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Dense Downtown vs. Suburban Dispersed: A Pilot Study on Urban Sustainability

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Abstract

This paper presents the initial findings of a ground-breaking two-year CTBUH-funded research project investigating the real environmental and social sustainability of people's lifestyles in a number of high-rise residential towers in downtown Chicago, and a comparable number of low rise homes in suburban Oak Park, Chicago – based on actual energy bills and other real data. The study is ground-breaking because, to date, similar studies have been mostly based on very large data sets of generalized data regarding whole-city energy consumption, or large-scale transport patterns, which often misses important nuances. This study has thus prioritized quality of real data (based on around 250 households in both high rise and low rise case studies), over quantity. In both urban and suburban cases, the following factors have been assessed: (i) home operational energy use, (ii) embodied energy of the dwelling, (iii) home water consumption, (iv) mobility and transport movements, (v) urban/suburban Infrastructure, and (vi) quality of life. The full results of this seminal study will be published in the form of a CTBUH Research Report publication in 2017. Presented below is an overview of the initial (and, currently, unverified) findings of the research, together with the limitations of the study that should be taken into account, as well as future plans for developing this important pilot study.

Keywords: Sustainability, Energy, Infrastructure, Density, High-rise buildings

1. Background to This Study: Urbanization and the Density Debate

Against the backdrop of United Nations statistics indicating 187,000 people urbanizing on the planet every day[1], the accommodation of these 2.4 billion new urban dwellers over the next 35 years is one of the key issues that need to be addressed in considering the continued existence of the human race on this planet. Over the past decade or so, it has become widely believed 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'. The concentration of people in denser cities – sharing land, space, infrastructure, and facilities – is typically thought to offer greater energy efficiency than the expanded horizontal city, which requires more land usage as well as a higher energy expenditure (and pollution creation) in both infrastructure and mobility. It has thus become widely assumed that the "dense vertical" city is more sustainable than the "dispersed horizontal" city and this concept has certainly become a large factor in the unprecedented increase in the construction of tall buildings globally over the last two decades, especially in the developing world (see Fig. 1).

Though this belief in the sustainability benefits of 'dense' versus 'dispersed' living is driving the development of many cities across the world, the principle has rarely been examined at a detailed, quantitative level. Studies to date have been mostly generic, 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 are now several decades out of date. For instance, a study of 32 cities by Newman & Kenworthy in 1989 (see Fig. 2) concluded that there was a strong link between urban development densities and petroleum consumption (Newman & Kenworthy, 1989). This study is still commonly cited, despite it being 27 years old. In addition, there are very few studies that also take into account a 'quality of life' aspect to dense urban vs. dispersed suburban living.

2. Research Objectives & Methodology

This research project thus places itself at this nexus. 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

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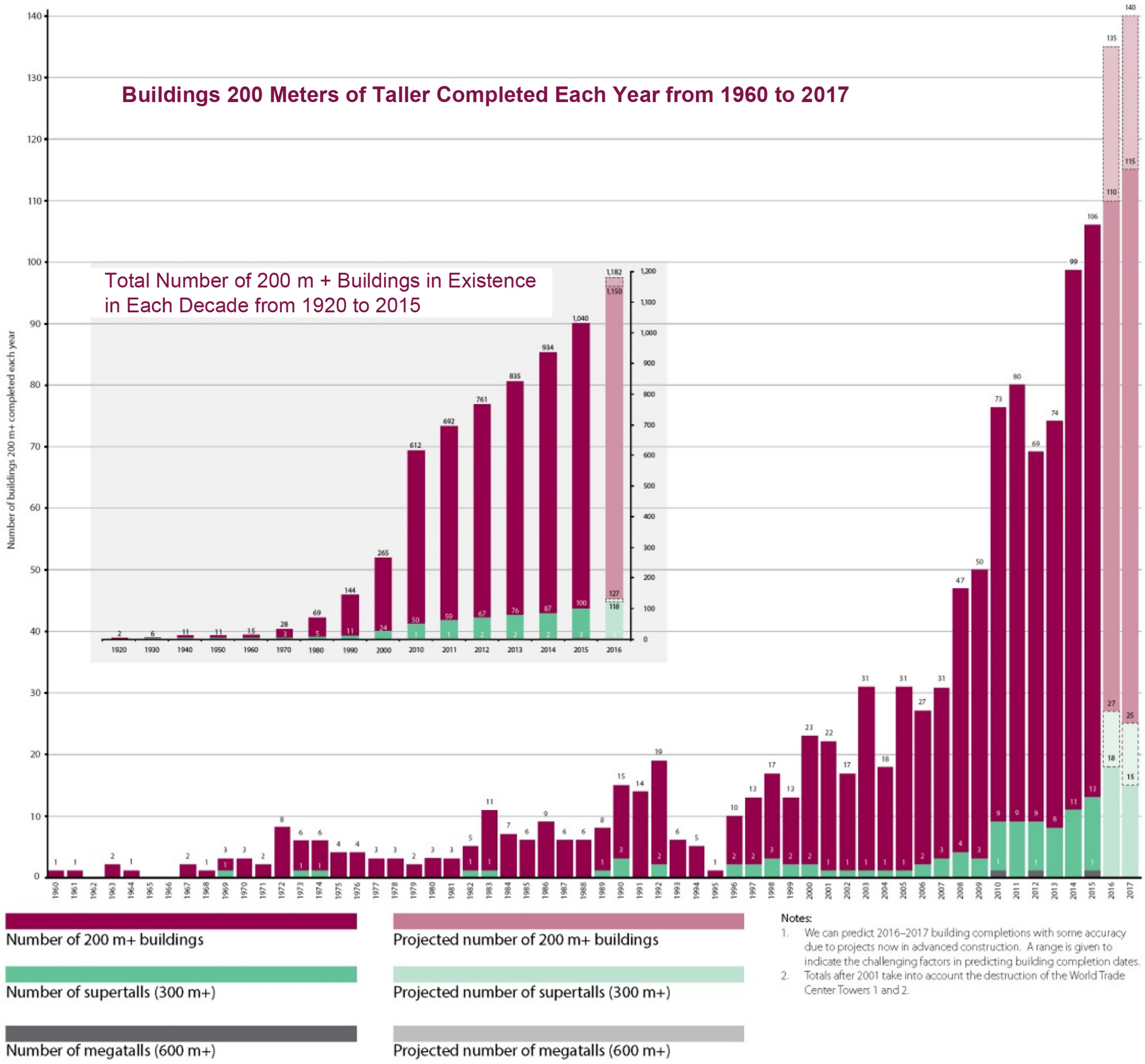

Figure 1. Tall buildings completed (and the Total Number in Existence) each year, over 200m, 300m and 600m from 1968, (as of Jan 2016) – showing the unprecedented increase in tall building construction over the last decade or two – driven largely by increasing population growth and urbanization, and the belief in dense high-rise development being more sustainable than dispersed low-rise development (Source: Council on Tall Buildings and Urban Habitat).

studies in six key factors; (i) home operational energy use, (ii) embodied energy of the dwelling, (iii) home water use, (iv) mobility and transport movement, including both private and public transport, (v) urban/suburban Infrastructure, and (vi) quality of life. Fig. 3 shows the analytical framework of the factors affecting sustainability that are embraced within this research.

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, investigating residents' satisfaction with life and a sense of community, etc.

The main vehicle for investigation was an on-line questionnaire, which required users to input numerous items of data, including uploading energy bills. Although it took more than one hour to complete the survey, over 500 responses were gathered from around 1500 individuals contacted.

3. Selection of Case Studies: Chicago

The U.S. population has continued to simultaneously urbanize as well as suburbanize. As a share of total population, the metropolitan population has increased from 69 percent in 1970 to 80 percent in 2000 (Hobbs & Stoops, 2002). Within metropolitan areas, however, the popula-

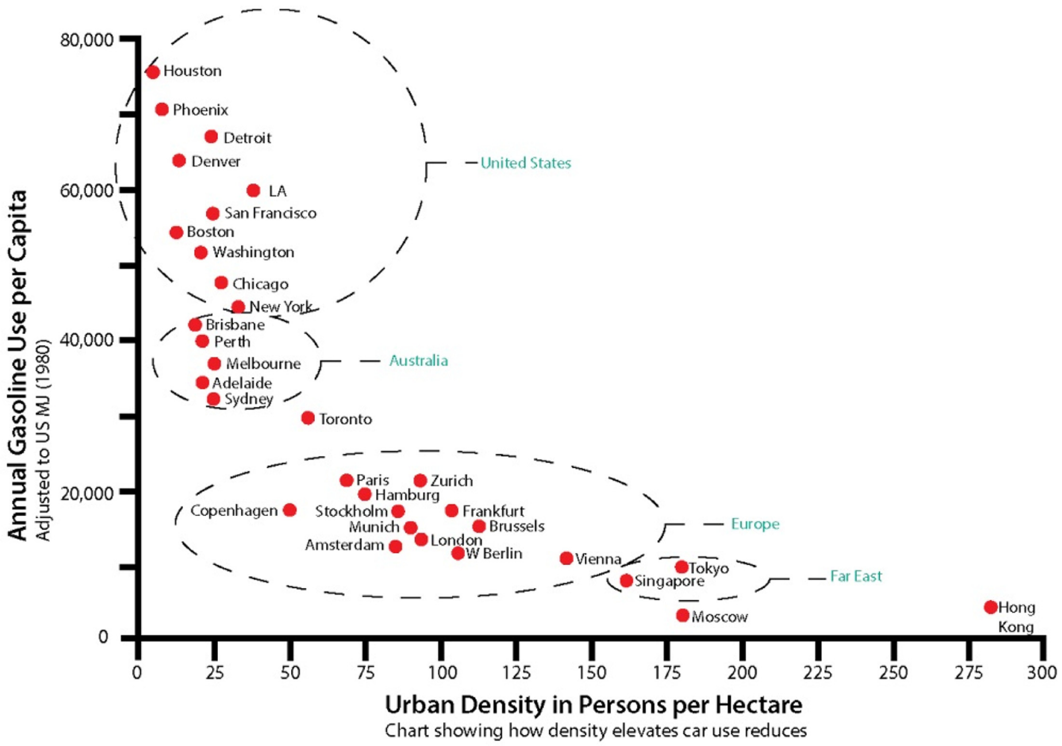

Figure 2. Density and gasoline use (Source: Newman & Kenworthy, 1989).

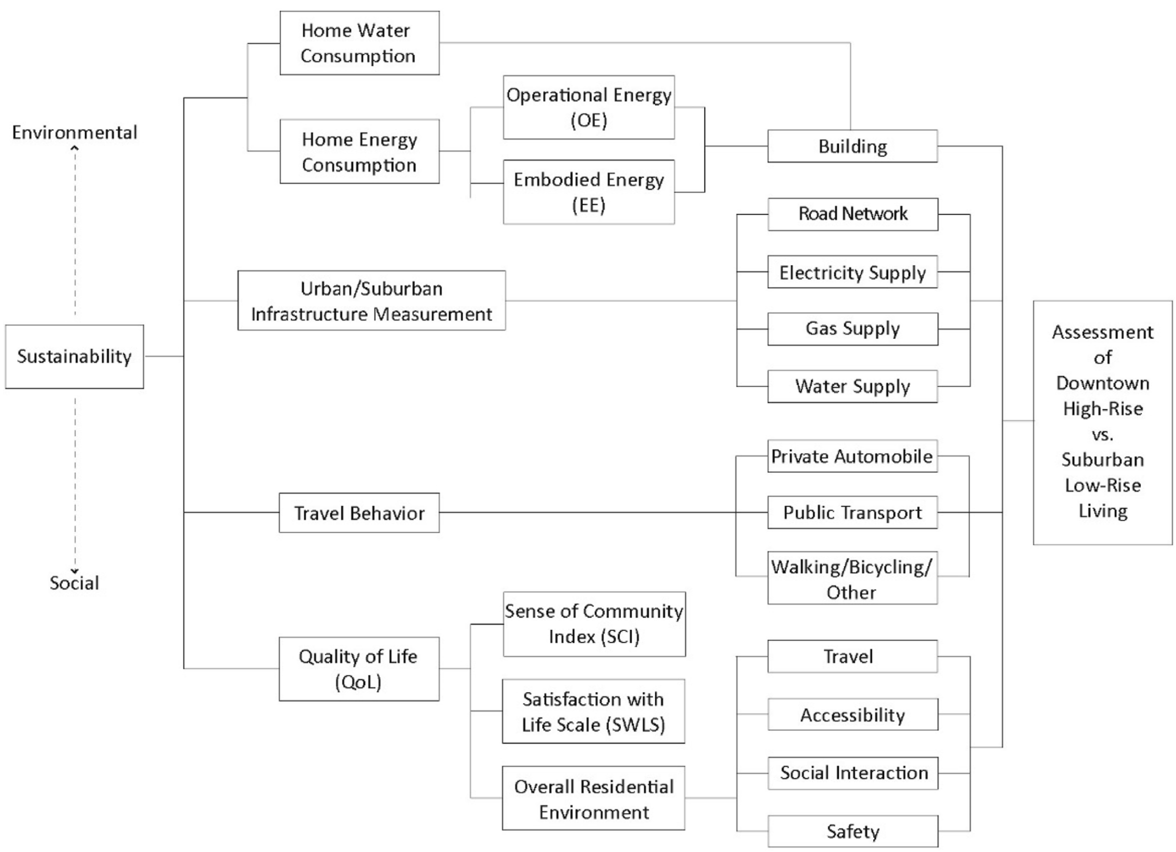

Figure 3. Analytical framework of the factors embraced in this study (Source: By Authors).

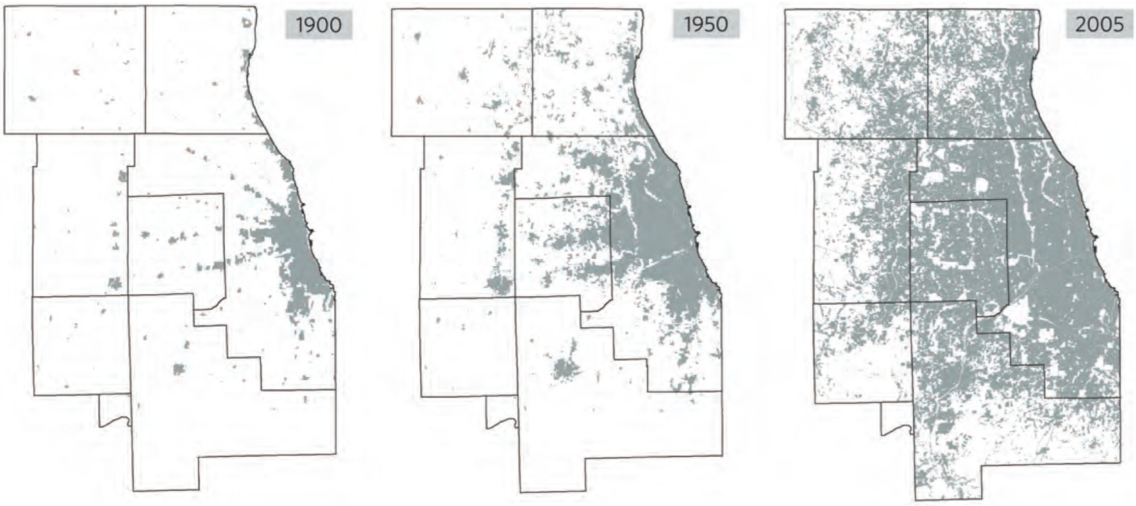

Figure 4. Developed land in Chicago, 1900, 1950 & 2005 (Source: CMAP, 2010, p. 66).

tion has continued to suburbanize. From 1970 to 2000, the U.S. suburban population more than doubled, from 52.7 million to 113 million (UIC, 2001).

This phenomenon is especially highlighted in Chicago, IL, where there has been a huge population shift from city to suburbs over the 20th century (see Fig. 4). The population of the actual City of Chicago (i.e. without it's outlying suburbs) peaked at 3.6 million in 1950, containing 70 percent of the wider metropolitan area residents. By 2000, 2.9 million Chicagoans made up only 36 percent of the wider metropolitan population (UIC, 2001), and the remaining 64% were thus distributed across suburbs. Actually, suburban sprawl in Chicago is even much 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" to "most sprawling" based on four factors: development density, land use mix, activity centering, and street accessibility. Chicago MSA (Chicago-Joliet-Naperville, IL) was ranked 26th out of 221 on the densest cities and towns list, placed even lower than Los Angeles, which has been widely considered as one of the most sprawling cities in the country (SGA, 2014).

Chicago is thus well positioned for a study exploring density vs. sprawl from a sustainability point of view. In addition, being the birthplace of the tall building and one of the main crucibles for experimentation in the typology in the century or more since then, Chicago is perfect for a study focused on urban density and tall buildings. In line with many other cities around the world over the past decade or two, it has seen both a suburbanization at the same time as a densification of its downtown area and a resurgence of people seeking high-rise urban living.

The study was thus undertaken based on two distinct case study sets: four residential towers in the City of Chicago as the downtown high-rise case studies, and Oak Park as the suburban low-rise case study. The relative geographic locations and connected transportation systems of these two areas are shown in Fig. 5.

3.1. Case Study Set 1: Chicago Downtown Residential Towers

All of the four downtown residential towers are located in areas of relative high urban density and served by numerous forms of public transport. Specifically, Aqua Tower is located on the edge of the Chicago Loop (approximate published density = 7,200 people/km^2), the Legacy at Millennium Park is located within the Chicago Loop, and the Commonwealth Plaza (two towers) is located on the edge of the Lakeview neighborhood (approximate published density = 12,000 people/km^2), about 8 km north of the Chicago Loop (US Census Bureau, CTBUH) (see Fig. 6). The choice of these four residential towers was mainly because of their unique locations, and the research team having a good relationship with each building ownership/management so as to encourage a high number of responses from residents. The varied towers were also chosen so as to enable a comparison across high-rise residential types and locations, as well as with the low-rise suburban scenario.

3.2. Case Study Set 2: Oak Park

Oak Park, a district accommodating 52,287 inhabitants (approximate published density = 4,262/km^2), is located 14 km from Chicago city center, and forms the low-rise suburb case study in this research (Source: American Community Survey, US Census Bureau). Oak Park constitutes a relatively dense mix of single-family homes and apartment blocks, with a very walkable environment, and is plugged into much of Chicagoland's public transport system (especially the mass transit CTA green and blue

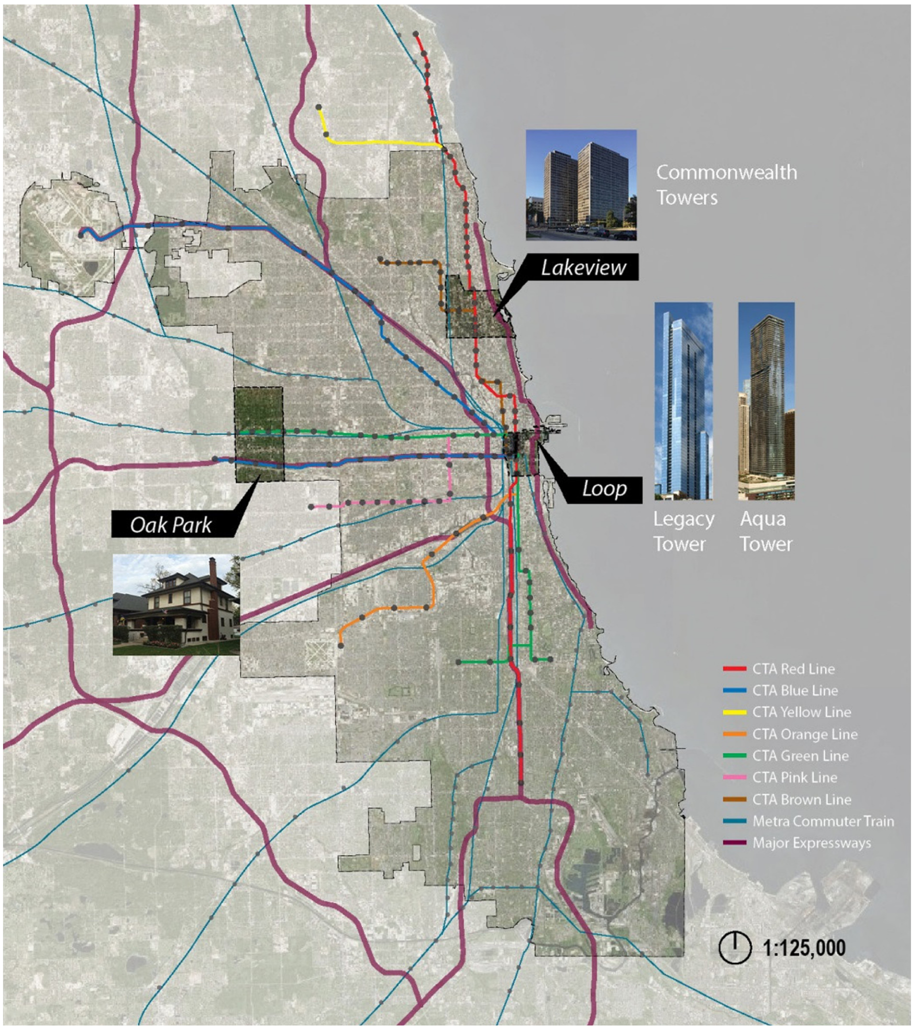

Figure 5. Locations of case study sets relative to central Chicago and major transportation systems (Oak Park for suburban low-rise homes, downtown Loop for Aqua and Legacy Towers, and Lakeview for Commonwealth Towers) (Source: Authors).

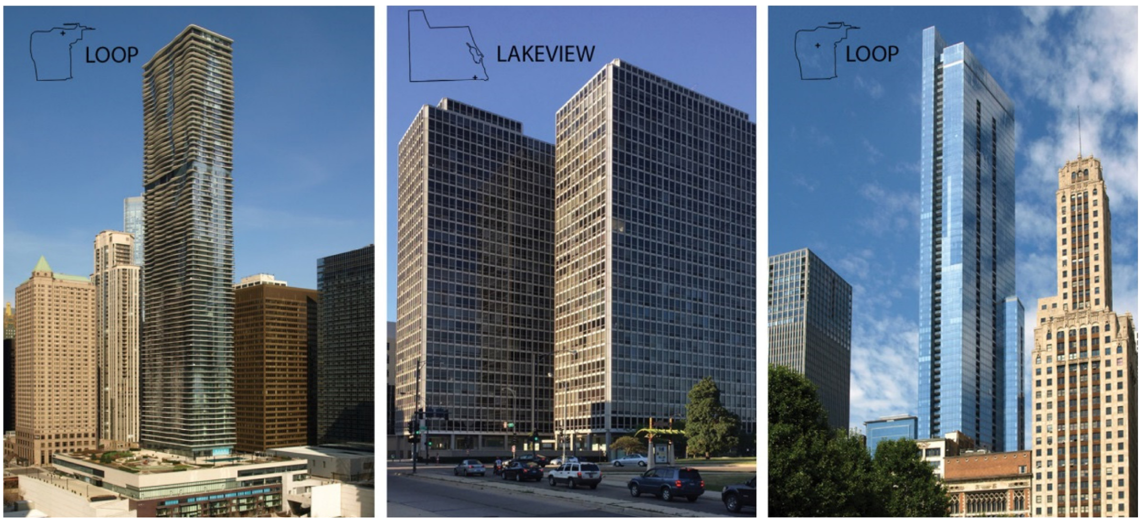

Figure 6. Buildings included in the downtown high-rise case studies (Left to Right): Aqua Tower, the two Commonwealth Plaza Towers and Legacy Tower (Source: Authors).

lines, and a main Metra train line).

The choice of this case study is perhaps surprising for those who are familiar with the Chicago urban agglomeration, since Oak Park is considered somewhat "sustainable" in many aspects, especially in comparison to most of the further outlying suburbs such as Aurora or Naperville, which would likely have shown a more marked contrast in the energy implications of transportation and supporting infrastructure to the downtown case studies than Oak Park. However, a large objective of this research project was to have applicability to many cities around the world, and thus to take a 'best case urban' versus 'worst case suburban' comparison would not be productive. Since the USA is one of the most energy-profligate nations when it comes to residential energy consumption, it is believed that Oak Park as a case study may be more akin, in agglomerated terms, to European or Asian situations, where there is good suburban access to public transport, and local amenities.

It should also be noted that one of the research team members and authors of this report resides in Oak Park and this was a significant factor in choosing this area as the "suburban low-rise" case study. As stated, the objective of the research was to get a high "quality" of data, rather than just "quantity", and thus choosing areas with a strong personal foothold was considered advantageous. This definitely had a positive impact on the project. Due to the personal encouragement of friends and neighbors to undertake the study, as well as enlisting the official help of the Village of Oak Park (the municipal authority), and the Schools District, 273 households in the suburban study alone engaged in the study, from the 565 approached (a response rate of 48%).

4. Survey Responses / Stakeholder Engagement / Household Demographics

Although it took more than one hour to complete the survey, 522 responses were gathered across both high rise and low rise scenarios, from 1561 households contacted, with 235 responses giving "completed" data (see Table 1). The response rate was thus 48% in the low-rise suburban scenario, 25% in the high-rise urban scenario, and 33% overall. Against published studies, these are very high responses rates, especially considering the complexity of the questionnaire, the time engagement needed, the supply of utility bills, and the highly personal nature of some information requested. As previously mentioned, this high response rate is at least partly due to the strong partnerships with municipal authorities and building owners/developers/architects, as well as the personal connection of members of the research team with the residents in the case studies selected.

Although the percentage of responders in the high rise scenarios was lower than the low rise, the total number of questionnaire responses in both scenarios (downtown high-rise = 249; and suburban low-rise = 273) is comparable, which is obviously beneficial as the sample sizes for the research project. The demographics and other relevant data from the surveys is shown in Table 2.

As can be seen from the results in Table 2, much of the demographic data is comparable across the high rise and low rise scenarios (gender, ethnicity, home ownership, etc). The biggest differences are in the number of retirees per household (20% downtown vs. 6% suburban), number of children under 18 in the household (6% downtown vs. 38% suburban), the average resident age (51 years of age downtown vs. 32 years of age suburban), average household income ($232,000 downtown vs. $182,000 suburban), and household size (1.9 people per household downtown vs. 3.3. people per household suburban).

Interpreting this data, we can conclude that these factors are all likely linked, with the high rise residences accommodating an older populace, with more retirees and certainly less children, and a higher disposable income[2]. This, at least in part, seems to confirm the notion that downtown high rise apartments are predominantly accommodating the "empty nesters" in many US cities, whilst a suburb such as Oak Park predominantly seems to cater for families. Specifically, the households embraced in this study in Oak Park include 273 children under 18 years old, approximately 38% of the total household members, whereas there are only 16 children, or approximately 5.5%, in the

Table 1. Respondee engagement (Source: Authors)

Responses				Downtown High-Rise	Suburban Low-Rise
	Aqua Tower (b)	Common-wealth Plaza	Legacy	Total: 4 Towers	Oak Park
Total No. of completed responses (a)	40	31	41	112	123
Total No. of partially completed responses (a)	29	32	76	137	150
Total No. of responses	69	63	117	249	273
Total No. of households contacted directly	264	375	357	996	565
Response rate	26.1%	16.8%	32.8%	25%	48.3%

Note: (a) Considering that not all questions were compulsory, a "Completed" questionnaire is considered as one where 60-100% of questions were answered. A 'Partially Completed' questionnaire is considered as one where less than 60% of questions were answered.
(b) Aqua Tower features 18 floors of hotel space (334 Rooms), 30 floors of rental apartments (474 Units) and 25 stories of owned condominiums (264 Units). Due to legal issues raised by the building owner and management, only condo residents (264) were able to participate in the survey.

Table 2. Basic characteristics of the two case study sets

Characteristics				Downtown High-Rise	Suburban Low-Rise
	Aqua Tower	Commonwealth Plaza	Legacy	Average: 4 Towers	Oak Park
Occupants (a)					
Female%	43%	46%	49%	47%	48%
White Ethnicity%	81%	85%	92%	87%	88%
Children (Under 18)%	4%	14%	2%	6%	38%
Retiree%	15%	18%	24%	20%	6%
Avg. Resident Age (yrs)	48.5	47.8	54.6	51.1	31.8
Household (HH) (a)					
Home Ownership%	93%	88%	84%	88%	88%
Avg. Residence Time (yrs)	4.2	14.7	2.4	7.1	10.2
Avg. Annual HH Income	254,000	153,000	280,000	232,000	182,000
Avg. Household Size (occupants)	1.8	2.0	1.9	1.9	3.3
Avg. GFA/HH (m^2)	132.0	128.2	181.1	147.1	226.4
Avg. GFA/person (m^2)	73.3	64.1	95.3	77.4	68.6
Car Ownership/HH	1.4	1	1.2	1.2	1.8
Car Ownership/person	0.8	0.5	0.6	0.6	0.5
# of Available Parking Spaces/HH	1.7	0.8	1.3	1.4	1.8
Building (b)					
Type	Condo Apartment Hotel	Condo	Condo	Condo	75% single family house, 15% 2-5 storey apartment/ condo building, 5% townhouse, 5% other[1]
Completion Year	2010	1956	2009	N/A	71.9% built before 1950 24.7% built 1950-1999 3.4% built after 2000
Height	250 m	77 m	262 m	N/A	Typically 10 m or lower
# of Floors	86	27	73		Typically 1-3
# of Units	738	375	357	N/A	Typically 1 per abode
Structural Material	Concrete	Steel/Concrete	Concrete	N/A	Wood Frame, Stone or Brick
# of Available Parking Spaces	1,271	293	449	N/A	N/A
Neighborhood (c)					
	Loop	Lakeview	Loop	N/A	Oak Park
Published Neighborhood Population	22,655	64,631	22,655	N/A	51,781
Published Neighborhood Density	7,200/km^2	12,000/km^2	7200/km^2	N/A	4,262/km^2
Distance to Chicago Loop	Walkable	6 km (average)	Walkable	N/A	11~16 km (average)
Public Transport System in Reasonable Walking Distance	All CTA Lines, All Metra Lines & Multiple Bus Lines	CTA Red, Purple and Brown Lines, Metra UP-N Line & Multiple Bus Lines	All CTA Lines, All Metra Lines & Multiple Bus Lines	N/A	Green & Blue CTA lines, Metra UP-West Line & Pace Buses

Source: Authors; (a) Data source: the survey completed by the households across all the cases; (b) Data source: Building management companies, CTBUH Skyscraper Center & U.S. Census Bureau; (c) Data source: U.S. Census Bureau & Chicago Metropolitan Agency for Planning (CMAP)

downtown high-rises case studies.

The data on household size has an impact on many other parts of this study, since much of the data is invariably reported per household, per person and per square meter. In the case of the high rise scenarios, the average Household size of 1.9 is almost half that of the Oak Park scenarios, at 3.3 people per Household. As we can see from the table, this then has an impact on the average Gross Floor Area of dwelling (GFA) and also car ownership per household. Whilst, as one might expect, the average GFA per

Household in the suburban setting is 53% greater than the high rise setting (226 m^2 compared with 147 m^2), when the actual number of people living in the household is taken into account, the suburban homes see a greater GFA efficiency, at 68.6 m^2 per person, compared with 77.4 m^2 per person in the high rise scenarios. A similar thing happens with car ownership, with 1.8 cars per household in the suburban setting compared with 1.2 cars downtown, but only 0.5 cars suburban compared with 0.6 for downtown, on a per person basis.

It must be stated that this demographic skewing towards comparing predominantly affluent, white, older/retired couples and singles in the high rise scenarios, with affluent, largely white families in the suburban scenario, became a major limitation of the research project. This is discussed more in the Limitations of the Study and Future Research section. It should also be noted that another factor affecting this research is that older people were more perhaps more likely to respond to the questionnaire, since they generally have more time to commit to taking such time-consuming surveys. Young professionals in the downtown scenarios are often busy with life and work, and were difficult to capture effectively in this research.

5. Analysis and Results

5.1. Home Operational Site Energy Use

This category comprises the site energy[3] used for space heating and cooling, hot water heating, lighting, cooking, appliance / equipment operation, and all other forms of home operating energy usage. Data was gathered by collecting and analyzing actual energy bills (i.e., electric, gas, and, for the high-rise towers, chilled water[4] bills) for a 12-month period, and all converted into MJ per year[5].

In the case of the high rise buildings, common areas and facilities (such as lobbies, corridors, elevators, centralized MEP plant services, etc.) were taken into account, and a share of these allocated across all households in the building on a share-of-total-floor-area-according-to-unit-area basis. The types of energy bills paid by building management as opposed to individual unit owners differed across all the high rise scenarios and are explained in the notes section of Table 3. It should be noted that it was not possible to obtain building energy bills for Aqua Tower, so that case study has been omitted from this part of the study.

As Table 3 shows, the findings of the energy audit are perhaps somewhat surprising, with the total energy consumption on a per square meter basis being similar across both high rise and low rise scenarios (1,258 and 1,202 GJ per annum respectively, thus actually 5% higher in the high rise buildings). The higher general floor area in the suburban homes means a greater energy consumption per household in the low-rise setting but, conversely, the more people living in those households meant that the energy consumption per person was less in the low-rise setting.

This is a perhaps surprising result, given the prevailing belief that single-family suburban homes, especially of the older type predominantly included in this research, are large, extravagantly-occupied and more energy-profligate, especially with a high envelope surface-area-to-floor-area ratio for greater potential heat loss/gain, whilst modern high rise buildings have more energy-efficient construction and building services and a lower envelope surface-area-to-floor-area ratio for reduced potential heat

Table 3. Annual operational energy (Source: Authors)

Utility Supply	Downtown High-Rise			Suburban Low-Rise
	Commonwealth Plaza (a)	Legacy (b)	Average: 3 Towers (c)	Oak Park
Building Management Paid				
Electricity (MJ/m^2)	150	585	368	N/A
Gas (MJ/m^2)	1,010	115	562	N/A
Chilled Water (MJ/m^2)	N/A	40	20	N/A
Individual Household Paid				
Electricity (MJ/m^2)	130	285	216	209
Gas (MJ/m^2)	N/A	N/A	N/A	994
Total (MJ/m^2/year)	1,290	1,229	1,258	1,202
Total (GJ/HH/year)	156	216	187	275
Total (GJ/person/year)	98	122	110	87

Notes on Energy Provision: (a) Commonwealth Towers: The electricity bills paid by Building Management covers air conditioning, lighting, and mechanical systems of the common areas, as well as chilled water for the whole building (common areas + individual units). The gas bills paid by Building Management cover the gas usage for heating the whole building (common areas + individual units), as well as cooking in individual units. Commonwealth Towers have their own chillers, with the energy consumed accounted for in the electricity bills paid by Building Management. The electricity bills paid by individual units cover air conditioning, lighting, and appliances of individual units. (b) Legacy Tower: The electricity bills paid by Building Management cover air conditioning, heating, lighting, and mechanical systems of the common areas. The gas bills paid by Building Management cover common area feature fireplaces, and cooking in individual units. The chilled water in the Legacy Tower is provided by the city's district chilled water system, Thermal Chicago, which serves over 100 buildings within the city. The electricity bills paid by individual units cover air conditioning, heating, lighting, and appliances of individual units. (c) Aqua Tower: It was not possible to include Aqua Tower in this part of the survey since energy bills for the common areas were unobtainable.

loss/gain, coupled with a high potential benefit of heat (or even cooling) share between residential units. But, although this might be true of other scenarios, it was not the finding here. It is also perhaps surprising that the energy comparison between the 1956 completed Commonwealth Towers, with their single-glass curtain wall, and the 2009 completed Legacy Tower, with its double-glazed curtain wall and modern facilities, was not greater (just 5% greater for the older building).

Although a large part of this anomaly may be linked to the limitations of this research study (i.e., that the high rise scenarios basically focused on building predominantly accommodating affluent, semi-retired people living in large area apartments), such energy consumption differences are indeed curious. Certainly in post-data reflection and follow up discussions with residents, the following two factors seem to play a role:

1. Though the construction and systems in the more modern high rise building are indeed more efficient than in the older high rise and single family homes, the higher provision of facilities (i.e., indoor pool, whirlpool spa, fitness center, library, communal room, etc.) is such that more energy is needed to operate them. Though this thus has a detrimental effect on energy use, one would expect that it would have a positive effect on Quality of Life, and satisfaction with the home in particular.

2. Resident control seems to be a significant factor. In a single family home the user has direct control of all operating systems and can dictate when certain systems (e.g., heat / cool) are operating, based on the preferences of a small number of people (i.e. the family). This is less flexible in a high rise building where, often, the MEP systems are running even if people don't want them. Some residents described scenarios where the central heating (or cooling) was on but residents had windows open because it was too hot / too cold inside the apartment. Further verification work in this area is needed.

5.2. Home Embodied Energy

Home Embodied energy is the energy consumed in all activities necessary to construct the building, including the embodied energy in the materials themselves, and the dir-

Table 4. Overview of published research studies on the initial embodied energy of high-rise buildings (Source: Authors)

Case Number	Type	No. of Floors*	Location	Total Building Area (m^2)	Structure	Envelope	Initial EE (GJ/m^2)	Source
1	Office	7	Melbourne, Australia	27,350	Reinforced concrete	Reinforced concrete façade panel	11.9	(Treloar et al., 2001)
2	Office	15	Melbourne, Australia	47,000	Reinforced concrete	Granite façade panel	16.1	
3	Office	42	Melbourne, Australia	99,350	Reinforced concrete	Concrete façade panel	18.0	
4	Office	52	Melbourne, Australia	129,950	Reinforced concrete	Granite façade panel	18.4	
5	Office	7-9	Japan	Various	Various	Various	9	(Suzuki & Oka, 1998)
6	Office	8	Japan	2,802	Steel reinforced concrete + Steel	Not Stated	10.1	(Oka et al., 1993)
7	Office	8	Japan	3,500	Reinforced concrete	Not Stated	11.2	
8	Office	18	Japan	22,861	Steel	Not Stated	11.9	
9	Office	25	Japan	21,600	Steel	Not Stated	8	
10	Office	31	Japan	88,049	Steel	Not Stated	10.5	
11	Residential	12	Sweden	2,802	Reinforced concrete	Not Stated	3.7	(Gustavsson & Joelsson, 2010)
12	Residential	15	Toronto, Canada	Not Stated	Not Stated	Not Stated	5.5	(Norman et al., 2006)
13	Education	19	Shijiazhuang, China	49,166	Reinforced concrete	Not Stated	6.3	(Chang et al., 2012)
14	Office	38	Bangkok, Thailand	60,000	Concrete	Brick and curtain wall	6.8	(Kofoworola & Gheewala, 2009)
15	Residential	40	Hong Kong, China	39,040	Not Stated	Concrete façade panel	7.2	(Chen et al., 2001)
16	Residential	40	Hong Kong, China	26,600	Not Stated	Concrete façade panel	7	
Average Initial Embodied Energy per square meter							10.1	
Average Annual Initial Embodied Energy per square meter, based on a 100-year lifespan							0.101	

ect energy used by the contractors / sub-contractors for all on-site and off-site activities to facilitate any construction, prefabrication, administration and transportation of goods. In addition, during a building's life, embodied energy is added through goods and services used in the maintenance and refurbishment of the home.

It was outside the scope of this research project to undertake the very detailed calculations of embodied energy for four high rise buildings and more than 200 homes of differing construction in Oak Park. Instead, then available published studies on initial embodied energy (i.e., not including retrofits and refurbishments during the life of the buildings) for both high rise and low rise buildings were gathered, and an average value of initial embodied energy per square meter was used for both sets of scenarios (see Table 4 and 5)[6]. Both scenarios were based on a 100-year life span for the buildings, which resulted in an averaged annual value of 0.101 GJ per square meter for the high rise scenarios, and approximately 30% less than this, 0.068 GJ per square meter, for the low rise scenarios. This higher embodied energy for the high rise buildings is perhaps expected, given the additional systems needed in a high rise building, and the greater stresses imposed on the structural, cladding and environmental services at height.

5.3. Water Consumption

The water consumption data was gathered by collecting and analyzing actual water bills for a 12-month period[7]. In the case of the downtown high-rise buildings, individual units are not metered and thus do not receive individual water bills, so the water bills collected from the building management cover the total water use of the entire buildings, including both indoor and outdoor activities. The allocation of water consumption to households was thus calculated on a share-of-total-floor-area-according-to-unit-area basis (see Table 6).

The findings show that the downtown high-rise buildings consume 34,320 gallons of water per household per year on average, which is only 39% of that consumed by the suburban low-rise households (87,523 gallon). This is likely due to the predominance of private gardens in the suburban setting and, of course, the higher number of people per household. This is borne out when considering the per person basis, with people in downtown high-rise buil-

Table 5. Overview of published research studies on the initial embodied energy of low-rise residential buildings (Source: Authors)

Case Number	Type	No. of Floors*	Location	Total Building Area (m^2)	Structure	Exterior Wall	Initial EE (GJ/m^2)	Source
1	Single-detached	1	Melbourne, Australia	291.3	Wood-frame	Brick veneer	13.4	(Crawford, 2012)
2	Single-detached	1	Melbourne, Australia	42.5	Wood-frame	Fiber cement cladding	7.5	(Myer et al., 2012)
3	Single-detached	1	Melbourne, Australia	42.5	Wood-frame	Fiber cement cladding	5.4	
4	Single-detached	1	Orebro, Sweden	130	Wood-frame	Wood panelling	3.7	(Adalberth, 1997)
5	Single-detached	1	Orebro, Sweden	129	Wood-frame	Wood panelling	6.5	
6	Single-detached	2	Orebro, Sweden	138	Wood-frame	Wood panelling	2.9	
7	Single-detached	2	Sweden	144	Not Stated	N/A	3.5	(Gustavsson & Joelsson, 2010)
8	Single-detached	1	Phoenix, USA	186	Not Stated	Wood Shingles	6.8	(Frijia et al., 2011)
9	Single-detached	1	Phoenix, USA	186	Not Stated	Brick	6.8	
10	Single-detached	1	Phoenix, USA	186	Not Stated	Painted Block	6.3	
11	Single-detached	1	Phoenix, USA	186	Not Stated	Stucco	6.2	
12	Single-detached	2	Phoenix, USA	186	Not Stated	Wood Shingles	5.4	
13	Single-detached	2	Phoenix, USA	186	Not Stated	Brick	5.4	
14	Single-detached	2	Phoenix, USA	186	Not Stated	Painted Block	5.1	
15	Single-detached	2	Phoenix, USA	186	Not Stated	Stucco	5	

Table 5. Overview of published research studies on the initial embodied energy of low-rise residential buildings (Source: Authors) (Continued)

Case Number	Type	No. of Floors*	Location	Total Building Area (m^2)	Structure	Exterior Wall	Initial EE (GJ/m^2)	Source
16	Single-detached	2	Melbourne, Australia	128	Not Stated	Brick veneer	14.1	(Fay et al., 2000)
17**	Single-detached	2	Melbourne, Australia	128	Not Stated	Brick veneer	15.2	
18	Semi-detached	2	Lingwood, UK	91	Wood-frame	Larch cladding	5.7	(Monahan & Powell, 2011)
19	Semi-detached	2	Lingwood, UK	91	Wood-frame	Brick veneer	7.7	
20	Semi-detached	2	Lingwood, UK	91	Masonry cavity wall	Brick cladding	8.2	
21	Single-detached	2	Toronto, Canada	Various	Wood-frame	Brick	4.6	(Norman et al., 2006)
22	Single-detached	2	Ann Arbor, USA	228	Wood-frame	N/A	6.6	(Keoleian et al., 2000)
23	Single-detached	2	Ann Arbor, USA	228	Wood-frame	N/A	7.3	
24	Semi-detached	2	Melbourne, Australia	123	Wood-frame	Brick veneer	6.8	(Treloar et al., 2001)
25	Detached	2	Gothenburg, Sweden	N/A	N/A	N/A	6.2	(Thormark, 2002a)
26	Various	Various	Various	Various	Various	Various	5.9	(Pullen, 2000)
27	Single-detached	Not Stated	USA	199.7	Wood-frame	Not Stated	6.4	(EPA, 2013)
Average Initial Embodied Energy per square meter							6.8	
Average Annual Initial Embodied Energy per square meter, based on a 100-year lifespan							0.068	

Table 6. Annual water consumption (Source: Authors)

Water Consumption	Downtown High-Rise			Suburban Low-Rise
	Commonwealth Plaza	Legacy	Average: 3 Towers	Oak Park
Water (gallon/m^2/year)	243	207	225	366
Water (gallon/HH/year)	31,153	37,488	34,320	87,523
Water (gallon/person/year)	15,576	19,727	17,652	24,266

dings consuming 17,652 gallon per year, on average, which is a more comparable 73% of people in the suburban low-rise homes (24,266 gallon).

5.4. Mobility and Transport Movements

Typical weekly mobility & transport movements for each person in each household was assessed through the questionnaire and extrapolated to monthly and annual vales for comparison. All modes of transport were assessed, including: walking, bicycling, automobile, and 3 forms of public transport - bus, CTA train (i.e., the City of Chicago's combination of elevated rail and underground subway mass transit system), and regional Metro train (similar to Amtrak, which provides medium- and long-distance inter-city rail service). In addition, all types of typical journeys were embraced, including: work, school, shops, restaurant/entertainment, family/friends and "other" (specify if applicable).

The journey to each primary destination allowed for two pattern inputs: primary journey pattern and secondary journey pattern. In each pattern, frequency (times per week), travel time (minutes), and distance (miles) via each mode of travel involved in this journey were examined. Thus, for example, the survey allowed for the responder to indicate a 10 minute walk followed by 30 minute train journey to get to work on three days of the week, and a 5 minute bicycle ride followed by a 40 minute bus journey to get to work on two days of the week. In addition, car ownership and the types of cars were investigated.

Table 7 summarizes the average weekly distances traveled by all modes of transport to all destinations for both downtown and suburban homes, presented on a per-household and per person basis.

As we can see, Oak Park households travel almost two-and-a-half times as far on a weekly basis as the downtown households (287 km downtown vs. 700 km suburban), although the time spent travelling on a per person basis is only 9% greater (6.6 hours downtown vs. 7.2 hours subur-

Table 7. Household travel data to all the destinations during a typical week (Source: Authors)

Travel Characteristics				Downtown High-Rise	Suburban Low-Rise
	Aqua Tower	Commonwealth Plaza	Legacy	Average: 4 Towers	Oak Park
Frequency (times)	22.6	26.8	18.6	22.7	40.9
Total Time per household (hrs)	11.2	16.5	10.1	12.6	23.7
Total Time per person (hrs)	6.2	8.3	5.3	6.6	7.2
Walk (km)	43.6	57.3	32.2	44.3	37.0
Bike (km)	1.8	16.4	6.0	8.0	4.8
Auto (km)	207.4	217.6	131.8	185.6	399.3
Bus (km)	3.5	52.0	3.1	19.5	9.3
CTA Train (km)	15.3	13.2	33.2	20.4	53.9
Metra Train (km)	4.8	1.6	11.3	6.0	194.7
Other (km)	2.9	1.0	4.7	2.9	0.8
Total per Household (km)	279.4	359.0	222.1	286.6	699.9
Total per Person (km)	147.1	179.5	123.4	150.8	212.1

ban).The breakdown of transport mode is 57% by private automobile, 37% by public transport, and 6% walking / cycling / "other" in the suburban scenario. Conversely, the downtown households travel 65% by private automobile, 16% by public transport, and 19% by walking / cycling / "other". The higher automobile / lower public transport use with the downtown households is potentially counter-intuitive, but it must be remembered that the distance travelled by car is much lower than in the suburban setting. These journeys are predominantly being undertaken to go shopping, or visit places outside the city (as opposed to work / recreation) and the higher walking / biking distance indicates that many of the journeys that are undertaken in the suburban setting by public transport, are undertaken on foot in the downtown scenario.

Within the four downtown residential towers, the Commonwealth Plaza households traveled the most by walking, bicycling and bus (likely because of their greater distance from CTA / Metra infrastructure), and the Legacy households traveled the most by both (for likely the exact inverse reason).

5.5. Urban/Suburban Infrastructure

Urban/suburban infrastructure includes all the networks and elements that are required to support inhabitation; roads, transportation, water, sewage, power, lighting supply, etc. This was by far the most difficult part of this study to assess, partly because of the shear amount of different infrastructure contained in any urban or suburban scenario, and partly because of the relative infancy of both the methodologies for assessing the embodied energy of infrastructure and the lack of previously published studies. To get some appreciation of the relative amount and density of infrastructure in both downtown and suburban scenarios, certain infrastructure networks in both locations were mapped (see Fig. 7 as an example). In addition, provision for networks running through the areas between the locations and the points of supply were factored in.

The infrastructure networks studied included; (i) road (surface area); (ii) electrical supply (length of supply network); (iii) gas supply (length of supply network); and (iv) water supply (length of supply network). In all cases the networks were assessed against the total population in each area, including a factor for daytime population gain/loss through shifting work patterns, from published Census data (basically daytime population gain in the downtown high rise scenarios, and daytime population loss in the suburban scenarios). This "infrastructure per person" figure was then transferred into "infrastructure per household" and "infrastructure per m^2 of household" figures using the average household size and GFA/household figures gleaned earlier.

Perhaps unsurprisingly, it is this assessment of infrastructure provision that shows the greatest difference between the urban and suburban scenarios, with the urban infrastructure provision per person in the downtown scenarios being much lower than in suburban scenarios, due to the more concentrated geographic area, and the higher number of people using such infrastructure, downtown. For example, the ratio of suburban-to-urban infrastructure provision for each network on a per person basis was approximated as follows: (i) Surface Area of Roads: +1200%, (ii) Electrical Supply network: +528%; (iii) Gas Supply network: +563%; and (iv) Water Supply network: +564% (see Table 8).

It is this area of the study that is currently under review and being developed. There are many significant assumptions and caveats made in these complicated assessments, and the figures reported above.

5.6. Analysis: Quality of Life

The Quality of Life (QoL) research relied on qualitative, rather than quantitative, data, with an extensive section of the questionnaire devoted to numerous questions focused on assessing both a Satisfaction With Life Scale (SWLS) and a Sense of Community Index (SCI). Published methodologies from Humanities fields were used,

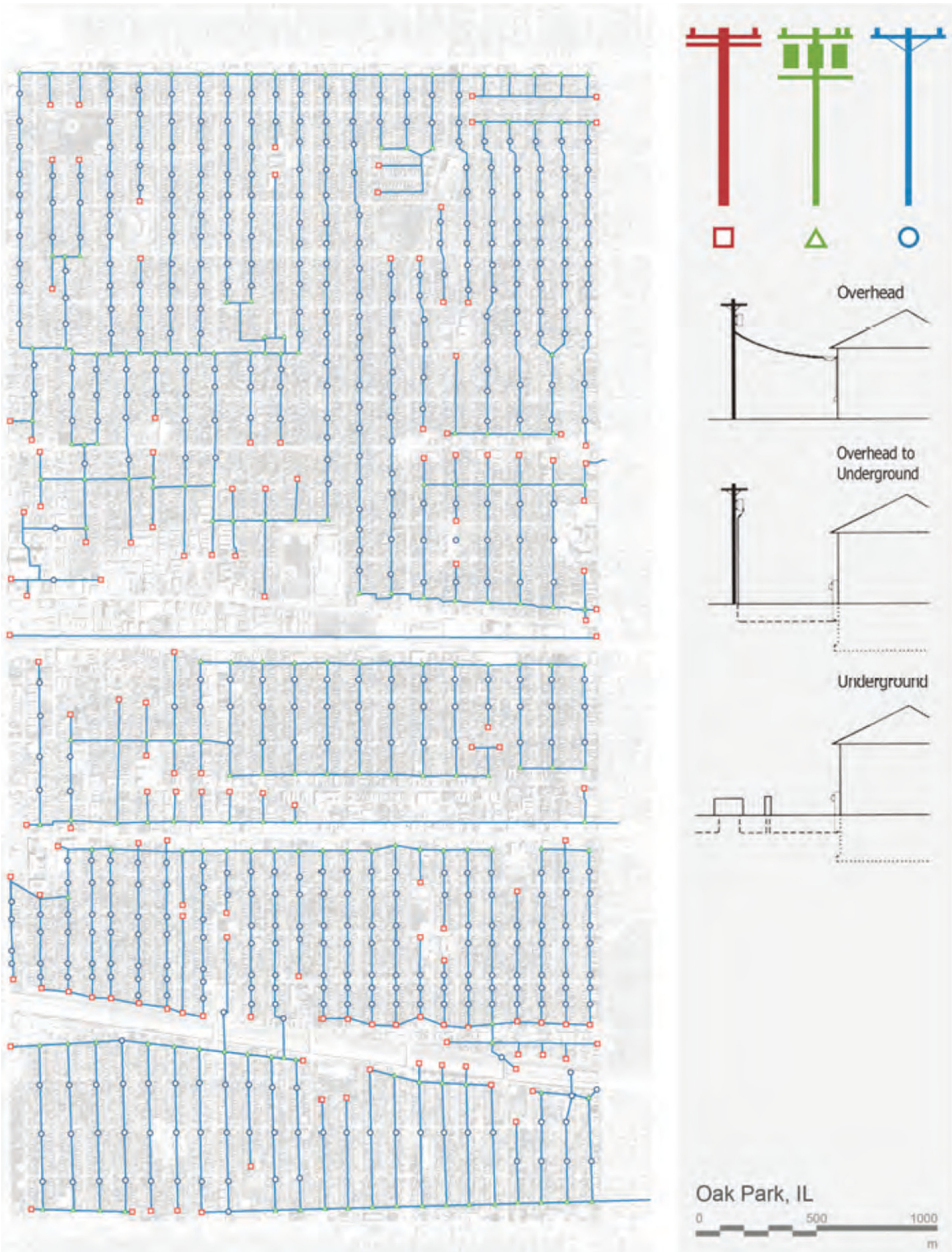

Figure 7. An example of infrastructure assessment: Overhead electrical cables mapping in Oak Park, IL (Source: Authors, with Illinois Institute of Technology students Ezgi Bay & Omar Almahdy).

Table 8. Measurement of urban vs. suburban infrastructure (Source: Authors)

Infrastructure Measurement	Downtown Chicago			Oak Park		
	Per Person	Per HH	Per sq.m	Per Person	Per HH	Per sq.m
Road Network (Surface Area) (sq.m)	6.75	12.83	0.09	81.15	267.80	1.18
Electricity Supply (Length of Cable) (m)	1.28	2.43	0.02	6.76	22.31	0.10
Gas Supply (Length of Pipe) (m)	0.60	1.14	0.01	3.38	11.15	0.05
Water Supply (Length of Pipe) (m)	0.86	1.63	0.01	4.85	16.01	0.07

including introducing regression analyses and other statistical tools to get as close to comparable results as possible. The questionnaire also embraced other satisfaction domains including travel, accessibility, social integration, safety and overall residential environment.

Perhaps unsurprisingly, given that the study involved evaluating predominantly affluent, white, semi-retired people in the high rise scenarios and affluent, white, middle class families in the suburban scenarios – both of whom had largely chosen to live where they reside – the Quality of Life indicators were high for both scenarios (see Table 9). Those living in the high rise buildings had a slightly higher SWLS score (4.18 as opposed to 4.01, out of a possible 5), whereas those living in the suburban scenario had a slightly higher Sense of Community score (3.90 compared with 3.6, out of a possible 5). However, when controlling for demographic differences, the study found that residence type (urban and suburban scenarios) was not significantly associated with a sense of community. The factor that was found to be most associated with a sense of community, perhaps unsurprisingly, was household size (i.e., the greater the number of household members, the higher the sense of community).

Table 9. Average scores of the QoL Indicators (Source: Authors)

Quality of Life (QoL) Indicators	Downtown High-Rise	Suburban Low-Rise
	Average: 4 Towers	Oak Park
Satisfaction with Life Scale (SWLS)	4.18	4.01
Sense of Community Index (SCI)	3.60	3.90
Other Satisfaction Domains		
Travel	4.55	4.29
Accessibility	4.76	4.31
Social Integration	4.46	4.19
Safety	4.44	4.2
Overall Residential Environment	4.67	4.28

6. Summary of Findings

Table 10 summarizes the key findings of this research, focusing on the ratio of Suburban-to-Urban values across all main data fields. Building operational and embodied energy are show on a GJ per square meter of floor space basis, whereas all other indicators are shown on a per person basis, so as not to allow the differing household physical size, or the number of people in each household, skew the results.

As mentioned in the relevant sections of this paper, operational energy across both high rise and low rise scenarios are virtually the same on a square meterage basis, whereas embodied energy in the low-rise scenario is approximately a third less than high rise. Water consumption is approximately a third more in the suburban setting than

Table 10. Summary of the key findings (Source: Authors)

Characteristics	Downtown High-Rise	Suburban Low-Rise	Ratio (%) of Suburban to Urban
	Average: 4 Towers	Oak Park	
Building Energy			
Annual Building Operational Energy	1.26 GJ/m^2	1.20 GJ/m^2	96%
Initial Building Embodied Energy	10.1 GJ/m^2	6.8 GJ/m^2	67%
Water Consumption			
Annual Water Consumption	17,652 gallon/person	24,266 gallon/person	137%
Travel Behavior			
Annual Travel Time	345.1 hrs/person	373.5 hrs/person	108%
Annual Travel Distance (a)	7,803 km/person	10,966 km/person	141%
Annual Travel Distance by Walk/Bike	1,425 km/person	656 km/person	46%
Annual Travel Distance by Automobile	2,050 km/person	6,256 km/person	305%
Annual Travel Distance by Public Transit	1,250 km/person	4,041 km/person	323%
Urban-Suburban Infrastructure			
Road Network (Surface)	6.75 m^2/person	81.15 m^2/person	1202%
Electricity Supply (Cable)	1.28 m/person	6.76 m/person	528%
Gas Supply (Pipe)	0.60 m/person	3.38 m/person	563%
Quality of Life			
Water Supply (Pipe)	0.86 m/person	4.85 m/person	564%
Satisfaction with Life Scale Score	4.18	4.01	96%
Sense of Community Index Score	3.60	3.90	108%
Overall Residential Environment Score	4.67	4.28	92%

Note: (a) The total travel distance is the sum of walk/bike + auto + public transit + “other”, but “other” is not list in this final comparison table.

downtown. People in the suburban setting spend only around 8% more time travelling than downtown residents, but manage a 41% increase of actual kilometers travelled. The Oak Park residents travelled only 46% of the distance travelled by downtown residents by bike/walking, but 305% of the distance travelled by automobile, and 323% by public transport. Examining the four fields studied for urban-suburban infrastructure provision (i.e., road surface area and lengths of electrical supply cables, gas supply pipes and water supply pipes), the suburban infrastructure showed an averaged 714% increase over the amount of urban infrastructure, on a per person basis. Quality of Life indicators were comparable across the two scenarios, with the downtown scenarios registering a slightly higher "Satisfaction with Life" and "Overall Residential Satisfaction" scores, and the suburban scenario registering a slightly higher "Sense of Community" score.

Whilst many of these results are perhaps as expected, it is the comparable operating energy across both scenarios that is perhaps the most surprising. Given that many homes in the Oak Park scenario are of old construction and presumably poorly insulated etc, it is surprising that they consume as much energy per square meter as a modern high rise residential building. Whilst some of this can be attributed to the high number of central facilities and amenities operating in a tall building, follow up discussions with some residents have indicated that a lack of control over the direct household environment (too hot / too cold) is also having a detrimental impact on high rise energy consumption.

By far the biggest difference between urban and suburban "sustainability", perhaps not surprisingly, seems to be in terms of urban infrastructure provision, with the urban scenario approximately a seventh of that provided in the suburban scenario. Whilst acknowledging that this part of the work was the most difficult to ascertain, and the calculations were far from an exact science, the study shows that it is perhaps this field where the most future work needs to be undertaken – to better understand both the operating and embodied energy of infrastructure provision, and how this can be maximized even further in a concentrated urban environment. Perhaps the most useful concluding statement to this pilot study then would be that all buildings need to take every effort to reduce both the energy expended in their materials / construction, and that consumed in their operation, but that the greatest benefit to sustainable cities of the future seems to be in the benefits of concentrated and shared land use and infrastructure.

7. Limitations of the Study and Future Research

Overall, this pilot study provides a quantitative comparison of the sustainability implications of Chicago downtown high-rise and suburban low-rise living, based on the collection of real data and best available data in the following areas: (i) home operational energy use, (ii) embodied energy of the dwelling, (iii) home water consumption, (iv) mobility and transport movements, (v) urban/suburban Infrastructure, and (vi) quality of life. It offers an initial understanding of the sustainability of residential life-styles across human, building, and infrastructure scales based on actual case studies in and around Chicago, IL.

Much has been learnt in the undertaking of this pilot study. Whilst work is currently continuing in order to verify all findings and publish the much more in-depth results in the CTBUH Research Report family of publications in early 2017, extensive thought is already being given to a more significant Phase 2 of the study, which would embrace a greater number of building types, households, socio-economic groups and, ideally, cities/locations/cultures. The extent of the study is largely dependent on the level of external research funding that can be obtained.

Regardless, the following factors are recognized as significant limitations in the study undertaken to date, which need to be addressed in any subsequent studies:

7.1. Limitation 1: Pool of Participants

The sample is not representative of the true population spectrum in urban and suburban areas of Chicago (or other cities for that matter). The majority of the residents across both urban and suburban scenarios are white (more than 87%) and wealthy (more than 87% of the households' annual income in both scenarios is higher than the median household income of the Chicago metropolitan area, which was about $60,000 in 2013). This limitation highly affects the study. For example, wealthy people might tend to consume more energy and feel more satisfied with their lives no matter where they live.

Several other demographic characteristics are very different between the urban and suburban scenarios. Those variables include age (the average age of the downtown residents is 51.1 years old, almost 20 years older than Oak Park residents), employment status (e.g., more retired people live in the downtown scenarios, with a 20% share vs. only 6% in Oak Park), and household size (e.g., the average household size of the downtown households is 1.9 people but in Oak Park this figure is 3.3 people). Certainly one of the biggest differences that affected the study, most notably in any assessments translated to a per person basis, was the much higher occurrence of children/families in the suburban scenario (6% of children in the downtown scenarios versus 38% in Oak Park). This higher number of children, and consequently people per household in the suburban scenario, skewed results somewhat. Any future research needs to ensure a better balance of demographics across both scenarios.

7.2. Limitation 2: Residential Location

Located only 11-16 km from Chicago city center, Oak Park constitutes a relatively dense amalgamation of single-family homes and apartment blocks, with a relatively walkable environment, and is plugged into much of Chicagoland's public transport system. Thus, Oak Park is not representative of a typical American suburb case though it may be more akin to European or Asian scenarios. A less dense outlying suburb such as Aurora or Naperville would likely show a far more marked contrast with downtown scenarios in the factors embraced in this study.

7.3. Limitation 3: High-Rise Building Type

Two of the four residential towers in this study, Aqua Tower and the Legacy Building, are taller than typical high-rise residential buildings. Specifically, both Aqua Tower (262-meter tall, 86-story) and the Legacy Building (250-meter tall, 73-story) can be almost categorized into the super-tall category[8], which typically consume more operational energy for elevators, water system, pumps, etc. than a more typical high-rise building. Moreover, both Aqua Tower and the Legacy Building are considered as luxury residential buildings in Chicago that offer numerous high-quality on-site management service and amenities, which certainly require much more operational energy than a regular residential tower.

7.4. Limitation 4: Energy Data Availability

Since the necessary information for an embodied energy (EE) calculation (i.e., quantities and specifications of materials in the buildings) was not available, the research did not undertake a full detailed assessment of the actual EE in the case study buildings, and instead, an extensive literature review on published building EE studies was conducted. However, few of the high-rise cases in the published research studies were residential, and unfortunately none of them were located in the U.S. Although the findings of this study provide a reasonable understanding of the EE of downtown high-rise and suburban low-rise buildings, the result would be more accurate if a detailed EE calculation of all the buildings was conducted based on the actual quantities and specifications of materials in the buildings.

Also, Aqua Tower was unfortunately excluded in the operational energy (OE) analysis since the energy usage data received from its building management was too limited to be used to conduct a reasonable OE analysis. Therefore, the high-rise OE results were not representative of all the four residential towers in this research. Future research should ensure that building management are fully in support of the study and will provide all relevant data.

7.5. Limitation 5: Quality of Life Indicators

Only limited variables were investigated to measure life satisfaction and a sense of community. Demographics such as gender, age, income, household size, etc. were tested in the study, but other variables that might also influence residents' life satisfaction, such as personality, health constitution, marriage status, etc. were not considered in the study or controlled for. The research thus shows that residents in downtown high-rises have a higher life satisfaction when controlling for these limited variables, but the results might be very different if more variables are considered.

8. Appendix

1. This urbanization is due to three predominant factors: (i) general population growth, forecasted by United Nations to increase from 7.2 billion in 2014 to 9.6 billion globally by 2050; (ii) the movement of people from countryside to city, motivated by an expectation of higher economic opportunity and quality of life; and (iii) the birth of more people in those cities. The latest reports from the United Nations estimates an annual global urbanized population increase of 68.3 million per year, which equates to a weekly rate of almost 1.3 million, a daily rate of around 187,000, and a total urban population increase of 2.4 billion by 2050. Source: United Nations, Department of Economic and Social Affairs, Population Division, (2015). World Urbanization Prospects, The 2014 Revision: Highlights. [online] Available at: https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf [Accessed 24 Jul. 2016]

2. Actually both high-rise and low-rise scenarios show a high affluence, at $232,000 and $182,000 average annual household income respectively – compared with the Chicago metropolitan average of $60,564. Source: American Community Survey, U.S. Census Bureau. 2013

3. 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 et al., 2007). The variance in Source Energy between a building using gas for heating/cooling or electricity for heating/cooling can be very high. So, since this study is predominantly focused on a comparison across building types with differing energy-use systems, and not a commentary on the suitability of those systems, all energy consumption figures in the study are based on "site energy".

4. The chilled water in the Legacy Tower 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.

5. The conversion of all site energy consumption into MJ or GJ, to enable comparisons across energy types and buildings, was undertaken by using published conversion factors (ASHRAE, 2013) in conjunction with the data

collected from utility bills. Thus, in the case of electricity, "kWh" was converted to MJ using the conversion: MJ = kWh × 3.6 MJ/kWh. In the case of gas, "therm" was converted to MJ using the conversion: MJ = therm × 105.5 MJ/therm. In the case of chilled water supply, "ton-hour" was converted to MJ using the conversion: MJ = ton-hour × 12.66 MJ/ton-hour)/6.1. This 6.1 figure is the estimated coefficient of performance (COP) for the electric motor driven centrifugal chillers used by Thermal Chicago's downtown chilled water loop. Unfortunately, the exact COP of the chillers was not available; a conservative estimate of 6.1 was used, as it is the COP for a baseline centrifugal chiller according to ASHRAE 90.1-2007.

6. The embodied energy research was conducted based only on studies published in peer-reviewed papers (27 low-rise residential building cases, and 16 high-rise building cases).

7. Please note that, due to the lack of water bills provided by building management on the Aqua Tower, it was not possible to include this building in this part of the study.

8. The Council on Tall Buildings and Urban Habitat (CTBUH) defines "super-tall" as a building over 300 meters (984 feet) in height. The Legacy Building is the current tallest residential building and 13th tallest building in Chicago, and Aqua Tower is the current 5th tallest mixed-used building and 10th tallest building in Chicago. Note: At the time of writing, there are only 106 completed super-tall buildings in the world and only 14 of these are purely residential (Source: CTBUH).

References

Crawford, R. (2012). An As-Occupied Life Cycle Energy Assessment of a Residential Building. In Proceedings of the 46th Annual Conference of the Architectural Science Association, Gold Coast, Australia, 14-16 November 2012.

Du, P. (2015). Environmental and social sustainability implications of downtown high-rise vs. suburban low-rise living: A Chicago case study (Doctoral dissertation, Illinois Institute of Technology).

Du, P., Wang, Z., and Gamburg, E. (2015). Tall Buildings as Extensions of Urban Infrastructure and Vitality. CTBUH Journal, (2015 Issue IV), 46-51.

Du, P., Wood, A., and Stephens, B. (2015). Life Cycle Assessment of Urban vs. Suburban Residential Mobility in Chicago. In *Proceedings of the ARCC 2015 Conference*, *Chicago*, *IL*, *USA* (Vol. 69).

Du, P., Wood, A., and Stephens, B. (2016). Empirical Operational Energy Analysis of Downtown High-Rise vs. Suburban Low-Rise Lifestyles: A Chicago Case Study. Energies, 9(6), 445.

Du, P., Wood, A., Stephens, B., and Song, X. (2015). "Life-Cycle Energy Implications of Downtown High-Rise Vs. Suburban Low-Rise Living: An Overview and Quantitative Case Study for Chicago Buildings", 5(3), 1003-1024.

Du, P., Wood, A., and Stephens, B. (2015). Life Cycle Assessment of Urban vs. Suburban Residential Mobility in Chicago. Architecture Research Centers Consortium (ARCC) 2015 Conference Proceedings. 6th-9th April, 2015. pp. 188-195.

Newman, P. W. G. and Kenworthy, J. R. (1989). "Gasoline Consumption and Cities", J. Am. Plan. Assoc. 55, 24-37.

Norman, J., MacLean, H. L., and Kennedy, C. A. (2006). Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. J. Urban Plan. Dev. 132, 10-21.

Note: Due to the limitation of the pages of the conference proceedings, the Reference Section here doesn't include the full references on this study. Full references will be found in the CTBUH Research Report, which will be released in 2017.