A COMPUTATIONAL APPLICATION OF URBAN NETWORK ANALYSIS ON WALKABILITY IN DESIGN DECISION MAKING

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ABSTRACT

Using the TOD neighborhoods of Waipahu on Oahu, which is comprised of two localities referred to as the West Loch Station and the Waipahu Transit Center Station, as a case study, the present work aims at investigating to what extend different aspects of the built environment may affect walkability in urban neighborhoods.

By means of Geographic Information Systems (GIS), spatial, network, and statistical analyses were performed on a selected set of components of the urban built environment. Residential density, commercial density, mixed land-use, and street connectivity were measured to determine how the following 8 urban aspects —mixed-land use, small blocks, interesting architecture, building density (commercial and residential), residents' physical activity, the impact of density and mixed-land use— affect transport mode or urban mobility.

To better understand the walkability patterns around these TOD neighborhoods, we applied the method to Portland, which is known for being a walkable city. As Jeff Speck claims, for a place to be walkable, it is all a question of proper balance of uses, so it is important to look for what is missing or under-represented in an urban setting, whether it is office, retail, dining, entertainment, housing, school, recreation, worship, or parking (Speck 2013).

The proposed graph-analysis framework can be used by professionals to improve planning and designing decisions to make cities more attractive and sustainable. However, it is not intended to replace the existing ways of evaluating walkability, but instead, it is to be seen as an additional layer of information to be introduced at an early stage of any project.

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PREFACE

This paper results from a few topics that have sparked my interest throughout the course of my studies. During my third year, I was concerned about the lack of activities on our University of Hawaii at Manoa campus, especially after 4 pm. After a few investigation field surveys and hours of observations, I created some maps, came up with some results for this research, and made a design proposal. The professor I had at that time suggested pursuing this research paper to present it to the University board. However, as I was still really young in the program, I did not follow his recommendation, but his positive feedback did leave a mark on me and that is probably what has motivated me to constantly expand my knowledge on topics, such as social and open spaces in our built environment.

During my fourth year, the school of Architecture had their studio in a building in downtown Honolulu. The goal of such an initiative was to introduce students to a potential professional environment like downtown Honolulu's financial, economic and governmental district. As a result of this new studio lifestyle, I was struck by the area's desolateness after 5 pm, except for a few bars located 5 blocks away from where we were. In response to this situation, I chose to rehabilitate the 1968 headquarter building of the Bank of Hawaii into a nightclub that I named "THE CLUB." The idea was again to revitalize downtown after 4 pm. The place was to be opened 24/7. During the day, it would offer spaces for both professional and casual meetings. On the different levels of the building, people could taste different cuisines in different types of restaurants—including French gastronomy—and enjoy green open spaces. Some branding ideas have also emerged in the process, such as VIP credit cards or VIP members cards. While working on this project, I started incorporating parametric methods of design.

In my fifth year, I designed a mixed-use tower of 650 feet, the podium of which was a series of open spaces built on a free facade concept. Each of these spaces was accessible by a ramp located in the center. My inspiration came from the Guggenheim museum in NYC and Le Corbusier's Five Points of Architecture.

During my sixth year, Professor Hyoung-June Park from the University of Hawaii hired me as a research assistant in the Future Lab for campus research. This work opportunity has not only marked the beginning of a successful collaboration between the two of us, but it has also allowed me to be more exposed to real life situations and more concerned about built environments in general.

Today's project marks the conclusion of my long academic journey in the exploration of urban spaces.

CHAPTER 1. INTRODUCTION

In accordance with the U.N. report entitled *Our Common Future* (WCED 1987), many scholars, planners, architects, government and civil societies agree to say that we cannot continue planning cities the way we have been doing. The world is facing important global challenges, among which there is food insecurity, energy scarcity, depletion of natural resources, pollution, climate change, social and political unrest, unequal growth, poverty, growing and aging populations, etc. And according to the United Nations statistics, the year 2007 marked the threshold of a new era since the world's urban population has become now more urban than rural. Indeed, more than 54 percent of the population worldwide live in cities, and 66 percent (two-thirds) is expected to be urban by 2050, with the most significant increase (90%) in Asia and Africa, and in small- and medium-sized cities ("World Urbanization Prospects The 2014 Revision Highlights" 2014). However, across countries, the level of urbanization is unevenly distributed with 53% of the world's urban population settled in Asia, and the rate of growth is unequal as it is faster in Asia and Africa. Moreover, the living conditions in cities vary a lot as some cities accumulate more wealth than others or show better signs of growth ("World Urbanization Prospects The 2014 Revision Highlights" 2014; Sorensen, Marcotullio and Grant 2004). Agenda 21, the U.N. global action plan that details the objectives to fulfill to enhance sustainable development in the 21st century, highlights the close interrelationship between poverty and environmental degradation. It states: "While poverty results in certain kinds of environmental stress, the major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialized countries, which is a matter of grave concern, aggravating poverty and imbalances" ("Agenda 21 - Chapter 4: Changing Consumption Patterns, Earth Summit, 1992"

1992).

Urbanization is high in Northern America with a level above 80 percent ("World Urbanization Prospects The 2014 Revision Highlights" 2014, 7), which shows how much cities are very important to Americans. However, as they grow, more infrastructure and services are needed, and more natural resources are required to build and run them. Based on the current rate of growth, the American system of urban planning will require too much energy to maintain its infrastructure. Mark Swilling warns us that "if we continue to design and build as if the planet can provide unlimited resources, then this near-doubling of the urban population will mean a doubling of the natural resources required to build and operate our cities – which is not sustainable" (Swilling 2016).

The goal of my doctorate thesis is to propose a parametric method for analyzing walkability around the TOD's rail stations on the island of Oahu, Hawaii in relationship to the Land-Use Ordinance and access to the other available means of public transportation. I am arguing that using traditional and already established methods of planning is one of the causes of poor city planning. The literature on the topic and the conversations I had with professionals have proven me that Honolulu, like many other cities worldwide, suffers from under-utilized spaces and poor city design. It is this ongoing battle on what 'good' city planning is that gave birth to the parametric method that my thesis is based on.

Using technology and a series of tools—ArcGIS, Excel, Rhinoceros 3D and Grasshopper 3D—can help to better understand the walkability factors that influence people's perception of liveability[1] in their community. It can also be used by professionals to improve planning and designing decisions to

1 I will use the British form of the word 'livability' because I think the composition of the word (verb 'live' and the suffix 'able') best illustrates the concept that will be explained later in this paper.

make cities more attractive and sustainable. However, I wish to be clear on the fact that the proposed method is not intended to replace the existing ways of evaluating walkability, but instead, it is to be seen as an additional layer of information to be introduced at an early stage of any project.

The paper will first look at some of the reasons why we cannot keep on planning cities the way we have been. I will then look into the shaping of cities to understand how car dependence has affected walkability in American cities. This paper will explain how a walkable environment contributes to a more sustainable and liveable city. This study aims (1) to analyze and assess the current walkability model of Waipahu (Oahu); (2) to evaluate mobility and connectivity around the future TODs stations by using four of the main criteria advocated by urban theorists, such as Jacobs (1961); and (3) to propose a computational application of a network analysis on walkability for design decision making; a method that can be put in use for any other factors that contribute to cities' liveability.

CHAPTER 2. SYNTHESIS OF KNOWLEDGE

MODERN ISSUES

According to the U.S. Environmental Protection Agency, the way we build our environment[2] and the mobility and travel decision we make[3] have significant direct and indirect effects on both human health and the natural environment[4] (EPA 2013, 2-3). While many companies are busy producing or working on alternative fuels ("Alternative Fuels And Advanced Vehicles" 2014) or developing new means of transportation, such as the "new kind of aircraft that will enable commuters to glide above crowded roadways" (Lowy 2017), others believe that, besides adopting a pro-environmental behavior, real changes also need to be made in the design of the built form to limit the environmental impact (Cervero 1998; Jabareen 2006), especially in America where cities use much more resources than European cities (Beatley 2000). And since urbanization is part of the problem because it is often associated with the idea of poorly planned development, Swilling believes "eradicating it in favour of liveable, accessible, multi-centred, high-density cities should become a shared global commitment" (Swilling 2016).

Accordingly, major changes need to happen in the transportation sector as well, not only because it generates the highest final energy consumption (IEA 2009), but because it has so greatly shaped the contemporary cities, and as a consequence, our lifestyles and quality of life too (Melosi 2005). Indeed, its impact on the land use patterns of cities is irrefutable if we consider the amount of land dedicated to the automobile as Melosi reports: "one half of a modern

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2 Factors that affect urban development include land use patterns, transportation infrastructure, and building siting and design.

3 Urban forms affect travel behavior: car trips (frequency and length), walking, biking, and transit use.

4 Urban forms affect ecosystem, habitat, endangered species, water quality, global climate, physical activity emotional health, community engagement, the number and severity of vehicle crashes.

American city's land area is dedicated to streets and roads, parking lots, service stations, driveways, signals and traffic signs, automobile-oriented businesses, car dealerships, and more" (Melosi 2005). In *The Transit Metropolis*, Robert Cervero also claims that many of the problems the automobile-dependent countries are facing—traffic congestion, air pollution, greenhouse gases and climate change, energy consumption, loss of open spaces, and social inequities —result from the decline of public transit in their cities (Cervero 1998, 39-61). That is why James Howard Kunstler, the ardent critic of suburban sprawl, asserts that the U.S cannot afford to cling to its suburban model. He writes, "American suburbia represents the greatest misallocation of resources in the history of the world. The far-flung housing subdivisions, commercial highway strips, big-box stores, and all the other furnishings and accessories of extreme car dependence will function poorly, if at all, in an oil-scarce future" (Kunstler 2007). That is why he urges everyone to find innovative solutions to encourage people to use less energy.

Indeed, the growing evidence of the dreadful consequences of our choices on the environment indicates that we, people of the poorer or the richer nations collectively, have no other options than (urgently) change the way we consume (Holden 2004, 92-93) because we cannot keep on depleting the world's reserves of minerals (including fossil fuels), gas, or even lose valuable farmlands as urban settlements keep on sprawling outwards (Swilling 2016). As Kunstler claims, "the key to understanding the challenge we face is admitting that we have to comprehensively make other arrangements for all the normal activities of everyday life" (Kunstler 2007), and that includes the need to put an end to our dependence on cars to create "lively, safe, sustainable and healthy cities" that are also "people-friendly" (The Royal Danish Embassy in London 2014). So, as Kunstler concludes, "for many of us, the twenty-first century will be less about incessant mobility than about staying where we are" (Kunstler 2007).

On July 13, 2009, in a discussion on urban and metropolitan policy, former President Barack Obama, who encouraged three national agencies (HUD, DOT, and EPA) to work together to build more sustainable communities, announced the fundamental shift in the federal goals when he said:

> For too long, federal policy has actually encouraged sprawl and congestion and pollution, rather than quality public transportation and smart, sustainable development. And we've been keeping communities isolated when we should have been bringing them together. And that's why we've created a new interagency partnership on sustainable communities, led by Shaun Donovan, as well as Ray LaHood and Lisa Jackson. And by working together, their agencies can make sure that when it comes to development -- housing, transportation, energy efficiency -- these things aren't mutually exclusive; they go hand in hand. And that means making sure that affordable housing exists in close proximity to jobs and transportation. That means encouraging shorter travel times and lower travel costs. It means safer, greener, more livable communities ("Barack Obama: Remarks In A Discussion On Urban And Metropolitan Policy" 2009).

However, following President Trump's inauguration, President Obama WhiteHouse.gov page on "Climate Change" has been replaced by a new one entitled "An American First Energy Plan," in which there is no mention of climate change and global warming anymore. In fact, the new government's goals are clearly stated as follows: "President Trump is committed to eliminating harmful and unnecessary policies such as the Climate Action Plan and the Waters of the U.S. rule." And the Trump administration priorities concerning the environment read as follows: "Our need for energy must go hand-in-hand with responsible stewardship of the environment. Protecting clean air and clean water, conserving our natural habitats, and preserving our natural reserves and resources will remain a high priority. President Trump will refocus the EPA on its essential mission of protecting our air and water" ("An America

First Energy Plan" 2017). This position is contrary to the one taken in Rio de Janeiro in Brazil in June 2012. The United Nations Conference on Sustainable Development, or "Rio+20", had confirmed the trends in urbanization too and had also urged leaders to make recommendations to reach "successful sustainable urbanization" for a better life in cities around the world ("World Urbanization Prospects The 2014 Revision Highlights" 2014, 18).

UNDERSTANDING THE MAKING OF THE CITY

In order to plan better cities we have to understand how cities have evolved and how, to use Melosi's terms, we have moved from "walking cities" to "automobile cities" (2005). It is generally accepted that the city was born in the East, on the banks of the Tigris, Euphrates, and Nile in the course of the third millennium BC. Later, from the first millennium, it spread around the Mediterranean to become an essential part of the Mediterranean and the European civilizations. Greece and Rome were mainly urban civilizations whose culture of the city has served as an urban model for later European societies including American cities.

To define the thresholds of civilization and urbanity, historians, sociologists and archaeologists, such as Childe (1950), Weber (1958) and Bairoch (1988) came up with a list of characteristics shared by cities—criteria that made cities evolve from the hunting and gathering, or farming communities or villages. The most objective traits that set cities apart include 1) the number of inhabitants—in thousands; 2) the dense and compact layout of the inhabited spaces (density of the population); 3) the agglomeration of living units in permanent settlements; and 4) the presence of monumental public architecture, the existence of an acropolis, enclosures or fortifications, and public buildings.

The other criteria, which relate to the city's socio-economic and political functions of the city, take into consideration: 1) the division of labor and craft specialization; 2) the concentration and redistribution of surplus; 3) the existence of commerce, trade or commercial relations (e.g. exchanges or markets) and business development at various scales, which includes "regular 'foreign' trades over quite long distances" (Childe 1950, 15); 4) social differentiation—or stratification— and emergence of a ruling class; 5) the development of arts and writing systems—or "scripts" (Childe 1950,14)— for the management of public affairs or record keeping; and 6) a political organization, and the emergence of group membership based "on residence rather than kinship" (Child 1950, 16); not a farming community since "the city is a settlement, the inhabitants of which live primarily off trade and commerce rather than agriculture" (Weber 1958, 66).

Hence, the city as a system of political organization began to grow from the eighth century in the Archaic Period. At that time, the city already had a number of characteristics that were specific to urban life: regular plans, organized streets, specific materials (stone, marble, brick, tiles), and a utilitarian architecture, including equipment and facilities, such as sewers, aqueducts, fountains, wells, cisterns, etc. In addition, with the emergence of an urban society, specific public places, such as civil and religious public monuments (forum or agora, or Curia ball, basilica, temples, markets) or recreational buildings (gymnasium, thermal baths, buildings for public spectacles) became essential parts of the urban lifestyle and the civic life. Hence, the civic center became the residence of many of the citizens and inhabitants of the city.

THE PUBLIC SPACE

At first, the definition of a public space was religious: it was a space dedicated to collective worship— sometimes with sacrifices around an altar—

or a place where large feasts mobilizing a large number of citizens took place. Soon it became a protected and sacred area (templum / temenos). These sacred spaces were either located on the edge of the central square, forum or agora or on high points of the city, as in the cases of the Capitol of Rome or the Acropolis in Athens.

In the second half of the sixth century, public spaces that were not exclusively related to a sacred use emerged. The development of monumentality and creativity in architecture began in the fifth century—and continued even in the Hellenistic period—in particular around public squares that became true civic centers to respond to the functional needs and to new political and administrative requirements. Covered colonnades, ornamentations, and decorative elements served two purposes: to exalt and glorify the city and to mark the city's power.

In short, all these collective spaces were places for walks, meetings, discussions, and exchanges. Nowadays, open public spaces are less likely to be the places of social and spatial expression of citizenship like the traditional Italian piazzas, the Greek agoras or the European town squares used to be. In *Cities for People*, the Danish architect Jan Gehl argues that life was better for people in the old days because cities were built following traditions that had been carried out through the centuries (Gehl 2010). Indeed, all cities followed the same pattern and were made with the same two basic blocks, which is the street and the square. Buildings were built along the streets and around a square, and expansion was done by adding small units that fit human scale. The representation of these two elements (buildings and streets) will reveal themselves to be key factors in the computational application describe later on in this research. Therefore, the three traditional functions of the public space—the meeting place, the marketplace and the connection space—were all organized in one place by people and for pedestrians only. That is why Karp et al. claim cities were then "small, compact and walkable, with a great number of spatial and economic functions" (Karp et al. 1991, 255).

Gehl (2010) asserts the changing role and shapes of public spaces occurred during the inter-war period and lasted up to the late twentieth century. He argues that it is the advent of the automobile around the 1920s and the democratization of cars that brought about a new paradigm since room had to be made for traffic. Melosi proposes three main stages in the chronology of transportation for the American city: 1) The "walking city before 1880; 2) the "streetcar city" between 1880-1920; and 3) the "automobile city" since 1920. However, he notes that the latter stage can be divided into two distinctive phases: the automobile city with the car as a 'recreational vehicle' period (1920-1945) and a 'freeway' period after World War II (Melosi 2005). As a consequence, designing for cars resulted in the disappearance of the traditional public spaces, the development of a new concept of the public square, and the rise of out-of-scale architecture. Changing values and norms also came along during the post-industrial period. One of its effects on the community was the rapid suburbanization of the built landscape, which has moved people further away from their jobs. Urban sprawling has generated fragmented cities and neighborhoods with lots of commuters and large areas of single-use. By creating a scission between work and home, and between core city and suburban communities on the periphery, 19th-century planners introduced the concept of Euclidean zoning, which has become the most common form of land-use regulation in the United States ("Types Of Zoning Codes | Recode.La" 2014).

In the sixties, the American-Canadian writer and activist, Jane Jacobs criticized the 1950's urban planning policies and noted the death of urban life. However, she believed, "cities have the capability of providing something for everybody, only because, and only when, they are created by everybody" (Jacobs 1961, 238). After more than fifty years of planners and architects' obsession with forms, more architects like Gehl and Jacobs are also convinced that good architecture is not about forms, but that it is rather about the interaction between form and people's use, as Jacobs explained when writing about parks: "How much a park is used depends, in part, upon the park's own design. But even this partial influence of the park's design upon the park's use depends, in turn, on who is around to use the park, and when, and this in turn depends on the uses of the city outside the park itself. Furthermore, the influence of these uses on the park is only partly a matter of how each affects the park independently of the others; it is also partly a matter of how they affect the park in combination with one another, for certain combinations stimulate the degree of the influence from one another among their components... No matter what you try to do to it, a city park behaves as a problem in organized complexity, and that is what it is " (1961, 433).

So today's new paradigm in city planning must take into account city dwellers' conviction that good cities are lively, attractive, safe, sustainable and healthy (Gehl 2010). One of the reasons why this research paper will focus on walkability is because these previously mentioned characteristics also apply to the topic.

DESIGN SOLUTIONS

With the pressing environmental and contemporary issues mentioned above, we are confronted with design problems. Nowadays, planners are encouraged to focus on providing a high and sustainable quality of life and protecting the world's natural environment by paying a closer attention to land use and transport policies (Lotfi and Solaimani 2009). Since Jane Jacobs, the strategy is to plan people-oriented cities as people's aspirations for a better quality environment is growing. In the search for possible solutions to improve the quality of lives in existing places or enhance liveability in future projects, a few 'new' concepts have emerged in the literature in the late twentieth-century. Some of the most frequently used ones include: sense of place, smart urbanization, Complete Communities movement, Transit-Oriented Development (TOD), Place-Maker, Smart-Cities, Smart-Growth, Eco-City, Green-City, or Garden-City, neighborhood planning, healthy communities, sustainable development, New Urbanism and urban villages, as mentioned in Grant's list (Grant 2006, 21). Having said that, the most current and popular terms are probably 'sustainability' and 'liveability.' However, as Andrews (2001), Evans (2002), Van Assche, Block and Reynaert (2010) and Wheeler (1998) observed, in most cases, there is no clear-cut differentiation between these two concepts, probably because they share a lot of common objectives, such as mixed uses, pedestrian-friendly streets, sense of place, safety, etc. But, as Van Assche, Block and Reynaert (2010) assert, the main difference between the two lies in the fact that sustainable development usually focuses on the future of both the environment and the next generations, whereas liveability mainly deals with the quality of present life and people's current wellbeing.

To create supportive and sustainable cities, it is important to understand what these two terms mean and what factors can influence people's perceptions of liveability, and consequently on the quality of life.

CONCEPT OF SUSTAINABILITY

In fact, the phrase 'sustainable development' first appeared in the 1987

Brundtland Commission report and its definition has become the most widely accepted one. It says development is sustainable when it "meets the needs of the present without compromising the ability of future generations to meet their own needs" ("Report Of The World Commission On Environment And Development: Our Common Future" 1987, 16). In the document entitled *"Our Common Future,"* the commission defines the rules that would help resolve the conflict between urban development and environmental issues. They clearly state the responsibilities that are required of all nations, industrialized and low-income ones, to improve the environment (WCED, chapter 2).

Jenks et al. observed that, since the Brundtland report, the need to pursuit sustainability as a policy goal has been recognized throughout the world: "Concern about the future of the world's environment and its resources is now an established fact of life, and this has been accompanied by expressions of good intention by governments worldwide" (Jenks, Burton and Williams 1996, 2). However, as John Pezzey noted in 1992, the concept of sustainability varies according to which idea is being emphasized, as shown in the non-exhaustive list of definitions he added in one of the appendixes at the end of his report (Pezzey 1992, 55-62). In a less global context, when applied to cities and urban development, the principles of sustainability aim at "improv(ing) the long-term human and ecological health of town and cities" (Wheeler 1998, 438-439). As for Newman and Kenworthy, they claim a city is sustainable "if it is reducing its resources input (land, energy, water, and materials) and waste outputs (air, liquid, and solid waste) while simultaneously improving its livability (health, employment, income, housing, leisure activities, accessibility, public spaces, and community)" (1999, 333). In *Reviving the City*, Elkin et al. argue that the sustainable city "must be of a form and scale appropriate to walking, cycling and efficient public transport, and with a compactness that encourages social interaction" (Elkin, McLaren and Hillman 1991, 12), so planning policies should "be based on the concepts of decentralized concentration and high-density mixed land-use" (Ibid).

To help better understand the different meanings and concepts behind the term sustainability, Jabareen (2004, 624) has identified seven domains of sustainable development in the literature on the subject. Figure 1 outlines 'the knowledge map' that can be used to examine each domain and the interrelation between them.

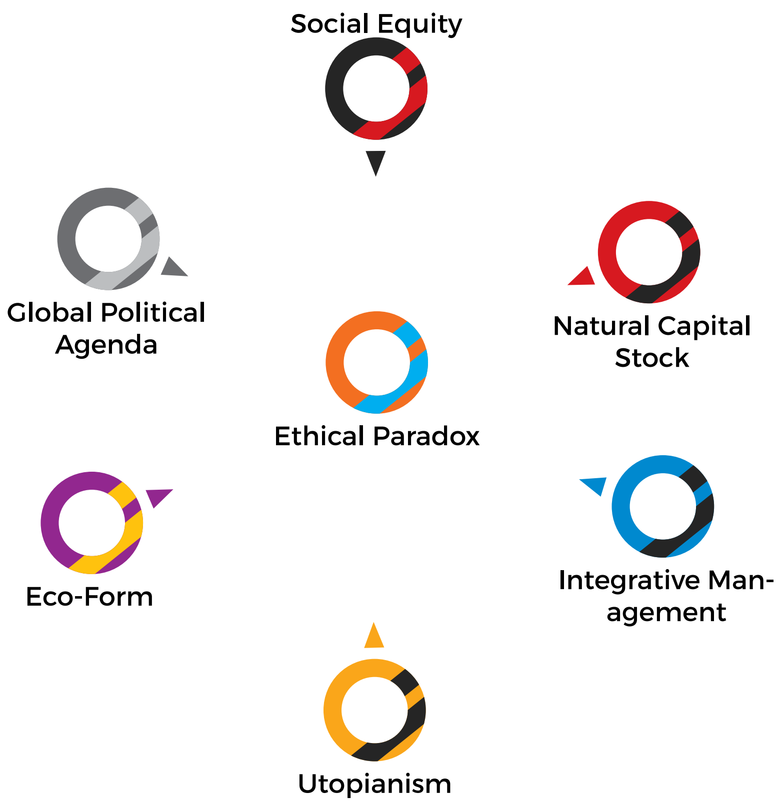

Figure 1. A conceptual framework of sustainable development (Based on Jabareen 2008, 188)

However, it is important to note that for the purpose of this research project, the analysis will mainly concentrate on the "Eco-Form" domain as presented in this conceptual framework because our goal is to study the walkability factors in a network analysis of the urban built environment.

As Jabareen's critical review of the multidisciplinary literature on sustainable development points out, scholars do not agree on one unique definition (2008, 192). For this reason, the Earth Charter (2000) affirms, "We urgently need a shared vision of basic values to provide an ethical foundation for the emerging world community. Therefore, together in hope we affirm the following interdependent principles for a sustainable way of life as a common standard by which the conduct of all individuals, organizations, businesses, governments, and transnational institutions is to be guided and assessed" ("The Earth Charter" 2000).

CONCEPT OF LIVEABILITY

So what is 'liveability'? Our perception of the liveability of a place can be influenced by a variety of personal factors, such as age, gender, education, interests, income, health, lifestyle, occupation, etc., or environmental factors, such as, geography and topology, location (urban or rural), climate, quality of the environment and quality of life (cost of living, air quality, safety, accessibility to shops and services, amenities, recreational facilities, health provision, etc.), mobility and transport, communication, etc. Sustainable cities are places where people want to live because they consider them as high-quality places (Bishop 1995). Even when considering liveability at a local level, there is no single definition for the concept as its interpretation also depends on the context. Hence, for the U.S. Department of Housing and Urban Development, liveable communities are "places where transportation, housing, and commercial development investments have been coordinated so that people have access to adequate, affordable and environmentally sustainable travel options near their homes" ("DOT, HUD Announce New Contracting Flexibility To Help Build

Sustainable, Livable Communities" 2012). The American Institute of Architects (AIA) describes liveability as follows: "Broadly speaking, a livable community recognizes its own unique identity and places a high value on the planning processes that help manage growth and change to maintain and enhance its community character" ("Livability 101" 2005). In regard to the question of liveability in small towns and rural areas, the Washington, D.C. non-profit organization Transport For America defines liveability as the capacity to provide "people, including seniors and those who cannot afford to drive everywhere, better choices about how to travel throughout their regions. It is about encouraging growth in historic small town Main Streets across America and a high quality of life with ample green space, biking or walking paths, and shopping, restaurants or healthcare located nearby and easily accessible" (Barry nd). On the other hand, the Administration's vision of liveability focuses on reducing car dependence by encouraging other alternatives, such as walking, biking, and transit. In this context, liveability, as presented by the former U.S. Transportation Secretary Ray LaHood, means "being able to take your kids to school, go to work, see a doctor, drop by the grocery or post office, go out to dinner and a movie, and play with your kids in a park, all without having to get in your car," which leads to "building the communities that help Americans live the lives they want to live–whether those communities are urban centers, small towns or rural areas"(cited in "A Year Of Progress For American Communities" 2016). For the nonprofit American Association of Retired Persons organization, now called the AARP, Inc., their definition of liveability focuses on the promotion of affordable housing, adequate choice of transportation and interaction among people. It says, a livable community is "one that has affordable and appropriate housing, supportive community features and services, and adequate mobility options, which together facilitate personal independence and the engagement of residents in civic and social life" (AARP 2005). In fact, there is no single way to foster livable communities. So instead of giving a single definition, the Partnership for Sustainable Communities (PSC), which includes the U.S. Department of Housing and Urban Development (HUD), U.S. Department of Transportation (DOT), and the U.S. Environmental Protection Agency (EPA), agreed on the 6 main principles that need to be considered when fostering liveable communities. They recommend to:

- "Provide more transportation choices;
- Promote equitable, affordable housing;
- Enhance economic competitiveness;
- Support existing communities;
- Coordinate and leverage federal policies and investment, and
- Value communities and neighborhoods" ("Livability Principles" 2013).

In *Planning The Good Community*, Grant comes to the conclusion that "people like attractive places, but they define a wide array of places as attractive. We find little consensus of the shape of the good community over time and space. While classical principles certainly have their adherents, they are not universally loved. The good community can come in a variety of shapes. What might be common about the concept of the good community is the state of mind and body of its inhabitants, rather than shape of its streets and squares. That is, in the good community, people can be healthy, happy, and productive" (Grant 2006, 227).

Therefore, there is no single strategy to improve the quality of life in cities since the assessment of what a place is like to live in depends on so many criteria, many of which are very subjective.

However, after having evaluated a few places according to their qualitative, quantitative, tangible and intangibles aspects, as represented in the diagram below, Project for Public Spaces (PPS) has found that public spaces are more likely to be successful if “they are accessible; people are engaged in activities there; the space is comfortable and has a good image; and finally, it is a sociable place: one where people meet each other and take people when they come to visit” (Project For Public Spaces 2009).

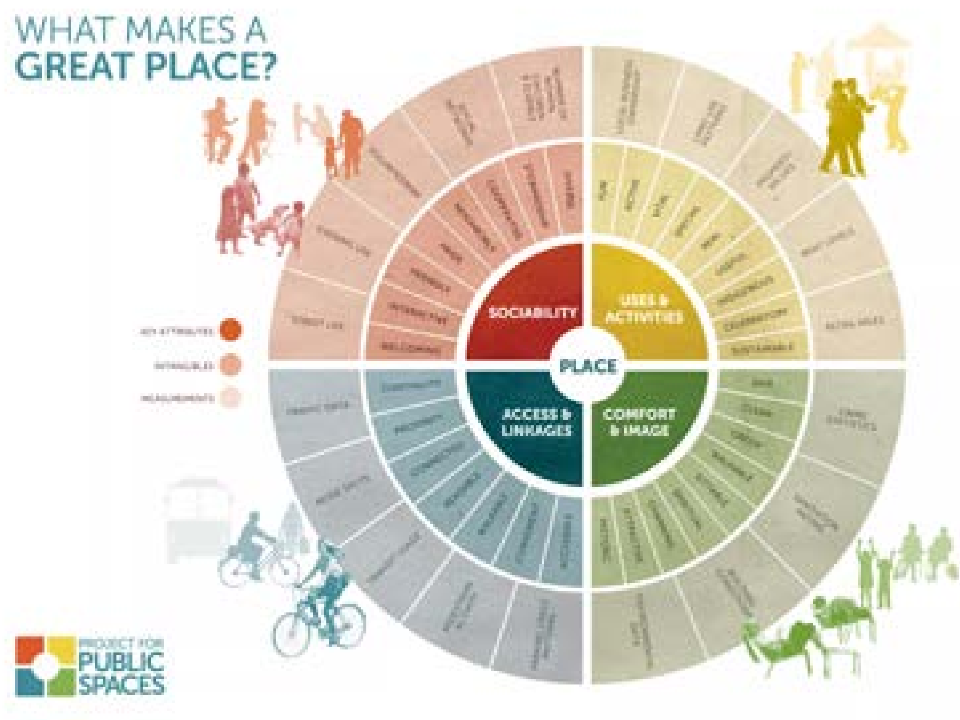

Figure 2. What makes a great place (From Project For Public Spaces 2009)

Lynch (1981), Myers (1988, 1989) and Whyte (1988, 2001), whose visions have influenced many, also agree that most of the physical attributes listed above contribute to making a city great and more liveable since they are factors that can influence a community’s life quality.

CONCEPT OF QUALITY OF LIFE

The concept of urban quality of life is not a new one; Plato said to have told Socrates (circa the 5th century B.C.E): "Socrates, we have strong evidence that the city pleased you; for you would never have stayed if you had not been better pleased with it" (cited in Lora 2008, 177). Myers notes that quality of life can depend on how people perceive what is available in the community. He says, "quality of life is constructed of the shared characteristics residents experience in places (for example, air and water quality, traffic, or recreational opportunities), and the subjective evaluations residents make of those conditions" (1987, 108-109), which implies that it is necessary to analyze community factors, resources, and services to measure quality of life. Because the meaning of the term 'quality of life' is so ambiguous, Veenhoven suggests a fourfold classification of qualities of life, which includes life 'chances' and life 'results' in relation with 'outer' vs 'inner' qualities. From this, we can imply that the four qualities of life are: livability of the environment, life-ability of the person, external utility of life, and inner appreciation of life (Veenhoven 2000, 4).

	OUTER QUALITIES	INNER QUALITIES
LIFE CHANCES	LIVABILITY OF ENVIRONMENT	LIFE-ABILITY OF THE PERSON
LIFE RESULTS	USEFULNESS OF LIFE	SATISFACTION WITH LIFE

Figure 3. Four qualities of life (Adapted from Veenhoven 2000, 4)

On the other hand, Murgante et al.'s review of the literature on the topic led them to propose a representation of the relationship between the seven dependent elements which play a significant part in attaining urban quality of life, namely, environmental urban quality of life, physical urban quality of life, mobility urban quality of life, social urban quality of life, psychological urban quality of life, economical urban quality of life, and political urban quality of life (Murgante et al. 2014, 242). The relationship between those aspects is illustrated in Figure 4.

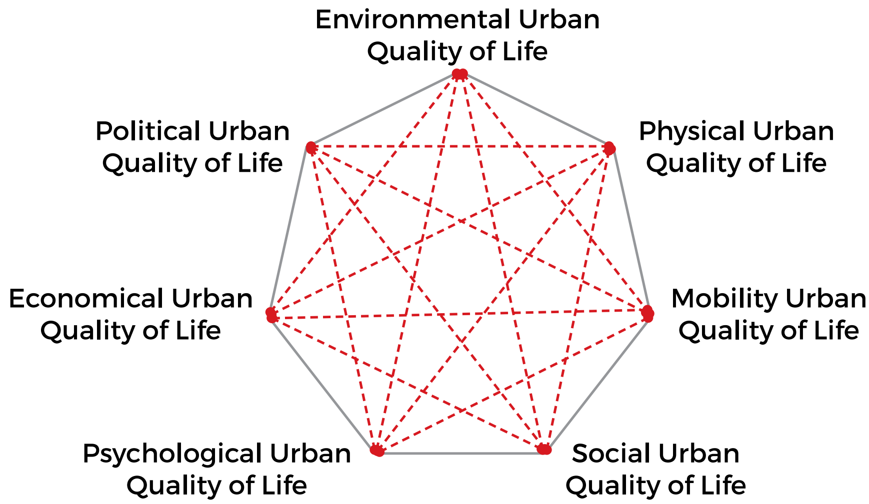

Figure 4. Urban Quality - Life Dimensions - Heptagon Shape (Adapted from Murgante et al. 2014, 242)

In their article on the "Principles Of Urban Quality Of Life For A Neighborhood," Serag El Din et al. (2013) present a table that sums up the relationship between the urban planning theories and approaches principles previously discussed and the seven dimensions of urban quality of life mentioned above. As an introduction to the measure of walkability factors, the table below highlights a few aspects that need to be accounted for and possibly analyzed in order to evaluate the quality of the urban environment concerning walkability. These principles have been chosen because of the availability of essential data. One of the questions to be answered is which type of urban quality the analysis is going to reveal at the end of the research.

	NEW URBANISM	SMART GROWTH	URBAN VILLAGE	INTELLIGENT URBANISM
ENVIRONMENTAL	- No principles dealing directly with environmental issues.	- Preserve open space and critical environmental areas. - Strengthen and direct development toward existing communities.	- Sustainability.	- Balance with nature. -Efficiency. - Appropriate technology.
PHYSICAL	**- Mixed land use. - Compact neighbourhood. - Eco-building.**	**- Mixed land use. - Adopt compact building patterns and efficient infrastructure design.**	**- Mixed-use and diversity. - Increased density. - Traditional neighbourhood structure**	No principles dealing directly with physical issues.
MOBILITY	**- Pedestrian and transit friendly neighbourhood. - Fine network of interconnecting streets. - Hierarchy of streets networks.**	**- Create walkable neighbourhoods. - Provide a variety of transportation choices.**	**- Walkability. - Connectivity. - Smart transportation.**	**- Balanced movement.**
SOCIAL	**- Provide civic building and public gathering places. - Provide a range of parks. - Create a range of housing types. - Reinforcing a safe and secure environment.**	- Encourage community and stakeholder collaboration. - Create a range of housing opportunities and choices.	**- Mixed housing.**	**- Conviviality. - Human scale. - Opportunity matrix.**
PSYCHOLOGICAL	- Architecture and landscape should be linked to context. - Preserve historic areas.	- Foster distinctive, attractive communities with a sense of place.	**- Quality architecture and urban design. - Quality of life.**	**- Balance with tradition.**
ECONOMICAL	No principles dealing directly with economic issues.			
POLITICAL	Control evolution	- Make development decisions predictable, fair and cost effective.	- No principles dealing directly with political issues.	- Regional integration. - Institutional integrity.

Figure 5. Urban quality of life VS Urban planning theories and approaches (Adapted from Serag El Din et al. 2013)

Instead of looking at the signs of quality of life, Lora proposes a taxonomy in which he draws a distinction between 'individual' and 'national' variables (in the table's columns) and the distinction between 'objective' variables and 'opinion' variables (in the table's rows) (Lora 2008, 9). Despite the fact that such a taxonomy can be another useful tool to evaluate the quality of life of a specific area, the quantifiable attributes mentioned below will not be studied as they mostly relate to personal variables and not to the urban built environment.

		INDIVIDUAL VARIABLES		"NATIONAL" VARIABLES	
		PERSONAL VARIABLES	VARIABLES CONCERNING THE INDIVIDUAL IN RELATION TO OTHER PEOPLE		
"OBJECTIVE" VARIABLES	FOUNDATIONS OF THE LIVES OF INDIVIDUALS OR OF A SOCIETY	ABILITIES	FAMILY CONDITIONS	POLICIES	
		• AGE • GENDER • PERSONALITY • PHYSICAL HEALTH • MENTAL HEALTH • EDUCATION • KNOWLEDGE • EXPERIENCE	**• MARITAL STATUS • CHILDREN • FAMILY STRUCTURE**	**• ECONOMIC (TAX, ECONOMIC REGULATION) • WORK (HIRING AND FIRING LAWS) • SOCIAL (SOCIAL SECURITY AND PROTECION)**	
			OTHER INTERPERSONAL CONDITIONS	**INSTITUTIONS**	
			• FRIENDSHIPS • COMMUNITY PARTICIPATION	**• RULE OF LAW • POLITICAL INSTITUTIONS • QUALITY OF PUBLIC ADMINISTRATION**	
	OBJECTIVE RESULTS	MATERIAL CONDITIONS OF LIFE	RELATIVE CONDITIONS OF LIFE	"NATIONAL" RESULTS	
		• INCOME • CONSUMPTION • HOUSING CONDITIONS • ACCESS TO HEALTH • ACCESS TO EDUCATION • ACCESS TO SOCIAL SECURITY • JOB QUALITY	**• INCOME QUINTILE • INCOME OF REFERENCE GROUP • SPATIAL SEGREGATION • DISCRIMINATION**	**• ECONOMIC (GDP, INFLATION) • HUMAN DEVELOPMENT (LIFE EXPECTANCY,...) • WORK (INFORMAL, UNEMPLOYMENT) • SOCIAL (POVERTY, INEQUALITY) • QUALITY OF ENVIRONMENT (NATURAL, URBAN)**	
OPINION VARIABLES	ASSESSMENT OF RESULTS	INDIVIDUAL ASSESSMENT OF RESULTS		"NATIONAL" AVERAGES OF INDIVIDUAL ASSESSMENT OF RESULTS	
		IN REGARD TO INDIVIDUALS THEMSELVES	IN REGARD TO THE SITUATION OF THE COUNTRY OR SOCIETY	IN REGARD TO INDIVIDUALS THEMSELVES	IN REGARD TO THE SITUATION OF THE COUNTRY OR SOCIETY
		• HAPPINESS • SATISFACTION WITH OWN LIFE • SATISFACTION WITH DOMAINS OF PERSONAL LIFE (STANDARDS OF LIVING, HEALTH, EDUCATION, JOB, HOUSING)	• GENERAL SITUATION OF COUNTRY • ECONOMIC SITUATION OF COUNTRY • OPINION ON DOMAINS OF SOCIETY (HEALTH SYSTEM, EDUCATION SYSTEM, EMPLOYMENT POLICIES, SUPPLY OF HOUSING, ETC.)	• HAPPINESS • SATISFACTION WITH OWN LIFE • SATISFACTION WITH DOMAINS OF PERSONAL LIFE (STANDARDS OF LIVING, HEALTH, EDUCATION, JOB, HOUSING)	• GENERAL SITUATION OF COUNTRY • ECONOMIC SITUATION OF COUNTRY • OPINION ON DOMAINS OF SOCIETY (HEALTH SYSTEM, EDUCATION SYSTEM, EMPLOYMENT POLICIES, SUPPLY OF HOUSING, ETC.)

Figure 6. Quality of life - Taxonomy of variables (Adapted from Lora 2008, 9)

CONCEPT OF WALKABILITY

For the New Urbanists, the solution to today's issues is not the American suburban model but rather the traditional walkable neighborhood of the past that is compact, walkable, and at human scale (a model that is more common in Europe), as stipulated in Principles 11 and 12 of their charter: "Neighborhoods should be compact, pedestrian-friendly, and mixed-use," and "many activities of daily living should be within walking distance." The Charter of the Congress for the New Urbanism lists the 27 principles that planners and designers should follow to create more coherent, cohesive and healthy communities ("The Charter Of The New Urbanism" 2015). So the principles emphasize mixed-use lands with affordable housing, traditional neighborhood, transit-oriented development and complete pedestrian-friendly street network.

The city planner and urban designer Jeff Speck is convinced that "walkability can help America be more economically resilient, healthier, and more environmentally sustainable." He defines the walkable city as one in which the car is "an optional instrument of freedom rather than a prosthetic device" (Speck 2013). He claims that four conditions must be simultaneously fulfilled to get people to walk rather than drive: 1) a proper reason to walk (balance of uses); 2) a safe walk (reality and perception); and 3) a comfortable (space and orientation); and an interesting walk (signs of humanity) (Speck 2013). Untermann's research shows that 70% of the American population could walk up to 500 miles for daily tasks, but their walks are limited to 400 meters (or *1/4* of a mile), mainly because of the poorly planned pedestrian environment (1984). According to Pucher et al. Americans don't walk a lot: only 9% of their trips are made by foot whereas it represents 36% in Sweden, for example (2003).

Hence, as Jane Jacobs claims, streets are an important part of the built form. She notes, "Streets and their sidewalks, the main public spaces of a city are its most vital organs.(...) If a city's streets look interesting, the city looks interesting; if they look dull, the city looks dull" (1961, 30). She argues that what makes a city vibrant is busy street life, or what she calls the "The ballet of the good city sidewalk" (1961, 50). Streets are also valuable since they "serve as locations of public expression" (Jacobs, Allan 1993). From his survey of more than 40 cities around the world, Allan Jacobs was able to sum up the most distinguishable qualities of good streets that need to be addressed when planning walkable environment and designing street network: 1) narrow lanes, which makes them safer; 2) small blocks because short distances are more comfortable; and 3) with buildings whose architecture is interesting (Jacobs 1993). According to Southworth (1996, 2005), particular attention must also be given to pedestrian paths in terms of paving, width, lighting, signage and landscaping. To recapitulate, the main qualities of a walkable, pedestrian-friendly, transit-supportive neighborhood design that are regularly mentioned in the literature include: attractive destination, proximity, access and connectivity, good transportation systems, pedestrian scale, lively streets, sense of safety, and visual appeal (Southworth 2006). The popularity of the website Walk Score — that ranks the best neighborhoods for pedestrian-friendliness — shows how much people value walkability. According to the CEOs for Cities' report, walkability even adds value to properties (Cortright 2009).

Forsyth's review of the literature led her to draw a classification with the different dimensions of the walkability concept. She notes that some definitions are centered around the community environment on the following themes: transversable, compact safe, and physically-enticing environments. Others are more concerned with the outcomes of walking (sustainable transportation option, exercise-inducing). Finally, walkability is presented as a solution to improve urban areas (2015, 3-4).

However, Breheny (1992) and Williams, Burton, and Jenks (2000) do not agree with the supporters of the compact city (Krier 1998; Duany, Plater-Zyberk, and Speck 2001). They found little or no correlation between density, sustainability and the reduced need to travel by car. So in "*The Compact City Fallacy,*" Michael Neuman claims, "The attempt to make cities more sustainable only by using urban form strategies is counterproductive" because "Form, in and of itself, is not measurable in terms of sustainability" (2005, 23). Hence, other factors have to be considered.

The five-minute walk or the quarter-mile pedestrian shed is commonly accepted as being the comfortable walking distance someone is willing to walk. In fact, the concept is not an idea of the "New Urbanism" movement since Clarence Perry used the notion when conceptualizing "The Neighborhood Unit" (in 1929) with a church, school, and shops, and bounded by major streets (Lerman

2015). His diagram shows a mix of uses, narrow streets, and short walking distances.

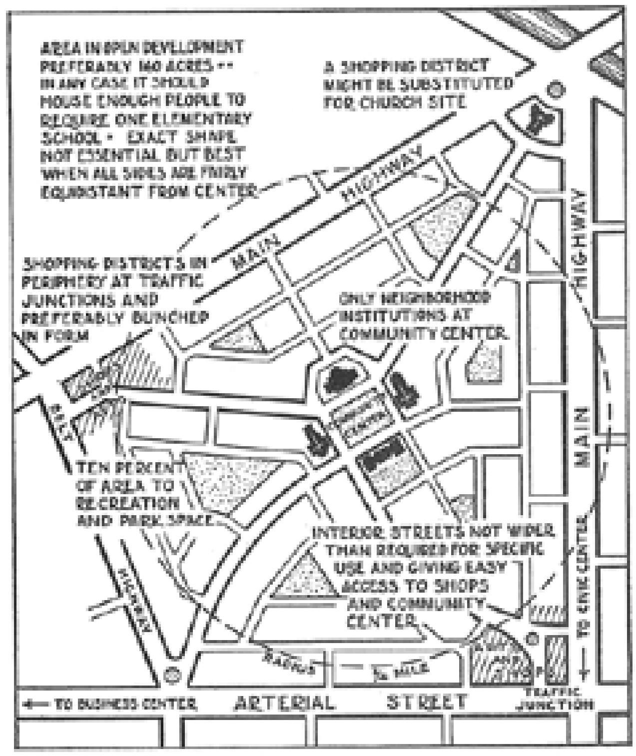

Figure 7. Neighborhood Unit Diagram. "New York Regional Survey, Vol 7" by Source. Licensed under Fair use via Wikipedia. (Also in Lerman 2015).

The problem with the *1/4* mile radius circle is that the distances between two points on a plane are given as a straight-line distance (also called Euclidean or "as the crow flies" distance), which means that it does not take into account safety rules (pedestrians must use sidewalks) and obstacles (walls, bridges, fences, traffic, the width or connectivity of streets). Therefore, despite the implementation of the *1/4* mile radius, the conventional suburban model lacks connectivity between places of residence, places of work, and recreational places, which makes the use of cars inevitable. On the other hand, the high level of connectivity found in traditional neighborhoods fosters walking as distances are shorter. Thus, as a result of this inefficient representation of the *1/4* mile radius circle, this computational application of urban network analysis proposes to measure the actual path available to pedestrians based on their location.

Since walkability, the quality of the pedestrian's walking experience, affects liveability, one of the strategies to enhance the liveability of places is to improve connectedness by properly connecting path networks free of any barriers or gaps (Southworth et al. 2004). Furthermore, a walkable city also requires proper transport infrastructures for cycling and transit. Speck asserts walkability around transit stations is essential since "every transit trip begins or ends as a walk" (2013).

TRANSIT-ORIENTED DEVELOPMENT

Transit-oriented developments, or TODs, whose principles are to create higher density, and mixed-use neighborhoods gravitating around high-quality rail or bus systems (Crewe and Forsyth, 2011) are commonly seen as one of the solutions to enhance sustainability because they contribute to reducing urban problems, such as automobile traffic congestion, air pollution, and poverty (Dawkins and Moeckel 2016). The Transit Oriented Development Institute claims that the benefits range from lifestyle to environmental to economic profits ("Transit Oriented Development" 2017).

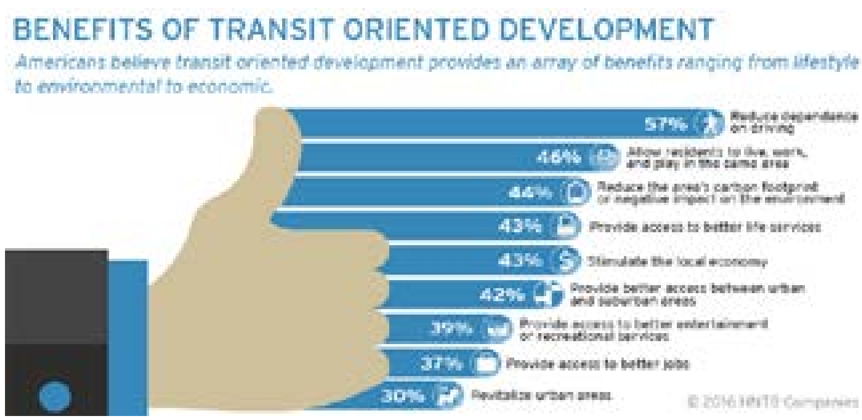

Figure 8. Benefits of TODs ("Transit Oriented Development" 2017)

As for the previous concepts described before (sustainability and liveability), there is no single definition of TOD. However, the California Department of Transportation (2002) proposes the following one: " Transit Oriented Development (TOD) is moderate to higher density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use" (California Department of Transportation 2002). A TOD's success depends on what Cervero and Kockelman (1997) call the 'three Ds' (density, diversity, and design). Two other Ds (destination accessibility and distance to transit) were added in 2001 (Ewing and Cervero 2001), and the seventh one, demographics, in 2010 (Ewing and Cervero 2010). The 7 Ds in relation with travel demands are illustrated below.

BUILT ENVIRONMENT	CONNECTIVITY	DEMAND MANAGEMENT
Design	Distance to Transit	Cost & Supply of Parking Space
Diversity	Accessibility of Destination	Demographics
Density		

Figure 9. Travel demands and the 7 Ds

It is undeniable that liveability, sustainability, quality of life or Transit-Oriented Development share common attributes. Hence, the analysis of walkability for my case study is only the beginning of the assessment process of these previously mentioned concepts.

On the whole, walkability is about proximity and connectivity between destinations. The purpose of this study is then to measure four of the characteristics of the physical environment that contribute to walkable communities within the five-minute walk: 1) residential density (number of residential units), 2) commercial density, 3) land use mix (the variety of land uses), 4) and street connectivity (the number of street intersections). I will use a computational method using mathematical network analysis methods to highlight the role each one of these components plays in shaping the walkability of the neighborhoods of my case study, separately or in combination.

CHAPTER 3. THE COMPUTATIONAL METHOD

THE PARAMETRIC APPROACH

Computers have been created to facilitate calculation and tabulation for the 1880 U.S. population census; a task that would have otherwise taken a lot of years, people and money to carry out manually (Zimmermann 2015). With the advancements in design software and computer hardware in recent years, 21st-century designers are facing a shift with the emergence of new sets of tools and concepts, such as Computational Design and Parametric Design. In regard to the environmental and societal issues mentioned in the first part of this thesis, a Parametric Design approach allows different modes of thinking about a project since it helps to analyze the link between buildings' performance (or sustainability) and environmental parameters (that are also essential aspects of design).

Wassim Jabi, who has written a lot on parametric design tools, defines the concept by writing, "Parametric Design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response. So, instead of only relying on intuition and tacit knowledge, parametric design allows you to think about the design process more explicitly and perhaps discover solutions that would have been otherwise missed" ("Parametric Design For Architecture: Wassim Jabi" 2016). Park et al., who admit that standard drafting tools (pens, pencils, erasers...) have their limitation, are well aware of the potential of computational associative thinking in design process when they note, "The absence of computational tools for the application of proportional theory in analysis and synthesis in design has been a persistent problem in the field of formal composition in architectural design" (Park, Economou and Papalambros 2005). However, despite the fact that designing architectural objects using digital technology is more common, it is far from being an easy process: a high level of parametric skills is needed to go beyond ordinary computerized design. Speaking at the Robert White's critical salon, the *Dark Side Club* in Venice, Patrick Schumacher, the advocate of the language of the parametric explains, "Parametricism can only exist via sophisticated parametric techniques. (...) Today it is impossible to compete within the contemporary avant-garde scene without mastering these techniques" (Schumacher 2008); an expertise that is mastered only by a few architects nowadays (Park et al. 2005).

Zaha Hadid and Patrik Schumacher's best illustrations of their mastery of generative design are probably Beijing Galaxy Soho tower[5] or their Leeza SOHO mixed-use tower.[6] Parametric sketching (implementing parameters in algorithmic protocols) allowed Zaha Hadid Architects to control the buildings' curvature, which gives them their unique forms and generates a new logic for the structural space frame that takes into account the urban system. This shows that new digital tools not only bring new techniques, but also a new style, as also illustrated in Frank Gehry's innovative and geometrically complex forms, like the EMP Museum in Seattle or the Walt Disney Concert Hall in Los Angeles.

In a study on computing proportionalities, Park et al. assert that a computational tool for proportional analysis and synthesis in architectural composition is invaluable, but it does require aesthetic appreciation. They state, "the ways that these numbers interact with one another is not just a mathematical problem but an aesthetic problem;" a problem which they address by revisiting Palladio's work (Park et al. 2005). Using the Palladian corpus

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5 ("Galaxy Soho / Zaha Hadid Architects" 2012)

6 ("Zaha Hadid Architects Releases Images Of Tower With The World's Tallest Atrium" 2017)

(plans, elevations, sections of Villa Rotonda with numbers inscribed on plates) mentioned in *Quattro libri dell'Architettura* as inputs for a parametric analysis, they were able to generate different iterations of the original villa Rotonda design. They were also able to verify and confirm the excellence of Palladio's treatment of proportional balance in the design of the Villa.

Today, the use of parametric methods makes verifying and creating proportional designs a lot faster. However, it is now admitted that collaborative Computer Aided Design (CAD) between the various disciplines in the architectural, engineering, and construction (AEC) domain is primordial to reach efficiency and quality both in the design and construction process (Rosenman and Gero 1998). Because of the time limit for this research, this cross disciplinary relationship will not be explored here. The priority will be put on the urban geometries of the city by using two attributes of measures: 1) urban forms, which fall in the domain of accessibility research analysis of patterns: accessibility, interaction, density, proximity between locations; and 2) land use attraction, which is a cognitive type of research (subjective dimension on the possible experience of the users in a built environment).

PLANNING TOOLS

Nowadays, the trend is toward multi-modal planning tools. Geographic Information Systems (GIS) technology is one of the most widely used tools to analyze and interpret parameters that can be computed in association to each other because it can be applied to a large number of fields like planning and zoning, public safety, environmental planning, and energy management. There are many definitions of GIS (Huxhold 1991, 27; Tomlin 1990, xi; Star and Estes 1991, 2-3; "Understanding GIS--The Arc/Info Method" 1992), but Esri[7]'s

7 An international supplier of (GIS) software.

proposition sums them all: a GIS software can "capture, manage, analyze, and display all forms of geographically referenced information. GIS allows us to view, understand, question, interpret and visualize our world in ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts" ("What Is GIS?" 2017). I plan to utilize this spatial analyst tool with my case study data to assess walkability to model walk sheds around transit stops.

With the local context of the studied area in mind, the analysis parameters that will be considered include street connectivity, the density of residential dwellings, land-use diversity and proximity to walkable destinations. For the purpose of this research, Rhinoceros 3D, Grasshopper 3D, ArcGIS 10.2 and Excel will be used; the last two will only be used at an early stage in the process for analysis purpose (data gathering and classification). Then, the combination of Rhinoceros and Grasshopper 3D will enable the writing of the algorithms that are needed to evaluate the large amount of information that play a part in creating architectural forms, assessing environmental conditions and even redefining urban geometries. The limits of this software only depend on the user's knowledge of algorithm and coding. In GIS, both vector and raster data will be used to represent spatial data. In a vector data model, the three basic symbols (points as XY coordinates, lines to connect vertices with paths, and polygons for areas) represent distinct and separate geographic information (spatial entities), such as the spatial location of walkable destinations, residential buildings, land-use categories and the road network. In a raster data model, data is represented in a matrix of cells organized in a grid (also referred to as pixels). Each cell contains real-world phenomena that are inherently variable, as for orthophotos (photographic maps) and digital elevation models. A more detailed explanation of the analysis process will be given in subsequent sections of this paper.

THEORETICAL FRAMEWORK

GRAPH THEORY

Graph theory, or the study of lines (vertices) and points (edges), has mainly been used in sciences (mathematics or computer science) and much less in urban planning and landscaping. Leonhard Euler (1707-1783), a mathematician of the 18th century, is recognized as the founding father of the theory. By solving the problem of the "Seven Bridges of Koenigsberg," he proposed a solution to a routing problem. He demonstrated that it was not possible to cross all seven bridges to go from and come back to a starting point without crossing a bridge twice. He concluded that "any graph with more than two junctions connected to an odd number of edges cannot be traversed by traveling through each edge exactly once" ("About Networks and Graphs" 2017). So he proved that connectivity is more important than the distance between two vertices. Therefore, since "Graph theory is a body of mathematics dealing with problems of connectivity, flow, and routing in networks" (Urban et al. 2009), this implies that Graph theory can be utilized in landscape networking planning as it is known to be a network theory.

Graph theory focuses on spatial attributes of the built environment. It was used to study the accessibility of places on U.S. Southeastern Interstate Highway System (Garrison 1960) or the highway network of northern Ontario (Burton 1962; 1963), for example. Dantzig (1960), Scott (1967), Hu and Torres (1969) and Dreyfus (1969) work on algorithms and methods to propose recommendations to best measure the shortest paths between the nodes of a transportation network; an evaluation that is important for estimating impact on time and budget, for instance. In their study of the Coastal Plain of North Carolina, Bunn, Urban, and Keitt (2000) show how they use a graphtheoretic approach, instead of other modeling techniques, to study landscape connectivity.

Hillier et al (1987) and Hillier (1998) use Graph theory to study architectural and environmental behavior, such as urbans space use and movement patterns on city streets to show how the physical environment, through spatial pattern, plays a significant part in human life. Tabor (1970) notes that the geometrical layout of urban settings and buildings can shorten or lengthen the time spent between two buildings or two areas in a city, which reveals the importance of the configuration of buildings and routes. Shapes with courts for example have greater distances because they create a diversion. Lynch (1960) also uses transportation network to study how individuals perceive and travel across the urban landscape and how the urban environment also affects people. To support his view of the city, he proposes a mental map that is composed of five elements: 1) paths (routes), 2) edges (boundaries or breaks), 3) districts that share common features, 4) nodes (strategic points or junctions), and 5) landmarks. The 2D urban geometries for my analysis will rely on his mental map.

What makes Graph theory useful is the fact that it is a heuristic approach: it can work even if very little data is available and it can easily be improved using results previously obtained.

GRAPH MEASURES IN URBAN PLANNING

The review of the literature has highlighted many of the important criteria that define walkable cities. However, to measure accessibility related to walkability, the two attributes I will study are urban forms and land-use attraction. I will also measure four indexes —residential density, commercial density, mixed land-use, and street intersections— to get more knowledge on the incidence on the following 8 urban aspects: mixed-land use, small blocks, interesting architecture, building density (commercial and residential), residents' physical activity, the impact of density and mixed-land use on transport mode, the impact of New urbanism development on housing values, and the impact of stations and built environment on transit transfer choices. The order in which these elements are listed here does not have any relevance at this stage of the analysis. Studying urban forms, or the layout of the city, will give me indication on encounter, density and proximity between locations, which will then allow me to generate patterns of accessibility (Anderson 1993). Land-use attraction has a more subjective dimension since its perception can be affected by one own's experience, by the attractiveness of a path or building (Tabor 1970), or transport network (Kansky 1963).

Mixed land uses	**Small blocks**	**Interesting architecture (eras)**	**Building density (residential vs commercial**
- Balancing index between residential and nonresidential daily uses - Index of four categories of housing types (i.e.., Single-family, multifamily, apartment, others) - Mean distance of all buildings to the nearest nonresidential daily use building - Mean distance of all buildings to the nearest commercial use building - Mean distance of all buildings to the nearest office building	- Net density of intersections (number of intersections/net administrative district area) - Ratio of 4-way intersections (number of 4-way intersections/all intersections) - Mean distance of all buildings to the nearest intersection	- Average built year of all buildings - Standard deviation for the built years of all buildings - Materials origins - Local architectural sense of place	- Net population density - Net employment density - Net density interaction (pop/emp) - Net density of nonresidential daily use floorages - Net density of nonresidential non-daily use floorages - Net density of office use floorages

Residents' physical activity level	**Impact of density & mixed land-use on transport mode**	**New Urbanism development on housing values**	**Impact of stations & built environment on transit transfer choices**
- Road length per unit area - Intersections per unit area - Ratio of three-way intersections to all intersections - Median perimeter of city blocks - Transit stop density - Percent of land area in retail uses - Retail employment per unit area - Entropy index	- Population density per unit area - Employment density per unit area - Entropy index of land use mix	- Ratio of street segments to intersections - Linear length of streets per housing unit - Number of city blocks per housing unit - Median perimeter of city blocks - Number of households per unit area - Diversity index of land use mix - Percentage of single-family households within a given distance from a retailer - Percentage of single-family households within a given distance from a bus stop	- Pedestrian-friendly parcels per 100m - Average sidewalk width - Intersections per 100m

Figure 10. The urban quality towards walkability and the use of 4 indexes

A graph can have different properties as illustrated in the figure below. For the purpose of this study, it will be an undirected, non-planar and cyclic model. The undirected model was chosen because we assume that streets can be traveled in both directions since I am studying walkability, and non-planar because streets have edges that can cross each other.

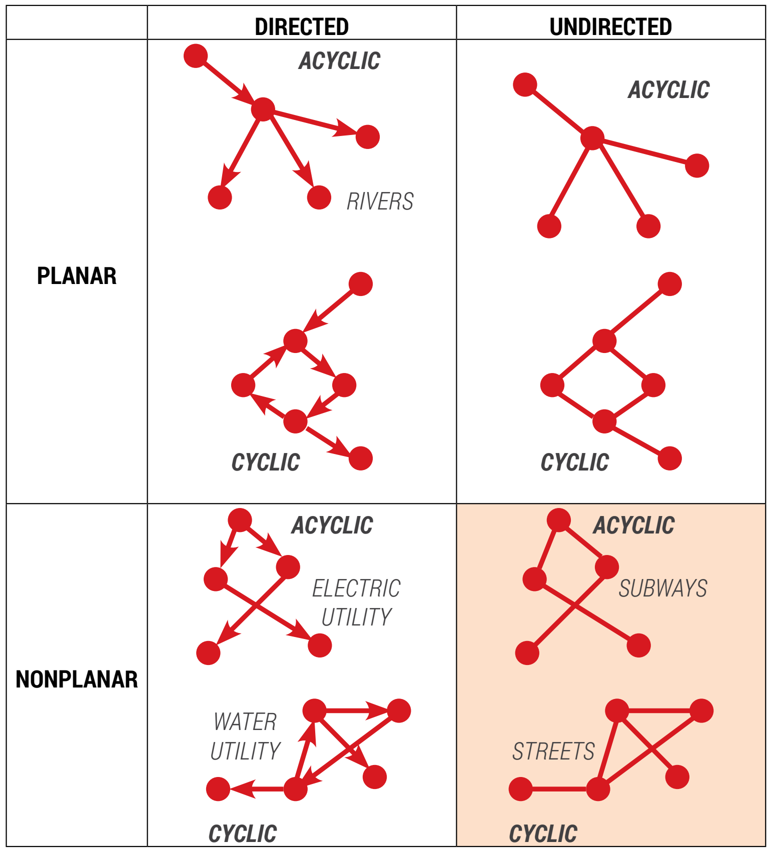


Figure 11. Graph Theory Properties ("About Networks And Graphs" 2017)

THE URBAN NETWORK ANALYSIS

The open-source Urban Network Analysis (UNA) toolbox[8] provides effective tools to describe and analyze the city's complex spatial layout by computing five types of graph analysis measures: *Reach*, *Gravity*, *Betweenness*,

8 It is a plugin-in built on-top of the GIS platform so other data from other tools can be used jointly. The toolbox was designed to facilitate the work of designers, architects and planners who have no access to GIS and architectural designs in Rhino.

Closeness, and Straightness. Three elements are combined to make an abstract representation of any urban environment: 1) *links* that are paths along which travel can occur; 2) *nodes* (or intersections) where paths cross and form public spaces; and 3) *buildings*, which are the central destination points of all human movements (arrival or departure points). The goal is to better understand the relationship between people and places (accessibility, proximity, and adjacency between places and people, for example). The given measures provide important information on how people use their city, what needs to be improved, or how efficient a plan is. The five metrics used to automate the calculations are described below.

Reach Index

Sevtsuk and Mekonnen define the *Reach* measure as the number of particular destinations that are found within a *Search Radius* on the street network (2012, 293). Hence, it measures and counts the number of destinations within any search radius. Destinations can be any infrastructure (buildings, bus stops, doors), jobs, transit stations, or any other nodes. Hence, the *Reach* centrality or network radius refers to the number of destinations that can be reached at the shortest path distance.

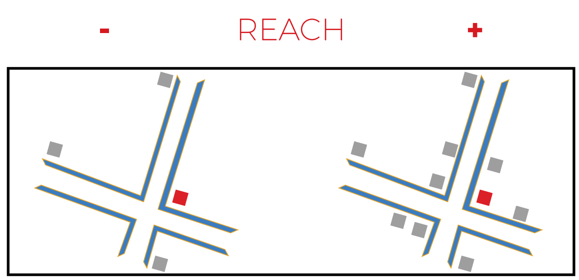


Figure 12. Visual illustration of the Reach Index

Gravity Index

The *Gravity Index* measures resistance factors, such as cost, distance, time, speed, etc., that affect the way a path in a network is crossed or a destination is reached, which explains why the *Gravity index* is one of the most commonly used spatial accessibility measures in transportation studies. A path with the lowest impedances is the most favorable one.

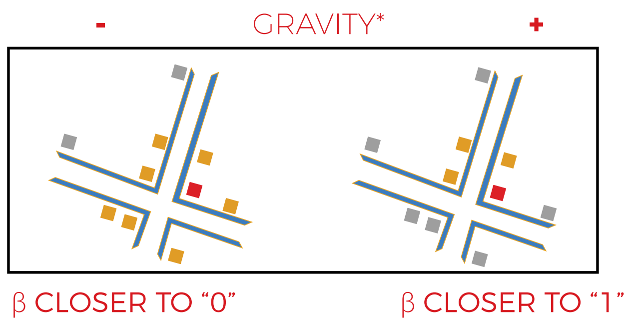


Figure 13. Visual illustration of the Gravity Index

Betweenness Index

Since the *Betweenness metric* looks at the "centrality" of a building (node), it is used to estimate the potential traffic at different locations of the network (Sevtsuk and Mekonnen 2012, 297).

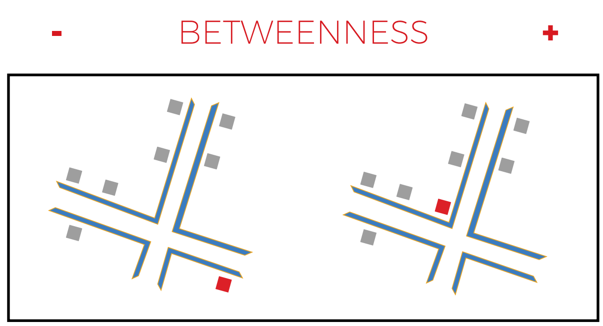


Figure 14. Visual illustration of the Betweenness Index

Closeness Index

The *Closeness index*, which shows how close each location is to all other surrounding locations within a short distance (Sevtsuk and Mekonnen 2012, 298), indicates how easily one can navigate through the network. A high closeness metric is more favorable as it means that the many connections make the place more reachable.

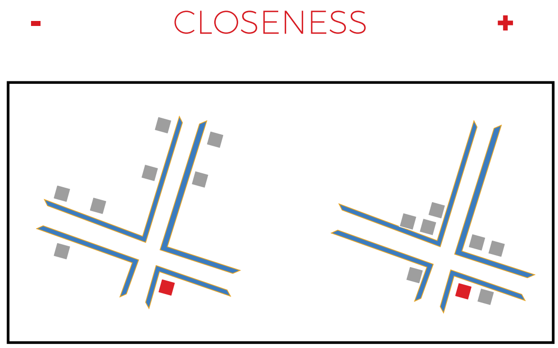


Figure 15. Visual illustration of the Closeness Index

Straightness Index

The *Straightness index* measures how direct the routes that connect to the surrounding elements are.

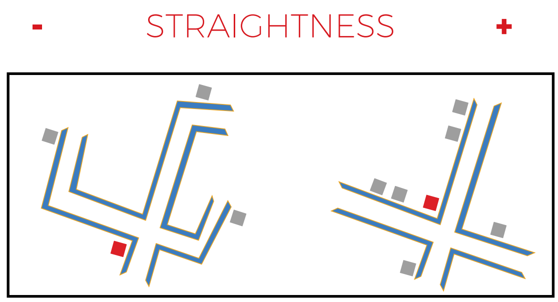


Figure 16. Visual illustration of the Straightness Index

Before transitioning into the analysis of the case study, we deem necessary to review the application of the 8 categories to the indexes of measure for the urban network analysis. The table below depicts this relationship, but only the aspects for which GIS data were available have been kept. So our study will then be affected and limited to the analysis criteria listed here.

	Mixed land uses	Small blocks	Building density (residential vs commercial
REACH	• Balancing index between residential and nonresidential daily uses	• Net density of intersections • Density of all buildings to the nearest intersection	• Net density of nonresidential daily use floorages • Net density of residential daily use floorages
GRAVITY	• Balancing index between residential and nonresidential daily uses	• Net density of intersections • Density of all buildings to the nearest intersection	• Net density of nonresidential daily use floorages • Net density of residential daily use floorages
CLOSENESS	• Balancing index between residential and nonresidential daily uses • Index of four categories • Mean distance of all buildings to the nearest nonresidential daily use building • Mean distance of all buildings to the nearest commercial use building • Mean distance of all buildings to the nearest office building	• Mean distance of all buildings to the nearest intersection	
STRAIGHTNESS	• Balancing index between residential and nonresidential daily uses • Index of four categories	• Net density of intersections	

	Residents' physical activity level	Impact of density & mixed land-use on transport mode	New Urbanism development on housing values
REACH	• Road length per unit area • Intersections per unit area • Transit stop density • Percent of land area in retail uses	• Building density per unit area	• Number of city blocks per housing unit • Number of households per unit area • Diversity index of land use mix • Percentage of residential households within a given distance from a retailer • Percentage of residential households within a given distance from a bus stop
GRAVITY	• Road length per unit area • Intersections per unit area • Transit stop density • Percent of land area in retail uses	• Building density per unit area	• Number of city blocks per housing unit • Number of households per unit area • Diversity index of land use mix • Percentage of residential households within a given distance from a retailer • Percentage of residential households within a given distance from a bus stop
CLOSENESS	• Road length per unit area • Intersections per unit area		• Linear length of streets per housing unit • Median perimeter of city blocks • Diversity index of land use mix
STRAIGHTNESS	• Intersections per unit area • Median perimeter of city blocks • Transit stop density • Percent of land area in retail uses	• Density per unit area	• Diversity index of land use mix

Figure 17. The urban quality and the use of 4 metrics

CHAPTER 4. CASE STUDIES

AREA OF ANALYSIS

The studied areas is the TOD neighborhoods of Waipahu on Oahu. Waipahu, with two rail transit stations planned, is in the southern area of the island in the district of Ewa district. Figure 13 shows the locations of the study area.

Figure 18. City and County of Honolulu ("Transit-Oriented Development Home" 2016)

Waipahu Neighborhood TOD is comprised of two localities referred to as the West Loch Station and the Waipahu Transit Center Station. The areas around the stations are currently mostly dedicated to commercial and industrial activities with very few residential zones. To foster improvements around those adjacent communities, the City proposes mixed-use zoning that will highlight "a connected Green-way Network, Multi-Family Housing, New Mini Parks and

Open Spaces, Boulevard Treatment along Farrington Highway and Parking Management and Park-n-Ride Facilities" ("Transit-Oriented Development Home" 2016).

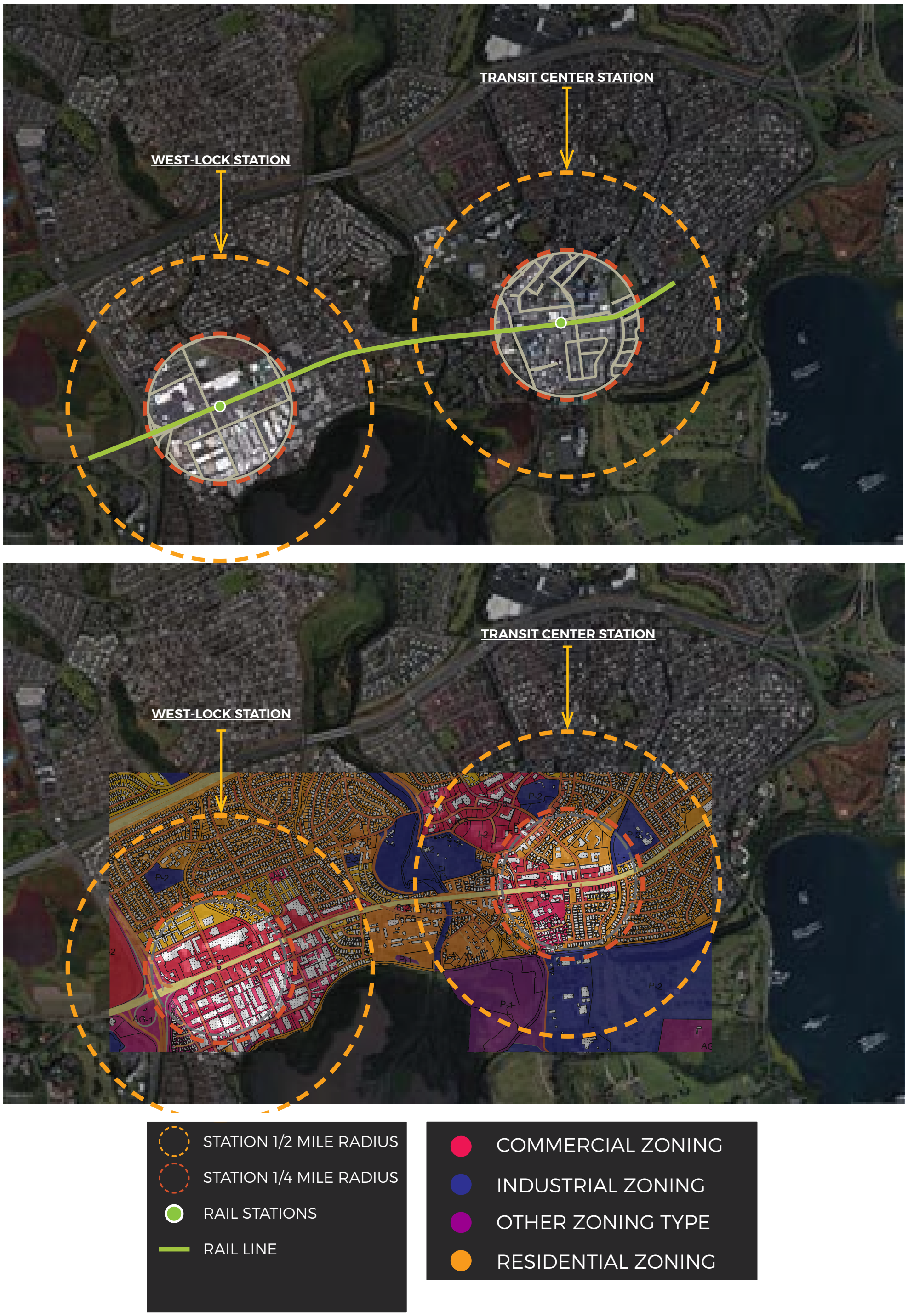


Figure 19. TOD stations location and existing Land-Use Ordinance

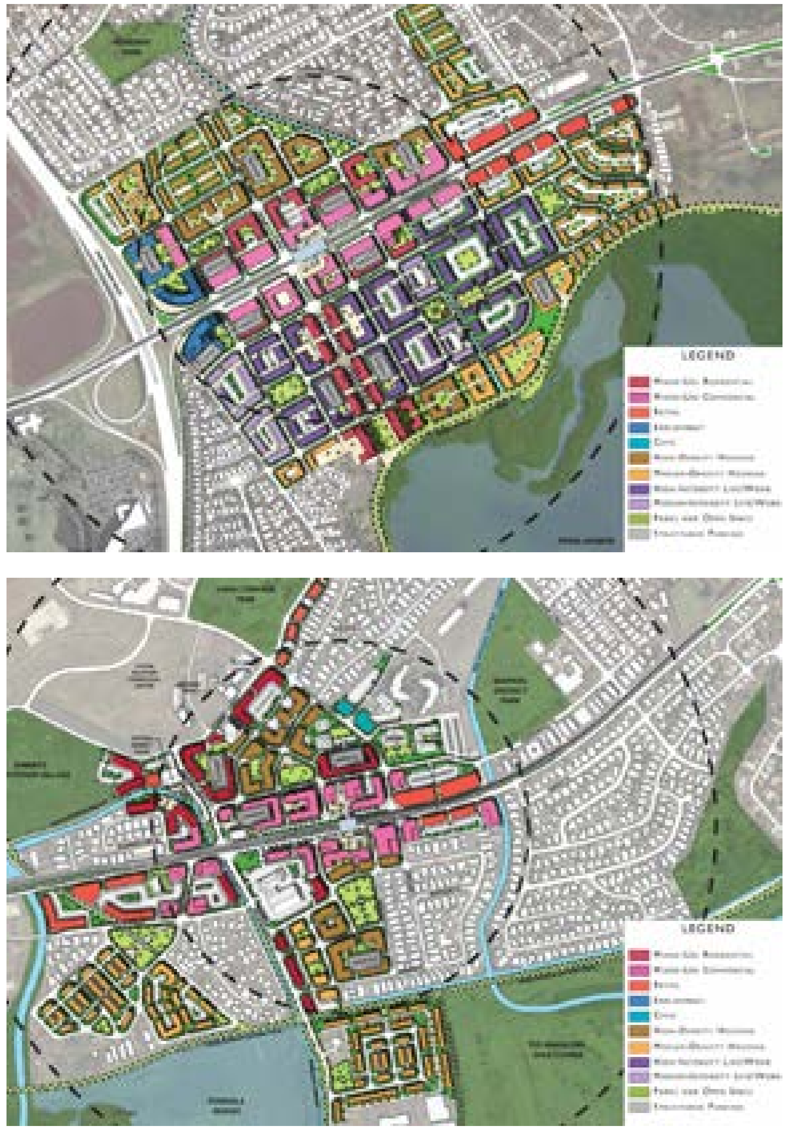


Figure 20. TOD stations location and proposed Land-Use Ordinance

ANALYSIS

THE DATA CLASSIFICATION

One of the most important steps is the organization of the data collected in ArcGIS and Excel. It is a rigorous process to avoid losing time or getting inaccurate data. The following table recaps the important information collected in Excel about 1) Buildings, 2) Public Transport, and 3) Tax Parcels. Of course, depending on the city being analyzed and the extent of the data, more or less information can be obtained, so it is not limited to the list shown below.

BUILDINGS ►►►	Coordonates: • X • Y	Buildings: • Heights • Volumes • Areas	Max Zoning Height: • 30' • 40' • 60' • 150' • 200'	Actual Building Heights • 0' to 30' • 30' - 40' • 40' - 60' • 60' - 150' • 150' - 200'	Actual Buildings Areas • Residential • Commercial • Industrial • Other Types
PUBLIC TRANSPORT ►►►	Coordonates: • X • Y	*Bikes:* • *# Racks*	*Subways:* • *# of stations*	*Bus:* • *# of stops*	*Rail:* • *# of stations*
TAX PARCELS ►►►	Coordonates: • X • Y	Parcels: • Area • *FAR*	*Network Connections* • *Streets / Pl / Ln* • *Hwy / Frw* • *Blvd* • ...	**Omitted** The values in *RED* have been omitted due to a lack of GIS data available for the cities. - This analysis solely relies on the accuracy of the GIS data provided by agencies. ***This can become a real issue.***	

Figure 21. Illustrative table of the data classification

THE DATABASE TRANSLATED INTO GEOMETRIES

Once the database is organized, we use Rhinoceros 3D to visualize the extent of the information that was gathered. As mentioned before, our geometries are represented by links for the street network and nodes for our buildings, street intersections, transit stops, public transport and any other points of interest.

STREET NETWORK

BUILDINGS CENTROIDS

TAX PARCELS CENTROIDS:

BUS STOP CENTROIDS

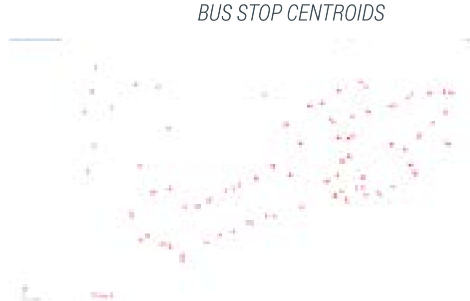


Figure 22. Visualization of the database into geometry

THE WEST LOCH STATION: Existing vs Proposed conditions

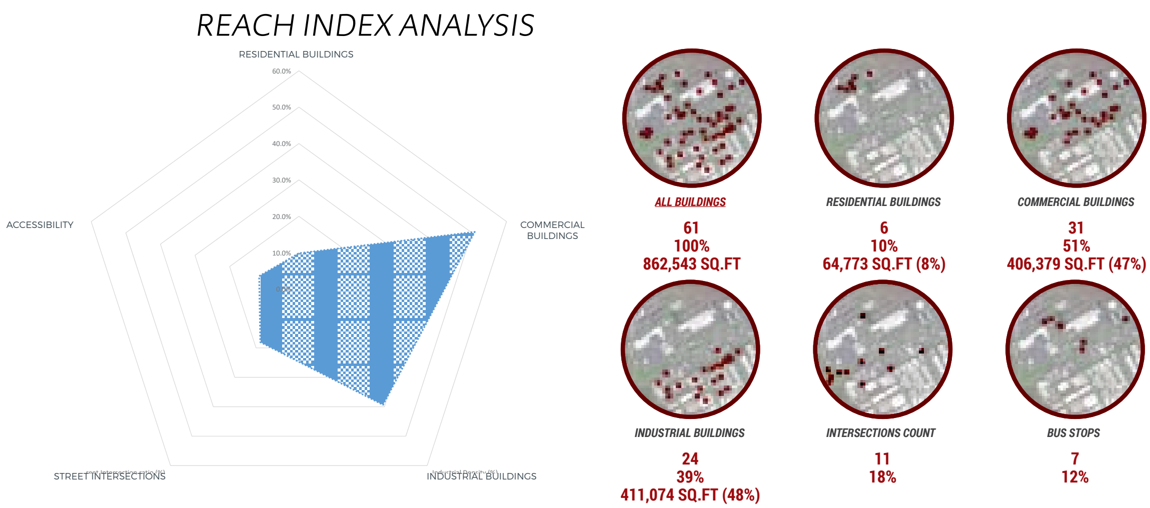


Figure 23. Reach analysis of West Loch existing conditions

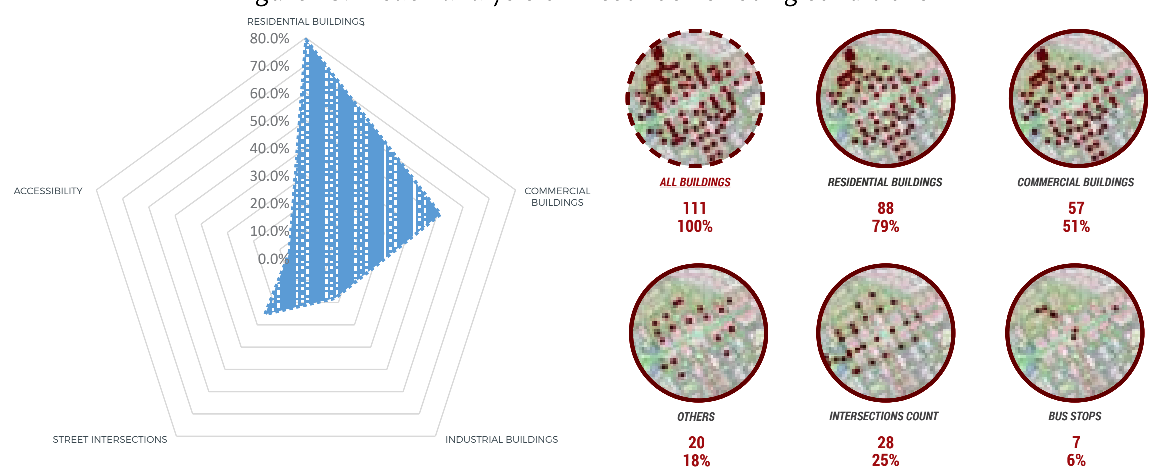


Figure 24. Reach analysis of West Loch proposed conditions

The future neighborhood plan shows an increase of residential and commercial location within a 5 min. walk surrounding the station. However, the ratio of street intersections and mix of transportation mode still remains low.

GRAVITY INDEX ANALYSIS

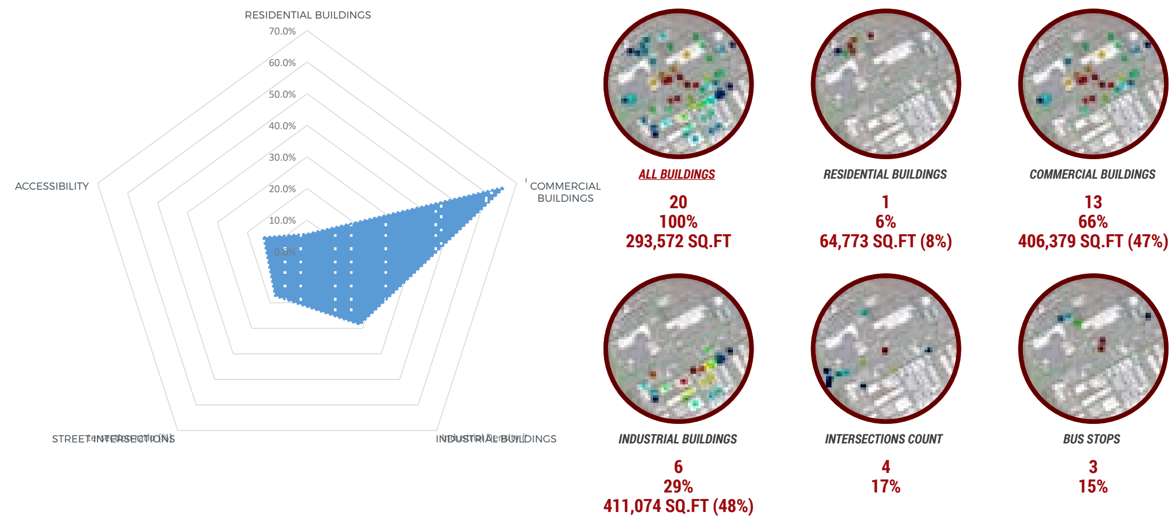


Figure 25. Gravity analysis of West Loch existing conditions

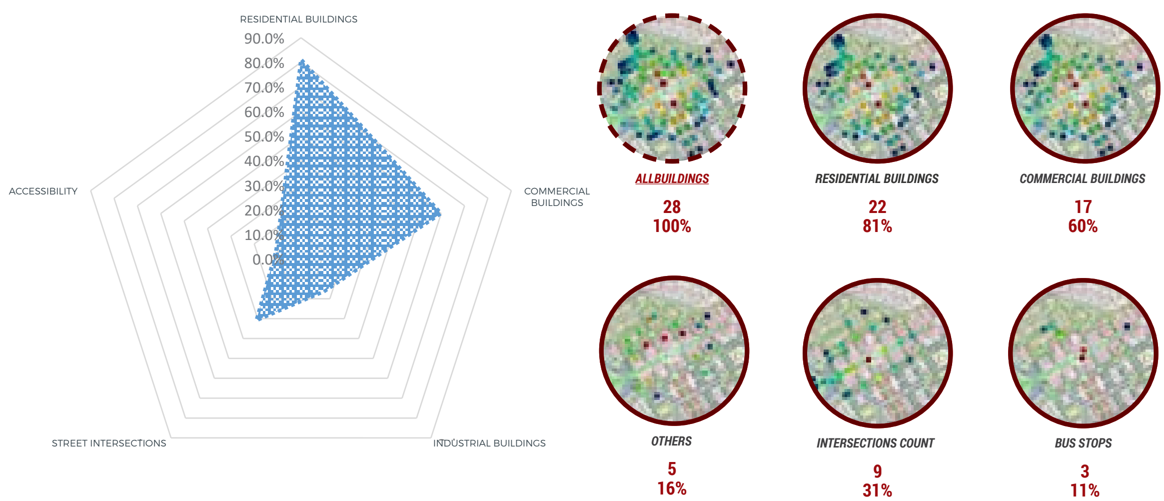


Figure 26. Gravity analysis of West Loch proposed conditions

The gravity index graph being close to the reach index indicates that the buildings' location seems to be close enough to each other, so they don't fall off of the range of the users' willingness to walk. The graphs consistency also indicates a correlation in the data between the distance travel and cost.

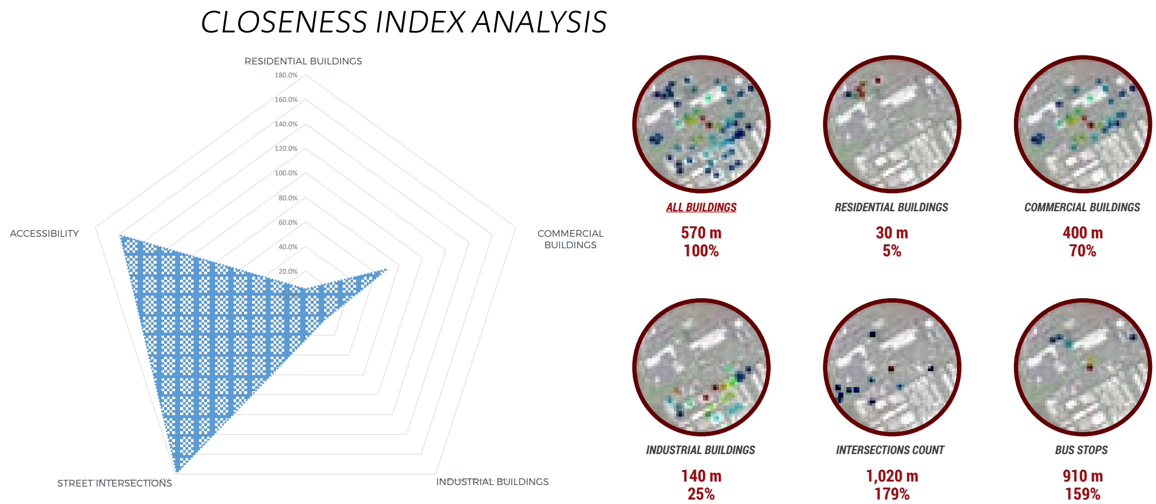


Figure 27. Closeness analysis of West Loch existing conditions

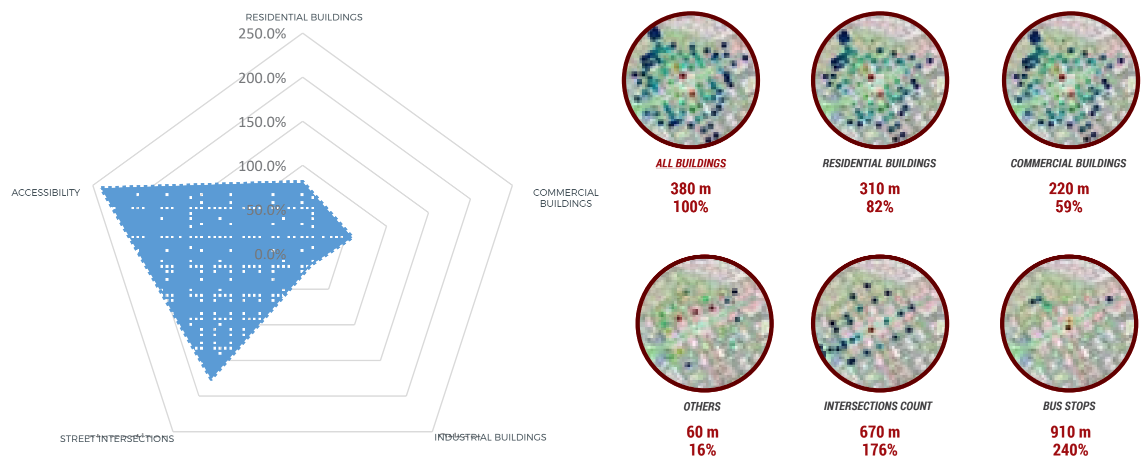


Figure 28. Closeness analysis of West Loch proposed conditions

The accessibility results show an average distance of travel 1.4 longer than the average distance from building to building, which means that pedestrians have to walk longer distances.

STRAIGHTNESS INDEX ANALYSIS

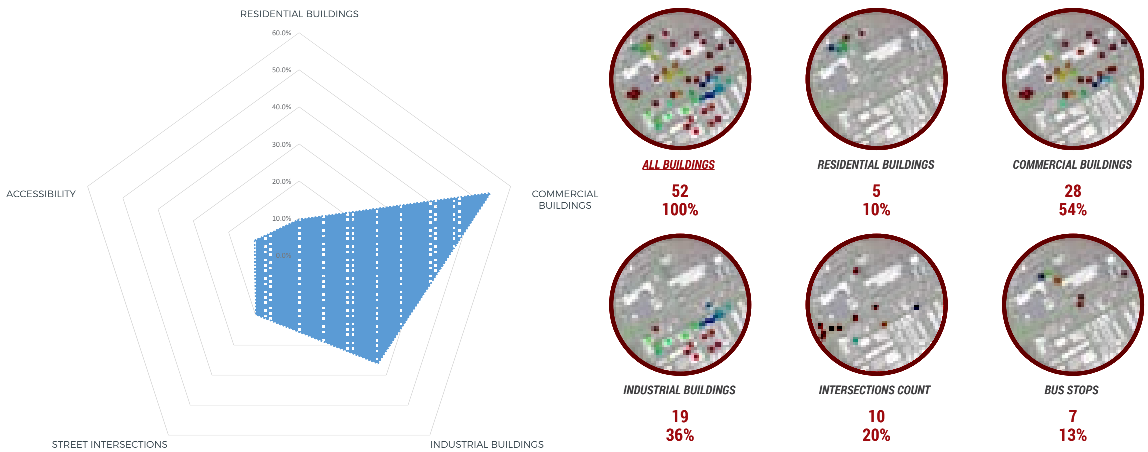


Figure 29. Straightness analysis of West Loch existing conditions

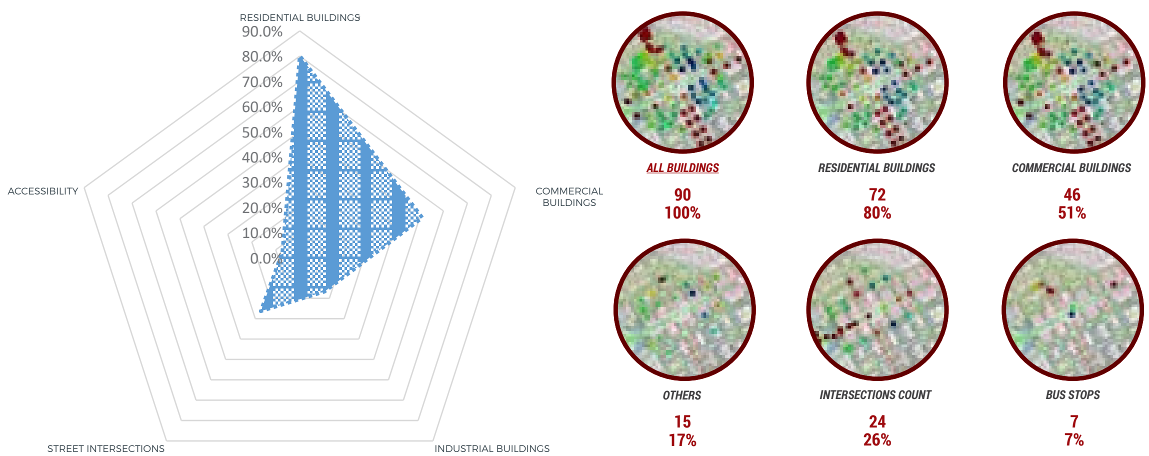


Figure 30. Straightness analysis of West Loch proposed conditions

In plan view and in data representation, it has been demonstrated that residential and commercial buildings are located along a more direct path to the station. This could also indicate that the station is located near a crossroad.

THE TRANSIT CENTER STATION: Existing vs Proposed conditions

REACH INDEX ANALYSIS

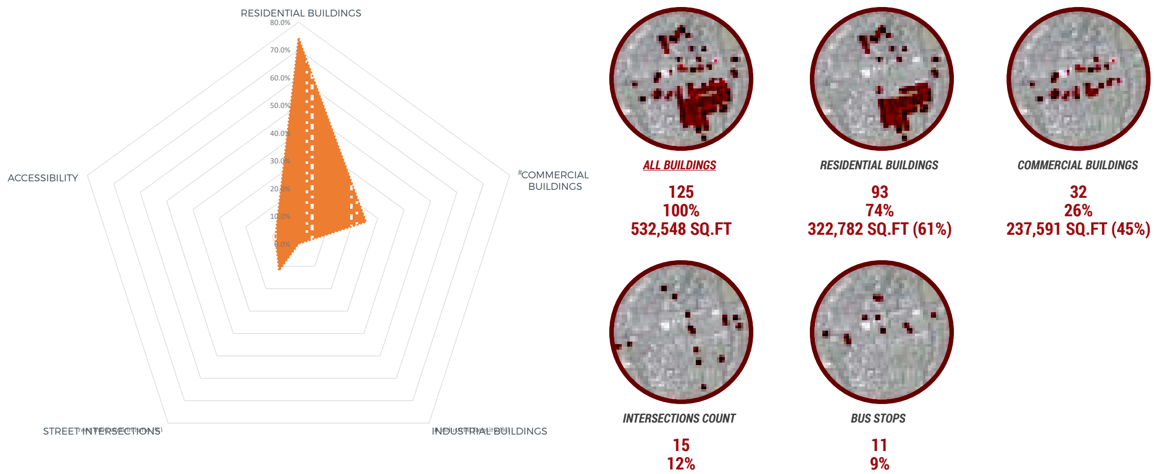


Figure 31. Reach analysis of Transit Center existing conditions

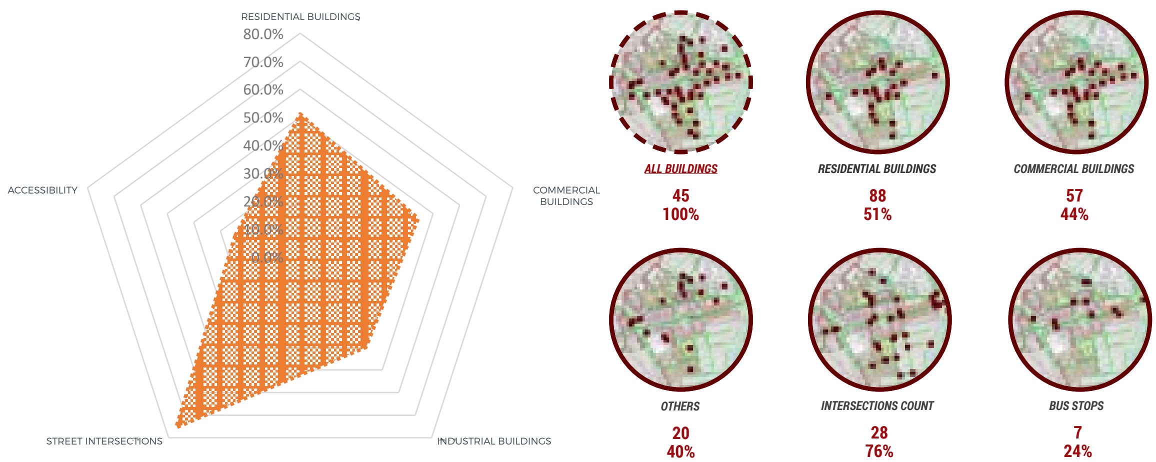


Figure 32. Reach analysis of Transit Center proposed conditions

The Transit center stations show a plan with moderate residential and commercial density while providing more intersections for possible interaction between buildings.

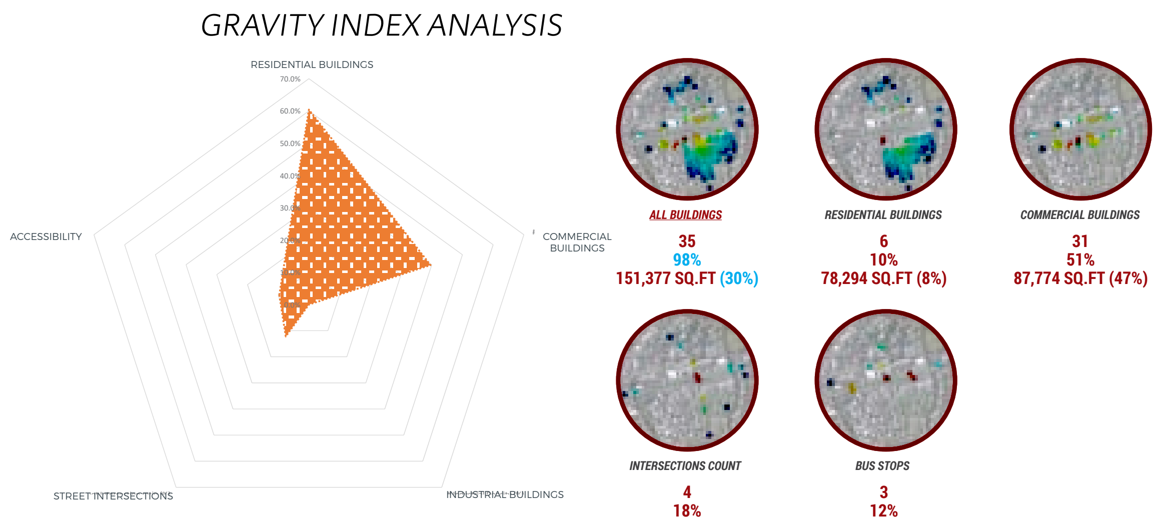


Figure 33. Gravity analysis of Transit Center existing conditions

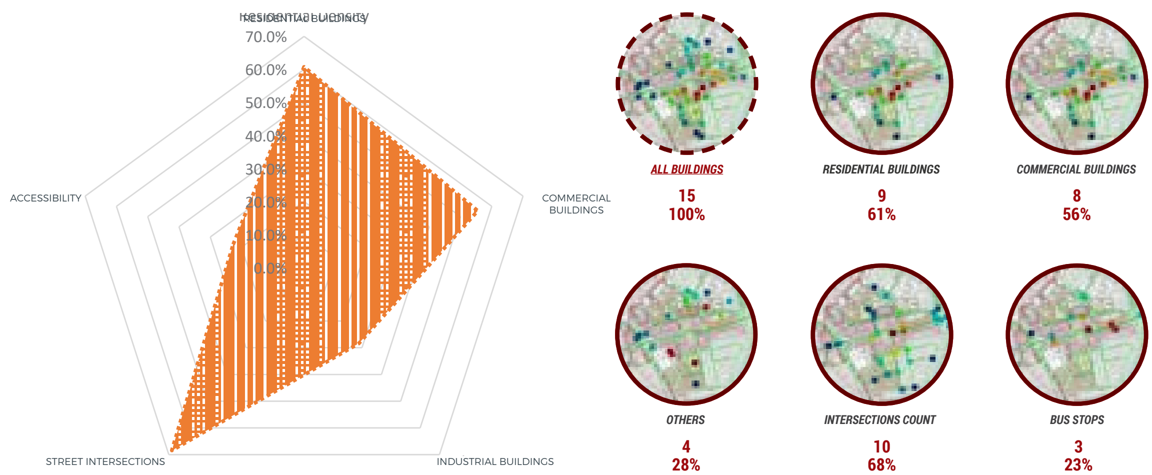


Figure 34. Gravity analysis of Transit Center proposed conditions

The gravity index being close to the reach index indicates that the buildings' location seems to be close enough to each other. Therefore, they don't fall off of the range of the users' willingness to walk. It also shows a more balanced ratio between intersections and buildings.

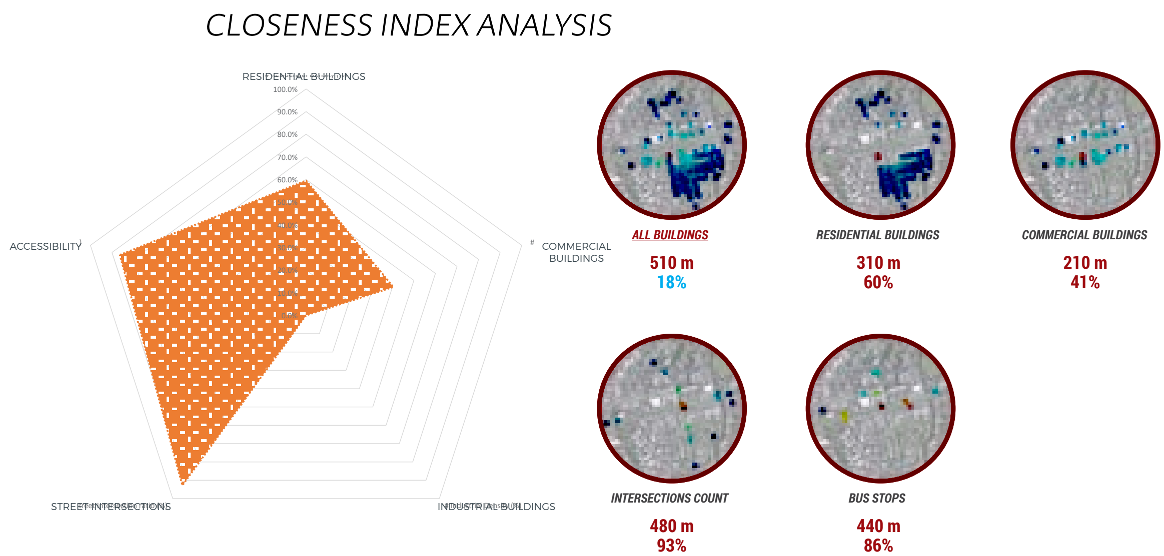


Figure 35. Closeness analysis of Transit Center existing conditions

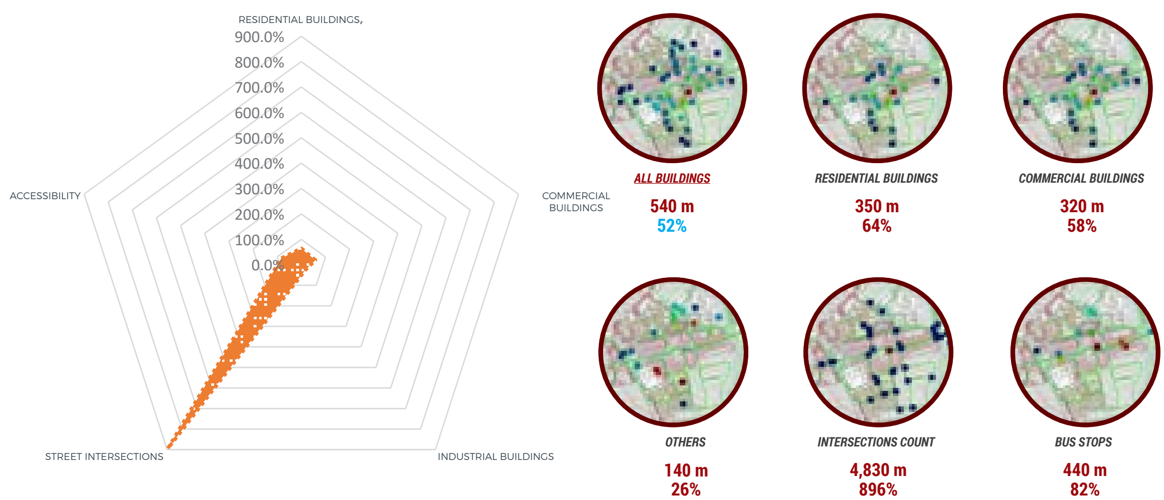


Figure 36. Closeness analysis of Transit Center proposed conditions

In this scenario, the closeness index of the street intersections is off the chart, which might indicate that the layout of the surrounding streets is not adequate.

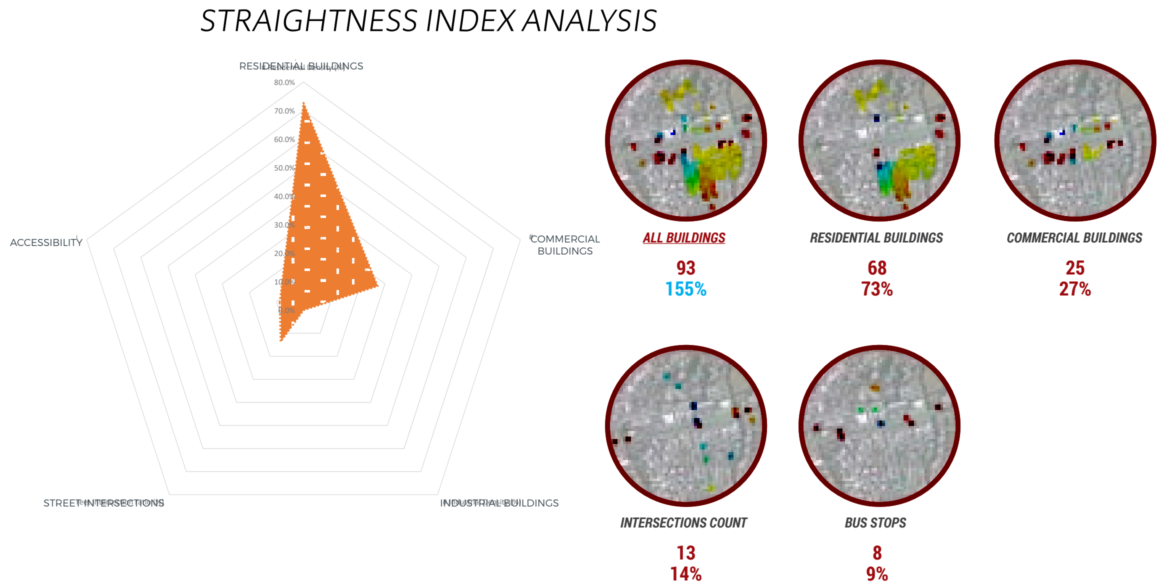


Figure 37. Straightness analysis of Transit Center existing conditions

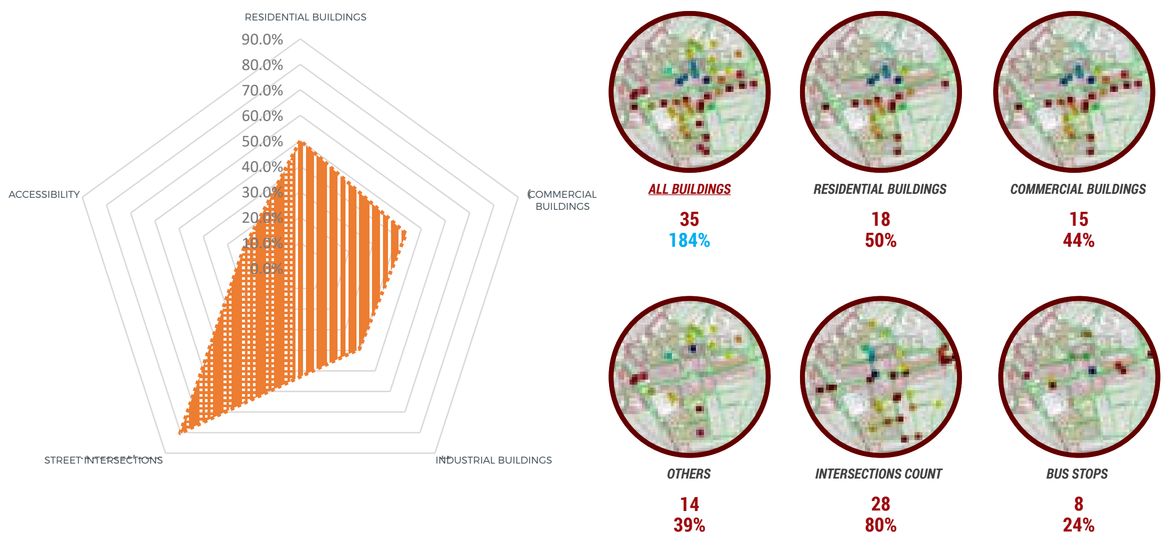


Figure 38. Straightness analysis of Transit Center proposed conditions

Although the closeness index indicates that street intersections are not close to the station, they are still located along a more direct path than other buildings.

CHAPTER 5. CONCLUSION

Despite the importance of the many other factors described in the literature and due to the time constraint, the main focus of this research paper on walkability has been limited to the analysis of 4 primary factors, namely residential density, commercial density, streets intersections, and mixed land use.

The computational method of analysis that I have used has proven to be consistent and accurate with the data gathered. The similitudes in the graph shapes indicate a correlation between data and graphic representations, which therefore validates the method.

Jeff Speck claims that for a place to be walkable, it is all a question of proper balance of uses, so he recommends looking for what is missing or under-represented in the urban environment, whether it is office, retail, dining, entertainment, housing, school, recreation, worship, or parking (Speck 2013). The illustration below depicts which criteria have been studied and what could be considered in a future analysis.

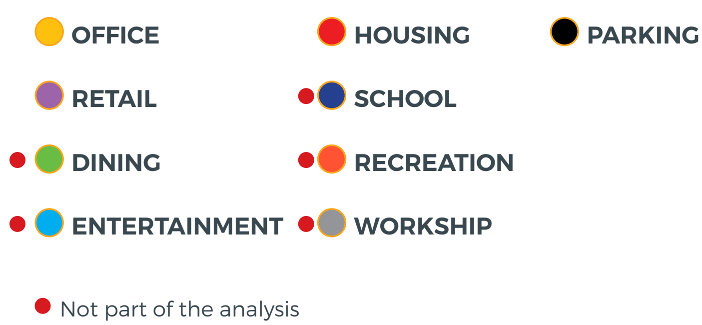


Figure 39. Building functions

The advantage of using such a computational method is that data can be built up and enriched at any time to provide a more refine or accurate definition that fits the needed level of analysis. It is both efficient and time saving, especially when working with large areas such as cities. The method provides architects with a set of inter-related information that they might not have considered otherwise. For a thorough examination, here is a non-exhaustive list of some aspects to consider when dealing with walkability issues:

- Footpath (width, surface and quality, road crossings, shared bike paths, near traffic, obstacles, signs)
- Facilities (seating, shelter, rubbish bins etc and their condition; shade, signage, lighting)
- Road crossings (how safe?, Types of crossings, traffic signals, clear views)
- Traffic (appropriate speed limits, devices to slow traffic, drivers obeying speed limits and road rules, cyclists using footpaths, appropriate barriers)
- Safety (feeling of safety, good lighting, other people around, visibility to others)
- Aesthetics (attractive area, attractive landscaping, interesting art, accessible shops, presence of litter)

Figure 40. Non-exhaustive list of urban characteristics

The following section will roughly expose other outcomes of using such a computational method. One of them is to be able to compare the same criteria in two different locations. The two cities illustrated in this set of charts are Waipahu near the transit center station and Portland near the NW 6th & Davis MAX station. Listed below are some of the observation that came out from the analysis.

- By comparing the ratio of total buildings to building usages, we understand that Waipahu demonstrates a variety of building types within the 5 min. walk radius, whereas Portland is mostly occupied by commercial buildings.

- The gravity index also indicates that the ratio of building types remains fairly balanced even at shorter distances from the station, which means that any one can have access to a large variety of building types (residential or commercial, public or private) during a 5 min. walk. This interpretation is obtained by comparing the reach and gravity charts.

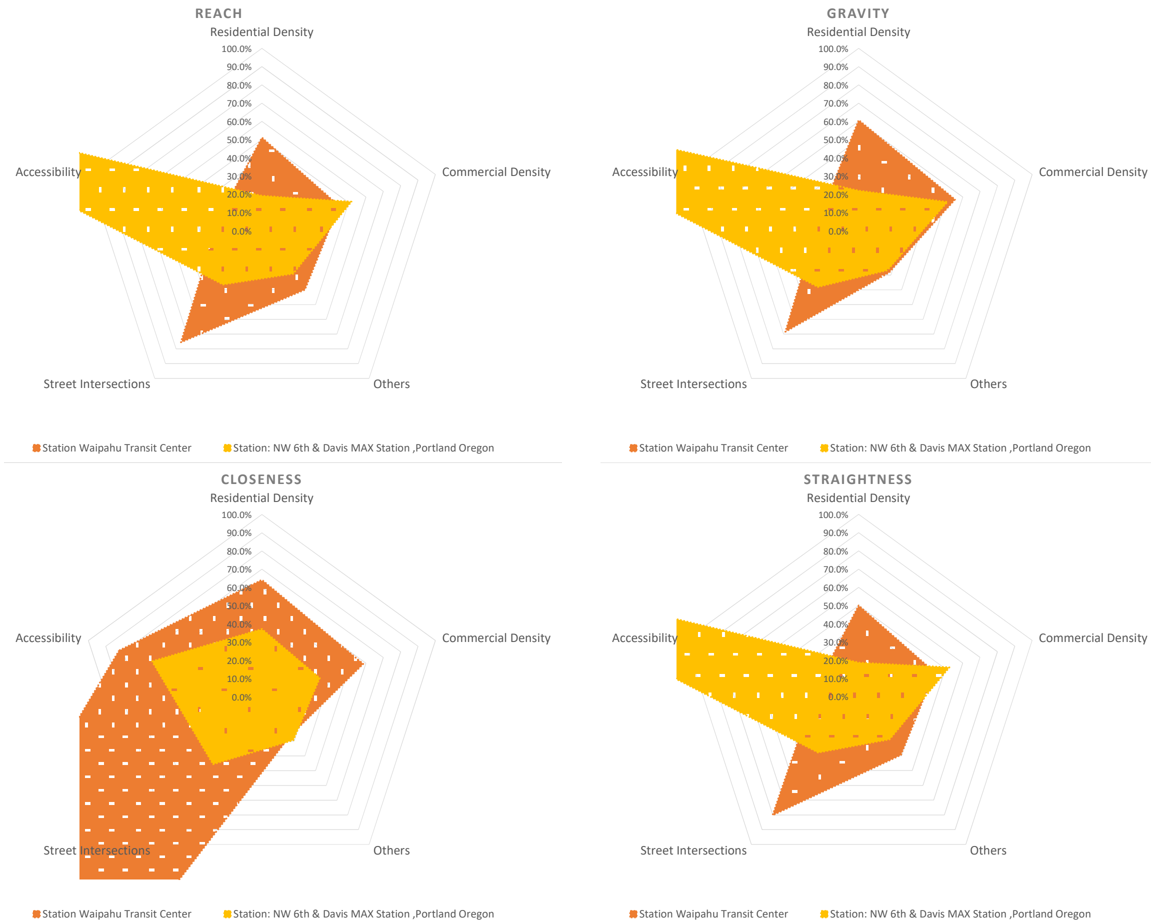


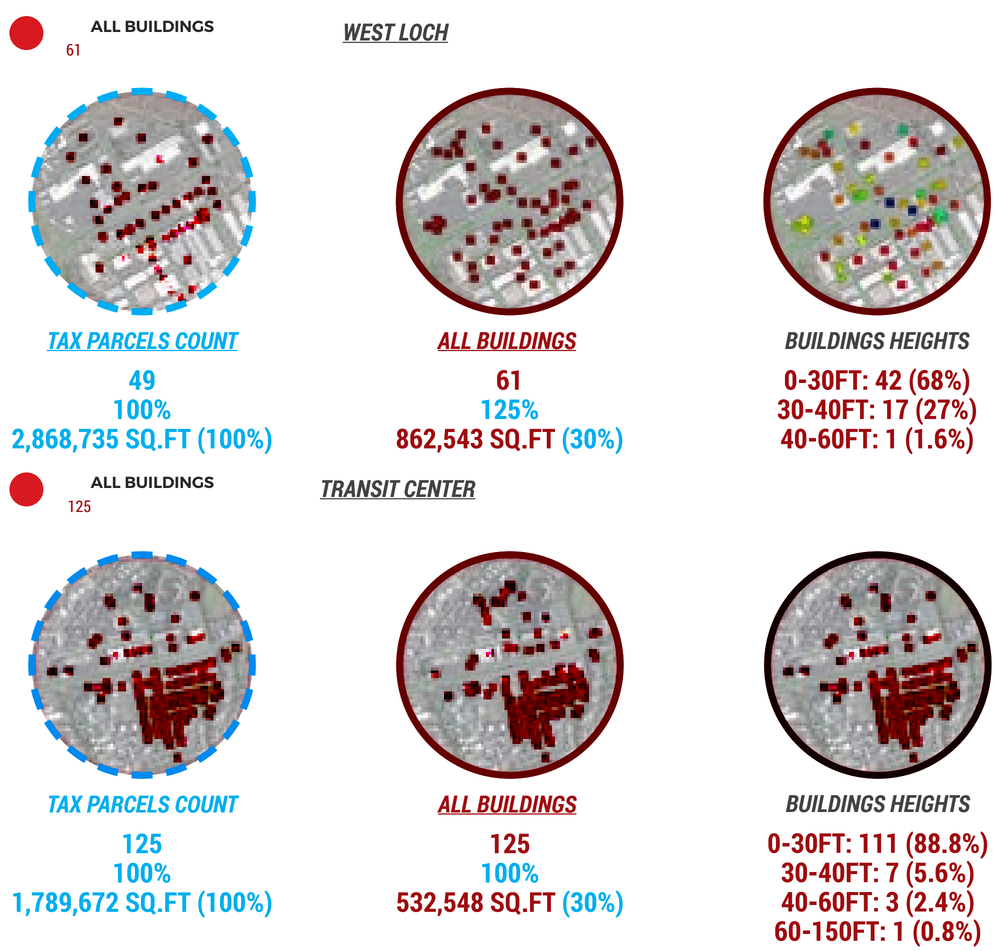
Figure 41. Correlation of the metrics

The closeness chart indicates how far points of interest are in the studied areas. Any result closer to the center of the chart (zero) indicates closer average distances. Furthemore, the closer the form of the data is to the radar chart, the more homogeneous the urban form is. In the case of Waipahu, it shows that the average distance between the station to any types of building is much greater than in Portland. The analysis of Waipahu street connectivity indicates that long distances must be traveled to be able to change direction. This condition leads to poor street interaction between people and buildings.

The accessibility of Portland is off the chart, which shows the city puts a real emphasis on people's accessibility to various locations.

In conclusion to this analysis, the urban form of Portland suggests that accessibility and smaller city blocks (number of intersections/buildings) have been prioritized over mixed-land usage and building types.

This computational method can also provide architects with many other sets of information, such as the ratio of land available and the actual amount of built surface; if a location is leaning towards densification or sprawling; or if it is mostly composed of low-rise buildings, as in the case of Waipahu, for instance. The analysis on building types was done by comparing the reach index and the gravity index of the buildings square footage to the tax parcels square footage and the buildings heights to their respective zoning height map. Such information on building types can have an incidence on an architect's decisions when considering view corridors or shading devices, for example.



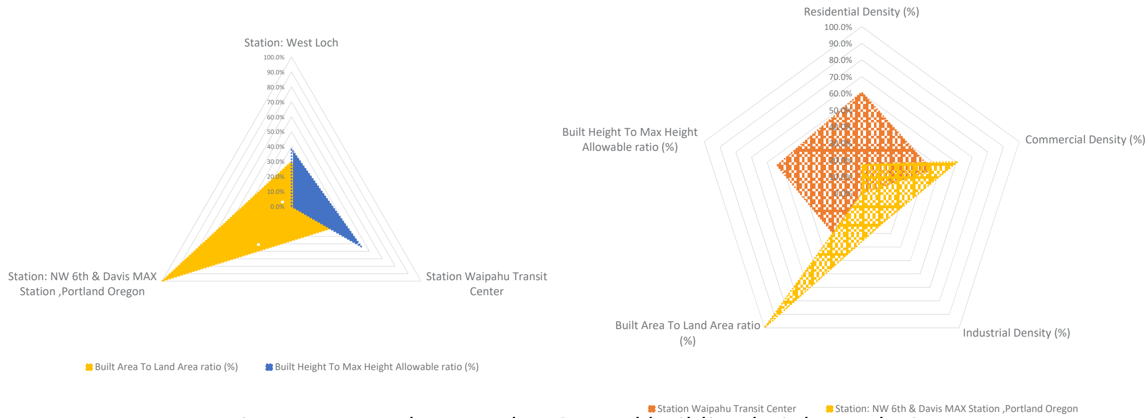


Figure 42. Land-usage density and building height analysis

The interaction between people and places is one of the key elements in successful cities. With this method of analysis, it is possible to visualize the potentiality of any street corner. The first example, represented in the following diagram, is a simulation of the betweenness index based on the future street intersections and the new proposed neighborhood plan of Waipahu. Based on the street patterns, the analysis indicates that the streets in red below have potential for more interaction with their surrounding.

Figure 43. Betweenness index of all street intersections to their surrounding buildings.

In the second example shown below the analysis was run by estimating the possible level of interaction between people and the buildings surrounding the rail station location.

Figure 44. Betweenness index of all street intersections in relation to the rail station.

In our constant search for better planning, a lot can be learned from European cities. Walkable streets are only one of the many aspects to study, whatever model the city is attempting to achieve.

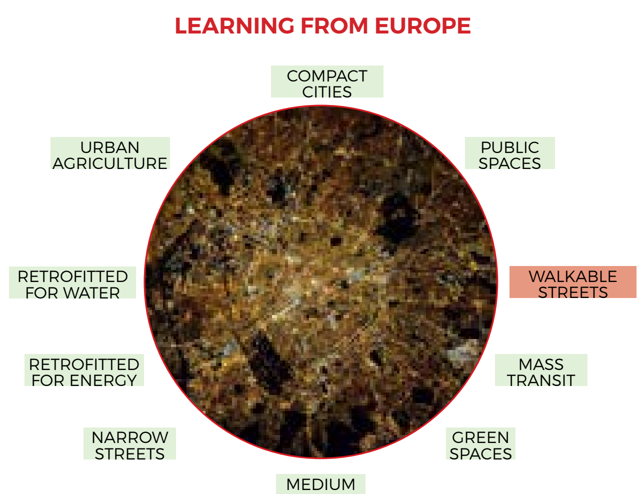


Figure 45. Extent of the scope of work toward better cities

The Computational application of Urban Network Analysis allows architects to be more involved in the process of urban planning and design, and to use their expertise to compare aspects of cities more efficiently. From walkability to the field of real estate, this method is only limited by the user's imagination.

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