studies have utilized building or neighborhood-scale data sets to evaluate major sustainability factors associated with residents' lifestyle across both dense urban centers and sprawled suburban areas. It is even more critical to puncture the assumptions on both sides of the density vs. sprawl debate in the USA, since the US population has continued to simultaneously urbanize as well as suburbanize. As a share of total population, the USA metropolitan population has increased from 69% in 1970 to 80% in 2000 (Hobbs & Stoops, 2002). Within metropolitan areas, however, the population has continued to suburbanize. From 1970 to 2000, the US suburban population more than doubled, from 52.7 million to 113 million[1]. These dispersed, automobile-oriented suburbanized patterns have resulted in the occupation of vast quantities of previously undeveloped land, and increasing vehicle miles traveled (VMT), which contribute to increased energy usage and greenhouse gas (GHG) emissions. Specifically, passenger vehicle travel on US highways has been increasing at a much faster rate than either population or developed land for several decades (see Figure 1.1).

This phenomenon is especially highlighted in Chicago, where there has been a huge population shift from city to suburbs over the 20th century (see Figure 1.2). The population of the City of Chicago peaked at 3.6 million in 1950, containing 70% of the wider metropolitan area residents. By 2000, 2.9 million Chicagoans made up only 36% of the wider metropolitan population (UIC, 2001), and the remaining 64% were thus distributed across suburbs. Actually, suburban sprawl in Chicago is even greater than imagined. A report released in 2014 by Smart Growth America (SGA) analyzes 221 US Metropolitan Statistical Areas (MSAs) and Metropolitan Divisions with a population of at least 200,000, and ranked cities from most dense

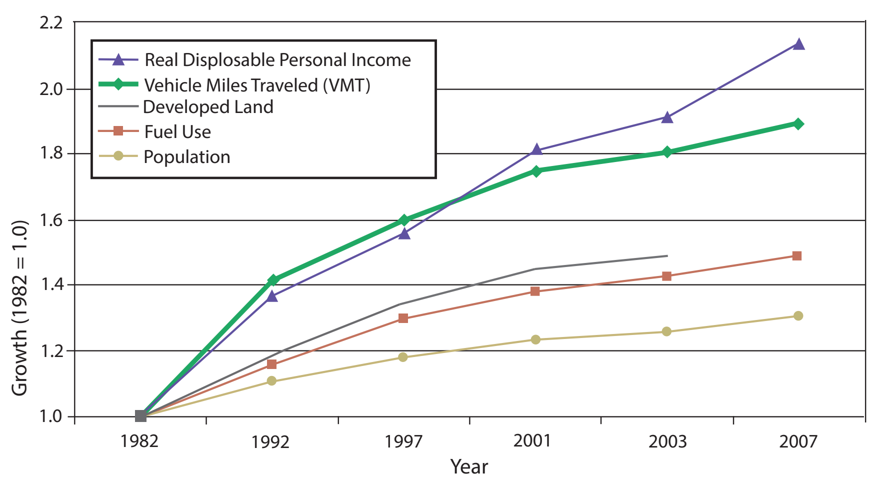

Figure 1.1. Growth in Real Disposable Personal Income, US Highway Passenger Vehicle Miles Traveled (VMT), Developed Land, Energy Consumption, and Population. Source: Transportation Research Board, 2009. Redrawn by CTBUH.

[1] Source: US Census Bureau. Actually, the US Bureau of the Census does not identify a location as "suburban." Metropolitan areas are divided into two classifications: (a) inside central city and (b) outside central city; many researchers treat the latter areas as suburban (Giuliano, Agarwal, & Redfearn, 2008). This understanding is applied to the research in this paper.

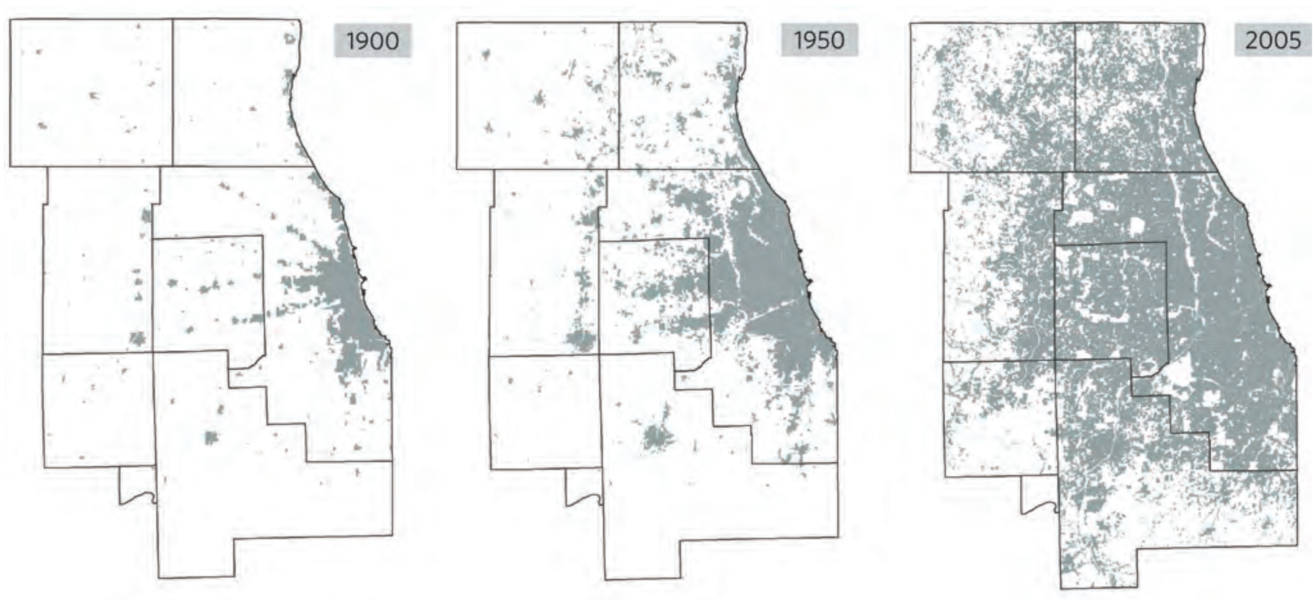

Figure 1.2. Developed Land in Chicago, 1900-2005. Source: CMAP, 2010, p. 66. Redrawn by CTBUH.

to most sprawling, based on four factors: development density, land-use mix, activity centering, and street accessibility. Chicago was ranked 26th on the densest cities list, even less dense than Los Angeles, which has been widely considered as one of the most sprawling cities in the country (SGA, 2014).

Location matters in terms of environmental implications. Many studies show a much lower energy or carbon footprint per person in the urban center than suburban areas, but these results are typically generated using a highly simplified equation, e.g. "total energy consumption or carbon emissions divided by total households/population," based on data sets at a city or regional scale. The research presented in this report moves beyond these large generic data sets to study actual household data at a much more detailed level.

1.2 Objectives and Significance of This Research

The fundamental objective of this research project is to investigate and compare the sustainability of people's lifestyles in multiple key areas from environmental and social perspectives, using Chicago based case studies. It is expected to provide details on home operational energy use; the embodied energy of the dwelling; home water consumption; mobility and transport movements, including both private and public transport; infrastructure networks; public open space; and quality of life, in both downtown high-rise and suburban low-rise living, using Downtown Chicago and the suburban community of Oak Park as case studies. Specifically, in both cases, the study sought to evaluate factors such as the actual monthly energy consumption of the homes; the embodied energy of the materials that comprise the buildings in each location; water usage by residential buildings, for both indoor and outdoor spaces; travel behavior via all modes of transport including automobile, public transport, walking, and biking; infrastructure networks including roads, highways, and alleys; and public open space including parks and

2.0 Research Scope, Methodology and Analysis of Data Sets

2.1 Sustainability Fields Assessed

The fundamental objective of the project is to quantitatively investigate and compare the sustainability of people's lifestyles across high-rise urban and low-rise suburban case studies in seven key factors; (i) home operational energy use, (ii) embodied energy of the dwelling, (iii) home water consumption, (iv) mobility and transport movements, including both private and public transport, (v) infrastructure networks, (vi) public open space, and (vii) quality of life. Figure 2.1 shows the analytical framework of the factors affecting sustainability that are embraced within this research. The key factors examined are outlined in more detail below:

Building Operational Energy

Tracking the operational energy usage of each residential unit (across both high-rise and low-rise scenarios) was one of the most important elements of this project. Real energy bills were collected over a 12-month period, also taking into account, in the high-rise case study, the energy required for the common areas and facilities, such as the lobby, corridors, elevators, centralized cooling plant, services, etc. (see Chapter 3).

Building Embodied Energy

This aspect of the research was conducted based on an extensive literature review of published embodied energy studies in high-rise and low-rise buildings. This study has relied on the mean values of embodied energy per floor area from existing literature as a reasonable estimate for the embodied energy of each building type herein (see Chapter 4).

Water Usage

Water usage data is based on real water bills from high-rise and low-rise case studies for a 12-month period. This included water usage for both indoor and outdoor functions, including swimming pools, irrigation, toilets, clothes washing, showers, etc. This data was used to determine the average water consumption per square meter, per household, and per person in both Downtown and Oak Park scenarios. (see Chapter 5).

Mobility and Transport Movements

Typical weekly mobility and transport movements for each person in each household were assessed through questionnaires, and then this weekly data extrapolated to annual values for comparison. All modes of transport were assessed, including by car, on-foot, by bicycle, and by public transport. Data recorded included travel distance, journey frequency, mode of transport, and travel time. In addition, car ownership and the types of cars were investigated (see Chapter 6).

Infrastructure Network Usage

The infrastructure network in this study is based on the road networks supporting the population in both the urban center and suburbs. Since many infrastructure networks follow road networks (e.g. electricity, gas, water and, of course, transport), both area and length of road surfaces were assessed in order to get some appreciation of the relative amount and density of infrastructure in both scenarios. The amount of infrastructure networks were assessed against the total population in each area, including a factor for daytime population gain/loss through shifting work patterns. The extent of "supporting" networks within the "connecting area" neighborhoods between city and suburb was also considered (see Chapter 7).

Public Open Space Usage

Public open space in this study included all the outdoor publicly-accessible social spaces that support interactions between people and their neighborhood. The area of public open space was measured, including both publicly-accessible green space and plaza space. This was also assessed against the population in each area, factoring in daytime population gain and loss throughout the day and week (see Chapter 8).

Quality of Life

This was perhaps the most difficult aspect of the study to quantify, since it normally relies on qualitative, rather than quantitative, data. This factor was assessed through comprehensive questionnaires with the primary responder in each residential household across both case study types. The questionnaire embraced aspects such as life satisfaction, sense of community, and satisfaction with accessibility, safety, social interaction, and mobility. (see Chapter 9).

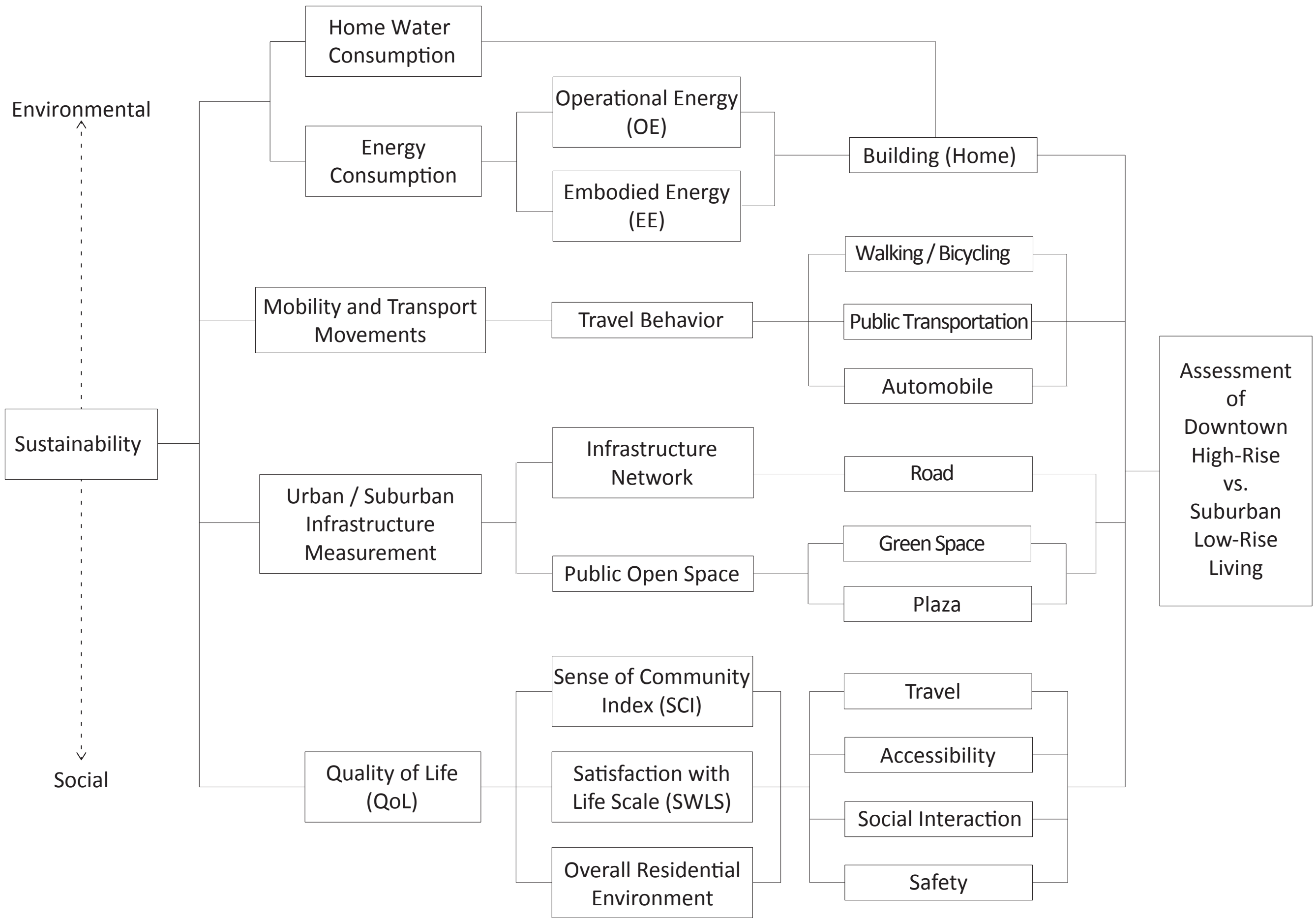

Figure 2.1. Analytical framework of the factors affecting sustainability that were embraced in this research project.

2.2 Data Collection

Though it also references large-scale already-published studies, the emphasis of this research project was placed on obtaining real quality data wherever possible. The main data collection vehicle became a comprehensive online survey created using SurveyGizmo[3] (see Appendix A for the survey items). The study launched in Oak Park in February 2014, and Legacy, Commonwealth Plaza, and Aqua in March, May, and June 2014, respectively. The survey remained open for approximately three months in each case, though energy and water bills for 12 months were collected. Participants were recruited by a combination of activities, including advertising on the websites of the buildings and their respective community groups; email solicitations to residents; advertising in the building and/or community newsletters; posting flyers in the buildings; mailing letters to targeted households; and giving presentations at social and community events. Although it took more than 45 minutes for a typical resident to complete the survey, more than 500 responses were received from the 1,500 individuals contacted directly. This 33% response rate can be considered quite high.

[3] SurveyGizmo is an online survey and form builder: www.surveygizmo.com. The authors would like to thank the Council on Tall Buildings and Urban Habitat (CTBUH) for its financial support for this tool. (see Appendix A for the survey items)

3.0 Building Operational Energy

3.1 Introduction

According to the US Energy Information Administration (EIA), the building sector (operations, construction and materials) consumed nearly half (47.6%) of all energy produced in the United States in 2012, and building operations specifically accounted for 41.7% of this (Figure 3.1) (Architecture 2030, 2013). Therefore, the way buildings are operated is a key factor in reducing the total energy consumption of cities. Operational energy (OE) is defined for this study as an ongoing and recurrent expenditure of energy that is consumed to satisfy the demand for day-to-day operations, including: heating, cooling, lighting, ventilation, appliances, equipment, etc.

3.2 Analysis Methods

For this research, the amount of annual Operational Energy (OE) was gathered from the participating buildings' and individuals' utility bills in both downtown and Oak Park residences. This included the following utilities:

- Electric
- Gas
- Chilled Water[9] (in the high-rise cases only)

The individual households in all locations were asked to either submit a copy of the most recent 12 months of utility bills, including electric and/or gas bills, or to enter the same data directly into the online survey. In addition, the management personnel at the downtown residential towers were asked to provide the most recent 12 months of utility bills[10], including electric, gas, and chilled water bills (if applicable), for the entire building.

Aqua was unfortunately excluded from this whole building operational energy analysis because the energy usage data received from its building management was too limited to be used to conduct a reasonable OE analysis. Aqua is a mixed-use building including condominiums, apartments, and hotel spaces, with all of the amenities accessible to all permanent and temporary residents. Unfortunately, its whole-building bills reflected usage for the entire building, and could not be broken down into the needed space types, and thus permanent condominium residents could not be assigned individual unit energy use.

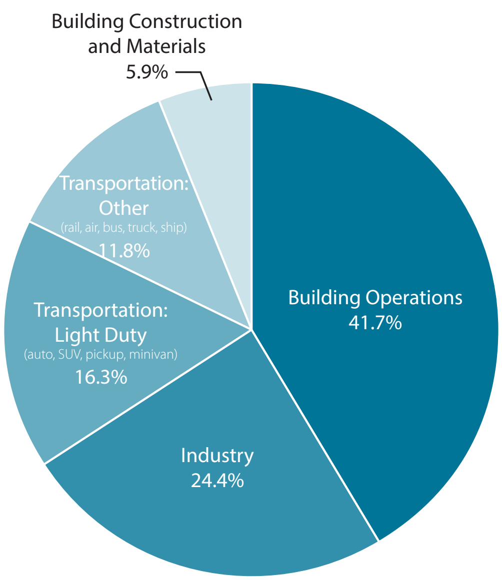

Figure 3.1. US Energy Consumption by Sector. Source: Architecture 2030, 2013. Redrawn by CTBUH.

[9] The chilled water in Aqua and Legacy is provided by the city's district chilled water system, Thermal Chicago, which serves over 100 buildings within the city. It is one of the most advanced, reliable, and efficient cooling systems in the world. The system includes five chilled water generation plants serving the Loop, West Loop, South Loop and River North areas. Commonwealth Plaza has its own chillers, so does not have chilled water bills from Thermal Chicago. (International District Energy Association, 2014; Climate Control Middle East, 2011)
[10] All the electric bills of the individual units/houses across both urban and suburban scenarios were ComEd bills, which typically show the past 13 months of consumption. So residents only had to provide the latest electricity bill in order to provide 12 months' data. See related survey questions in Appendix A.

The whole-building bills for different residential towers covered different operational categories and service areas. For example, the whole-building bills at Legacy covered electric, gas, and chilled water usage for all public areas, plus usage of heated and chilled water within individual units. Conversely, the whole-building bills in Commonwealth Plaza covered electric and gas usage in public areas as well as for cooking, heating, and heated and chilled water within individual units.

Since this study was predominantly focused on a comparison across building types with differing energy-use systems, and was not a commentary on the suitability of those systems, all energy consumption figures in the study are based on *site energy*[11]. Energy units shown on all utility bills (electric, gas, chilled water) were all converted to megajoule or gigajoule to enable comparisons across energy types and buildings.

Because of slight differences in the survey launch and completion dates across the building case studies (see Section 2.2, Chapter 2), the collected utility data did not fall in the exact same 12-month period for all households. Further, some of the collected utility data did not cover a full 12-month period. For example, the electricity usage data provided by Home A may have covered only 10 months from March 2013 to December 2013, while the natural gas usage data provided by Home B covered 11 months from May 2013 to April 2014. Therefore, two approaches were taken to provide a comparable 12-month dataset for as many homes as possible:

(i) First, the 12-month period of April 2013 to March 2014 was chosen as the common analysis period for annual OE use, because it was the period of time that contained the largest number of overlapping utility bill responses.

(ii) Second, any missing data on monthly energy use for individual homes during any remaining months in this 12-month period were estimated by simple and/or multiple linear regression models between monthly energy use, monthly cooling degree days (CDD), and/or monthly heating degree days (HDD)[12]. The regressions were constructed using only the months for which there were utility bill data. This approach, emphasizing cooling degree days and heating degree days, was considered appropriate because heating and cooling end-uses account for nearly half of the annual energy use in a typical US home, making space conditioning the largest energy expense for most homes (US EIA, 2014). Only those buildings/households that provided at least eight months of energy usage data across all the applicable energy source types (i.e., electric, gas, and chilled water where applicable) were included in the regression analysis.

For the cases that used electricity for cooling and gas for heating, a linear regression model was used to predict the missing electricity usage associated with CDD, and another linear regression model was used to predict the missing gas usage associated with HDD. For the downtown residential towers that use the city's district chilled water system for cooling, a linear regression model was used to predict the missing chilled water usage associated only with CDD, based on the Equation Set 1 as shown in Table 3.1.

In the cases that use electric energy for both cooling and heating, a multiple linear regression model was used to predict the missing electric usage associated with both CDD and HDD, based on Equation Set 2 in Table 3.1. The various site energy metrics from the collected utility bills (i.e., "kWh" for electricity bills, "therm" for gas bills, and "ton-hour" for chilled water bills) were all converted to gigajoule (GJ) using Equation Set 3 in Table 3.1.

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[11] Site energy is considered as the energy directly consumed at a facility, typically measured with utility meters (i.e., the energy consumed directly by the buildings in their location). Some studies consider "Source Energy," which is the sum of the energy consumed at a facility as well as the energy required to extract, convert, and transport that useful energy to the facility (Deru, 2007). The variance in Source Energy between a building using gas for heating/cooling or electricity for heating/cooling can be very high, so the focus in this study became on site energy only.

[12] Cooling degree days (CDD) is the number of degrees that a day's average temperature is above 18°C (or 65°F), reflecting the demand for energy needed to cool a home. Heating degree day (HDD) is the number of degrees that a day's average temperature is under 18°C (or 65°F), reflecting the demand for energy needed to heat a home. See Appendix B for monthly degree days in 2013 and 2014 for the City of Chicago and Oak Park.

4.0 Building Embodied Energy

4.1 Introduction

Embodied energy (EE) is the energy consumed in all activities necessary to support a process or produce a product, and comprises a direct and an indirect component (Baird & Aun, 1983). Building embodied energy typically consists of two main elements: initial embodied energy (EEi)[18] and recurring embodied energy (EEr)[19]. The building embodied energy analysis in this study only accounted for initial embodied energy, due to the limited availability and reliability of data for recurring embodied energy in both low-rise and high-rise buildings.

4.2 Analysis Methods

The research did not undertake a full detailed assessment of the actual embodied energy in the case study buildings, since the necessary information for EE calculation (i.e., quantities and specifications of materials used in the buildings) was not available[20]. Instead, an extensive literature review on published building embodied energy studies was conducted, in order to quantify typical values for each type of construction. Initial embodied energy varies with location, but more significantly varies with respect to the building materials being supplied, rather than climate, temperature and other operational factors. Initial embodied energy mainly consists of the energy consumed in the acquisition, processing, and manufacturing of raw materials into building products, and in delivery and construction on site. Also, it is worth noting that embodied energy has typically been estimated as a much smaller contributor to the overall life-cycle energy consumption for residential buildings, compared to operational energy use (Cole, 1998; Keoleian et al., 2000; Ochoa et al., 2002; Ramesh et al., 2010). Therefore, this study has relied on the mean values of EE per floor area from existing literature as a reasonable estimate for the EE of each building type herein. The information collected across previously published studies included: building type; height (number of floors); project location; area (m^2); structure/envelope material; research method[21]; EE (GJ/m^2); and source - see tables to follow.

4.3 Energy Analysis: Suburban Low-Rise

Table 4.1 shows an overview of published research studies on building EE for low-rise residential buildings. As Figure 4.1 shows, estimated building EE across each study varied from as little as 2.9 GJ/m^2 to as much as 15.2 GJ/m^2, with variations driven by a combination of differences in estimation methodology and the case study itself (e.g., different buildings used different structural systems and exterior walls, which required different levels of embodied energy). Overall, the average EE value of these low-rise cases (1-2 stories) is 6.8 GJ/m^2.

The single-detached house with wood-frame structure dominated the building characteristics and, as this was also the dominant building type in Oak Park, the average of the studies (6.8 GJ/m^2) was simply applied across each home in our research study. Therefore, this study relied on the average value of EE (6.8 GJ/m^2) of all the cases in the published research studies as a reasonable estimate for the low-rise residential buildings in Oak Park.

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[18] Initial embodied energy of a building is the energy use incurred during initial construction of the building.

[19] Recurring embodied energy is the embodied energy in the materials used in the rehabilitation and maintenance of a building, since many of the materials used in building construction/fit-out, etc. have a limited life span.

[20] The original idea for the low-rise EE section of the research study was to apply different average EE values calculated from published research studies to the actual low-rise residential buildings in Oak Park. The residents in Oak Park were thus asked to report their building information including building type (single-family house, duplex, townhouse, apartment/condo building, or residential over retail), height (number of floors), construction system and exterior wall material (vinyl siding, stucco, brick, fiber cement, wood, concrete block, or aluminum) in the survey. However in reality, the limited published research studies did not have such data and thus did not enable such an approach.

[21] EE analysis methods include process analysis, input-output (I-O) analysis and hybrid analysis (Bullard, Penner, & Pilati, 1978; Treloar, Owen, & Fay, 2001; Treloar, Love, & Holt, 2001). A process analysis has been defined as "the determination of the energy required by a process, and the energy required to provide inputs to the process, and the inputs to those processes, and so forth. I-O analysis as "the use of national economic and energy data in a model to derive national average EE data in a comprehensive framework." Hybrid analysis has been defined as "the combination of process analysis and I–O analysis data"(Treloar, Love, & Holt, 2001). Hybrid analysis combines both process analysis and I-O analysis in order to reduce the errors that are typically found among both. Hybrid EE analysis methods typically include process-based hybrid analysis (total energy intensities derived using I–O analysis are applied to product quantities derived using process analysis) and I–O-based hybrid analysis (process analysis data is substituted into the I–O framework) (Treloar, Love, & Holt, 2001).

Case Study Number	Type	No. of Above-Ground Floors	Location	Floor Area	Structure	Exterior Wall	Embodied Energy	Research Method	Source
1	Single-detached	1	Melbourne, Australia	291.3 m^2	Wood-frame	Brick veneer	13.4 GJ/m^2	Unknown	(Crawford, 2012)
2	Single-detached	1	Melbourne, Australia	42.5 m^2	Wood-frame	Fiber cement cladding	7.5 GJ/m^2	Process	(Myer, Fuller, & Crawford, 2012)
3	Single-detached	1	Melbourne, Australia	42.5 m^2	Wood-frame	Fiber cement cladding	5.4 GJ/m^2	Process	(Myer, Fuller, & Crawford, 2012)[1]
4	Single-detached	1	Orebro, Sweden	130 m^2	Wood-frame	Wood panelling	3.7 GJ/m^2	I-O	(Adalberth, 1997)
5	Single-detached	1	Orebro, Sweden	129 m^2	Wood-frame	Wood panelling	6.5 GJ/m^2	I-O	(Adalberth, 1997)
6	Single-detached	2	Orebro, Sweden	138 m^2	Wood-frame	Wood panelling	2.9 GJ/m^2	I-O	(Adalberth, 1997)
7	Single-detached	2	Sweden	144 m^2	Unknown	unknown	3.5 GJ/m^2	I-O-based hybrid	(Gustavsson & Joelsson, 2010)
8	Single-detached	1	Phoenix, USA	186 m^2	Unknown	Wood Shingles	6.8 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
9	Single-detached	1	Phoenix, USA	186 m^2	Unknown	Brick	6.8 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
10	Single-detached	1	Phoenix, USA	186 m^2	Unknown	Painted Block	6.3 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
11	Single-detached	1	Phoenix, USA	186 m^2	Unknown	Stucco	6.2 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
12	Single-detached	2	Phoenix, USA	186 m^2	Unknown	Wood Shingles	5.4 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
13	Single-detached	2	Phoenix, USA	186 m^2	Unknown	Brick	5.4 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
14	Single-detached	2	Phoenix, USA	186 m^2	Unknown	Painted Block	5.1 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
15	Single-detached	2	Phoenix, USA	186 m^2	Unknown	Stucco	5 GJ/m^2	I-O-based hybrid	(Frijia, 2011)[2]
16	Single-detached	2	Melbourne, Australia	128 m^2	Unknown	Brick veneer	14.1 GJ/m^2	I-O-based hybrid	(Fay et al., 2000)
17	Single-detached	2	Melbourne, Australia	128 m^2	Unknown	Brick veneer	15.2 GJ/m^2	I-O-based hybrid	(Fay et al., 2000)[1]
18	Semi-detached	2	Lingwood, UK	91 m^2	Wood-frame	Larch cladding	5.7 GJ/m^2	Process	(Monahan & Powell, 2011)[3]
19	Semi-detached	2	Lingwood, UK	91 m^2	Wood-frame	Brick veneer	7.7 GJ/m^2	Process	(Monahan & Powell, 2011)[3]
20	Semi-detached	2	Lingwood, UK	91 m^2	Masonry cavity wall	Brick cladding	8.2 GJ/m^2	Process	(Monahan & Powell, 2011)[3]
21	Single-detached	2	Toronto, Canada	Various	Wood-frame	Brick	4.6 GJ/m^2	I-O-based hybrid	(Norman et al., 2006)
22	Single-detached	2	Ann Arbor, USA	228 m^2	Wood-frame	Unknown	6.6 GJ/m^2	Process	(Keoleian et al., 2000)
23	Single-detached	2	Ann Arbor, USA	228 m^2	Wood-frame	Unknown	7.3 GJ/m^2	Process	(Keoleian et al., 2000)
24	Semi-detached	2	Melbourne, Australia	123 m^2	Wood-frame	Brick veneer	6.8 GJ/m^2	I-O-based hybrid	(Treloar, Love, & Holt, 2001)
25	Detached	2	Gothenburg, Sweden	Unknown	Unknown	Unknown	6.2 GJ/m^2	Process-based hybrid	(Thormark, 2002)[4]
26	Unknown	Unknown	Various	Various	Various	Various	5.9 GJ/m^2	I-O	(Pullen, 2000)[5]
27	Single-detached	Unknown	N/A	199.7 m^2	Wood-frame	Unknown	6.4 GJ/m^2	I-O	(EPA, 2013)
Average	N/A	1.6	N/A	155 m^2	N/A	N/A	6.8 GJ/m^2	N/A	N/A

Notes:
[1] *Cases that were an energy-efficient model.*
[2] *The models developed in this study used four different exterior wall materials across five different sizes including 139, 186, 228, 279 and 325 m^2. Only the models with the size of 186 m^2 were included in this table since 186 m^2 is considered to be the typical single-family house size in the US. According to the US Census, the average floor area of a single-family house completed in the Midwest region from 1973 to 2010 was estimated to be 183 m^2 (US Census, 2017).*
[3] *This study was based on a low-energy affordable house (91 m^2) constructed in 2008, and examined the embodied energy in three scenarios, by changing the structure and wall material parameters.*
[4] *This case study consisted of 20 apartments in four two-story rows. Each apartment has a net residential floor area of 120 m^2.*
[5] *This research was conducted using 25 houses as case studies, which ranged in size from 91 to 320 m^2 and varied in structure/material. The EE in the table is the mean value.*

Table 4.1. Overview of published research studies on the embodied energy (EE) of low-rise residential buildings.

5.0 Water Usage

5.1 Introduction

Water is necessary for human existence, but is, however, a finite resource subject to ever-increasing demand. Along with population and urban growth, the demands on public water supply have been increasing. Global water use was found to have grown at twice the rate of human population within the last century (UN Water, 2017). The United States Geological Survey (USGS) states that total water withdrawals for public supply in the US in 2005 were 167.3 billion liters per day, 316% of the 53 billion liters per day withdrawal in 1950. In the same period, the United States' population has only increased 194% from 150 million in 1950 to 295 million in 2005 (US Census Bureau, 2017). This means that water withdrawals in the US grew 1.6 times more than population in the same time period.

Public water supply is typically divided into three usage categories: domestic, commercial, and industrial. In the US, domestic water supply, which includes all uses at a residential level, including potable drinking water, toilets, clothes washing, showers, faucets, outdoor (e.g. swimming pools, irrigation, outdoor cleaning, etc.), leaks, and so on, and it makes up the largest portion of the three use categories, at 57% (USGS, 2010). Figure 5.1 shows that the largest domestic consumption in Chicago of water is by outdoor uses, followed by toilet usage, and cloth washing (Sustainable Chicago, 2015).

5.2 Analysis Methods

The amount of annual water consumption per household was gathered from the participating buildings' and individuals' water bills in both downtown and Oak Park residences. The downtown high-rises included households in three existing residential towers, the Legacy at Millennium Park and Commonwealth Plaza (2 towers)[23]. The water consumption data for Legacy and Commonwealth Plaza was provided by each building's management. Data included the total water consumption of both common areas and individual units, within the whole buildings; individual residences did not have individual water bills. Thus, the whole-building bills[24] covered all water usage for the high-rise examples.

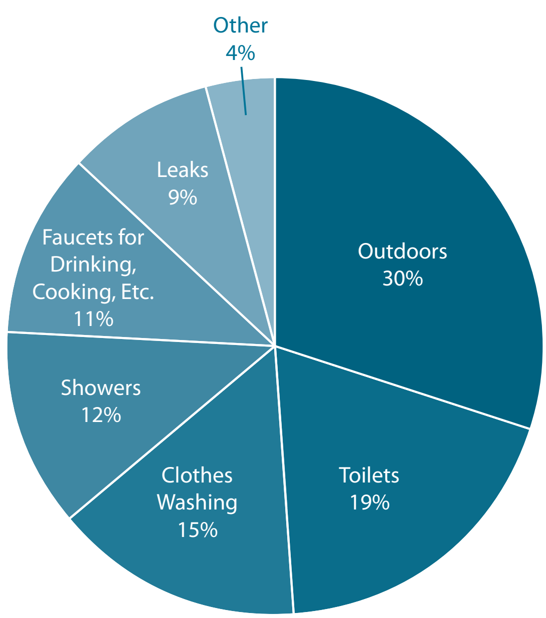

Figure 5.1. Residential Water Use. (Sustainable Chicago, 2015). Redrawn by CTBUH.

[23] Aqua was unfortunately excluded from the water consumption analysis because the data received from its building management was too limited to be used to conduct a reasonable water consumption analysis. Unfortunately, the whole-building water bills reflected usage for the entire building, and could not be broken down into the three space types, including condominiums, apartments, and hotel, for this study. Thus permanent condominium residents could not be assigned individual unit water consumptions.

[24] Both buildings reported a full 12-month water usage data for the required year-long time frame. Commonwealth Plaza pays bills on a bimonthly basis, thus receiving six bills per year, while Legacy pays bills on a monthly basis, thus receiving 12 bills per year.

The whole-building water data was considered against the total floor area of the buildings to determine total water consumption per floor area. It was then converted to a per-household, and per-person basis, based on the demographic data of the towers, as seen in previous Table 2.8 on Page 42.

The water consumption data for the Oak Park residences was collected via the same online survey (see Appendix A), as well as via the Oak Park municipal government. The individual households were asked to either submit a copy of the most recent four consecutive water bills[25] or to enter the same data directly into the online survey. Water data for each household was used, in conjunction with the total floor area and household size of each residence, to determine the average water consumption per square meter, per household, and per person in Oak Park.

The common unit to express water usage was per 1,000 liters of water (k.liter)[26]. Similar to the operational energy data, the collected household data did not fall in the exact same 12-month period for all households, because of differences in survey launch and completion times. For Legacy, water consumption was reported in monthly bills from March 2013 to February 2014. At Commonwealth Plaza, water consumption was reported in bimonthly bills collected from November 2012 to October 2013. In Oak Park, water consumption was reported in quarterly bills covering the period from August 2012 to September 2013 (See Appendix D for full individual household usage in Oak Park)[27]. Because 70% of residential water consumption is based on indoor usage and not subject to seasonal changes, as shown in Figure 5.1, and consumption covered a full 12-month period with all seasons, this slight mismatch in the months covered was deemed to not be a significant factor affecting the collected water consumption data.

5.3 Water Usage: Downtown High-Rise

Based on total water usage, whole building area, average area of household, and average household size, the water usage in the high-rise

"Total water withdrawals for public supply in the US in 2005 were 316% of the per day withdrawal in 1950. Water withdrawals in the US have grown 1.6 times more than population in the same time period."

[25] Sixty-five households in Oak Park reported their full 12-month water data for the required year-long time frame. Individual residences pay water bills on a quarterly basis, thus receiving four bills per year.
[26] In the survey the unit of water consumption was asked in gallons, as the majority of the survey takers were American. Gallons were then converted to 1,000 liters (k.liters) for the calculation analysis in this chapter, in order to apply a global standard to the results.
[27] Due to different quarterly billing cycles for Oak Park residences, water bills varied from an August 2012-July 2013 billing cycle to a October 2012-September 2013 billing cycle. Full details of quarterly water usage per residence are shown in Appendix D.

It is widely assumed that the "dense vertical city" is more sustainable than the "dispersed horizontal city." This concept has certainly been a large factor in the unprecedented increase in the construction of tall buildings globally over the last two decades, especially in the developing world. The concentration of people in denser cities — sharing space, infrastructure, and facilities — is typically thought to offer much greater energy efficiency than the expanded horizontal city, which requires more land use, as well as a higher energy expenditure in infrastructure and mobility.

Though this belief in the sustainability benefits of 'dense' versus 'dispersed' living is driving the development of cities from Toronto to Tianjin and from Sau Paulo to Shanghai, the principle has rarely been examined at a detailed, quantitative level. Studies to date have been mostly based on large data sets of generalized data regarding whole-urban energy consumption, or large-scale transport patterns. In some cases, seminal studies are still informing policy that is now several decades out of date. For instance, a study of 32 cities by Newman & Kenworthy in 1989 concluded that there was a strong link between urban development densities and petroleum consumption (Newman & Kenworthy, 1989). This study is still commonly cited, despite being 28 years old. Crucially, there are very few studies that also take into account a "quality of life" aspect to urban vs. suburban living, in addition to differences in energy use patterns.

Chicago, the city in which this research has taken place, is uniquely positioned for a study exploring density vs. sprawl from a sustainability point of view. The birthplace of the tall building and the main crucible for experimentation in the typology in the century or more since then, Chicago also has an ever-growing suburban area that is typical of most US cities. And yet, again in line with many other cities around the world over the past decade or two, it has seen suburban growth alongside densification of its downtown area and a resurgence of people seeking high-rise urban living.

This research report offers a quantitative evaluation of long-held assumptions, and with sometimes surprising results. The ground-breaking study quantitatively investigates and compares the sustainability of people's lifestyles in both urban and suburban areas from environmental and social perspectives, using actual energy bills collected from households, as well as other direct research methods.. It fills significant research gaps in our knowledge of the sustainability of urban density compared to suburban sprawl, in terms of both environmental and social sustainability. This is an indispensable resource for urban planners, architects, utilities, developers, and anyone else with a stake in shaping the future of the built environment.

Research Undertaken in Conjunction With:

Council on Tall Buildings and Urban Habitat

IIT College of Architecture
ILLINOIS INSTITUTE OF TECHNOLOGY