Linking Services to Material Stocks:
A GIS-based material stock-service analysis from island and city perspectives

by

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Authors Declaration

I hereby declare I am the sole author of this thesis. This a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be electronically available to the public.

Abstract

Recent years have seen a growing interest in sustainable development and the shift towards a more resource efficient economy. The concept of “social metabolism” views a socioeconomic system as a system of material throughput. Societies organize materials and energy flows from nature (and by way of trade with other societies) for its reproduction and maintenance. A large part of these flows gets accumulated as part of the built environment (also called “material stocks”) to deliver critical services to society such as transport, health, education, housing, etc. The more stocks, the more flows are required to maintain the stocks. This dynamic feedback loop is called the “material-stock-flow-service” nexus. For a shift towards a more resource efficient economy, accounting for material stocks, its composition, and long-term dynamics of in-use materials is fundamental.

This research presents a methodology based on a spatial approach using Geographic Information Systems (GIS) for quantifying and analyzing stocks and services associated with buildings. A bottom-up approach was adopted for identifying in-use stocks in two study areas, (a) Grenada, a small island developing state in the Caribbean, and (b) the City of Kitchener, which is a rapidly growing urban area in Ontario, Canada. This research was conducted from both city and island perspectives to assess the socio-economic metabolism of buildings and their relationship with services in two different geographic contexts. Estimated primary construction materials include cement, aggregates, steel, and timber. In a North American context, masonry brick was a widely occurring building material in Kitchener, and therefore was also accounted.

This study found that 125 tonnes per capita of material stocks were accumulated in Kitchener in 2016, equivalent to 29,000 kilo tonnes. A total of 132 tonnes per capita was estimated in Grenada in 2014, equivalent to 14,012 kilo tonnes of material stock. In terms of services, the residential class was the highest occurring in both Grenada and Kitchener accounting for 93 tonnes per capita and 89 tonnes per capita, respectively. Tourism and commercial service classes were the next highest in Grenada accounting for 12% and 5% of total in-use stocks. In Kitchener, educational services were second at 7.3% of total in-use stocks and commercial services were third at 7.1%. When exploring scenarios of future stocks in Grenada based on indicators such as population, and tourism visitors, if visitors continue to increase during a 20-year period, tourism stocks will likely rise by almost 50%. This will significantly impact Grenada’s economy, since an increase in tourism stocks can lead to a shift in GDP, potentially leading to a large reliance on tourism as a primary source of income. More frequent extreme weather events related to climate change also threatens the supply of critical services to society. For example, located in Grand Anse (0.28 km^2 enumeration district) are 18% of the total tourism material stocks equivalent to 308,494 tonnes. If another disaster event such as Hurricane Ivan were to occur, these large agglomerated stock areas could devastate Grenada and put the economy in decline until re-construction can occur. Mapping the spatial distribution of material stocks can help communities to mitigate and plan for the effects of climate change, especially since most of Grenada's built infrastructure is located along coastal areas. This study demonstrates how to link material stock accounting with the services that they provide, thus enhancing understanding of the socio-economic metabolism of cities and small island nations, which is important for planning and sustainable development.

Keywords: Material stock-flow-service nexus, GIS, spatial analysis, industrial ecology, socio-economic metabolism, material intensity, Small island developing states (SIDS), Grenada, Kitchener

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Chapter 1: Thesis Introduction

1.1 Introduction

Extensive use of raw materials in construction due to increasing urbanization is contributing to more intensive material extraction, which subsequently leads to a scarcity of natural resources. From a consumption point of view, this increased urbanization has led to large material stock increases in which infrastructure in the built environment has been the largest resource sink, equating to half of the current material being extracted from the earth's crust (Arora, Raspall, Cheah, & Silva, 2019; Hu, van der Voet, & Huppes, 2010). Studies have found that historical census data shows material stock from 1981 to 2017 increasing by 360% in one Latin-American city, and an almost 10-fold rise in material extraction from 1900-2010 globally (Krausmann et al., 2017a; Mesta, Kahhat, & Santa-Cruz, 2018). Energy consumption during the operation phase of building construction has contributed to 30-40% of total global greenhouse gas emissions (Wong & Zhou, 2015). Small island developing states (SIDS) tend to feel the majority of the effects of climate change due to increasing greenhouse gas emissions, because they are some of the most climate vulnerable nations (Sjostedt & Povitkina, 2017). SIDS are located in largely hazard-prone regions where a large concentration of their population resides along coastal zones, exposing them to extreme weather events that result in the loss of lives, livelihoods and shelters (Sjostedt & Povitikina, 2017). Understanding where vulnerabilities and critical services lie can help with planning for these vulnerabilities and further risk management.

This intensification of material consumption has resulted in an increase in industrial ecology methods to help predict the stock and flow of these materials. Emerging industrial ecology methods are being employed to understand the metabolism of islands, cities, and countries around the world to reduce rapid consumption. Several studies have now been conducted examining stocks from both national and global scales, as well as focusing on various types of materials (Gontia, Nageli, Rosado, Kalmykova, & Osterbring, 2018; Guo, Miatto, Shi, & Tanikawa, 2019; Kleemann, Lederer, Rechberger, & Fellner, 2016; Mastrucci, Marvuglia, Popovici, Leopold, & Benetto, 2017). In order to understand the flow of these materials, socioeconomic metabolism is a research field that has been growing, which aims to understand the interaction of these materials and the human environment. Socioeconomic metabolism is the set of material flows that occur within a society and often begin with extraction of materials from nature. These materials are then stored as ‘in-use’ material stocks while they are being used within the system. When materials are no longer needed they flow out of the system as waste and a small portion is recycled or down-cycled (Kennedy, Cuddihy, & Engel-Yan, 2007). In-use stocks provide important services for society in the form of shelter, mobility, education, communication, and more. These service demands coincide with material flows, since their age, accumulated amount, and growth rate explain how much and what is needed within the system (Fishman, Schandl, Tanikawa, Walker, & Krausmann, 2014). Understanding the configuration and quantity of these in-use stocks will help determine future waste flows, potential recycling initiatives, and reduce emissions (Bergsdal, Brattebo, Bohne, & Muller, 2007; Krausmann, Schandl, Eisenmenger, Giljum, & Jackson, 2017b).

Besides knowing how much material, it is also important to know where resources are stocked in the built environment. Thiscan help planners and researchers identify where the physical stocks are located, to help better predict the recycling of materials in the future. Geographic Information Systems (GIS) can be utilized as a tool to identify where these stocks are spatially located and distributed, along with monitoring how they change over time (Tanikawa, Managi, & Lwin, 2014). A spatial approach, which includes GIS software and geospatial data sources, can help to determine how much material stock occurs in each service sector and in what capacity. This is important for improved prediction of building usages, building composition, and estimates of materials, which is required for supporting increasing urbanization and growing populations.

1.2 Research Goals and Objectives

This research conducts a material stock analysis (MSA) from a spatial perspective, identifying distributions of material stocks and examining their relationships with services in the built environment. This research was conducted on two different study areas, including a Caribbean small island case study (Grenada) and a North American city case study (Kitchener, Ontario). This research builds on previous work conducted in Grenada by Symmes et al. (2019) by addressing assumptions made in the material stock accounting methodology and further considers material stocks on the island from a services perspective. From the island context, the main questions that guided this research were:

1. How can assumptions in material stock methodology affect overall material stock accounts?

2. What are the concentrations of material building stocks and services in Grenada?
3. Where are the concentrations of material building stocks and services located?
4. What are the driving factors underlying these patterns of stock-service accumulation?

The main objectives used to address these questions are to:

- Conduct an accuracy assessment of building heights and associated occupancy classes based on a previous GIS-based material stock analysis methodology developed by Symmes et al. (2019).
- Conduct an updated material stock analysis of Grenada by evaluating key assumptions of the methodology and performing an accuracy assessment based on field data and observations.
- Evaluate services associated with occupancy classes to understand the local economy of Grenada based on indicators to assess how material stocks will potentially grow in the future.

From the city context of Kitchener, Ontario, two main questions that guided this research were:

1. What are the concentrations of building material stocks and services?
2. Where are the concentrations of material building stocks and services located?
3. Do these services change over-time?
4. How do we reduce construction waste and move towards a more material-cycle society?

The main objectives used to address these questions are to:

- Identify different material typologies within the city, as well as the occupancy classes of buildings.
- Calculate the material intensities of different construction types of occupancy classes along with physical attributes (basement, height, roof composition, etc.) to calculate an overall estimate of total stocks in the city.
- Evaluate services associated with occupancy classes as potential drivers of material stocks and assess how these stock-service relationships change over time.

1.3 System Boundaries

System boundaries are established to help define what is considered inside a system, anything outside of the boundaries is considered outside the system. Therefore, in the context of a country all imports are goods and materials that enter the country and all outputs are goods and materials that leave the country. Anything existing within the boundary is considered domestic. Any buildings pre-existing and newly constructed, are considered 'in-use' building stocks. The system boundary for the study areas are material building stocks and their services within each geographic context. Materials include concrete, timber, aggregates, steel, and brick (brick was only considered for the City of Kitchener). The first geographic boundary, Grenada, is a Small Island Developing State (SIDS). Grenada was chosen since there is previous material stock research and data already established in the area. Moreover, small island developing states are at the forefront of the climate crisis, since they are faced with extreme weather events and sea level rise (UNDP, 2017). The second geographic system boundary, the City of Kitchener, is an urban city in Ontario, Canada. Over the last century, a large portion of the population is shifting to urban areas and material consumption has increased 10-fold (Stephan & Athanassiadis, 2018). The rationale for choosing Kitchener was because of the increasing shift of the residential population moving to urban areas and a recognized need to manage the increasing demand for finite resources more sustainably. Geographic boundaries come into play when considering how natural disasters and the economy of imports and exports can have different development effects in different areas. Considering an island boundary vs a land-locked city boundary, there are different influences that pose challenges to development and reconstruction after a natural disaster occurs. For example, the relative isolation and limited physical size of SIDS results in more reliance on imported goods, while shipping of resources in and out of the boundary takes longer than road or railway transport (Sjostedt & Povitkina, 2017). This can affect the rate of recovery for islands, since rebuilding requires larger amounts of imported goods and delays access to critical services (Sjostedt & Povitikna, 2017). City boundaries in large developed countries tend to have more readily available access to goods within their countries, cutting down on expenses and import costs during the recovery and reconstruction efforts after a natural disaster. Sections 1.4.1 and 1.4.2 describe these study areas in more detail.

1.3.1 Grenada

Grenada is a SIDS located in the Southern Caribbean. It is 344 square kilometres in area and is composed of three islands including the main island of Grenada (shown in Figure 1.1), and two smaller islands: Carriacou and Petite Martinique. According to the Work Bank (2017) in 2017, Grenada had a population of 107,825, which equates to a population density of 313 persons per sq. km. Grenada is ranked as a middle-income nation where agriculture and tourism are two of the main sectors of Grenada's economy. Due to Grenada's dependency on imports and the small and open nature of SIDS, their economy is highly vulnerable to external shocks (UNESCO, 2006). These external shocks can be both in the form of natural disasters, as well as economic instability.

In the past, declining trade of agricultural products, competition, and declining aid, has lowered Grenada's economic activity resulting in restriction on social services (UNESCO, 2006). According to Grenada's Annual Economic Review, agricultural production is down due to abnormal weather patterns, affecting production of major crop exports (MFPEPD, 2018). However, Grenada's economy is on a path of growth, having experienced its sixth consecutive year of growth (MFPEPD, 2018). The economy grew from a 3.9% increase in 2016 to 5.1% in 2017 and is expected to grow to 5.2% at the end of 2018. Grenada is becoming a sought-after tourism location generating economic growth shown by the average GDP growth of 5% each year since 2013 (IMF, 2017; MFPEPD, 2018; World Bank, 2017). Throughout the year in 2018, a total of 345,252 people visited Grenada, where 35% were visitors staying in a resort or other accommodation and 65% of visitors were from a cruise ship (Grenada Tourism Authority, 2017). Approximately 43% of these stayover guests stayed in hotels with an average visit length of 9.3 days (MFPEPD, 2018). Grenada has experienced an increase in their construction sector over the years with new hotels being built in response to tourism demands, as well as housing developments for students attending St. George's University (MFPEPD, 2018).

Due to the open and independent placement of SIDS, they are extremely vulnerable to increasing natural hazards and Grenada is no exception (UNDP, 2017). Due to its tropical mountainous terrain, many buildings in Grenada are located in low-lying coastal areas and are threatened by increasing sea level rise and extreme weather events. Natural disasters can have lasting impacts on SIDS local economies. In the wake of Hurricane Maria and Irma, the MFPEPD (2018) stated that the damage from the hurricanes "has reduced the appetite of US students for pursing degrees in the Caribbean" (pg 1). Approximately, 20% of Grenada's Gross Domestic Product (GDP) is from St. George's University and therefore, this can have adverse fiscal implications (MFPEPD, 2018). Grenada's vulnerability to natural hazards can significantly change economic activity and hinder development from moving forward. Therefore, being able to quantify in-use stocks and services can help to identify future economical trends and where these key GDP contributors are located so that Grenada can manage its economy and material flows more effectively.

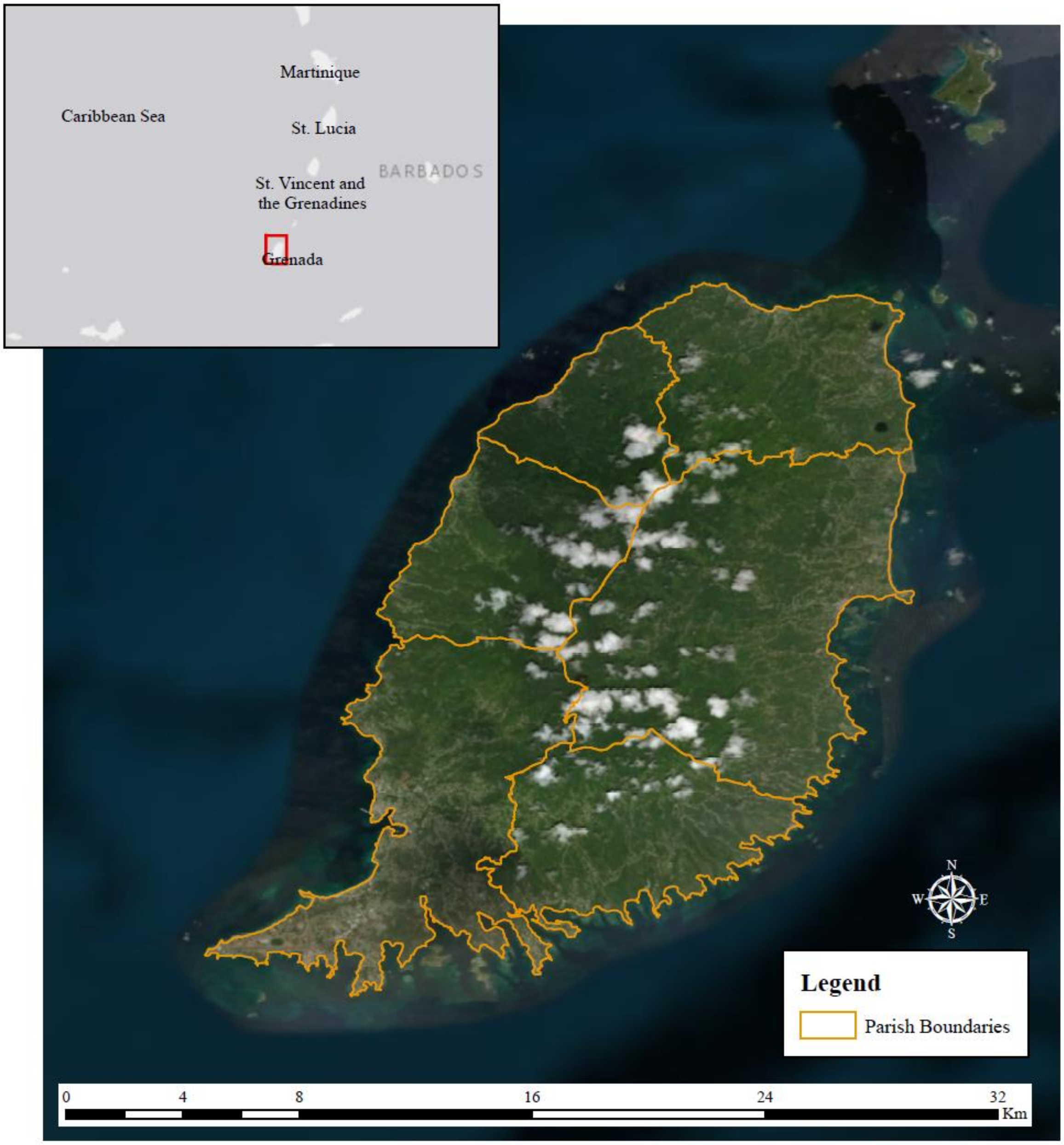


Figure 1.1: Map of the main island of Grenada showing Parish boundaries in orange.

1.3.2 The City of Kitchener, Kitchener, Ontario

The City of Kitchener is located in Southwestern Ontario in the Saint Lawrence Lowlands and is a city boundary within the Regional Municipality of Waterloo in Ontario, Canada. It is one of seven city/township areas within the Region and is approximately 137 sq. km. with a population size of 233,222 (Statistics Canada, 2016) and a population density of 1,702 people/km^2. The City of Kitchener boundaries and planning intensification areas are shown in Figure 1.2. The population of Kitchener has been growing steadily and has increased approximately 6% from 2011-2016, surpassing both provincial and federal population rates (CBC, 2017). In 2016, there were 92,215 households and roughly 70,000 buildings (Statistics Canada, 2016). Approximately 62% of these households own their home and the other 38% rent. Rental rates are approximately 6% higher than the provincial and national level (Statistics Canada, 2016). This surge in population requires housing and infrastructure services resulting in a large flux of construction materials.

In addition to population growth rate considerations, the selection of the City of Kitchener as a study area was also due to data availability and site accessibility for interviews and data collection. Kitchener has a large number of building footprints that contain descriptive data and year of construction from the late 1800's to 2016. This information includes building occupancies, year of construction, and other descriptive information that aided the identification of material compositions of each building occupancy class. Assessing the growth and in-use stocks also help to predict where waste will go when infrastructure is demolished, as well as open up new avenues for potential material recycling (Reyna & Chester, 2014). Examining the City of Kitchener from a service perspective also helps to identify which services are higher or lower and if there are patterns of increasing or decreasing services. This information would help in further understanding the built environment and to identify what patterns exist.

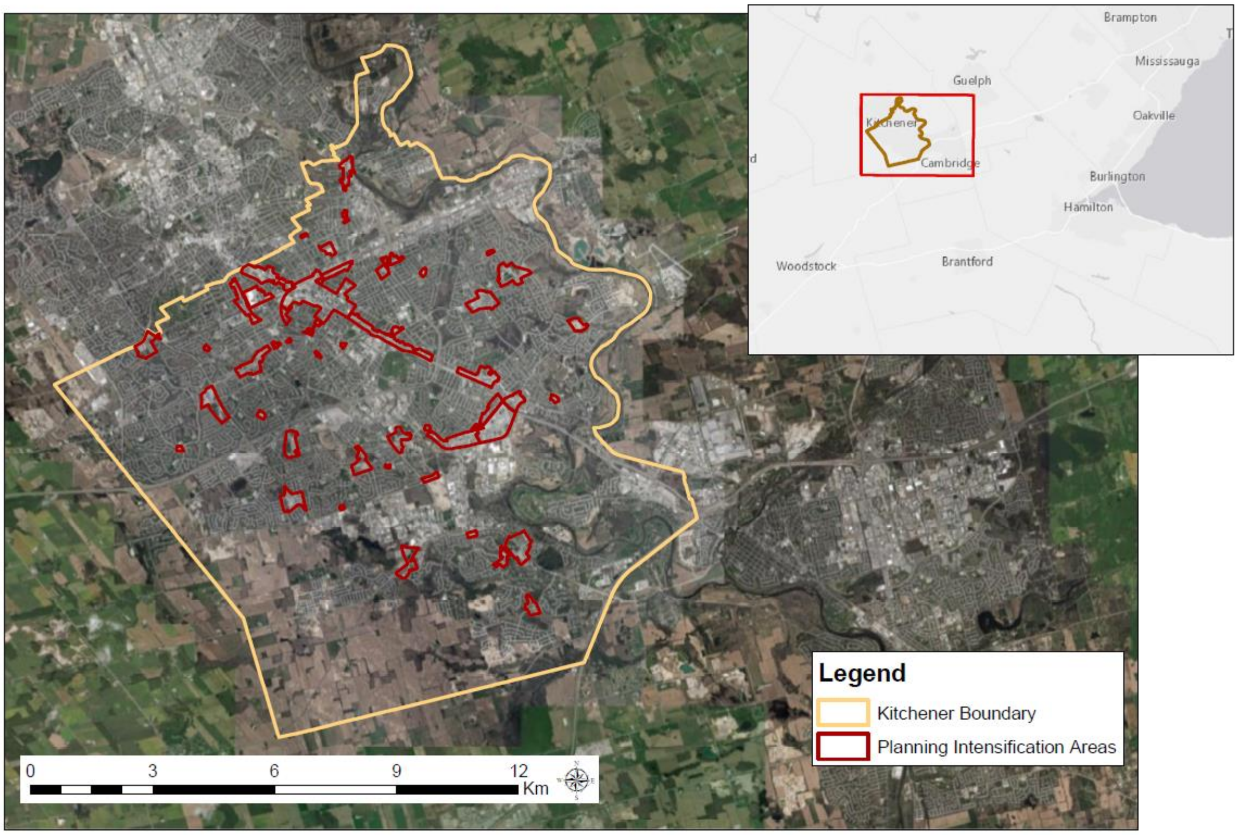


Figure 1.2: *Map of the boundary of the City of Kitchener, within the Region of Waterloo, outlined in yellow, and the planning intensification areas in red.*

1.4 Literature Review

The construction industry is a large contributor to economic development, as well as resource extraction. Almost 50% of primary resources that are extracted go into material manufacturing for construction purposes (Muller, Hilty, Widmer, Schluep, & Faulstich, 2014). As demand for construction increases, these extracted materials become stocked in the built environment. These resources are stocked until buildings depreciate and thus become construction waste. According to a report by the World Bank in 2012, there is a global collective of 6.5 million tons of construction waste each year which is expected to double by 2025 (World Bank, 2012). Material stocks are the materials that are added during construction that become stocked in the built environment. At the end of building life cycle or demolition, these material stocks become removed as construction waste and go to the landfill. A key question is how do we reduce this waste and move towards a more material-cycle society? To determine where these materials are flowing or are stored requires different modeling approaches. This literature review evaluates the material stock accounting approach, which mainly quantifies the stock size and composition to help estimate how much material is stored in the existing building stock. This literature review also gives context to why material stocks and the services they provide contributes to understanding socioeconomic metabolism in both the island and city contexts. Understanding the material stock-services nexus results in accounting for materials that can potentially be recycled to both reduce the waste moving to landfills and primary resource extraction, as well as explaining what is potentially driving these patterns of stock-services.

1.4.1 Socioeconomic Metabolism

Sustainable development and sustainability research are evolving fields that explore the dynamic social and environmental factors affecting societies in the midst of climate change and finite resources. Falling under this 'umbrella' of sustainable development research is the concept of socioeconomic metabolism (SEM), in which resource use and social goals overlap. A system boundary is defined that examines both societal and natural flows (Dombi, Karcagi-Kovats, Toth-Sziita, & Kuti, 2018; Pauliuk & Hertwich, 2015; Sabau, 2010), which often refers to an account of materials and energy flows into, within, and out of a socio-economic system (Kennedy et al., 2007). Socioeconomic metabolism can serve as a paradigm for understanding the flow of and interactions between material and energy that occurs between nature and society (Pauliuk & Hertwich, 2015). The socioeconomic demand of materials ultimately determines how much will flow in and out of a system (Gordon, Bertram, & Graedel, 2006). This can originate from domestic extraction and a large amount may be imported materials (Fishman et al., 2014).In order to further explore how to characterize a society's 'metabolic' flow, this research is based on a conceptual framework summarized in Figure 1.3 and is based on buildings stocks. Materials flow into a system (from domestic and imported sources) and become 'in-use', at the end of the lifecycle or when materials are no longer being used, the materials flow out of the system into waste or become recycled. Other components of society's 'metabolic' flow can include road stocks, energy flows, material flows, and biomass (Arora et al., 2019; Gontia et al., 2018; Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017). In the context of this thesis, socioeconomic metabolism of building stocks and core respective materials will be examined.

Certain socio-economic factors can also contribute to directional trends in social metabolism in terms of the built infrastructure (Dombi et al., 2018; Fishman, Schandl, & Tanikawa, 2015; Wang, Chen, Ma, Chen, & Chang, 2018). These socio-economic factors can be development indicators and services that are required by society. They contribute to the increase of accumulated building stock as demand rises. First, a certain amount of building stock is required to provide essential services to societies, such as schools, transportation hubs, residential areas, etc. (Fishman et al., 2015). For example, when populations increase, the infrastructure demand for residential housing must be met, thereby increasing residential construction. Studies that have researched development drivers often observe population or GDP as a growth trend in the context of building stocks (Fishman et al., 2014; Krausmann et al., 2009). Fishman et al. (2015) found that affluence was also a major driver of material stock accumulation in Japan. As material stock increased with a growth rate of 78% over nine years, there was a 63% growth rate in affluence (Fishman et al., 2015). Other studies have found that consumption patterns, new technologies and potential variations in economic and political conditions can influence societal needs (Wang et al., 2018). Weisz and Steinberger (2010) explained that material consumption may be due to various factors such as operational energy demands of buildings in certain climates, quality of buildings, floor area demand for residents, income and location. In order to better understand the socioeconomic metabolism of the building stock, it is important to connect where fluctuations in demand in the economy can drive the accumulation of building stocks.

1.4.2 Services Within Socioeconomic Metabolism and Stock Research

As socioeconomic metabolism (SEM) is being applied to various human-ecological interactions, there is a further need to explore how this interacts with services. Services are typically a product of SEM; different services are provided by different systems. For example, within a road system, transportation is provided as a service, as well as public transportation services. Exploring services as an aspect of material stock accounting is new for both socioeconomic metabolism research as well as material stock accounting (Haberl et al., 2017). This is one of the first material stock studies to develop and define a more services-oriented approach to assessing material stocks. In this study, a ‘unit of service’ is defined as the amount of building material stock required for a service to meet the demands of a population. Thus as more services are required, resources flow into the system and this results in higher ‘units of service’ for meeting rising demand. Haberl et al. (2017) states that “resource flows do not suffice to provide services… but they can in a combination with material stocks such as building or infrastructure” (pg 1049). The breakdown of material stocks and flows into tangible units of service that can be used to assess how a society functions also helps to explain key service requirements (Haberl et al., 2019). Being able to reduce resource use is less of a challenge if there is little to no detriment to social well-being (Haberl et al., 2019; Lanau et al., 2019). This requires an understanding of not only resource flow, or value added (GDP), but also examining stocks from a services perspective. Therefore, in this particular case, a unit of service can be defined as the amount of material used to supply a specific public need. Key services provided by building infrastructure can further aid our understanding of socioeconomic metabolism processes where a potential reduction in resources will not reduce services contributing to societal well-being.

Considering the conceptual framework in Figure 1.3, an increase of inputs into each system can also refer to an increase in economic growth (Fischer-Kowalski, 2011). Socioeconomic systems produce and use up consumable products and services. These are typically provided from products of industrial systems and take form as durable and non-durable services (Fiskel, 2006). Durable goods are known as the goods that are kept for a long period that provide services to

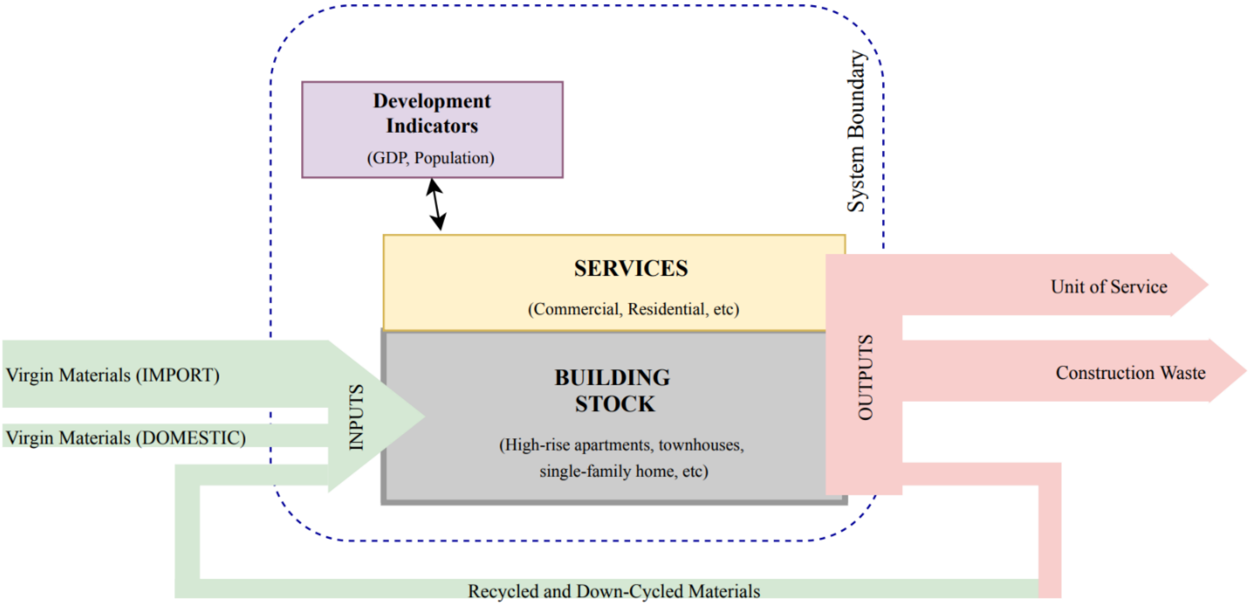


Figure 1.3: *Socio-economic metabolism conceptual diagram showing in flows and outflows of construction material and their interactions with the building stock and services.*

societal systems such as cars, electronics, or furniture. Non-durable goods are those that have a short lifetime such as most food and clothing items. Inputs to these systems are typically the materials needed for manufacturing these durable and non-durable goods, such as steel, cotton, agricultural resources, timber, etc. There is also a large input from the ecological system both from the outputs of ecological systems and the services that ecological systems provide. These durable and non-durable goods are products that provide services derived out of societal systems. Driving most of these durable and non-durable goods consumptions are population growth and GDP, hence more infrastructure is needed as the economy increases and there are more demands for services (Fiskel, 2006).

Indicators for building services are seldom explored in the context of stocks. Haberl, Wiedenhofer, Erb, Gorg, and Krausmann (2017) state that "socio-metabolic research has not yet fully incorporated material stocks or their services, hence not completely exploiting the analytical power of the metabolism concept" (pg 1). This thesis seeks to explore a material stock analysis (MSA) and services that building infrastructure provides. This will help determine what type of economic society is currently present and what kind of output services are found in the context of building stocks. Building stocks provide services to people in the form of shelter, transportation, enjoyment, and communication (Haberl et al., 2017). Societal needs can drive much of the infrastructure services that are present in societies; for example, the m^2 of living space is a driver of how much residential material is stocked in the built environment (Haberl et al., 2017). In a socio-economic system, such services that are output are considered to be 'units of service'. These services include shelter, education, commercial, health and more. Certain societies have different units of service. High tourism driven economies tend to have higher units of service such as hotels and commercial buildings. Industrialized cities and societies tend to have high industrial services such as processing plants and manufacturing facilities (Krausmann & Fischer-Kowalski, 2013). There can be different units of services across system boundaries as there are different influences that come into play.

Increasing economic activity inevitability entails the use of natural resources, however, the inputs are dependent on material and economic intensity (Steinberger, Krausmann, Getzner, Schandl, & West, 2013). Some theories of environmental dependency exist in the context of development (Steinberger et al., 2013). For example, in early stages of development, agricultural activities tend to dominate and biomass becomes the most important resource category. Later, in the context of colonisation of nature, societies tend to move from agrarian to industrial societies (Krausmann & Fischer-Kowalski, 2013). Relatively high industrializing nations tend to use up large amounts of materials as they are in a rapid building and development stage, providing jobs, and leading to a demand for residential building services (Steinberger et al., 2013). After an industrialization period, a higher economic gain and higher GDP period may entail transitioning into a more service-oriented society in which education, commercial, health, and a more diverse economy are the main services in demand (Steinberger et al., 2013). A transition to a more service-oriented society and diverse economy can also eventually help push environmental goals forward, as more money is invested into green infrastructure and technology (OECD, 2016; Steinberger et al., 2013). Measuring these services from a building stock perspective can help to explain and better understand the socio-economic systems as they pertain to buildings and interactions between the economy, society, and the built environment.

1.4.3 Material Stock Research

Material stock analysis (MSA) is a type of industrial ecology method used to study material composition and intensities in the built environment. This includes quantifying materials that buildings are currently composed of, such as steel, reinforced concrete, brick or wood (Marcellus-Zamora, Gallagher, Spatari, & Tanikawa, 2015). There are two main analytical approaches when it comes to MSA, referred to in the literature as bottom-up and top-down approaches (Augiseau & Barles, 2017; Lanau et al., 2019). However, due to data availability, geographic scale, difficulty of obtaining outflow data, varying purposes, and data requirements, researchers have chosen to describe their approaches in a more descriptive manner (Augiseau & Barles, 2017; Lanau et al., 2019; Symmes et al., 2019). In defining top-down approaches researches have described studies as flow-driven or stock-driven (Augiseau & Barles, 2017). Of these flow-driven and stock-driven approaches there has been prospective studies (forecasting future stocks based on historical inputs and output flows) and retrospective studies (reporting historical stock evolution over time) (Kapur, Keoleian, Kendall, & Kesler, 2008; Kohler & Hassler, 2002; Muller, 2006). Bottom-up approaches are often separated into static or dynamic methodologies; dynamic bottom-up approaches are just multiple static ‘snapshots’ of the stock over time (Lanau et al., 2019).

Top-down approaches use socio-economic indicators, material consumption, and industry statistics to identify required materials for manufacturing and construction of future stocks

(Tanikawa et al., 2015). This approach is defined by Lanau et al. (2019) as “a mass-balance principle where a change in stock is the result of the difference between inflows and outflows of materials over time” (pg 8504). The stock-driven approach examines population and income data to model demand of materials, helping to identify drivers of material stocks and flows (Tanikawa et al., 2015). Hu et al. (2010) conducted a study in Beijing predicting inflow and outflow as a function of socioeconomic factors (Hu et al., 2010). This study found that GDP and lifetime of dwellings are factors that will drive future construction and demolition waste (Hu et al., 2010). This approach can be useful in identifying correlating factors of affluence and population with future material stocks and associated services. The flow-driven approach examines national consumption and industry statistics of materials as well as import and land-use statistics (Augiseau & Barles, 2017; Kapur et al., 2008). Kapur et al. (2008) conducted a flow-driven approach for cement stocks in the United States. The research found that approximately 85% of concrete is still in use and the cement stock per capita has doubled over the last 50 years (Kapur et al., 2008). Based on retrospective flow dynamics, estimates of future material flow increases and decreases can be predicted. Drawbacks to top-down accounting is that historical shipment and consumption data are based on national levels through industry statistics (Lanau et al., 2019). Therefore, these methods rarely account for individual products on small scales like cities and individual buildings, but rather global and national levels (Lanau et al., 2019).

The bottom-up approach is defined by Tanikawa, Fishman, Okuoka, & Sugimoto (2015) “as an inventory of end-use objects in a defined area at a given point in time… often ‘snapshots’ of the material stocks” (pg 779). Studies using a single ‘snapshot’ in time are often referred to as a static bottom-up approach. The dynamic approach is multiple ‘snapshots’ over time to examine temporal changes of material stocks. For this study, a static bottom-up approach was adopted as it was deemed more appropriate for a local scale and efficient use of GIS (Lanau et al., 2019; Zhu, 2014). The bottom-up approach is used when identifying the end-use objects at a certain point in time (Tanikawa et al., 2015). It usually is a ‘snapshot’ in time of materials contained within a defined area, and associated material intensity, referring to a specific material found in a single unit (Tanikawa et al., 2015). Bottom-up approach methodology, as described by Condeixa, Haddid, and Boer (2017), is usually utilized on a smaller scale such as a city or region. This method extrapolates material intensities of constructed areas, which often includes all infrastructure and buildings in the area (Condeixa et al., 2017). This approach is advantageous as it provides a detailed understanding of the physical arrangement of MS, especially for studies focusing on a defined area and spatial scale. A study conducted in Japan by Tanikawa et al. (2014) used this approach to examine the losses of buildings and infrastructure from a tsunami (Tanikawa et al., 2014). They found that using this approach was useful in calculating the waste overflows and disposal of the infrastructure at one point in time (Tanikawa et al., 2014). Drawbacks to the bottom-up approach is the highly data and labour-intensive requirements in defining material intensities and mapping them back to each individual building (Lanau et al., 2019). Various other literature has utilized the bottom-up approach as it was found to be one of the most common material stock analysis methods when examining a city or region.

Remote sensing/GIS techniques often support the bottom-up approach, providing a spatial dimension for locating intensive human activities and development (Tanikawa et al., 2015). Analysis from satellite images and orthophotos are used along with known geographical distribution of stocks. Correlations can then be used to estimate similar building types and compositions (Tanikawa et al., 2015). Satellite images are usually captured at a particular time and place, representing another example of a ‘snapshot’ approach for examining stocks and flows. A GIS 3D aspect of latitude, longitude and height can be used to calculate the gross volume of buildings and then applied in combination with building composition data (Sugimoto, Morita, & Tanikawa, 2015). Utilizing GIS can enable spatial analysis of stocked materials, displaying where the stocks are located (Marcelllus-Zamora, 2015). This can help to identify areas of higher material composition that can be vulnerable to destruction (e.g., natural disasters) or where large outputs of construction waste can potentially be recycled.

Buildings and resource use patterns, as well as their societal functions have been a focus of study in recent years due to the recognized importance of managing these materials and construction minerals (Haberl et al., 2017). Dematerialization is the ultimate goal for material efficiencies so that the inputs are reduced, but the services produced are still the same. Dematerialization is defined by van der Voet, van Oers, and Nikolic (2005) as “the reduction of the throughput of materials in human societies coming from tradition of regarding economies not only from a monetary value, but also in physical terms” (pg 122). This includes sustainability and environmental impacts of certain products and can occur in any part of the SEM framework. In the context of buildings, when services are needed, they are provided from construction, thereby increasing mass material flows. This entails critical linkages and interlinkages that become a part of strategies for reducing waste outflow and increasing resource efficiency (Cheng, Hoff, Spataru, van der Voet, & VanDeveer, 2018). ‘Nexus thinking’ is a conceptualization of linkages and connections; in this research, services are linked with the broader societal conditions under which they occur, which use up certain resources to provide services that meet societal demands (Schaffartzik & Wiedenhofer, 2017). Pauliuk and Hertwich (2015) state that “socioeconomic metabolism, developed in material flow analysis and material flow accounting, is a powerful boundary object that can serve as paradigm for studying the biophysical basis of human society” (pg 84). Delving into this type of research can help link what services are needed to maintain a certain level of material comfort within a society (Fischer-Kowalski et al., 2011).

1.5 GIS-based Material Stock Estimation Methodology

The following section details the main methodology applied to both study sites of Grenada and Kitchener using geographic information systems (GIS) and MSA. An overview of how the material stocks, qualitative information, occupancy classes, and services were determined/collected is provided. This section also details the definitions of services and their respective codes used for both study sites. Utilizing similar codes and definitions of both occupancy classes and services helps to provide some consistency/uniformity when examining the two very different study sites. GIS was employed in both studies in Grenada and Kitchener to evaluate the spatial distribution of construction materials within the study areas and to develop geodatabases that could be used for future studies. The characterization of these stocks is based on a bottom up approach, previously explained in Section 1.5.3.

1.5.1 Calculating Material Stocks

MSA is an industrial ecology approach used to study material composition and intensities in the built environment (Marcellus-Zamora et al., 2015). Bottom-up methodologies are typically used for instantaneous measurements of in-use material stock and can be quite intensive in nature (Mesta et al., 2018). This is because the methodology starts at the ground level collecting information on each individual building. The approach quantifies the material intensities of individual building occupancy classes (e.g., hotels, single-family homes, low-rise apartment buildings), which are applied to estimate the total material stock for a given study area. The flow of material stock, outlined in Figure 1.4, starts with an addition to stock in the form of construction.

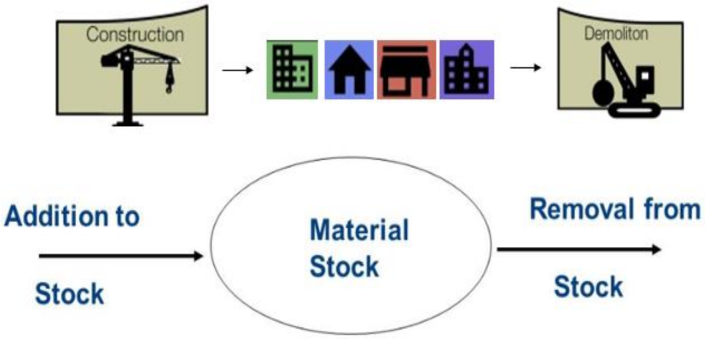


Figure 1.4: *Material stock analysis based on building infrastructure (Vasquez et al., 2016).*

Once construction is complete, this addition to stock in the form of construction shapes the in-use stocks. At the end-of building lifecycle, these buildings are demolished and material flows to the landfill in the form of construction waste (Vasquez, Lovik, Sandberg, & Muller, 2016).

Figure 1.5 shows a methodology flow diagram that summarizes how material stocks were calculated for both case studies in this thesis. Each section is outlined in more detail within the subsequent methodology sections to estimate a final quantity of total material stocks associated with each study area.

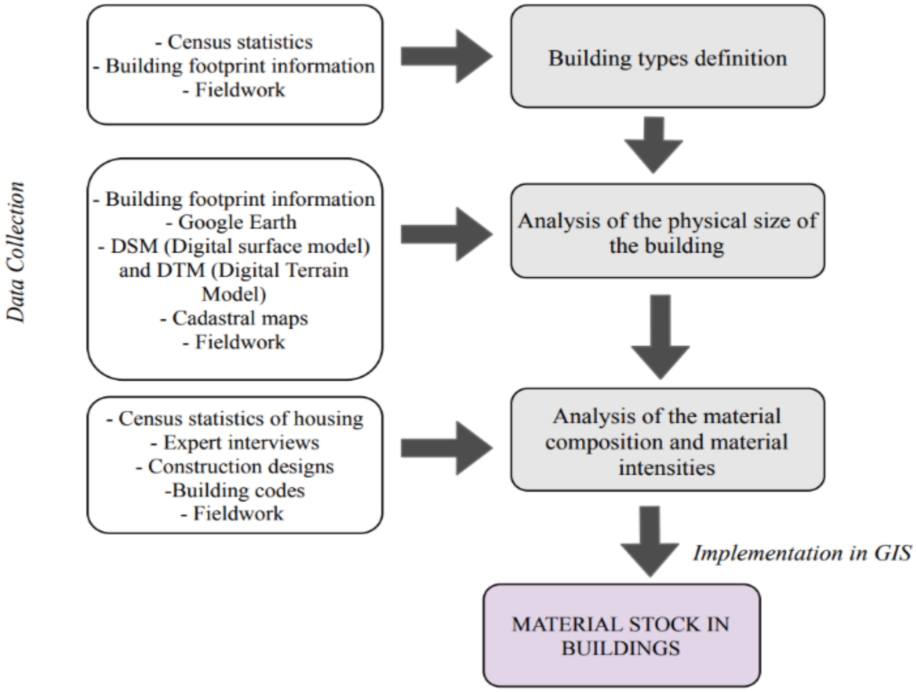


Figure 1.5: *Methodology flow diagram (modified from Mesta et al., 2018).*

1.5.2 Data Collection and Creating a Geodatabase

In order to conduct a spatial analysis of building stocks, building footprints and spatial data were required. A geodatabase was created for both study areas outlining various built features. The data was imported into respective geodatabases for ease of use and with the same coordinate system. Metadata for both Grenada and the City of Kitchener geodatabases and all of the spatial information collected along with their sources are provided in Appendix B.1 and C.1, respectively. Utilizing spatial information is a beneficial method of identifying the location of geographic phenomena. Spatial methodologies can assist cities and small island countries in examining relationships and making predications about historical data and the current state of affairs (Sugimoto et al., 2015).

1.5.3 Physical Size of Building

The MSA methodology is dependent on building size information that is collected within a GIS environment. Therefore, in order to obtain an accurate estimation of the size of individual buildings, it is important to have georeferenced building footprints. These building footprints can provide length and width dimensions that allow total building area to be calculated. In order to estimate the height of these buildings, a digital surface model (DSM) and a digital elevation or terrain model (DEM or DTM) are required. This data should be collected at a high enough spatial resolution to capture sufficient details of small building footprints, which will also ultimately affect the accuracy of building area estimates. However, many study areas (especially in the island context or developing countries) lack the spatial infrastructure to provide up-to-date data on building heights. Therefore, studies often adopt a Gross Floor Area (GFA) assumption, which assumes that each occupancy class has the same number of floors or levels across the entire study area (Mesta et al., 2018; Symmes et al., 2019). In order to examine these different methodologies, the Grenada study employs a GFA approach, whereas the City of Kitchener study adopts a gross volume (GV) calculation methodology as accurate height information is available for each individual building.

1.5.4 Occupancy Classes

A critical step in conducting an MSA involves defining material typology inventories through archetypes (Lanau et al., 2019). These archetypes can also be defined as occupancy classes and are divided into different classes due to heterogeneous building compositions. Buildings are grouped into occupancy classes using the domain of building occupancy class codes, as indicated in Table 1.1 This process differentiates the buildings when conducting GFA and GV calculations. For Grenada, the occupancy class codes were assigned by the occupancy classification system employed by Symmes et al. (2019). For Kitchener, building footprints already had attribute information on building occupancy classes available and these were subsequently mapped back to the codes in Table 1.1.

***Table 1.1:** Domain codes for each building occupancy class in both Grenada and the City of Kitchener.*

Code	Building Occupancy Classes		
111	Cathedral	331	Detached Garage
112	Church	340	Residential-area single-family dwelling
121	Educational Campus Building	341	Duplex dwelling
122	Stand along public/secondary school	351	Group Home
123	Day care centre	352	Nursing Home
124	Laboratory/Research centre	353	Prison/Jail/Reformatory
131	Major hospital building	411	Large multi-unit hotel building
132	Minor hospital/health centre building	412	Small hotel cottage/villa
141	Government/Institutional	510	Stadium
142	Government Other Building	520	Recreational centre
210	Commercial	521	Community centre
211	Commercial Entertainment	522	Indoor recreational
212	Commercial Mall	523	Library
213	Commercial Recreation	530	Historic Building
214	Gas Station/Repair/Specialties	541	Art Gallery
220	Urban-area mixed commercial	542	Museum
230	Industrial	610	Seaport
231	Assembly/Retail	620	Airport
232	Manufacturing	630	Bus terminal
240	Commercial/Dwelling mix	710	Communications
241	Urban - area commercial /dwelling mix	720	Other utility buildings
242	Rural/residential-area commercial/dwelling	721	Storage Building
310	Urban-area single-family dwelling	722	Parking Garage
321	High density apartment building	723	Warehouse
322	Low density apartment/duplex building	810	Agricultural
323	Rowhouse	811	Farm Building
330	Rural-area single-family dwelling	812	Garden Centre/Greenhouse

1.5.5 Material Intensities

In the literature, there are various examples of material intensity coefficients (MIC) that have been derived for a wide variety of study sites [e.g. Italy (Miatto et al., 2019), Vienna

(Kleeman et al., 2016), Grenada (Symmes et al., 2019), Brazil (Condeixa et al., 2017), Singapore (Arora et al., 2019)]. However, MICs are site-specific and based on a variety of different building styles and building codes. These building codes can change over time and the building styles can also vary based on weather and climate regimes in different regions (Ortlepp, Gruhler, & Schiller, 2016; Tanikawa et al., 2015). For example, in a study conducted by Tanikawa et al. (2015), the authors found that Japan tends to retrofit many buildings with higher load bearing capacities due to historic and predicted seismic activities and hence, MICs are typically developed on a more local scale in Japan. Some studies such as Kleemann et al. (2016), have utilized a subset of buildings to develop a sample that is based on construction files and on-site material analysis.

There are two main units of analysis for identifying material intensities throughout the literature, which are conducted by measurements of, (a) gross floor area (GFA), or (b) gross volume (GV) (Kleemann et al., 2016; Mesta et al., 2018; Miatto et al., 2019; Schebek et al., 2017; Symmes et al., 2019). Gross floor area (GFA) is calculated from building footprints and is frequently used when considering homes/study areas with high homogeneity in their building heights and introduces the assumption that building heights for certain occupancy classes are uniform (Mesta et al., 2018; Symmes et al., 2019). Gross volume (GV) is calculated using building height and building footprints to introduce a third dimension to material intensities (Miatto et al., 2019; Schebek et al., 2017). Therefore, if detailed height information is available, more accurate building material stock calculations can be conducted, considering the exact height of a building and volumetric estimations.

1.5.6 Services

A critical research gap in material stock accounts is not only accounting for the amount of material but also distinguishing the function of a building and the services it provides (Haberl et al., 2017). This was achieved by breaking down building uses into service categories in order to provide distinguishing definitions of each category of service. While standard bottom-up driven accounts of material stocks provide data on the overall consumption of materials, they rarely account for the specific uses of materials in the context of different services they provide (Miatto et al., 2017). In order to define different services at the building level, it is important to associate the different building typology classes with their respective services. Table 1.2 shows the different service categories and their definitions for each building typology that fell within each respective category. This provides a streamlined approach to both Grenada and Kitchener study areas in which similar buildings typologies for both study areas were grouped into common services that they provide. For identifying service categories in other study areas, Table 1.2 provides an example of a classification scheme for service categories that can potentially be applied to existing material stock accounts. New material stock accounts of both domestic and non-domestic buildings can also utilize this classification scheme to assess building typology-service relationships.

Table 1.2: *Classification scheme of service categories and their corresponding types of buildings and uses*.

Service Category	**Definition of buildings that fall within service category**
Agriculture	Barns and agricultural outbuildings.
Commercial	Commercial are buildings that include anything that involves consumption or things for a consumer. This includes shopping malls, shopping centres, grocery stores, restaurants, and large box stores.
Cultural	Associated with cultural enterprises including museums, historical sites, and churches.
Health	A public/private service providing medical care. Including hospitals, health care buildings, and research centres.
Industrial	Warehouses and any industrial enterprises.
Institutional - Education	Any educational buildings including private or public. Also includes primary, secondary and post-secondary schools.
Institutional - Other	Any government buildings or associated institutions such as day care, nursing homes, and municipal buildings.
Mixed use	Mixed use includes commercial and residential dwelling buildings.
Recreational	Anything that encourages recreation, mostly includes community buildings or recreation centres, gyms and stadiums
Residential/Shelter	Residential homes, apartment buildings, and anywhere that is classified as permanent living accommodations
Tourism	Hotels and resorts to accommodate outside guests and any buildings associated with this.
Transportation	Different transportation ports including airports, seaport and any bus terminals.
Utilities (Energy, Communications)	Utilities include energy plant and any communication buildings.

1.5.7 Qualitative Information: Surveys

Semi-structured surveys were conducted in this research with the aim of better understanding the relationship between services and material stocks at the local scale, as well as providing a better understanding of quantitative material stock results. Surveys are increasingly being used to help inform decision-making and to help support quantitative data findings (Toews et al., 2016). Synthesis of both qualitative and quantitative information assist decision makers in making more informed decisions about the future of infrastructure resources, both from a natural disaster perspective and a planning perspective (Toews et al., 2016). Interviews were conducted for both Grenada and Kitchener following a semi-structured interview approach (Appendix A.1). Planners, construction contractors, educators, government officials, and tourism stakeholders were interviewed to provide insights into the construction and building sectors and the services they provide within the study areas.

Most of these stakeholders were contacted by phone or e-mail sending a generic recruitment letter outlined in Appendix A.2. A recording device was used for all interviews and the information was transcribed. All interview materials went through the University of Waterloo ethics approval board. A list of the various experts interviewed is provided in Appendix B.2. for Grenada and Appendix C.2 for the City of Kitchener. Interviewees were classified only by their job title for confidentiality and ethical reasons.

1.6 Thesis Structure

The built environment plays a critical role in society’s socio-economic metabolism and to understand the composition of this stock is important for sustainable development and planning. Materials contained in the built environment can be useful for potential monitoring of future stocks and social transitions. This work considers both residential and non-residential buildings, to give an overall estimate of building stock throughout both study areas and the units of service these stocks provide through a static bottom-up approach. This thesis follows a manuscript style and has four major chapters. Chapter 1 starts with an introduction to the thesis, followed by a literature review discussing the theoretical background of material stock methodology, material stock-services, and socioeconomic metabolism. A conceptual diagram of this research, an overview of methodological approaches applied in this study, and an introduction to the two selected study areas are also detailed in Chapter 1. Chapter 2 examines the small island nation of Grenada and why material stock-service analysis is applicable in the small island developing state context. Chapter 3 examines the City of Kitchener and why material stock-service analysis is important in a city context. Chapter 4 discusses the similarities and differences of these case studies and makes recommendations for future research, as well as applications for sustainable development and disaster management.

Chapter 2: An Assessment of the Building Height Assumption in Material Stock Research and a Material Stock Analysis Account of Building Stocks and Associated Services in a Small Island Developing State: A Case Study of Grenada

2.1 Introduction- The Island Context

Small island nations are some of the most climate-vulnerable nations exposed to the intensity and frequency of natural disasters, which cause disproportionately high economic, social, and environmental impacts. Small islands account for less than 1% of global greenhouse gas emission yet are the most vulnerable to increasing sea-level rise and climate change (UNDP, 2017). In the 2017 Atlantic hurricane season, hurricanes Harvey, Irma and Maria, caused damages to critical infrastructure estimated to have cost over $200 billion USD (Symmes et al., 2019). Damages to buildings (or *material stocks*) result in immediate loss of critical services and create a large volume of debris (Garcia-Torres et al., 2017). However, there are more factors than just climate change that contribute to these exacerbated social, economic and environmental impacts.

Accounting for current building infrastructure can assist planners and policy makers in promoting sustainable material cycles, where damaged home materials become recycled into new infrastructure instead of using mass amounts of virgin materials. This paper provides a framework for a material stock account for Grenada using a Geographic Information Systems (GIS) approach, to gain insights into different services that exist and how they are distributed in Grenada. This study also highlights opportunities for managing existing infrastructure based on what stock services exist and where they might increase in the future. A GIS method was employed to estimate the building stocks and their associated services (educational, residential, etc.) based on building footprint area, height data, occupancy classes, and material composition during a 2014 'snapshot' in time. Examining building stocks from a spatial perspective is important for applications in planning and decoupling resource flows. By analyzing the interrelations between stocks and services it will allow researchers to develop highly innovative indicators of eco-efficiency and open new directions for research that will help to better understand biophysical foundations of transformations towards sustainability (Haberl et al., 2017). There is potential to apply the methodological approach described in this paper to other small island countries, especially those vulnerable to natural disasters and climate change.

2.2 Methodology

In the island context, different methodological approaches were utilized in this research for assessing material stocks and the services they provide in Grenada. The overall methodology for material stock accounting used in this thesis was previously described in Section 1.6, while this section details the specific methodological approaches adopted for the case study of Grenada and completed steps of analysis. Different methodological approaches were employed due to the different GIS datasets gathered within Grenada and the availability of information.

2.2.1 Assignment of Occupancy Classes

The material stock accounting methodology described in Section 1.6 requires a set of material intensities either derived from gross volume or gross floor area estimates. In this section, gross floor area was utilised, which requires a set of building classifications that are then used to estimate building heights. Symmes et al. (2019) employed this methodology for Grenada and estimated each "occupancy class" based on an assumption of floor levels adopted for the entire study area. This was done through a classification system based on visual interpretation of satellite imagery, expert consultation, and fieldwork photos, which is described in detail by Symmes et al. (2019). This classification system was subsequently used with available building data and ancillary spatial information, such as land-use and geo-location in order to differentiate buildings into 25 classes of occupancy use (Symmes et al., 2019). However, this methodology did not account for the variability within each occupancy class and can potentially over- or underestimate total material stocks in the study area. To improve estimates of building heights, accurate height information is required for individual buildings rather than grouping heights per occupancy classes. Unfortunately, Grenada's spatial data infrastructure is still underdeveloped, and fieldwork or ground validation measurements were required to assess variability in building heights and to assess assumptions made in the GIS-based material stock accounting methodology by Symmes et al. (2019).

2.2.2 Fieldwork

Fieldwork was conducted to examine the material stocks and their associated services in Grenada. This was conducted throughout various parts of the island, as shown in Figure 2.1. Attribute information was collected on GPS units including: number of levels, type of building (school, bank, home, hotel, etc.), main construction type (brick, stucco, concrete block, etc.), and building height. Two different methodologies were used to estimate building height:

- Estimation based on number of floor levels: 703 buildings were sampled and the number of floors in each building were assessed and recorded in the field.
- Estimation based on building height measurements: 64 buildings were sampled and building height was measured using a clinometer instrument. Building height was calculated based on the angle provided by the clinometer and distance measured from the base of the building (calculation shown in Appendix B.3).

After the number of floor levels were estimated, building occupancy classes were investigated based on a confusion matrix methodology for accuracy assessment and to identify where the most variability occurred. Confusion matrices have mainly been applied in remote sensing research for accuracy assessment of image classification results, especially land cover maps. Nevertheless, confusion matrices can be used when comparing any set of assumed values (usually nominal or categorical data) to verified field data to assess prediction accuracy. In this research, the fieldwork verified values were compared with the assumed building floor levels based on occupancy classes adopted from Symmes et al. (2019). This methodology seeks to examine the assumption that occupancy classes have the same number of floor levels and are associated with similar land-use types, which are indicative of the services that they provide.

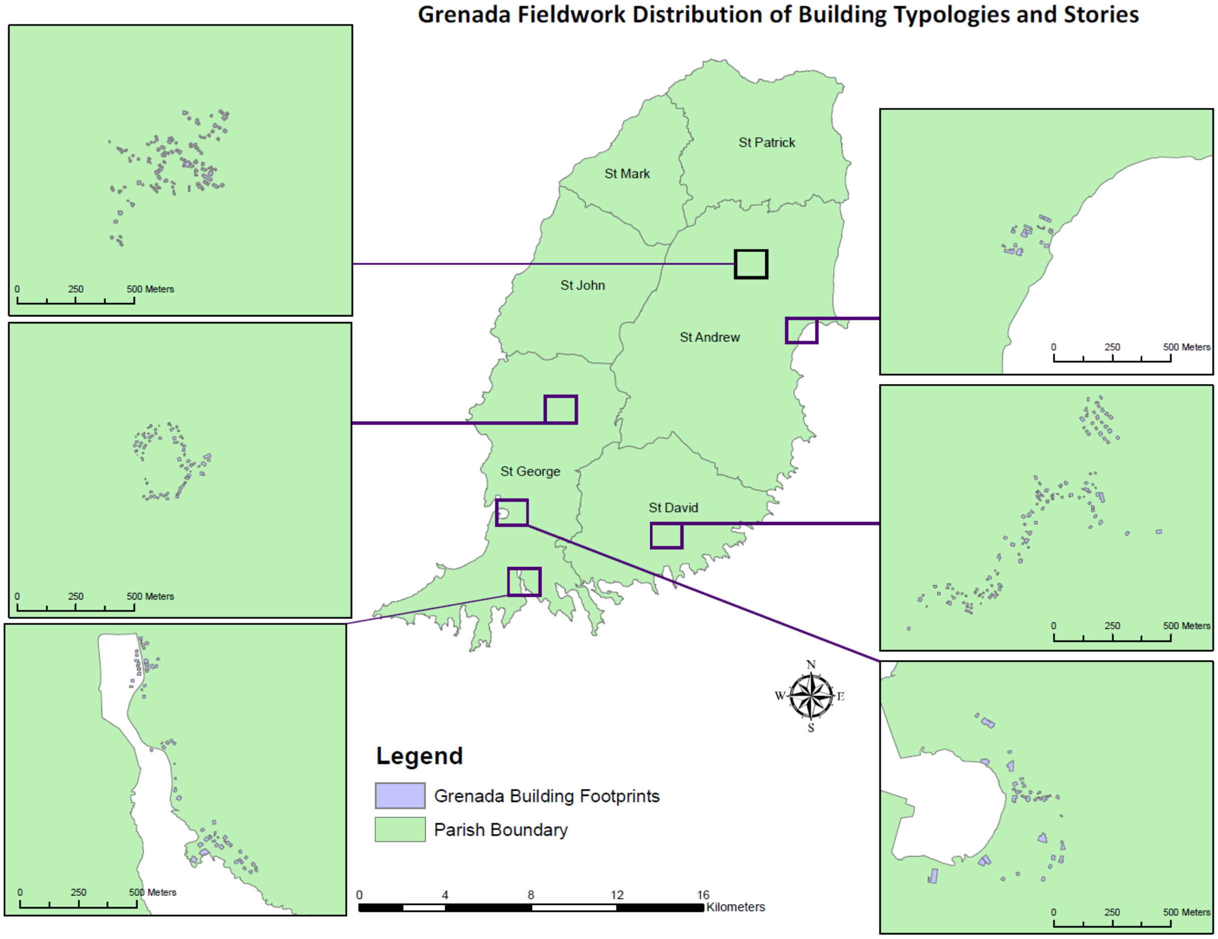


Figure 2.1: *Grenada fieldwork distribution of occupancy classes and storeys collected from various parts of the island.*

2.2.3 Material Stock Accounting

The total material stock on Grenada was calculated by mapping building attribute information to their respective material intensity coefficients. Appendix B.4 includes the derived material intensity coefficients utilized in this thesis and adapted from Symmes et al. (2019). The material intensity coefficient was multiplied by the gross floor area and the number of floor levels based on certain occupancy classes (GFA_{OC}). This equation has been used in previous GIS-based material stock studies when employing the gross floor area estimate (Mesta et al., 2018; Ortlepp et al., 2016; Symmes et al., 2019; Tanikawa & Hashimoto, 2009). The total material stock MS_i for Grenada is the sum of all the building materials that were derived from each material intensity estimate i (concrete, timber, steel, or aggregate). These material intensity estimates are divided by occupancy classes where one or more material intensity typology has been assigned ($MI_{i,oc}$).

$$MS_i = \sum_{OC} MI_{i,OC} \times GFA_{OC}$$

MS = Material stock

i = material intensity for individual material class (concrete, timber, steel or aggregate)

MI = material intensity (see chart in Appendix B.4)

oc= occupancy class (defined in Section 1.6.3)

GFA = gross floor area (the *oc* refers to how many floor levels the occupancy class is estimated at).

After calculating the total material stock, a per capita amount for the current population in Grenada was estimated.

2.2.4 Assessment of Services Associated with Stocks

To gain a further understanding of the service-stock nexus, building occupancy classes were grouped into appropriate services based on the definitions of these service groups, which were described in Section 1.6.3. ArcGIS software was used to automate the updating of these fields by creating an attribute domain class for services in which the appropriate services were assigned to their respective occupancy classes. These fields could then be summarized in a variety of ways, including services related to individual materials, total materials, and their spatial distribution in Grenada.

Scenarios for the future potential stocks within Grenada were derived using development indicators including GDP per service sector, tourism scenarios based on Statistics from the Grenada Tourism Authority (2017), and population trends. Various scenarios were developed over a time scale from 2014 to 2035 to predict the increase of building stocks in Grenada. The purpose of these scenarios was to determine which service categories were most affected by changes in building stocks in Grenada. Four scenarios were derived, including commercial, education, residential and tourism scenarios, as described in Table 2.1, and were based on the trended growth of development indicators from the current material stock account in 2014 (i.e., the base scenario).

Table 2.1: *Scenarios of predicted increases of service-related stocks based on future development indicators.*

Scenario	**Definitions and development indicators**
Base Scenario	Material stocks are unchanged from 2014. Inputs and outputs to the system remain the same.
Commercial Scenario	Material stocks based on an increase in tourists visiting Grenada both from stayover and from cruises. This scenario models an increase in commercial activity from incoming tourists.
Education Scenario	Material stocks modelled on an increase in the education service sector based on GDP contributed per service sector.
Residential Scenario	Modelled increase in residential material stock based on demand from an increase in population. Housing demands rise when total population increases. The residential scenario was calculated based on rate of population change from the base scenario and historical information.
GDP Scenario	Comparing GDP values with predicted infrastructure changes as a % of the average GDP per service sector.
Tourism Scenario	Material stocks modelled based on an increase in tourism stayovers and room availability.

2.3 Results

The following section describes the results of this study based on the methodology previously described in Sections 1.6 and 2.2. Results of testing the building height assumption for material stock estimation are described and the corresponding differences in total material stock are reported. These material stocks are then explained in terms of their relationship to services and to identify what services have the largest output per unit of service. The future of services in Grenada is assessed based on trends in building stocks in relation to the country's GDP, population growth, and tourism statistics.

2.3.1 Testing the Building Height Assumption for Material Stock Accounting

In order to assess the assumption of floor levels associated with buildings, fieldwork was conducted to obtain building heights in Grenada. A sample of 64 buildings was assessed on the ground. Figure 2.2 shows a box plot of the number of building floor levels (based on a hinge of

1.5) with their corresponding building height measurements, while Table 2.2 shows the quartile ranges of these values. These results demonstrate that there is no significant overlap between the floor levels and their building heights. This means that building heights for storeys are specifically set at different intervals and there are significant differences in building heights between the different number of floor levels assumed. Based on the results of this analysis, we can be reasonably confident in our assumptions of building heights and floor levels adopted for material stock accounting.

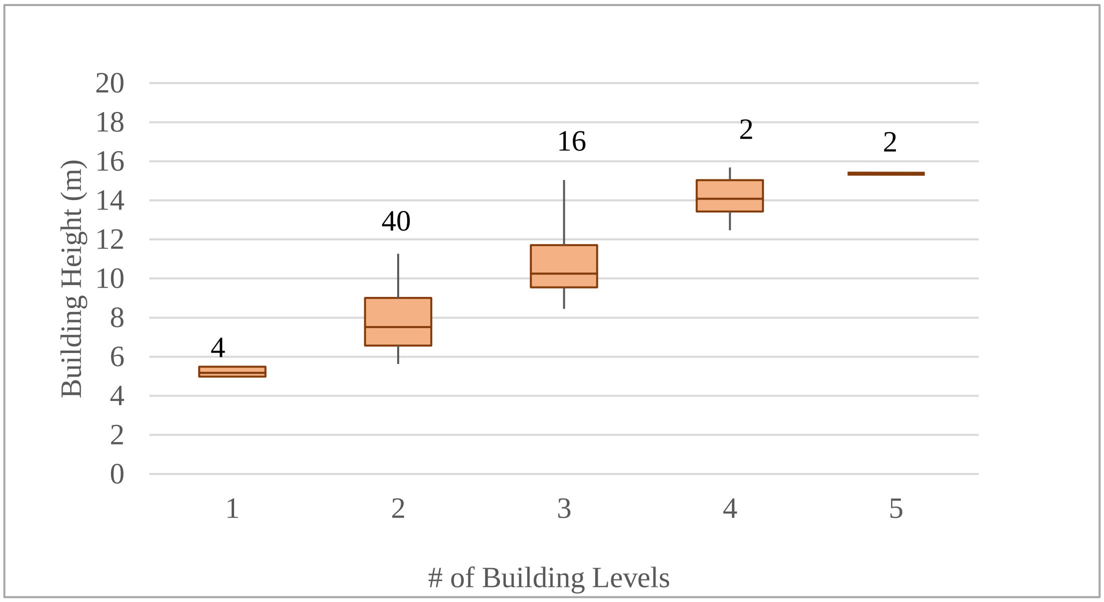
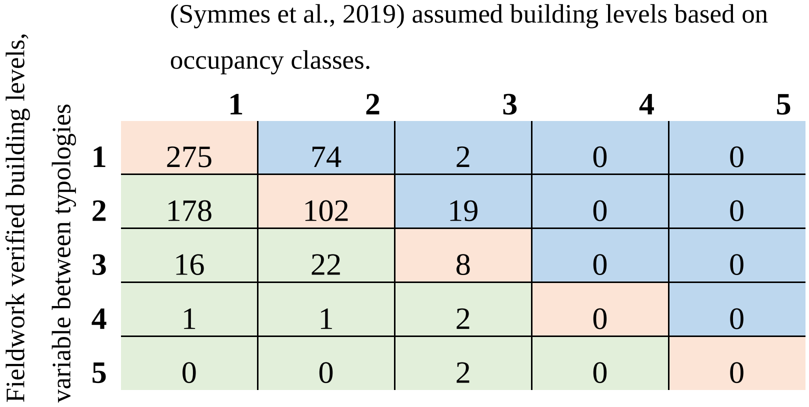


Figure 2.2: *Box plot of fieldwork building height compared to the number of building floor levels observed.*

Table 2.2: *Quartile range of building height in meters within Grenada, collected from fieldwork measurements.*

# of Building Levels	**1**	**2**	**3**	**4**	**5**
Minimum	4.98	5.63	8.45	12.47	19.73
1st Quartile	4.98	6.25	9.18	13.11	19.73
Median	5.18	7.21	9.89	13.755	19.73
3rd Quartile	5.39	8.2	10.86	14.4	19.73
Maximum	5.4	10.46	14.19	15.04	19.73

In order to assess the impact and sensitivity of height assumptions on total material stock estimation, different approaches are needed to understand how much material is either not accounted or over-estimated based on the building height assumption. During fieldwork, 702 samples were collected on building floor levels from different occupancy classes. From those 702 samples, 689 samples also included their fieldwork verified occupancy class (some are missing from the 702 samples due to misidentification of building occupancy classes in the field). The confusion matrix, shown in Figure 2.3, compares assumed or predicted values from Symmes et al. (2019) and fieldwork verified observations of building floor levels (i.e., accurate values). It was found that the most discrepancy or error in assumptions occurred between the one and two building floor categories. Symmes et al.'s (2019) assumptions of building floor levels resulted in an underestimation of 32% of total material buildings surveyed for floor levels and an overestimation of 14% of observations. Out of the 32% underestimated samples, 80% were assumed to be one storey buildings, which should have in fact been classified as two storey buildings. This results in an underestimation of 28,720 tonnes of material, which is equivalent to about 10% material stock out of the 702 samples collected.



(Symmes et al., 2019) assumed building levels based on occupancy classes.

Fieldwork verified building levels, variable between typologies

	1	2	3	4	5
1	275	74	2	0	0
2	178	102	19	0	0
3	16	22	8	0	0
4	1	1	2	0	0
5	0	0	2	0	0

Figure 2.3: *Confusion matrix of assumed versus fieldwork verified building floor levels of 702 buildings in Grenada.*

These calculated differences account for a significant amount of material stocks when considering the entire system boundary and therefore, demonstrates that more consideration should be given to improving the accuracy of building floor levels assumptions when estimating material stocks via a bottom-up approach. Out of the 14% overestimated samples, 78% were assumed to be two storey buildings, which were identified to be one storey buildings in the field. This high percentage of overestimation and underestimation in material stocks of one and two storey buildings, respectively, suggests that further investigation and verification of building heights is required. The pie charts in Figure 2.4 that compare all buildings, further demonstrates that there is an underestimation from one to two storey buildings, since Symmes et al. (2019) shows a higher percentage of one storey buildings (67%) than compared to fieldwork observed levels (50%).

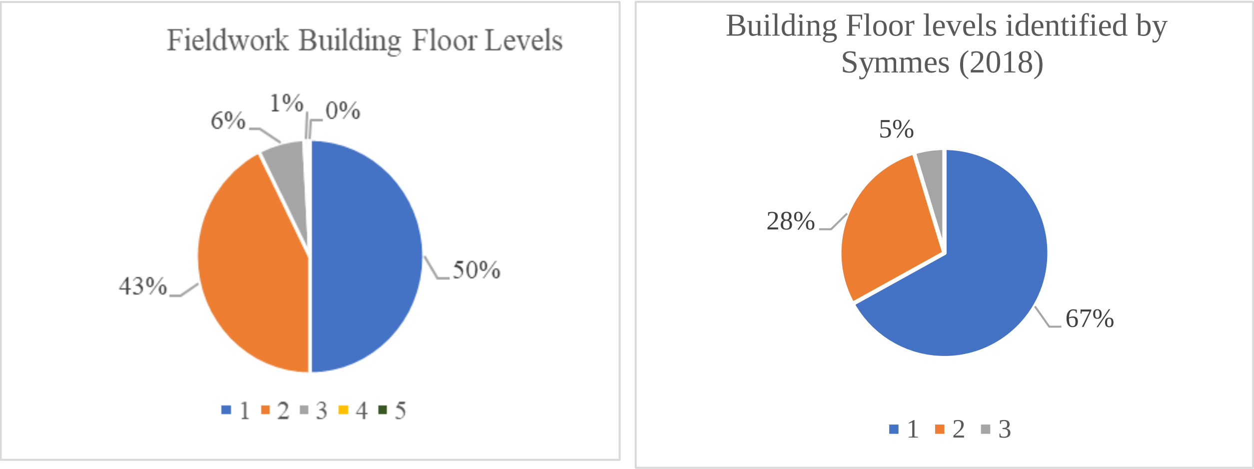


Figure 2.4: *Pie charts of the number of building levels collected from fieldwork compared to the same buildings identified by Symmes et al. (2019).*

Due to the assumption that occupancy classes have the same building levels, these occupancy classes should be assessed to determine whether any misclassification exists where the same storeys are misidentified [i.e., comparing Symmes et al. (2019) estimated values with fieldwork verified values]. A confusion matrix was generated for all occupancy classes, shown in Appendix B.5. This was done for all 689 building samples collected from fieldwork on occupancy classes. From the confusion matrix, 45% of all occupancy classes were identified correctly. The residential class accounted for 75% of total fieldwork observations. Misidentified occupancy classes for residential class accounted for 36% of total fieldwork observations and 90% of these were between rural-area single-family dwellings (code 330) and residential-area single-family dwellings (code 340) (32% of total fieldwork observations). It was shown that similar to the previous testing of building floor level assumptions, one and two storey buildings resulted in the most variability in the residential occupancy class, specifically rural-area single-family dwelling (code 330) and residential-area single-family dwelling (code 340) categories. Figure 2.5 shows that the residential class accounted for the largest differences between predicted and field-verified values. See Appendix B.4 for other occupancy class comparisons. Due to these results, it is important to adjust the assumptions accordingly. Therefore, 32% of previously classified rural-area single-family dwellings were modified to residential-area single-family dwelling classifications throughout Grenada.

Fieldwork verified occupancy classes	Assumed Values by Symmes et al. (2019)					
	242 - Rural/ residential - area commercial/ dwelling mix	310 - Urban-area single-family dwelling	322 - Low density apartment building	330 - Rural-area single-family dwelling	331 - Detached Garage	340 - Residential-area single-family dwelling
242 - Rural / residential-area commercial / dwelling mix	0	0	0	9	0	2
310 - Urban-area single-family dwelling	0	0	0	1	0	1
322 - Low density apartment building	0	0	0	0	0	1
330 - Rural-area single-family dwelling	0	0	0	154	0	0
331 - Detached Garage	0	0	0	6	0	2
340 - Residential-area single-family dwelling	0	0	4	222	0	115

Figure 2.5: *Confusion matrix of assumed versus fieldwork verified residential building occupancy classes buildings in Grenada.*

When assessing the spatial distribution of results (Figure 2.6), values that were misestimated were located in mainly residential towns, such as Willis and St. David’s. In the past, these areas were considered rural areas, but now mainly two storey residential-area single-family dwellings (code 340). Therefore, in these two areas 32% of previously coded *rural area single family dwellings* became *residential single-family dwellings*.

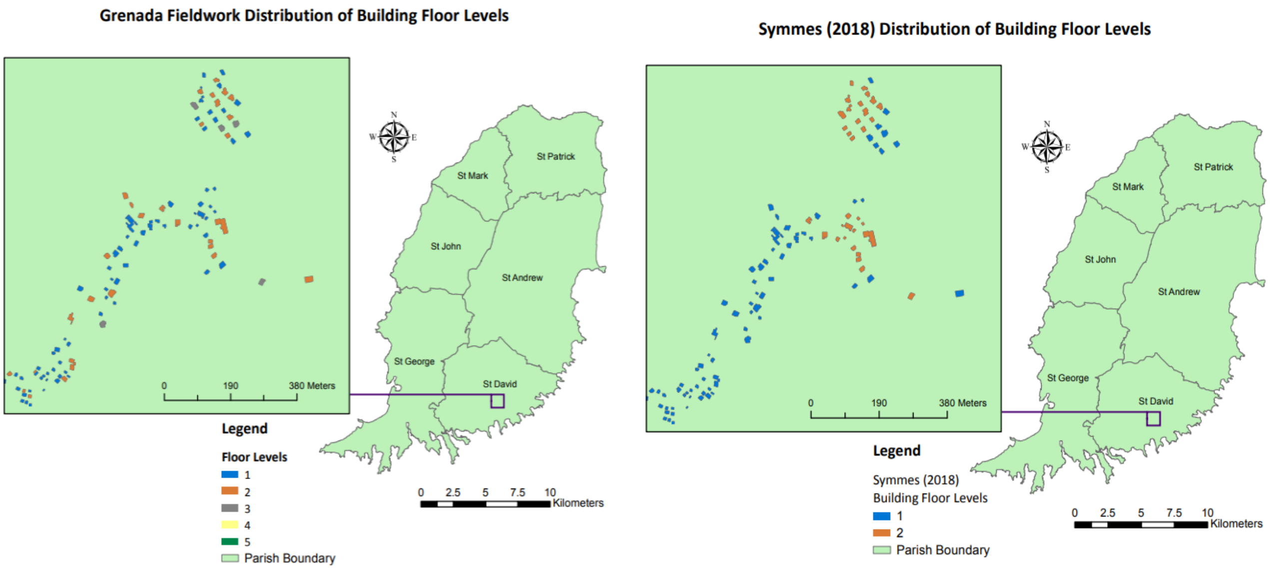


Figure 2.6: *Grenada fieldwork distribution of floor levels and Symmes et al. (2018) distribution of building floor level comparison within a study site selected from St. David's parish.*

The results of the confusion matrices were applied to the whole study area to find erroneously identified occupancy classes from Symmes et al. (2019). This methodology of conducting a confusion matrix for testing building floor levels assumptions with field observations within occupancy classes is also an important additional step that should be conducted in any material stock account methodology.

2.3.2 Differences in Total Material Stock Estimations

Total material stocks on Grenada were re-calculated based on the accuracy assessments conducted on building heights and occupancy classes in this study. This resulted in a total material stock output of 14,012 kilo tonnes, equating to 132 t/capita. Compared to Symmes et al. (2019), the resulting difference was 2,053 kilo tonnes and 20 t/capita [Symmes et al. (2019) estimated 112 t/capita]. For the distribution of key construction materials (shown in Figure 2.7), concrete was the highest at 78% of the total stock account, followed by aggregate at 16%, timber at 5%, and steel at 1%. The distribution of materials in this study differed from Symmes et al. (2019), showing a distribution of 85% concrete, 8% aggregate, 4% timber, and 3% steel. Nevertheless, these estimates show that the majority of buildings were concrete-intensive.

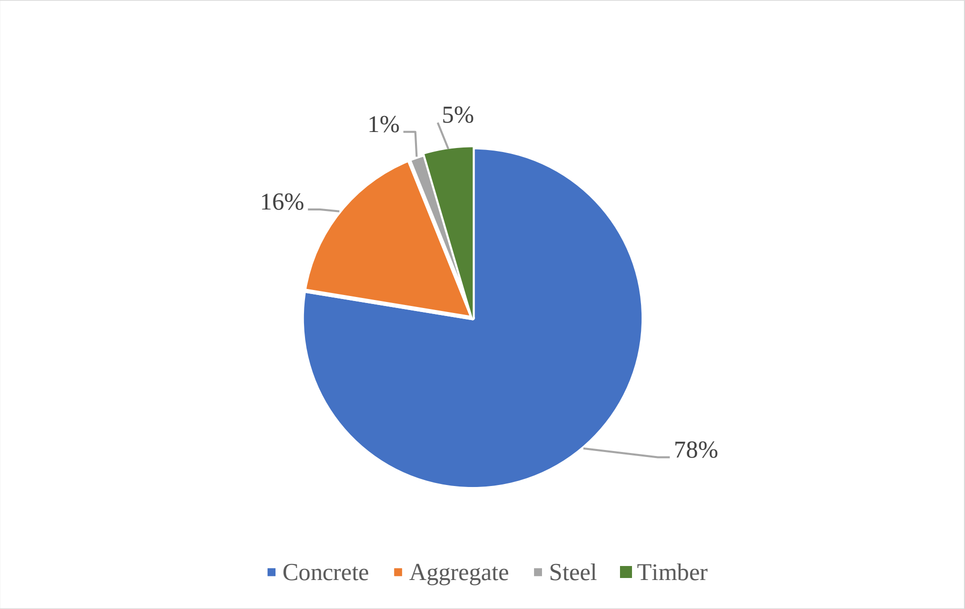


Figure 2.7: *A pie chart of key construction material distribution in Grenada.*

The spatial distribution of these stocks is shown in Figure 2.8, where the total material stock distribution in Grenada is mapped, while Figure 2.9 shows the percentage distribution in each enumeration district. From these maps, it is shown that a large accumulation of stocks is specifically found around cities/town areas and along the coast, likely related to residential settlements and tourism developments. St. George's, the capital city of Grenada, has a large amount of accumulated stock. Examining the distribution at the level of enumeration districts, it is shown that 15% of total stocks are located in and around the airport and main resort areas in the southwest of the island.

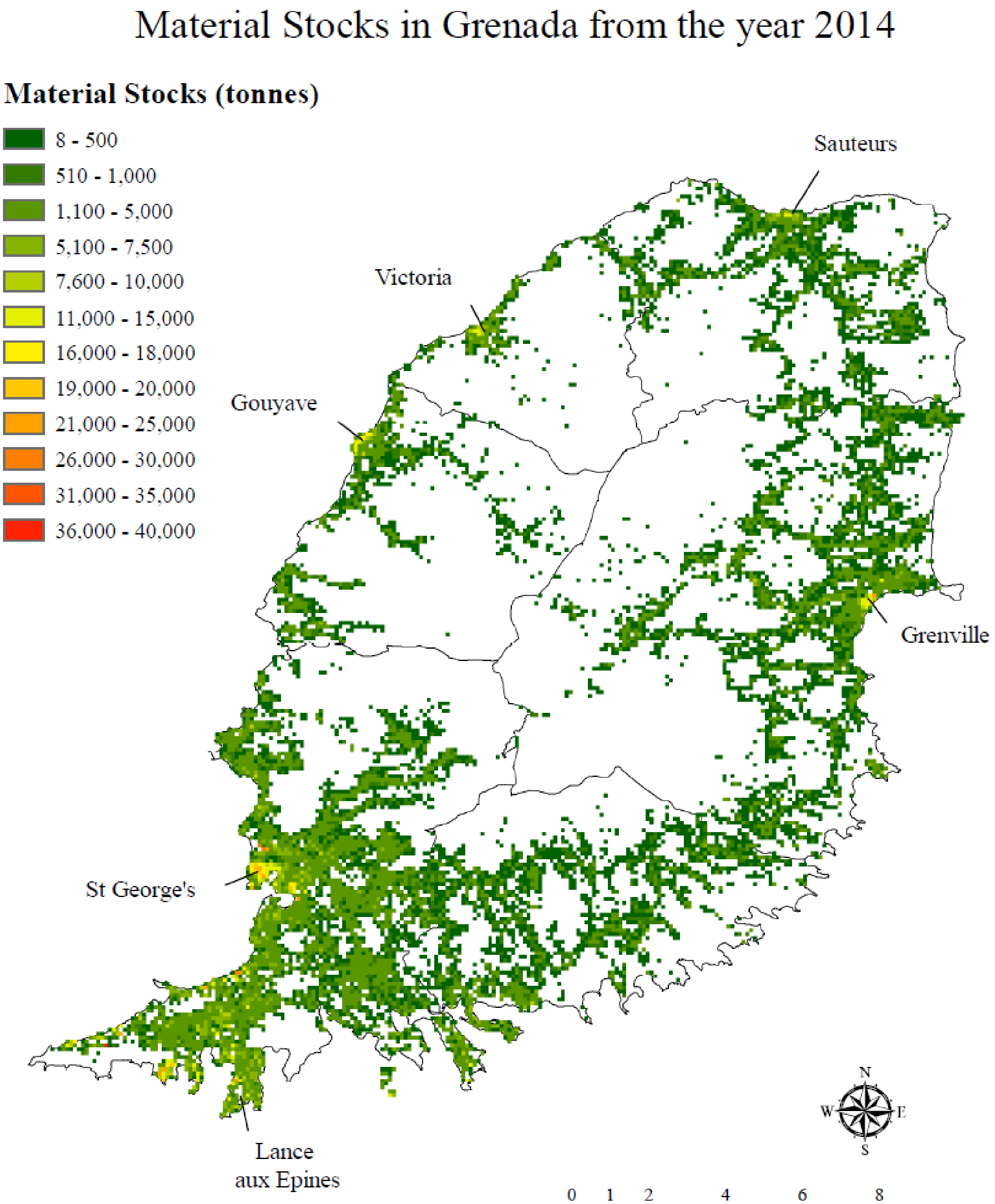


Figure 2.8: *Map of the main island Grenada showing the material stock account in the year 2014.*

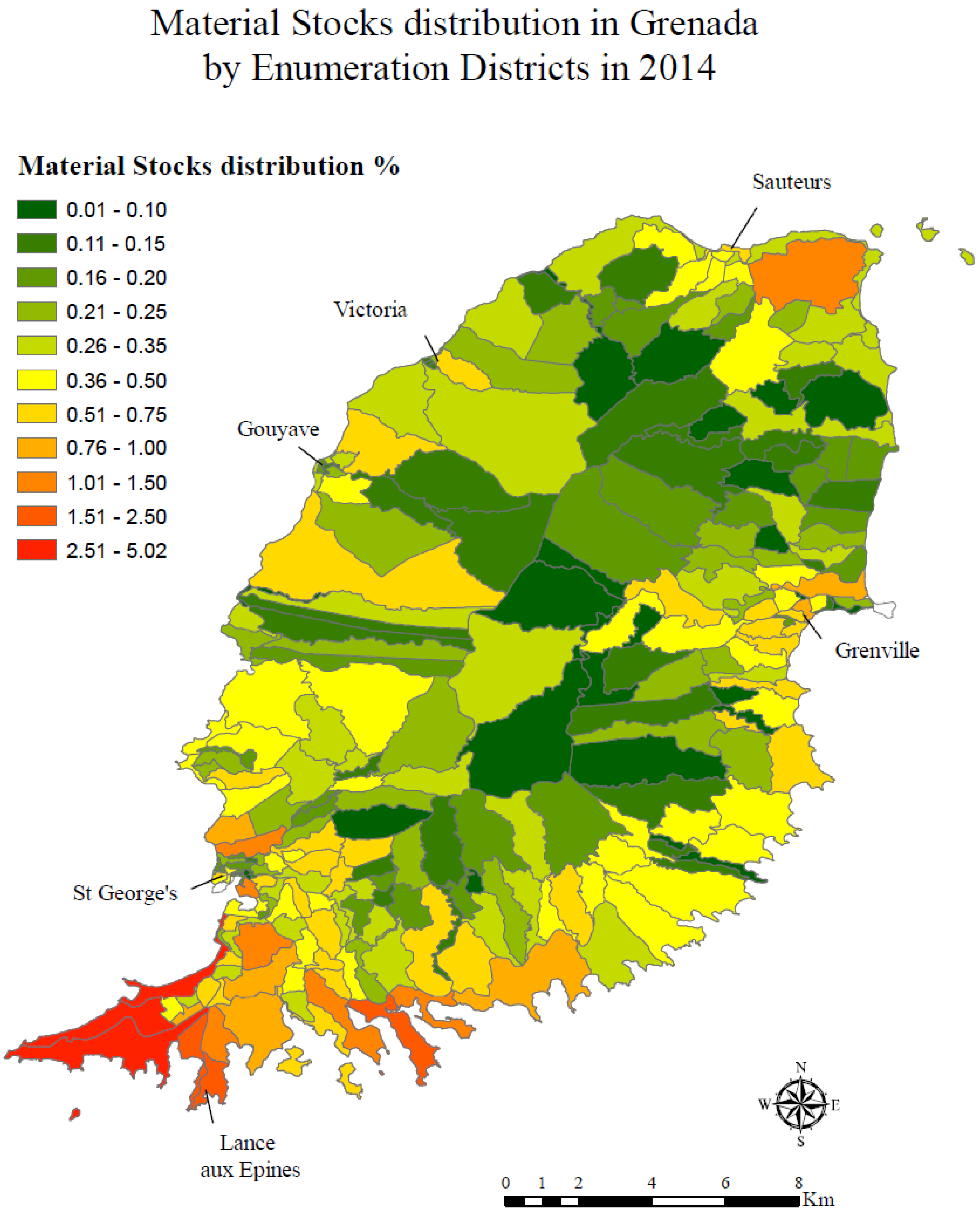


Figure 2.9: *Map of stock distribution in Grenada by enumeration district showing major city areas in 2014.*

2.3.3 Material Stock and Associated Services

The service categories associated with the newly calculated material stocks were assessed (methodology described in Section 1.6.4). It was found that the residential stocks were the highest occurring at 93.39 t/capita and a total of approximately 9.9 million tonnes, accounting for 71% of total material stocks in Grenada. Tourism was the second highest service, accounting for 12% of the total material stock at 15.9 t/capita. The top four services accounted for 92% of the total building stock with commercial and education accounting for lesser amounts (5% and 4% of total material stocks, respectively). Table 2.3 and Figure 2.10 show the distribution of material stocks across service categories, also demonstrating that agriculture was the lowest occurring category.

Table 2.3: *Material stock services of buildings in Grenada, shown by total tonnes, and materials (in tonnes) per capita.*

Services	Material Stocks (tonnes)	Materials per Capita (2014)
Residential	9,932,564.58	93.39
Tourism	1,694,507.57	15.93
Commercial	761,881.71	7.16
Institutional - Education	554,085.50	5.21
Mixed Use	258,498.42	2.43
Transportation	230,255.05	2.16
Recreational	109,102.65	1.03
Cultural	70,005.45	0.66
Institutional - Other	51,436.54	0.48
Health	38,370.83	0.36
Industrial	31,1575.79	2.93

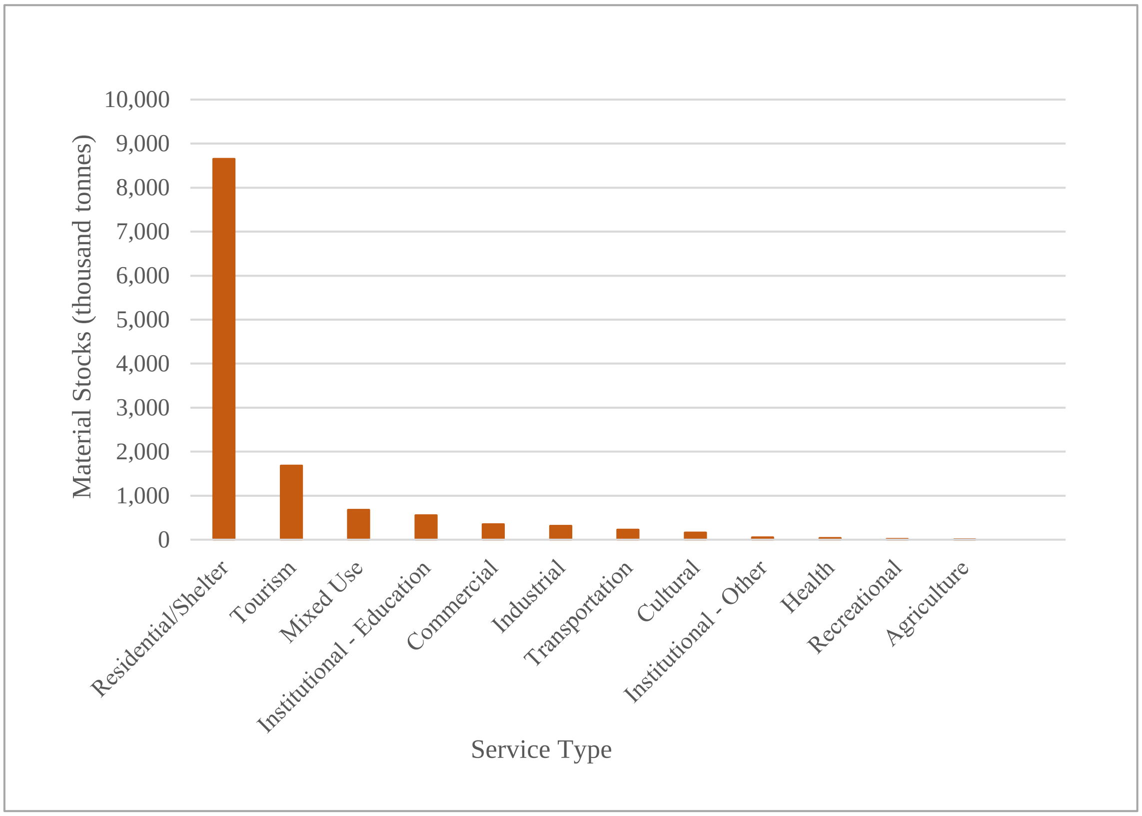


Figure 2.10: *Material stock in thousand tonnes within Grenada by service type.*

GIS software was used to map where material stocks were located and spatially distributed in Grenada. Figure 2.11 shows that tourism areas are largely concentrated in enumeration districts located near large beach locations and close to the airport. Commercial areas are located in towns and residential areas. A large education stock was observed where St. George's University is located, which accounts for 43% of the total education stock. Tourism stocks are centered around airport and coastal areas. Located along Grand Anse – an enumeration district of 0.28 km^2 – is 18% of the total tourism stock at 308,494 tonnes. Commercial stocks are highest surrounding St.George's (the capital of Grenada) and the cruise port, where 35% equating to 268,458 tonnes of commercial stocks are located. Commercial stocks are also high in other urban locations including Grenville, and Sauteurs.

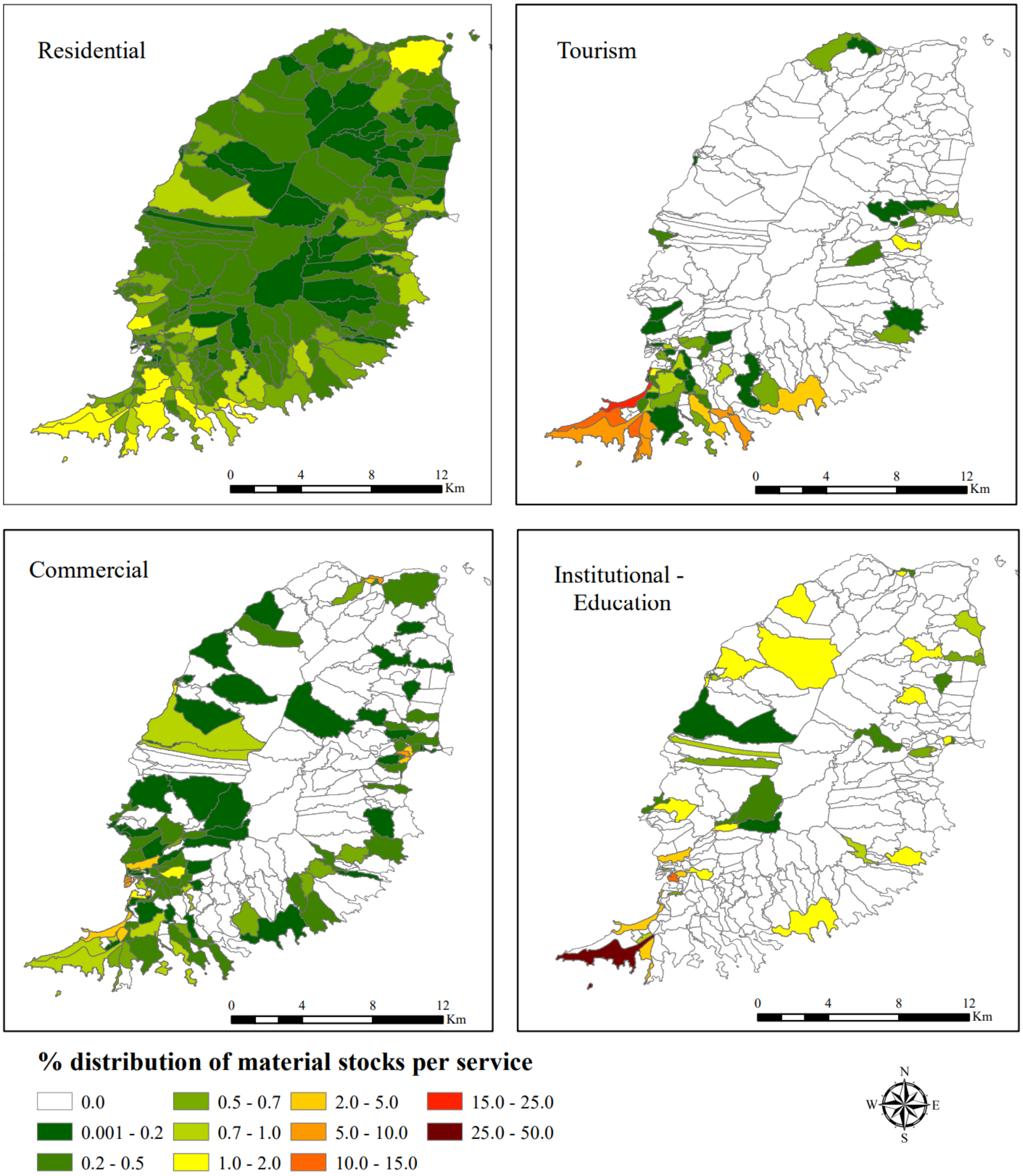


Figure 2.11: *Material stock distributions and associated services for Grenada in 2014 by Enumeration District.*

2.3.4 Development Indicators for Grenada

To further understand the service-stock nexus, Figure 2.12 shows that services have been increasing overtime (tourism, commercial, and education) from 60% in 1977 to 67% in 2017. In terms of changes overtime from 1977 to 2017, it was shown that agriculture decreased at a rate of approximately 0.3%, industry increased marginally at 0.04%, services increased at 0.2%, and manufacturing increased slowly at 0.03%.

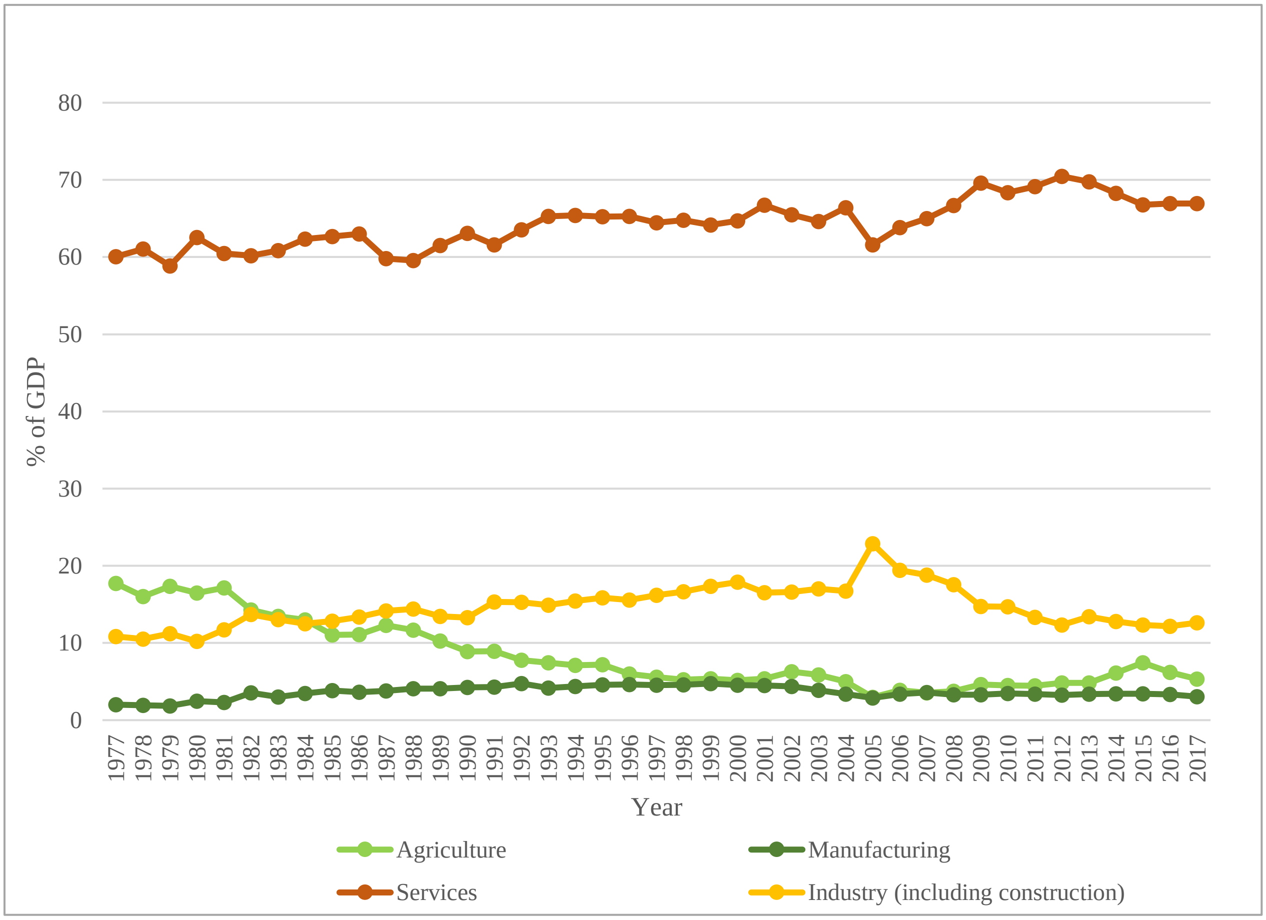


Figure 2.12: *Grenada's GDP percentage of value added per sector (data from the World Bank, 2019).*

In terms of population growth indicators, Figure 2.13 shows that Grenada's population has grown 0.3% from 1961-2017. There have been gradual changes in population overtime with decreases noted in 1969-1979 and 1987-1991, but the population has slowly increased in recent years. There was an emigration in 1969-1979 which an expert eluded was due to a boom of the oilfields in Trinidad and Tabogo and therefore Grenadians moved for work. Another decline in population occurred in the late 1980's -1991 which was likely due to political unrest and economic problems (Britter, 2014; Pool, 1989). In the last 15 years Grenada's population and GDP has been slowly increasing.

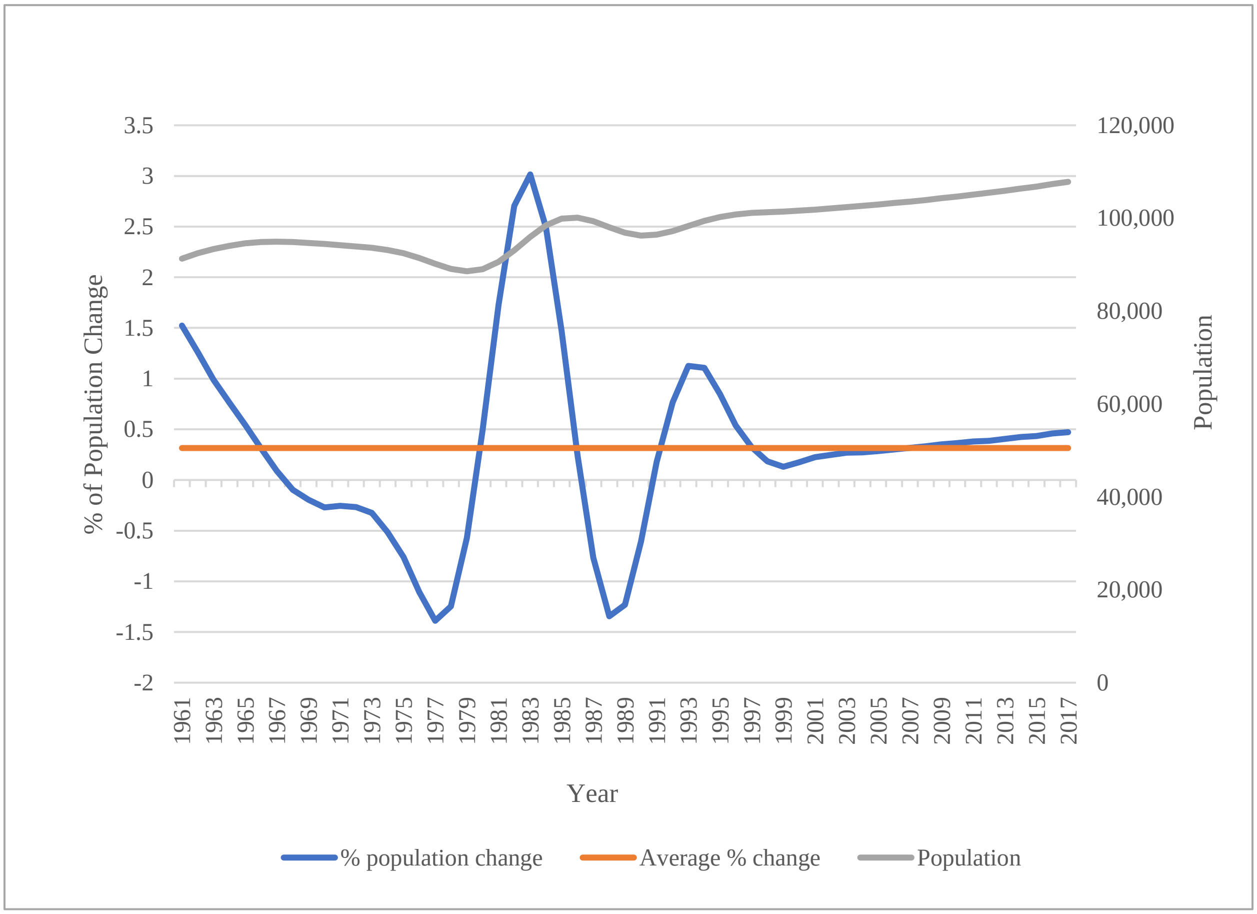


Figure 2.13: Population change in Grenada overtime from 1961 to 2017. Total population represented on the right axis.

Tourism data was also examined in Figure 2.14 to assess whether tourism has increased or decreased in recent years. According to data provided by the Tourism Bureau (2018), tourism stayovers have been increasing since 2009 by approximately 3% each year (including predictions). From 2009 to 2018, the actual increase (without predictions) was an average of 4% each year. There was an average of 1.3% increase in the number of total rooms available from 2009-2018 which implies that extra infrastructure was added, resulting in an increase in building stocks. A spike in available rooms occurred in 2012-2013, which according to interviews with local experts was due to Sandals resort construction, and this is still steadily increasing.

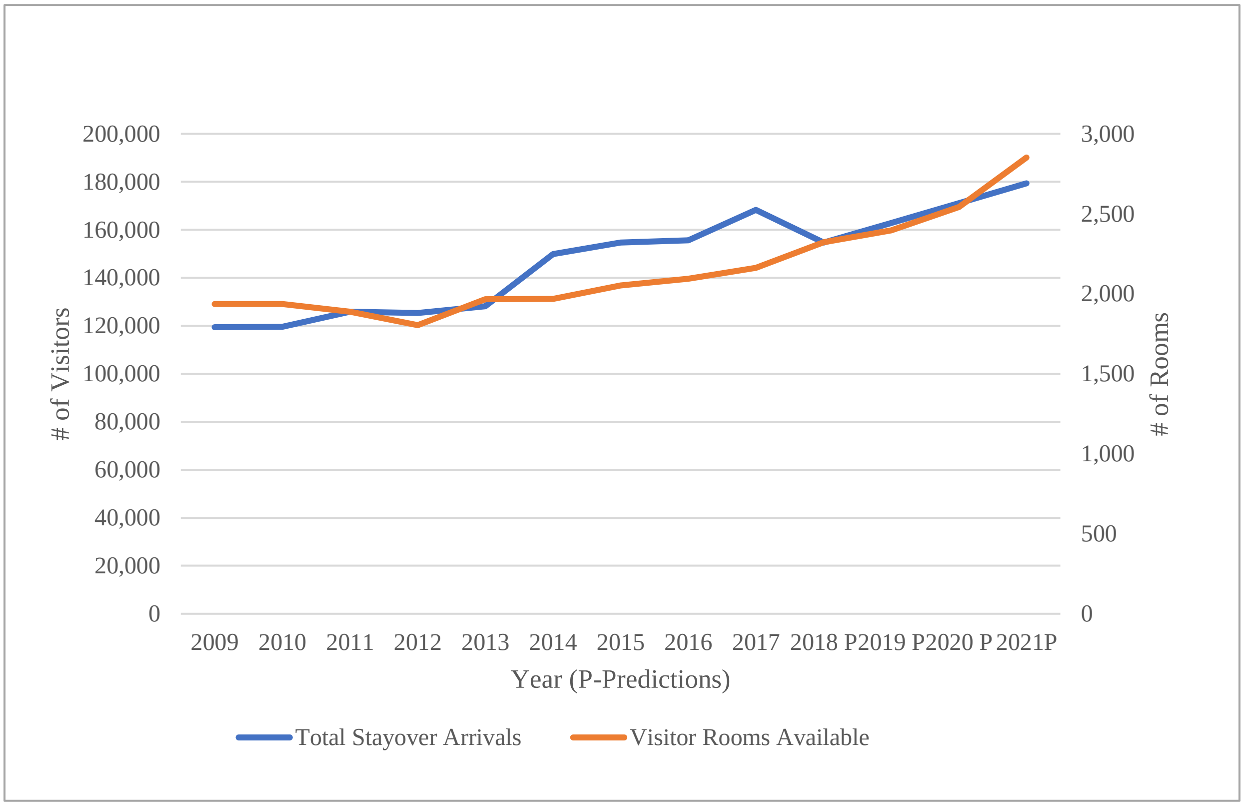


Figure 2.14: *Tourism stayovers and increasing room availability in Grenada.*

2.3.5 Changes in Services: Scenarios for Grenada

In order to determine what development indicators and their scenario predictions mean for building stocks, scenarios were run according to the methodology described in Section 2.2.4. These scenarios were based on a percentage change of GDP, population, or tourism stayovers/visitor rooms available. Each of the scenarios were run to assess potential increases to building stock in Grenada overtime. The modelled percentage of change used for potential fluctuations within the material stock outputs are shown in Table 2.4. These scenarios were modelled using the calculated 2014 material stocks as a baseline and then for years after, the previous years were used as the new baseline for the stocks. The formula generated for calculating the scenarios over time was:

$MS_{/year}$= material from the previous year x the change indicator

The change indicators were derived based on the development indicators from Tables 2.12-2.14. For example, GDP for the industrial sector increased by 0.04% and therefore, material stock increases associated with industrial services were calculated to be the material stock from the year before multiplied by 0.0004. It is important to note that these scenarios consider that the increase is directly related to the increase in GDP and population. However, this is not always the case, since there are more factors that can potentially influence the increase of material stocks. Constraints of this methodology and future factors to consider are discussed further in Section 2.4 at the end of this chapter.

From Table 2.4 the first GDP scenario represents the change in GDP from Figure 2.12, divided equally into each of the respected service classes. GDP is realistically not split equally between all service classes; therefore, a second GDP scenario was run considering GDP contribution from Education and Tourism. However, this is conducive if the gained revenue from these sources are also re-invested into infrastructure for these services. Therefore, both GDP scenarios were run. The first tourism scenario was based on the number of rooms available from the percentage change outlined in Figure 2.14. The second tourism scenario was the number of tourism visitors. Commercial service class was also considered to change at the same rate because increasing visitors would boost commercial activities. All other service classes considered the first GDP scenario percentages change for those that did not change from scenario to scenario based on inflation. The Residential scenario only considered the percentage of population change over-time and all other classes remained the first GDP scenario. Following these trends over-time can be an important way to see if there are shifts in the economy or where future stock-services are changing.

Table 2.4: *Percentage of change used for deriving each scenario and service class when modelling changes to material stocks.*

Services	**1. GDP Scenario (%)**	**2.Current % of total GDP (Considering Education and Tourism)**	**3.Tourism Scenario based on # of Rooms available (%)**	**4.Tourism Scenario Distributed by Tourism # of Visitors**	**5.Residential Scenario (%)**
Residential	0.02	0.02	0.002	0.2	0.32
Tourism	0.02	0.05	1.3	3.2	0.02
Commercial	0.02	0.02	0.02	3.2	0.02
Institutional - Education	0.02	0.04	0.02	0.02	0.02
Mixed Use	0.02	0.02	0.02	0.02	0.02
Transportation	0.02	0.02	0.02	0.02	0.02
Recreational	0.02	0.02	0.02	0.02	0.02
Cultural	0.02	0.02	0.02	0.02	0.02
Institutional - Other	0.02	0.02	0.02	0.02	0.02
Health	0.02	0.02	0.02	0.02	0.02
Industrial	0.04	0.02	0.04	0.04	0.04

Running each of the scenarios showed different fluctuations in material stocks over the 20-year period (refer to Figure 2.15). For the tourism scenarios, shown in Figure 2.15a, which modelled an increase in tourism-related services compared to other service sectors, the greatest change in material stocks was observed over time. This scenario suggested that an extra 1.6 million tonnes of material stocks would result (increasing 48%), while the number of room availability statistics generated about half of the material stock with an extra 528,000 tonnes (increasing 24%). Examining the future stocks through GDP percentage of tourism at 23.3% (World Travel and Tourism Council (2018)) and dividing that by the service distribution of the GDP rate of change gave a final rate of change at 0.05% resulting in 17,881 tonnes (increasing 1%). The tourism scenario also showed that commercial-related stocks would increase by 714,000 tonnes (increasing 48%).

For the GDP scenario, increasing the commercial stock, outlined in Figure 2.15b by the change of GDP from all services (0.02%) resulted in an increase of 3,207 tonnes (only increasing by 0.4%). The same result occurred for Institutional-Education services, shown in Figure 2.15c, which observed an increase of 2,332 stocks (increasing 0.4%). However, when running education by its individual GDP percentage, at 20% of GDP (OECS, 2017), it was found that stocks doubled to 5,847 tonnes with an increase of 1% over time. The residential class, outlined in Figure 2.15d, changed by 6.5% with a total addition of 689,000 tonnes when considering population change. However, when considering GDP, these stocks only went up by 0.7% with 69,000 tonnes of additional material stock.

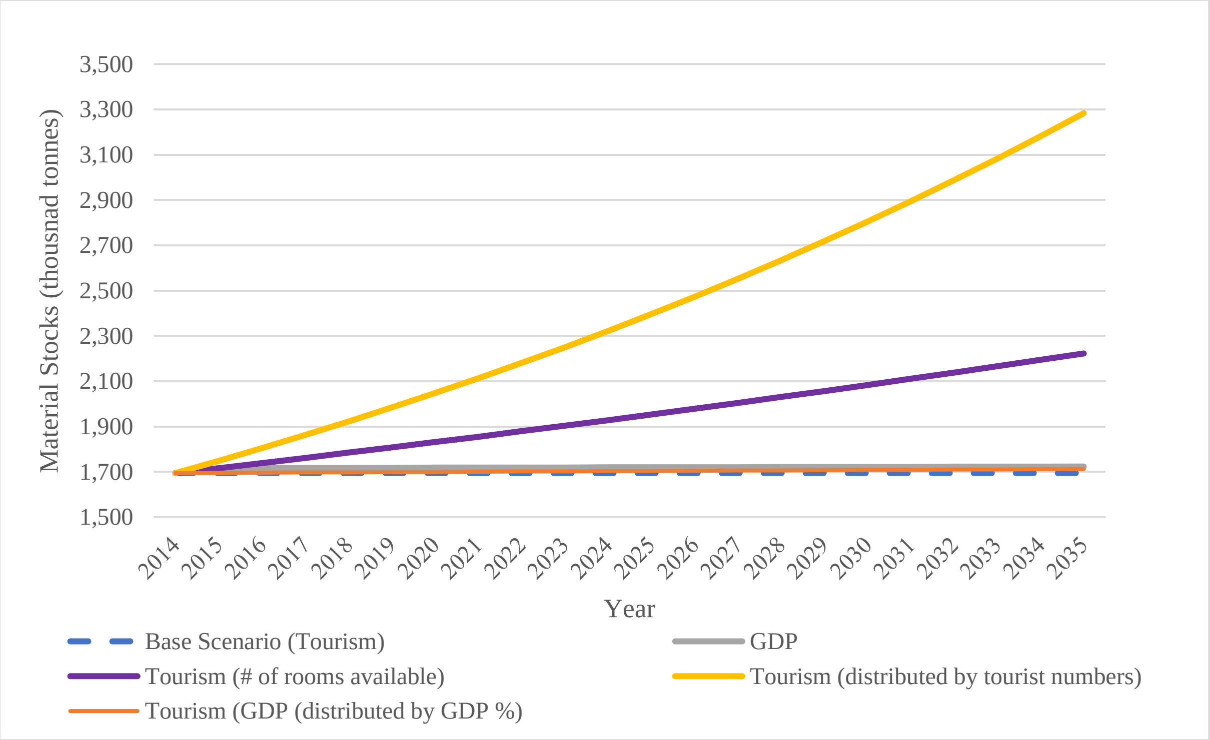


Figure 2.15a: *Tourism MS increase in stocks over a 20- year span.*

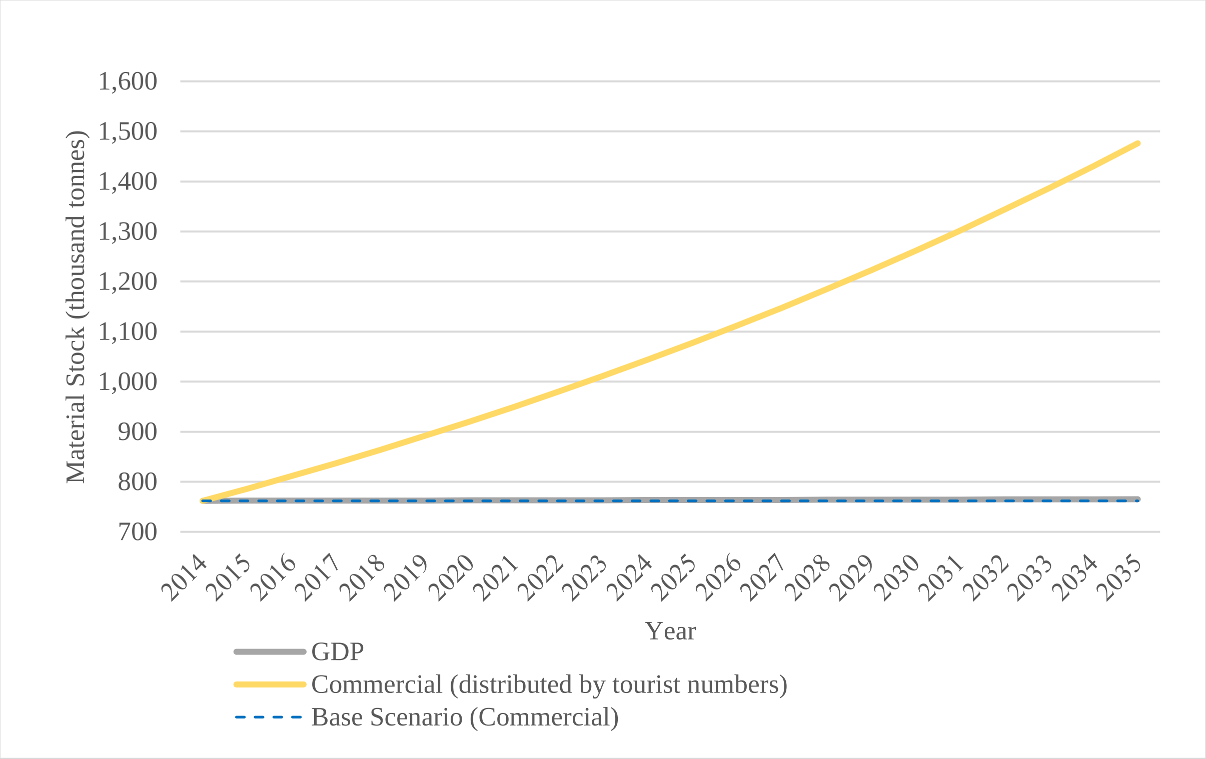


Figure 2.15b: *Commercial MS increase in stocks over a 20-year span.*

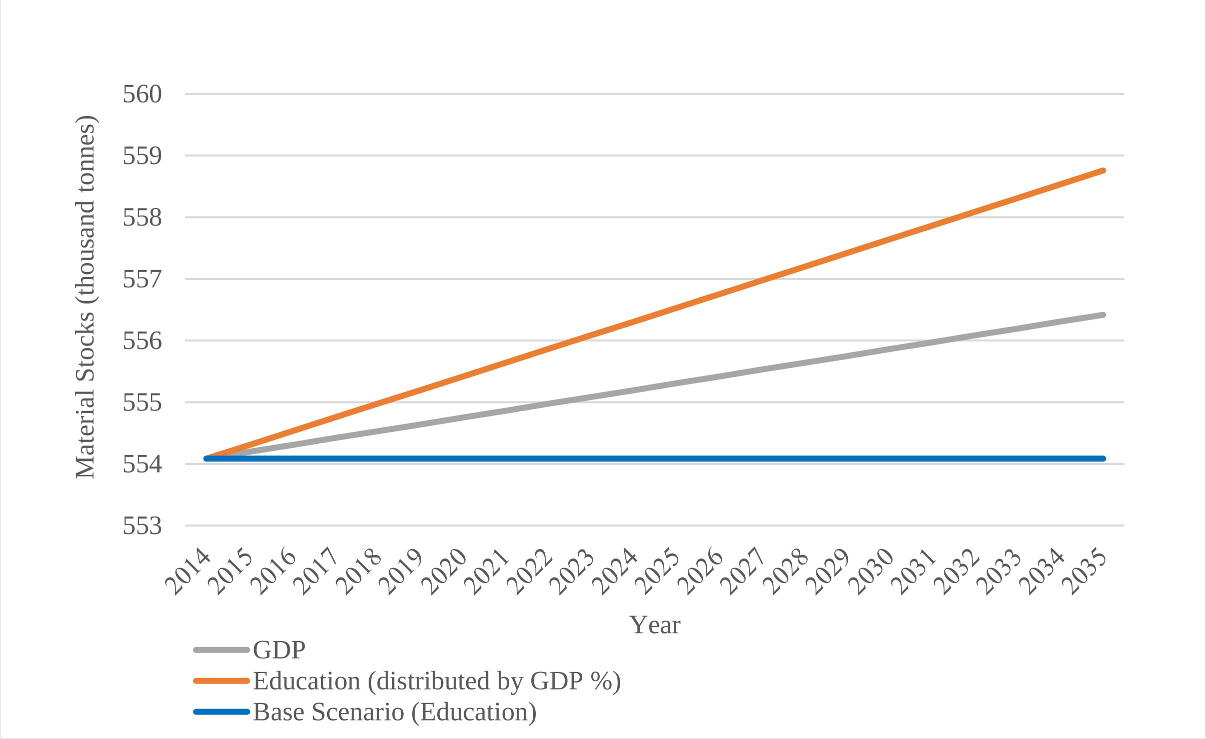


Figure 2.15c: *Education MS increase in stocks over a 20-year span.*

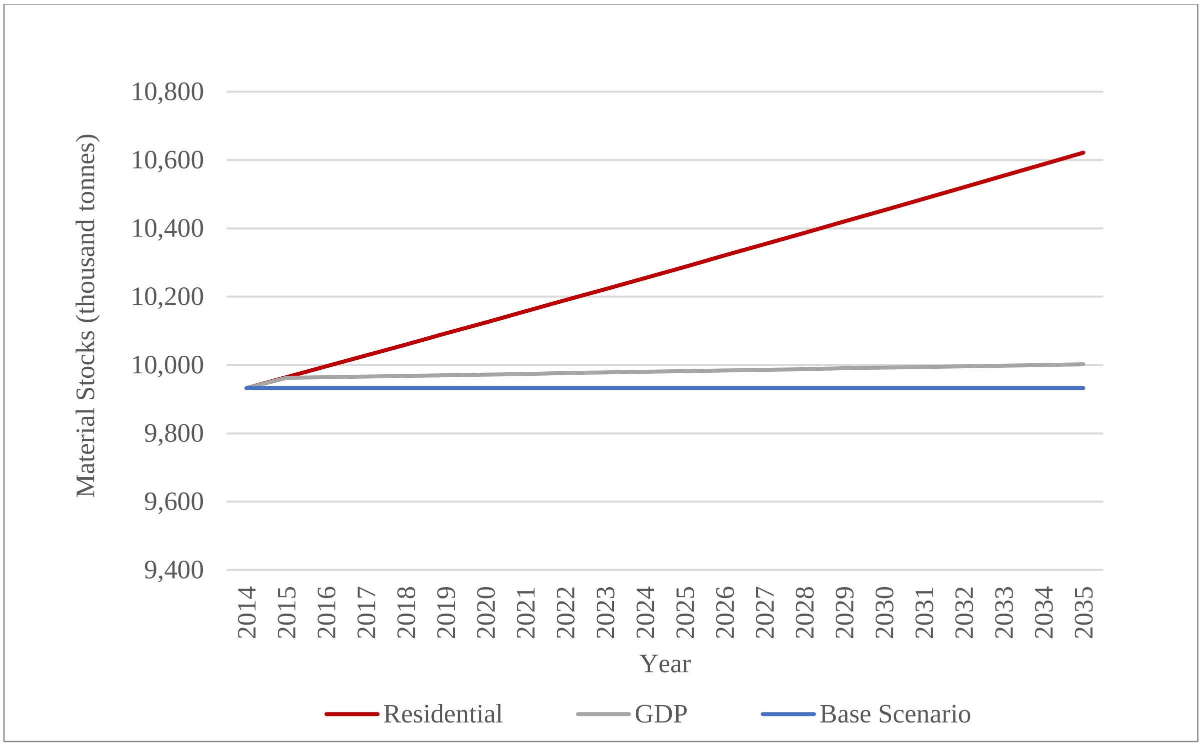


Figure 2.15d: *Residential MS increase in stocks over a 20-year span.*

Figure 2.15: *Graphs showing different scenarios when running potential increase of material stock based on indicators aforementioned.*

2.4 Discussion

The following section discusses the results from the MS analysis and services in Grenada and what it means for the small island nation. This section includes what the accumulated stocks and their associated services suggest and potentially why these results are occurring as well as limitations and future work. For further discussion of what this research means in a broader context and how it compares to other similar studies, see Chapter 4.

2.4.1 Material Stocks and Associated Services

Grenada MS accounting resulted in a total of 14,012 kilo tonnes of stock equating to 132 t/capita. Of these stocks 93.4 t/capita was associated with the residential occupancy class, and 15.9 t/capita for tourism. This is a large amount of stock per capita for tourism and drives up the total tonnes per capita in the country. In Grenada, a large portion of services are required for a ‘floating population', since a large percentage of the country's GDP is from tourism and education activities. Grenada has a 'floating' population that visits each year and is almost three times the size of the residential population at 467,817 in 2017 (Grenada Tourism Authority, 2017). Of this population, 64% come in from cruises, and therefore, do not utilize any hotels or buildings for stayover accommodations. However, 36% of visitors or 168,368 people stay overnight in hotels. The average length of stay is about 9 days (Grenada Tourism Authority, 2017); therefore if a semi-permanent population of visitors is considered and divided evenly throughout the year, this means that at any one time there are about an extra 4,106 people at a 'snapshot in time'. Considering the floating population as an addition to the current population, Grenada has a stock roughly equivalent to 126 t/capita. This does not consider the people coming in from the cruises, where commercial areas are built up to accommodate such travellers; or education, in which international students make up 89% of the student body at St. George's University (SGU, 2019). MS accounts do not consider that most hotels and commercial areas are built for this large influx of people, therefore, Grenada's stock account per capita is quite high even though most of the buildings used for these services are not used by the current population.

The top four services in terms of the building stock within Grenada make up 92% of the total stock. These were residential stocks at 71%, tourism at 12%, commercial at 5% and education at 4%. It is interesting to note that a large majority of Grenada's GDP is from tourism, commercial, and education. A lot of these services are provided to the visiting population as 43% of the education stock is from St. George's University. Approximately 35% of the total commercial stocks are located around St. George's where the cruise ships dock. This study provides a new perspective when considering how materials are distributed in societies, especially SIDS, where a large portion of their material stock is used for visitors.

Built environment stocks represent an extensive potential reservoir of secondary raw materials and measuring them accurately can help to manage waste disposal at the end of a building's life cycle. It is important to account stocks as accurately as possible and evaluate assumptions in material stock literature to help determine potential mis-accounted stocks due to assumptions. This study provides a method of evaluating the building height assumption of the GFA approach in material stock accounting previously developed by Symmes et al. (2019). There will inherently be assumptions when conducting material stock accounts and the most accurate way to address these assumptions is conducting fieldwork on each individual building. However, it is not efficient or feasible to conduct fieldwork on each individual building within an area of interest. Therefore, improving height information through processing of remote sensing data will provide a third dimension, allowing for more accurate accounting of building volume. This addresses the assumption that buildings in the same occupancy class have the same number of levels. This is especially important to consider in SIDS where the rate of recovery is slower, so more accurate accounting of individual buildings through height information aids disaster risk planning in individual communities. In Grenada, it was found that from Symmes et al. (2019) original stock estimate (using the assumption all occupancy classes have the same number of storeys) approximately 32% of fieldwork samples were underestimated resulting in 28,720 tonnes of materials not accounted. This was an overall effect of 2,043 kilo tonnes or 20 t/capita when applying this to the whole study area. Considering end of building life cycle or effects from a potential natural disaster, large amounts of potential material outflow not accounted for can have detrimental impacts to waste facilities. In SIDS this can also mean large monetary implications when cleaning up after natural disasters as construction wastes would be higher than originally budgeted. Therefore, accurate accounts of MS studies are needed to provide accurate statistics to manage final amount of waste disposal (knowing potential recycling amounts), accurately predicting waste outflows, prediction of potential stock affected from natural disasters, and future development.

2.4.2 Spatial Distributions of Stocks and Services

Examining these stocks spatially shows that the majority of Grenada's population resides along low-lying coastal areas, since all major towns are located along the coast. A large MS hotspot was observed in St. George's and Grenville, two major cities in Grenada. Looking at the stock-services by enumeration district, different patterns occur spatially. The institutional-education class shows that 43% of total educational stocks are located in the south-east, where St. George's University is located. The rest of the distribution is spread throughout Grenada, likely where local primary and secondary schools are located. Commercial areas are distributed throughout Grenada, but typically found in areas where residential land use is also higher (i.e., around towns and village areas). A large portion of tourism stocks are situated in the southeast part of the island where the airport, large resorts, and large beach areas (Grande Anse beach) are located. Specifically, the Grand Anse enumeration district – a 0.28 km^2 area – where 18% of total tourism stocks are found.

Knowing where these stocks are located and the distribution of these from a service perspective helps to address a key strategy of the Grenada Government in *assessing the vulnerability of assets* (Government of Grenada, 2017). It provides insight into the distribution of these stocks to determine where vulnerabilities lie, especially when considering sea-level rise and climate change. If another natural disaster like Hurricane Ivan were to occur, the agglomerated service stock areas could devastate Grenada and put the economy in a decline until re-construction can occur. Symmes et al. (2019) found that in a 3-metre sea-level rise scenario in Grenada, 33% of tourism MS will be exposed, 37% of commercial/industrial MS will be exposed and residential buildings are the least vulnerable at 5%. Being able to assess the spatial distribution of MS can be a valuable tool, especially since planners can utilize these tools to locate accumulated materials, which can be useful information for planning for future sea level rise or other extreme weather events.

2.4.3 Potential Future Stock-Service Changes

In order to better manage these material stocks and consumption patterns, scenarios were run to assess potential future changes in services over-time. Utilizing the systems history of past indicators including GDP, tourism statistics, and population can help understand the potential of future stock scenarios (Wiedenhofer, Steinberger, Eisenmenger & Haas, 2015). The scenarios generated were based on a linear relationship between building stocks and their respective change indicator, therefore, if one increased then the other increased. However, this is not always the case. For example, if tourism visitors increase, this could potentially result from an increase in visiting cruise ships, which would have less impact on accumulated material stocks in Grenada. The units of service would also be from different sectors, since more commercial buildings would be required than hotels. Therefore, the increase in the number of rooms can be deemed to be more likely to occur and result in an increase of 538,000 tonnes by 2035. This is more likely to occur than the increase in tourism numbers, that doubled tourism material stock at 1.6 million tonnes, because visitors could be staying on a cruise ship, be students visiting, or coming to visit family and therefore not staying in hotels. This increase of material stock for tourism is already occurring as evident during fieldwork when two large scale resorts were observed being built (Silver Sands and Kawana Bay). Commercial stocks increased by 48% or 714,000 tonnes when considering an increase in visitors. Education increased by 5,847 or 1% when considering its total contribution to GDP (20%) in Grenada. Considering GDP rate changes over time commercial stocks increased

0.4%, educational services increased 0.4%, and residential stocks increased by 0.7%. Examining these services and stocks over time will help to predict how much of Grenada's economy and resource flows will be driven by these different services. These potential stock changes can also lead to a shift in GDP, resulting in a reliance on tourism as Grenada's primary source of income. Stocks and the services provided are closely linked to emissions and resource use, thus knowledge of the drivers and patterns of these dynamics can help predict future flows (Lanau et al., 2019). However, more work needs to be done to better understand the relationship between services and stocks and to understand why these relationships occur. Being able to predict services and to integrate past trajectories can help predict the accumulation of material stock and their functions in the future, helping with the maintenance of and shift towards more energy-efficient systems (Haberl et al., 2019). By utilizing this information, planners and policy makers can provide services that are needed in the future by employing buildings currently used for services that are no longer needed (Lanau et al., 2019).

2.4.4 Limitations and Future Work

Limitations are described in the following section including recommendations for future research. In terms of the methodology, conducting gross floor area estimates inherently have assumptions in determining a building's height (Mesta et al., 2018; Symmes et al., 2019). Comparing the classification system developed by Symmes et al. (2019) (i.e., assigning the number of levels based on the occupancy class) to the fieldwork collected data, it was found that most of the building heights fall within a certain height threshold and are at least differentiable. This analysis verifies that this is a good overall approach if building levels are relatively uniform or consistent throughout an occupancy class. The fieldwork observations also suggest that significant variability of heights exist even within building occupancy classes, which could have potential impacts on material stock estimates. This offset can have significant impacts when managing waste outflows, especially in SIDS where large scale vulnerabilities are inherent due to enhanced effects from climate change. Therefore, it is important to address these assumptions as this can have impacts on the management and estimation of waste flows, as well as identifying where vulnerable areas are located.

SIDS tend to be limited in terms of data availability and resources, hence creating an accurate and comprehensive account of MS and services can be challenging and involve collecting copious amounts of primary data in the field. The data that is available can also face challenges of errors and accuracy. The planning department of Grenada does not have an up to date GIS layer for building footprints and the most up to date was for 2014. Therefore, this layer does not consider new builds after 2014, which were observed during fieldwork data collection. Currently a data footprint layer does not exist for Carriacou and Petite Martinique, the small islands that are part of Grenada, therefore, only the main island of Grenada was considered within the MS account in this study. This provides challenges when examining services and assessing how to effectively manage each part of Grenada from a planning perspective. In terms of services that the tourism industry and St. George's University provide, each has been growing rapidly and new buildings may not have been captured in this analysis due to older data sources. One expert reported that within the last 10 years, there were at least one or two large hotels or additions to existing hotels being constructed each year. Therefore, new constructions of both non-residential and residential buildings post- 2014 were not included in the MS stock account in this research.

The local government of Grenada has recently flown a LIDAR survey that would be useful for improving gross floor area calculations in future studies; however, this imagery was difficult to access due to data sharing issues and cost (Ministry of Finance, 2017). Developing a new building footprint layer from LIDAR survey data is also a very technical and time-consuming process, which requires time to develop and may form a future direction of research beyond the scope of this study. Future efforts to produce an updated building layer with accurate height information will be important to improving material stock estimates of this study, as well as making results more conducive for disaster risk management and sustainable development planning.

In future studies, having more defined attributes for buildings such as the year of construction will assist with assessing changes in material stocks over time. Having this type of information would also indicate the flows of different building materials to certain geographic locations. This also has planning implications as the building code can change over time. Being able to examine what year buildings were constructed will help identify vulnerable areas where buildings have yet to be retrofitted for better resiliency. On an economic scale, it would also be interesting to examine affluence over-time and whether it relates to an increase in material consumption used for buildings on the island. A local expert explained that in Grenada when a house is built, landowners tend to build one floor at a time as income is available. Therefore, a large percentage of residential homes converted from 1 storey to 2 storeys is based on income. Examining material stock-services on a temporal scale will also help to assess whether Grenada's economy is shifting further towards tourism or whether there is growth in other service sectors. From GDP indicators, it seems that Grenada is slowly shifting into a service economy, since agriculture has been steadily decreasing and manufacturing and industry are remaining fairly steady. Assessing these shifts over time will help determine local economic trends further and how local communities can plan for sustainable growth.

Chapter 3: Accounting for Building Stocks and Services in a North American Context: A Case Study of Kitchener, ON, Canada.

3.1 Introduction- The Urban Context

The world's population has been moving through a transition in which most of the world's population is now living in urban areas. Urbanization rates have been increasing in the past couple decades as most cities house over 50% of the population, which is expected to increase by 60% in 2030 (Clark, 2003, Sahely et al., 2003). The large rise in urban populations has resulted in doubling of the world's present urban infrastructures. These urban areas can be defined as socio-economic systems where not only energy, waste services, housing services, and transportation are needed, but it is also an integrated system with increasing influxes of innovation, environmental concerns, production, construction, and wealth (Clark, 2003; Reyna & Chester, 2014; Kennedy et al., 2007). In light of this, cities face considerable infrastructure issues including lack of infrastructure, deterioration of older infrastructure, and the need for more sustainable development (Sahely et al., 2003).

A battle for sustainable development requires new knowledge of development and socio-economic metabolic systems. Urban metabolism analysis is a way to quantify the fluxes of inputs into a system; in this research, the inputs being examined are building materials. New knowledge will require adequate accounting for quantification of development resources including building materials, such as concrete, brick, timber, aggregate and steel (Clark, 2003). Large amounts of energy and materials are used in the construction of buildings and large amounts of building materials are outputted as waste at the end-of-life cycle of buildings (Kleemann et al., 2016). These pathways have significant environmental impacts that are difficult to remediate and shift towards more recycling, and are poorly understood (Reyna & Chester, 2014). Quantifying and accounting for the materials within these flows is a start to understanding the fluctuations that occur over time and what can be done to manage these pathways and to reduce their impacts. Mobilizing this type of new knowledge and science towards sustainable development and meeting the U.N. Sustainable Development Goals (SDGs) should be a common goal across the world (Haberl et al., 2019). This thesis chapter helps to assess services and building materials in a North American context, capturing a 'snapshot' of material stocks in 2016. Stored in urban systems are large amounts of material resources including concrete, steel, wood, non-metallic minerals, etc. In order to assess how much material stocks can be put back into circulation, it is important to know how much materials are stored in the built environment in the first place.

3.2 Study Area

A static snapshot of material stocks in 2016 was examined to help quantify the composition of material stocks and how they were distributed within the City of Kitchener, ON, Canada. The City of Kitchener was chosen as the study site for material stock accounting from a city perspective because its increasing population and the shift of rural populations to urban areas. Kitchener has a population growth of 6% in the last five years, exceeding provincial and national growth levels (CBC, 2016). Construction is constant and new high rises are being built every year to alleviate development pressures due to increasing populations. GIS data is widely available from the City of Kitchener GIS department and makes the city an ideal study site when conducting spatial analysis. Kitchener is one of 35 census metropolitan areas in Canada and is ranked as the 10th largest metropolitan area due to the Waterloo-Kitchener-Cambridge (Tri-City) boundaries, with Kitchener being the largest population of the three (Statistics Canada, 2016). As development in the City of Kitchener occurs, this material stock account will help to understand the material stocks and units of services provided within the city. Additional information on the City of Kitchener geographic location and statistics is aforementioned in Section 1.4.2.

3.3 Methodology

This section summarizes the methodological approach adopted to achieve the goals of this thesis and to further inform socioeconomic metabolism. All the methods are applied within the City of Kitchener, which is a defined urban system boundary. This builds on the general methodology described in Section 1.6 and are the steps taken to quantify and map the in-use materials in 2016 within the City of Kitchener. The steps used to approach this research involves assigning building occupancy classes and typologies to calculate material intensities. These material intensities are then used to output associated quantities of building materials. Finally, these buildings are grouped into associated services and this coupled relationship is examined over time.

3.3.1 Assigning Building Occupancy Classes

In order to derive an urban building infrastructure map, identifying occupancy classes for each building was necessary. The goal of classifying buildings into occupancy classes is to define groupings of building typologies, which have similar material compositions (e.g., concrete, wood, etc.). These occupancy classes were assigned based on the specific use-type of the building, such as whether each building was a townhouse, single family home, low-rise apartment building, industrial building, secondary school, etc. (refer to Table 1.1). Most of the building footprint information within the City of Kitchener had building occupancies identified, but they were not all organized, free of errors (e.g., spelling mistakes), or consistent. Some buildings were also missing essential information; therefore, the data was grouped into similar classes together and re-coding them to ensure that all the buildings were assigned to a single occupancy class.

3.3.2 Assigning Building Typologies and Material Intensities to Occupancy Classes

Material intensities are a foundation for building material stock accounts and are a set of material intensities typologies that accurately represent the construction styles within the study area. In order to estimate the large infrastructure stock located within the City of Kitchener, the material intensities of certain building typologies need to be defined. Much of the building infrastructure is based on how the developer and civil engineers go about designing homes. Therefore, it is difficult to calculate material intensities for a large area, where buildings have various architectural styles and structures. Studies have calculated material intensities by the year of construction, utilizing material changes in construction types, and the most popular materials of that era (Mesta et al., 2018). Studies have also utilized blueprints and civil engineering expertise to derive more accurate results (Hussain et al., 2014; Kleemann et al., 2016). However, these studies usually only examine a couple of buildings on a local scale and not across a city-wide building scale.

Another way of calculating material intensities of buildings, particularly over a large study area, is by identifying building typologies. Therefore, obtaining an accurate estimate of material intensity output is often a subjective process. In the City of Kitchener there are 11 different material intensity classes, defined from the largest majority of building structures examined within the City of Kitchener. This was based on a combination of fieldwork, examining remote sensing data, and confirming building topologies with construction experts. Definitions of these classes with figures from fieldwork are shown in Appendix C.4.

For this study, material intensities were generated for five main construction materials including aggregate, wood, concrete, brick and steel. These were generated based on main structural design components for the building typologies found from: building permits, various Canadian construction experts, the National Building Code of Canada (2015), and secondary online building design drawings. The National Building Code of Canada (2015) sets a standard for minimum building requirements, for example, if multifamily large apartment buildings exceeded a certain height (building levels), the load bearing requirements change according to the Code and that affects the volume of concrete estimated within the structure, as well as the size of footing or raft slab.

Gross volume (GV) is often used when height information is readily available and of good quality. GV was selected as an appropriate method for this case study of Kitchener, because GFA (as described in Section 1.6.5), does not account for the influence that building height has on the amount of total materials and similar building typologies can have varying heights. Therefore, calculating GV for Kitchener would produce a more precise representation of the mass of materials present. An example of a subset of calculations for deriving material intensity is shown in Appendix C.5 (an example is shown for residential homes and low-rise apartment buildings and not for other building types), along with the constants used to obtain the weight of materials after volume was calculated. These calculations were completed for each building and its building typology class. Amounts of material intensity per cubic metre were averaged to determine a single material intensity value for each category. The results of these calculations in kg/m^3 are shown in Table 3.1.

Table 3.1: *Material Intensity Calculation break down of materials and material intensity classes in kg/m^3.*

	Aggregate	**Concrete**	**Timber**	**Steel**	**Masonry (Brick)**
Foundation with reinforced concrete					
Foundation - Strip Footings	-	15.5	-	-	-
Foundation - Ground Slab	59.71	29.86	-	0.34	-
Floors	-	-	0.72	-	-
Walls (Vinyl Siding)	-	71.84 (basement wall)	2.04	0.51	
Walls (Brick exterior)					60.17
Roof- Frame	-		0.66	-	-
Roof – Covering	-		0.4	-	-
Total a. (brick exterior)	59.71	117.2	3.82	0.85	60.17
Total b. (vinyl exterior)	59.71	117.2	3.82	0.85	-
Foundation without reinforced concrete					
Foundation - Strip Footings	-	15.5	-	-	-
Foundation - Ground Slab	59.71	29.86	-	-	
Floors	-	-	0.72	-	
Walls (Vinyl Siding)	-	71.84 (basement wall)	2.04	-	
Walls (Brick exterior)	-			-	60.17
Roof- Frame			0.66		
Roof – Covering			0.4		
Total a. (brick exterior)	59.71	117.2	3.82	-	60.17
Total b. (vinyl exterior)	59.71	117.2	3.82	-	-
Concrete Structure 1 (under 4 storeys (12m))					
Foundation - Footing	115.84	29.86			
Foundation - Ground slab on grade		57.92		0.66	
Floors		70.68		5.61	
Walls (Other)		265.68		0.76	
Walls (Brick exterior)					117.8
Roof		125.41			
Total	115.84	549.55		7.03	
Total a. (brick exterior)	115.84	549.55		7.03	117.8

Concrete Structure 2 (under 4 storeys (12m))					
Foundation - Footing	115.84	29.86			
Foundation - Ground Slab on grade		57.92		0.66	
Floors		62.32		5.31	
Walls (other)		132.84	3.98	0.38	
Walls (Brick exterior)					117.8
Roof		26.67		0.09	
Total	115.84	309.61	3.98	6.44	
Total a. (brick exterior)	115.84	309.61	3.98	6.44	117.8
Concrete Structure - Steel Reinforced (higher than 12m)					
Foundation - Raft Slab	-	111.25	-	2.10	-
Floors	-	62.32	-	5.31	-
Walls	-	321.36	-	-	-
Roof	-	26.67	-	0.09	-
Total	-	521.6	-	7.50	-
Steel Structure - Steel Walls					
Foundation - Pad footing	-	17.09	-	-	-
Foundation - Ground slab (Floor)	-	75.06	-	1.74	-
Walls - Structure and Steel Walls	-	-	-	1.85	-
Roof - Frame	-	-	-	0.91	-
Roof - Covering	-	-	-	1.02	-
Total	-	92.15	-	5.52	-
Steel Structure - Precast					
Foundation - Pad footing	-	17.09	-	-	-
Foundation - Ground slab (Floor)	-	75.06	-	1.74	-
Walls- Structure	-	-	-	1.85	-
Walls - Precast	-	130.32	-	2.20	-
Roof - Frame	-	-	-	0.91	-
Roof - Covering	-	-	-	1.00	-
Total	-	222.47	-	7.70	-

The material intensities used for the final calculations of material stock and input into ArcGIS software are shown in Table 3.2. These intensities (t/m^3) were the total of each building feature and material intensity class. In order to utilize these material intensities in geographic locations that do not have accurate height information and material intensity databases, values of material intensities were converted to kg/m^2 and are displayed in Appendix C.3. This was done through multiplying the average height of one storey buildings in each separate material intensity typology class and finding the resulting average material intensity.

Table 3.2: *Final material intensities summarized within each building occupancy class (kg/m^3).*

(kg/m^3)	**Aggregate**	**Concrete**	**Timber**	**Steel**	**Masonry (Brick)**
Foundation with reinforced concrete					
Total a. (brick exterior)	59.71	117.2	3.82	0.85	60.17
Total b. (vinyl exterior)	59.71	117.2	3.82	0.85	-
Foundation without reinforced concrete					
Total a. (brick exterior)	59.71	117.2	3.82	-	60.17
Total b. (vinyl exterior)	59.71	117.2	3.82	-	-
Concrete Structure 1					
Total	115.84	549.55	-	7.03	-
Total a. (brick exterior)	115.84	549.55	-	7.03	117.8
Concrete Structure 2					
Total	115.84	309.61	3.98	6.44	-
Total a. (brick exterior)	115.84	309.61	3.98	6.44	117.8
Concrete Structure - Steel Reinforced					
Total	-	521.6	-	7.50	-
Steel Structure - Steel Walls					
Total	-	92.15	-	5.52	-
Steel Structure - Precast					
Total	-	222.47	-	7.70	-

In order to breakdown the occupancy classes into percentage distribution of different material intensities, questionnaires were distributed to eight local experts. The questionnaire outlined the different building occupancy classes and their material typologies as shown in Table 3.3. The distribution column was left blank for two experts to complete and to confirm material typology classes (expert profiles are detailed in Appendix C.2). The experts confirmed that it was difficult to provide an accurate distribution and provided best guess estimates based on their background and professional knowledge. The final distribution adopted for this study was an average of the distribution values provided by the two experts and based on U.S. housing statistics for the Northeast region, assuming that similar construction styles would result in similar distributions of material typologies (United States Census Bureau, 2018). Table 3.3 shows the final distribution of these material intensity classes for different building occupancy classes.

Table 3.3:*Distribution of building occupancy classes and their associated material intensities as it pertains to material typologies.*

Building Occupancy Classes	**Material Typologies according to Intensities**	**Distribution (%)**
Residential – Single family homes, duplexes, townhouses	Foundation with reinforced Concrete (a. Brick exterior)	35
	Foundation with reinforced Concrete (b. Vinyl exterior)	35
	Foundation without reinforced (a. Brick exterior)	15
	Foundation without reinforced Concrete (b. Vinyl exterior)	15
Apartment (Low-rise)	Concrete Structure 1 and 1 a.) brick exterior	25, 25
	Concrete Structure 2 and 2 a.) brick exterior	25, 25
Apartment (High-rise)	Concrete Structure - Steel reinforced	100
Health (Hospitals)	Concrete Structure 1 a.) brick exterior	100
Cultural (churches, museums, etc.)	Concrete Structure 1 a.) brick exterior	50
	Steel Structure - Precast	50
Recreational (Stadiums, clubhouses)	Steel Structure - Steel Walls	100
Transportation (Bus station, etc.)	Concrete Structure 1	
Mixed Use	Concrete Structure 1 and 1 a.) brick exterior	25, 25
	Concrete Structure 2 and 2 a.) brick exterior	25,25
Commercial (Malls)	Steel Structure - Precast	100
Industrial (Warehouses, etc.)	Steel Structure - Steel Walls	100
Institutional - Education	Concrete Structure 1 a.) brick exterior	100
Institutional - Government buildings	Concrete Structure 1	50
	Concrete Structure 1 a.) brick exterior	50
Utilities (Energy, Communications)	Concrete Structure 1	100

Assigning material intensities to these classes when typologies of individual building are unknown requires random assignment of typologies to get the best typology estimates (% distribution category in Table 3.3). This was necessary, because it would otherwise be a large undertaking to identify each building individually in the field, especially considering that there were over 60,000 residential buildings in the city. As a result, local experts were consulted and an appropriate distribution of building typologies within the study area was determined. However, since each individual building is assigned a specific building typology and differed in size and areal footage (e.g., a majority of buildings might be assigned to one typology and skew the results), it is necessary to assess the uncertainty of estimates within each building category. A Monte Carlo simulation was applied to reduce uncertainty by simulating multiple different scenarios in which random assignments of the typologies would be distributed in the buildings of the respective occupancy classes. For example, the mixed-use occupancy class has four different types of material intensity assignments (Concrete Structure 1 and 1a and Concrete Structure 2 and 2a.) and therefore each is assigned to 25% of the total mixed-use buildings. The Monte Carlo simulation was automated using R-coding and each code was modified according to the distributions and the intensity assignment. There were five occupancy classes and five different codes were run – an example of the R-code for mixed use is provided in Appendix C.6. This code assigned random buildings with the proportion of material typologies outlined in Table 3.3, based on the material intensities outlined in Table 3.2 (i.e. 25% for mixed use were assigned Concrete Structure 1, 25% for mixed use were assigned Concrete Structure 1a, 25% for mixed use were assigned Concrete Structure 2, 25% for mixed use were assigned Concrete Structure 2a) and produced total stock estimates and individual material totals for each building. The ‘counter’ in the code is the number of iterations run to generate different material stock totals each time. This helps to reduce uncertainty in the prediction of material stock where the material typology for each individual building is unknown.

3.3.3 Total Material Stocks

For the City of Kitchener, the material intensities were calculated as a function of total gross volume of the buildings and reported as kilograms per cubic metre within a GIS environment. The total material stock mass was calculated using gross volume based on the equation below modified from Kleeman et al. (2016). This results in a database of material intensities of different building typologies, gross volume of the building stock, and mass of the building stock within Kitchener.

$$M_j = (GV_x \times MI_j)$$

GV_x= gross volume of a building (m^3)

MI_j = specific material intensities for material mass (t/m^3) for a set building typology (based on Table 4.2 (above)).

M = mass of material stock in the building category (t/m^3)

j = building typology class

The total material stock for Kitchener (*M*) is the combination of all the masses of each building category (*j*) and each class of building materials.

3.3.4 Temporal Changes in Services

Services were grouped into categories previously described in Section 1.6.4. These were assigned based on the occupancy classes identified within the City of Kitchener building layer. The City of Kitchener also provided year of construction within their building layers. In order to create a composition of these services over time, building layer attribute information was utilized to provide an estimate of which services increased or decreased over time.

3.4 Results

The following subsection presents the results of the methodology previously described in Sections 1.6. and 3.2. By combining the material intensities with the physical attributes of each building, a total material stock of both domestic and non-domestic classes was derived. The quantity and services of all the building material stocks are described in this section. The spatial distribution of these stocks and their associated services are also shown on city scale maps.

3.4.1 Monte-Carlo Simulation for Calculating Material Stocks

Total material stocks of approximately 70,000 buildings in 2016 was 29,000 kilo tonnes, equivalent to 125 t/capita. The Monte Carlo simulation was run on five occupancy classes including mixed use, institutional-other, apartment low-rise, cultural and residential categories. Results showed that after about 10,000 iterations, the distribution appeared to level out, indicating minimal subsequent changes. Box plots were constructed for 1, 10, 100, 1,000, and 10,000 iterations to visualize the distribution, as shown in Appendix C.6. From these box plots, the median was selected as the optimal value for calculating total material stock, which occurred between the

1st and 3rd quartile ranges. The median was selected as the optimal value because shown by the distributions of box plots in Appendix C.6, there was a large amount of variation in between the minimum and maximum box plot ranges. Even the higher number of iterations (10,000 and 20,000) showed large variation between the minimum and maximum values. Using the mean value could skew the results lower or higher because of such extreme values, so the median value of 20,000 iterations was selected as the final material stock total. However, because of the large variability, material stocks between the 1st quartile and 3rd quartile are just as likely to occur as the median, therefore these numbers were also generated to assess the range between them, as shown in Tables 3.4a-e. These material stock totals are shown in Tables 3.4 and were applied back to the building layer, so that final material stock quantity and per capita estimates could be calculated.

Table 3.4: *Tables a-e shows the results of the Monte Carlo simulation analysis for each different occupancy class group expressed in total material tonnes.*

Table 3.4 a: *Residential buildings.*

Residential (not including apartments)		
	1st Iteration	20,000 Iterations
Aggregates	4,231,260	4,231,260
Timber	270,699	270,699
Concrete	8,305,203	8,305,203
Steel	42,080	42,094
Brick	2,735,045	2,744,538
1st Quartile		**15,583,778**
Median	**15,584,288**	**15,593,796**
3rd Quartile		**15,603,803**
Difference	**9,508**	

Table 3.4 b: *Cultural buildings.*

Cultural		
	1st Iteration	20,000 Iterations
Aggregates	42,050	52,053
Timber	0	0
Concrete	318,749	346,995
Steel	6,680	6,622
Brick	42,761	52,934
1st Quartile		**439,670**
Median	**410,240**	**458,605**
3rd Quartile		**477,507**
Difference	**48,365**	

Table 3.4 c: *Apartment buildings.*

Apartment Low Rise		
	1st Iteration	20,000 Iterations
Aggregates	389,138	389,138
Timber	6,755	6,408
Concrete	1,438,863	1,459,744
Steel	22,614	22,665
Brick	187,648	181,933
1st Quartile		**2,047,642**
Median	**2,045,018**	**2,059,889**
3rd Quartile		**2,071,829**
Difference	**14,871**	

Table 3.4 d: *Institutional-other buildings.*

Institutional - Other		
	1st Iteration	20,000 Iterations
Aggregates	215,617	215,617
Timber	0	0
Concrete	1,022,895	1,022,895
Steel	13,085	13,085
Brick	109,468	109,482
1st Quartile		**1,343,826**
Median	**1,361,065**	**1,361,079**
3rd Quartile		**1,378,389**
Difference	**14**	

Table 3.4 e: *Mixed use buildings.*

Mixed Use		
	1st Iternation	20,000 Iterations
Aggregates	54,525	54,525
Timber	785	937
Concrete	211,357	202,156
Steel	3,193	3,170
Brick	25,820	27,748
1st Quartile		**284,136**
Median	**295,679**	**288,536**
3rd Quartile		**292,868**
Difference	**7,143**	

3.4.2 Material Stocks

In terms of types of materials occurring in the Kitchener study area, concrete was the highest overall stock accounting for 68% or 84.7 t/capita (Figure 3.1). Aggregate was the second largest class with 18% of total materials, equivalent to 23 tonnes/capita. Timber was the lowest occurring stock. However, if total gross volume is considered (see Table 3.5), timber actually exceeds steel at 514 m^3 in gross volume, accounting for 4% of the total material gross volume. However, since timber does not weigh as much as steel, its material stock (kg/m^3) was lower. Even though aggregate is not as prevalent in non-domestic buildings, residential buildings comprise of the majority of stocks (71% of total material stocks in the residential class) and 25% of the total gross volume of materials.

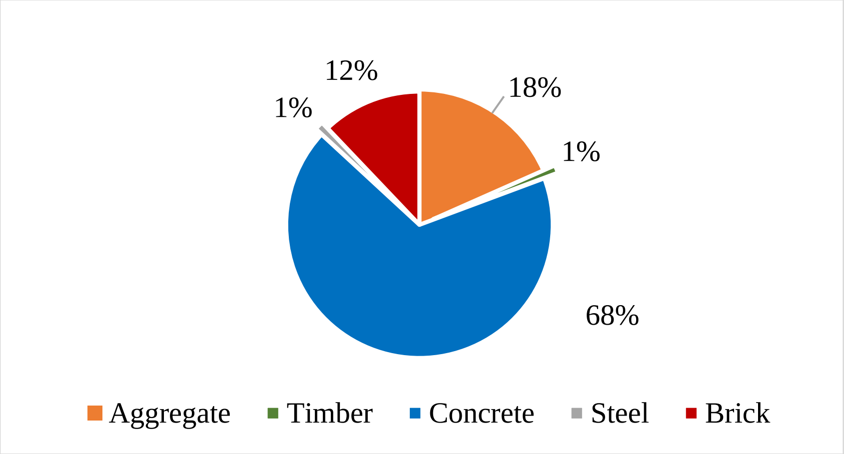


Figure 3.1: *Material Stock material distribution within the City of Kitchener.*

Table 3.5: *Material stocks by construction material outlining mass, volume, and percentage of each.*

Building Material Type	Total material in weight (kg/m^3)	Material in t/capita	Gross Volume of material (m^3)	Gross volume (% of total materials)
Concrete	19,666,591	84.7	8,194	60
Aggregate	5,364,640	23.0	3,353	25
Timber	277,825	1.2	514	4
Brick	2,827,875	15.2	1,471	10.7
Steel	303,933	1.3	39	0.3

When the spatial distributions of material stocks are mapped in Figure 3.2, it is evident that a large accumulation of stocks is located in downtown Kitchener along King Street, where a concentration of high-rise apartment buildings are located. Concentrations of neighbourhoods and largely residential buildings are located throughout Kitchener as also mapped in Figure 3.2 are pockets of residential neighbourhoods separated by major roadways.

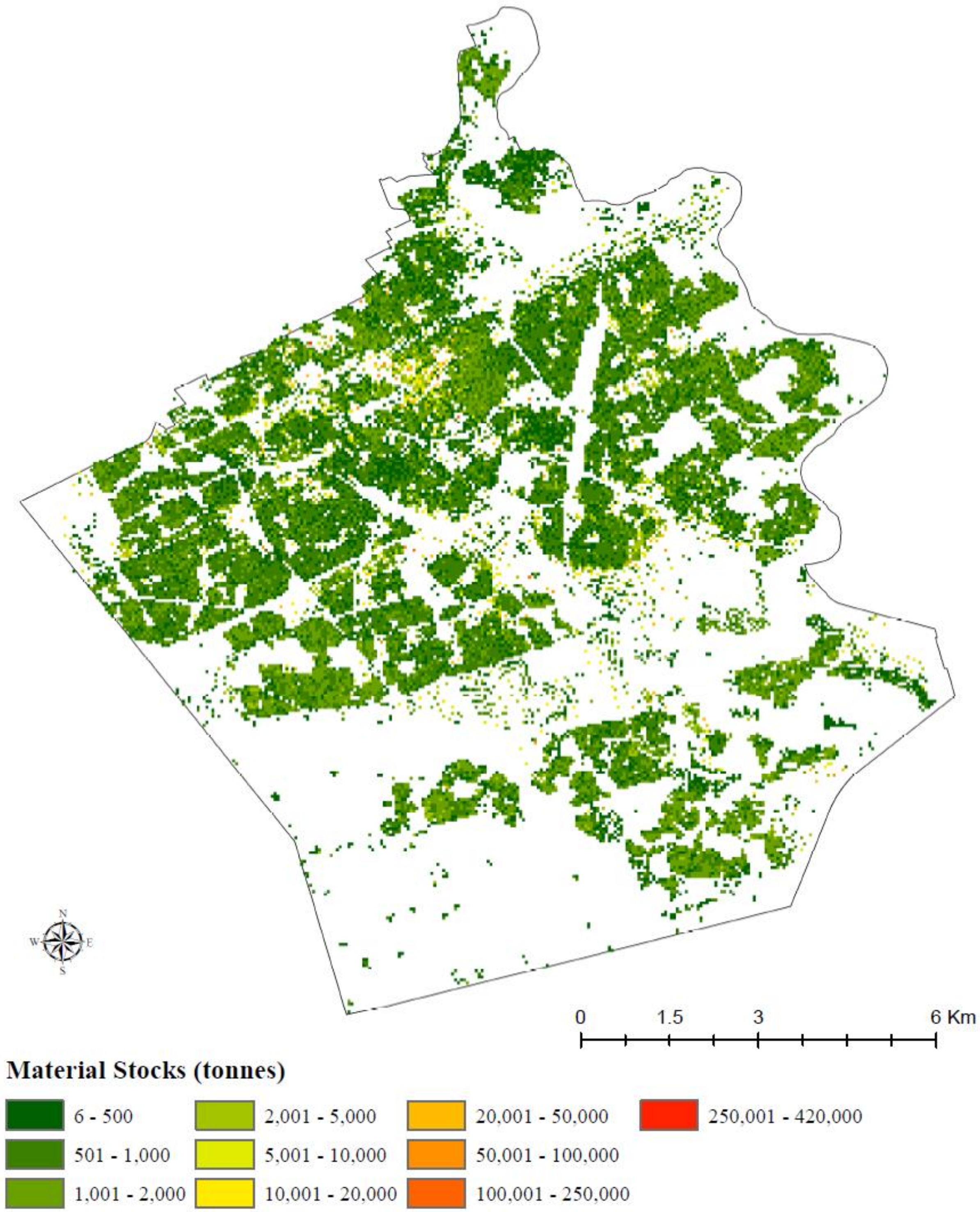


Figure 3.2: *Map of material stock distribution within the City of Kitchener in tonnes.*

3.4.3 Material Stocks and Services

The top five service categories within the City of Kitchener accounted for 94.7% of the total material stock. The residential class accounted for the highest category, making up 71% of total material stocks, equivalent to 89 t/capita. Other service categories were much smaller, Institutional-Education at 7.3%, Commercial at 7.1%, Institutional-Other at 4.7%, and Industrial at 4.6%. The distribution of the other service categories is shown in Table 3.6 and Figure 3.3.

Table 3.6: *Service distribution within the City of Kitchener shown in total tonnes and t/capita.*

Services	**Aggregate (t)**	**Timber (t)**	**Concrete (t)**	**Steel (t)**	**Brick (t)**	**Total (t)**	**(t/capita)**
Residential	4,620,398	277,106	12,829,094	108,818	2,926,471	20,761,891	89.0
Institutional - Education	31,2075	-	1,480,498	18,939	317,355	2,128,867	9.1
Commercial	-	-	1,998,033	69,154	-	2,067,188	8.9
Institutional - Other	215,616	-	1,022,895	13,085	109,482	1,361,079	5.8
Industrial	-	-	1,259,615	71,353	-	1,330,968	5.7
Health	86,173	-	408,812	5,229	87,631	587,847	2.5
Cultural	52,053	-	346,995	6,621	52,934	458,605	2.0
Mixed Use	54,524	937	202,156	3,170	27,747	288,536	1.2
Utilities	26,540	-	125,911	1,610	-	154,063	0.7
Recreational	-	-	75,404	4,271	-	79,675	0.3
Transportation	3,464	-	16,434	210	-	20,108	0.1

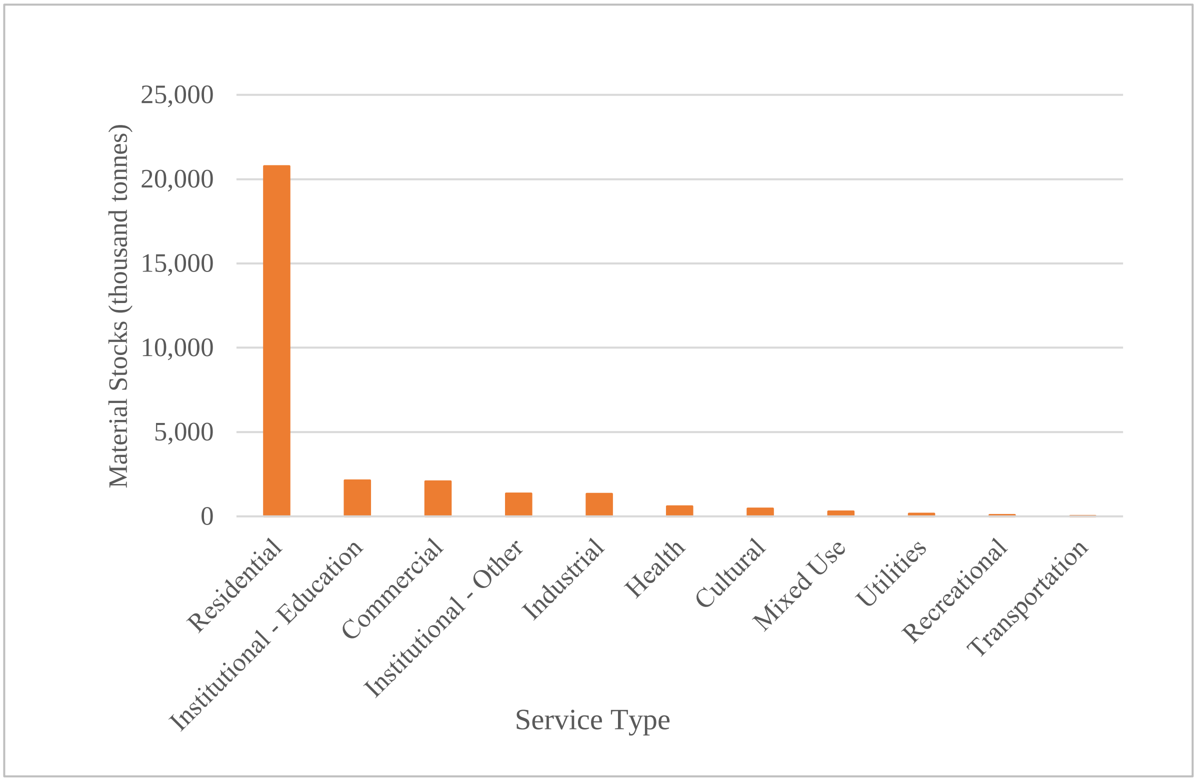


Figure 3.3: *Material stock in thousand tonnes and associated services within the City of Kitchener.*

The spatial distribution of material stocks according to service categories are shown in Figure 3.4, demonstrating that residential services are especially dispersed throughout the city. There were noticeably large areas were not occupied by residential land use at all, such as sites located along Hwy 7 and 8, conservation areas, and industrial parks. For commercial buildings, a distinct linear distribution of commercial buildings along major roads was evident. This corresponds to major travel routes where goods and services are concentrated. Industrial buildings also showed a distinct spatial pattern, where a large accumulation of material stocks related to industrial services occurred in the south and slightly east of the city along major roadways.

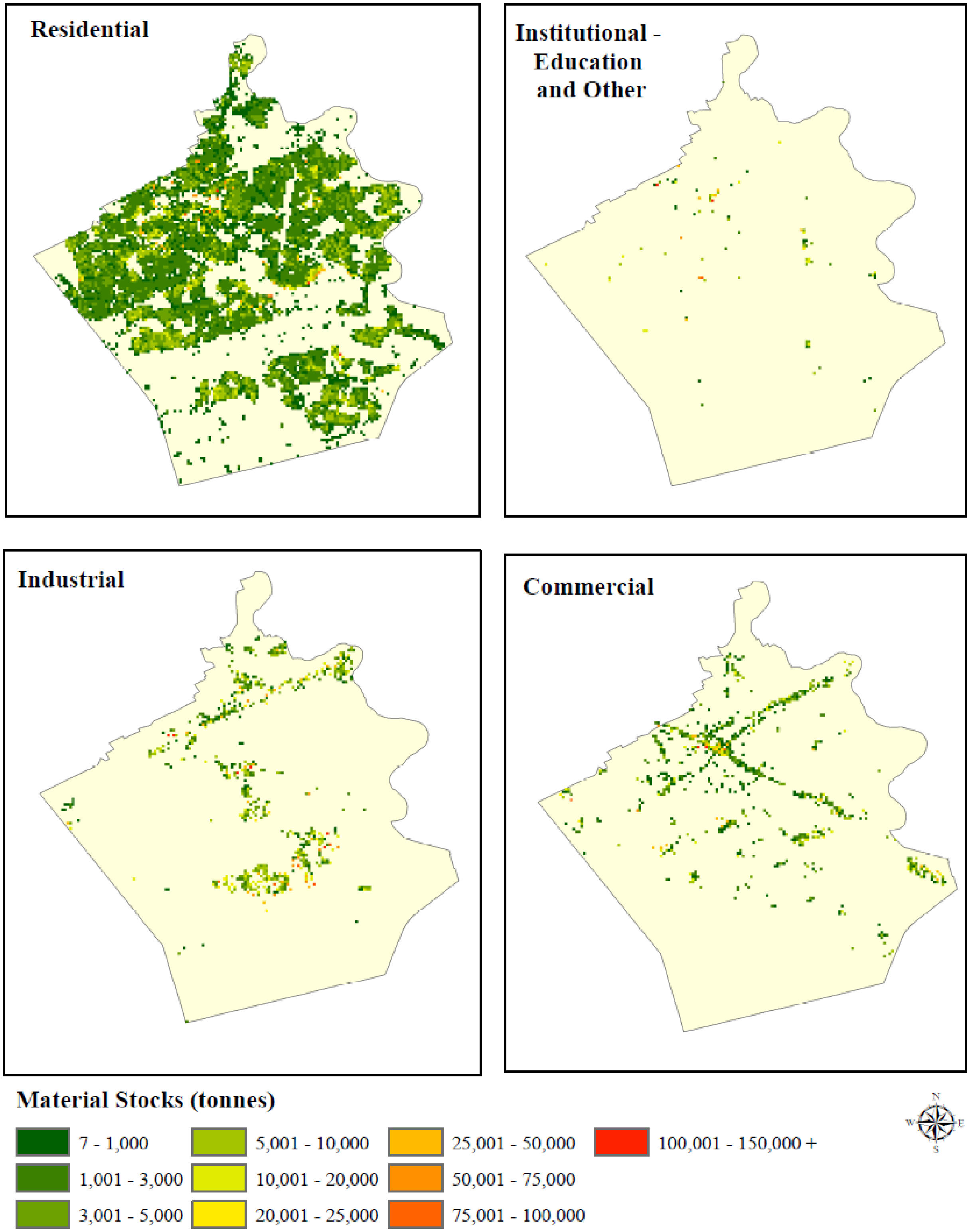


Figure 3.4: *Map of residential, institutional-education and other, industrial, and commercial service categories in the City of Kitchener.*

3.4.4 Temporal Changes of Services

Examining services over time is a key way to observe transitions in the economy and where fluctuations of building stocks may have occurred. Residential services and how they vary over time are shown in Figure 3.5 as material in-puts over decadal periods. There was data available for 85% of total homes. It was shown that construction was highest in the period from 2000-2010. Construction started to increase in the 1950's and from the 1950's to 1990's there was a large construction boom.

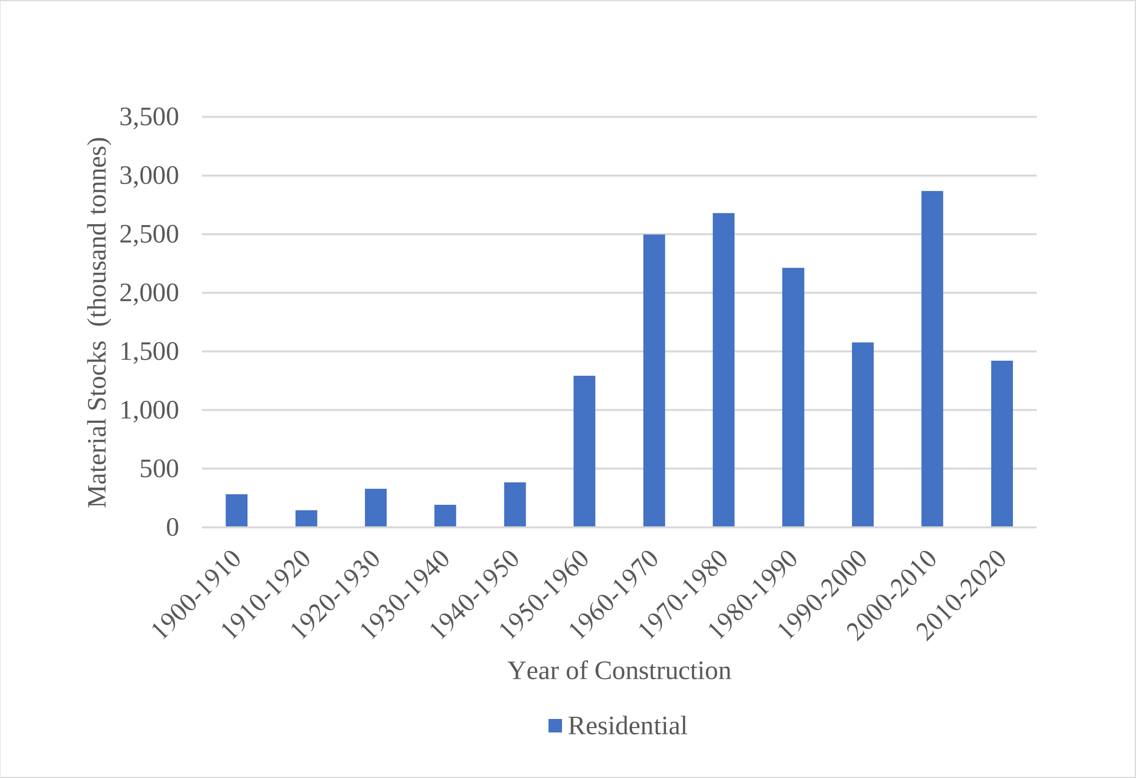


Figure 3.5: *Material Stocks over time in 10-year periods for the City of Kitchener. This graph shows 85% of residential homes in the City of Kitchener and the year they were constructed as well as how many in-use material stocks were added at the time.*

For other service sectors of material stock, Figure 3.6 shows the addition of these stocks over-time. The graph shows 23% of all institutional-education buildings, 18% of all other institutional buildings, 15% of commercial and 5% of industrial buildings. From this 10-year time scale, there was a large growth of education buildings during the 1960-1970's through to the 2000's. Looking at the boom of buildings there was a large construction phase of educational buildings in 1960-1970. In the last decade, most of the non-residential construction has been industrial and commercial buildings.

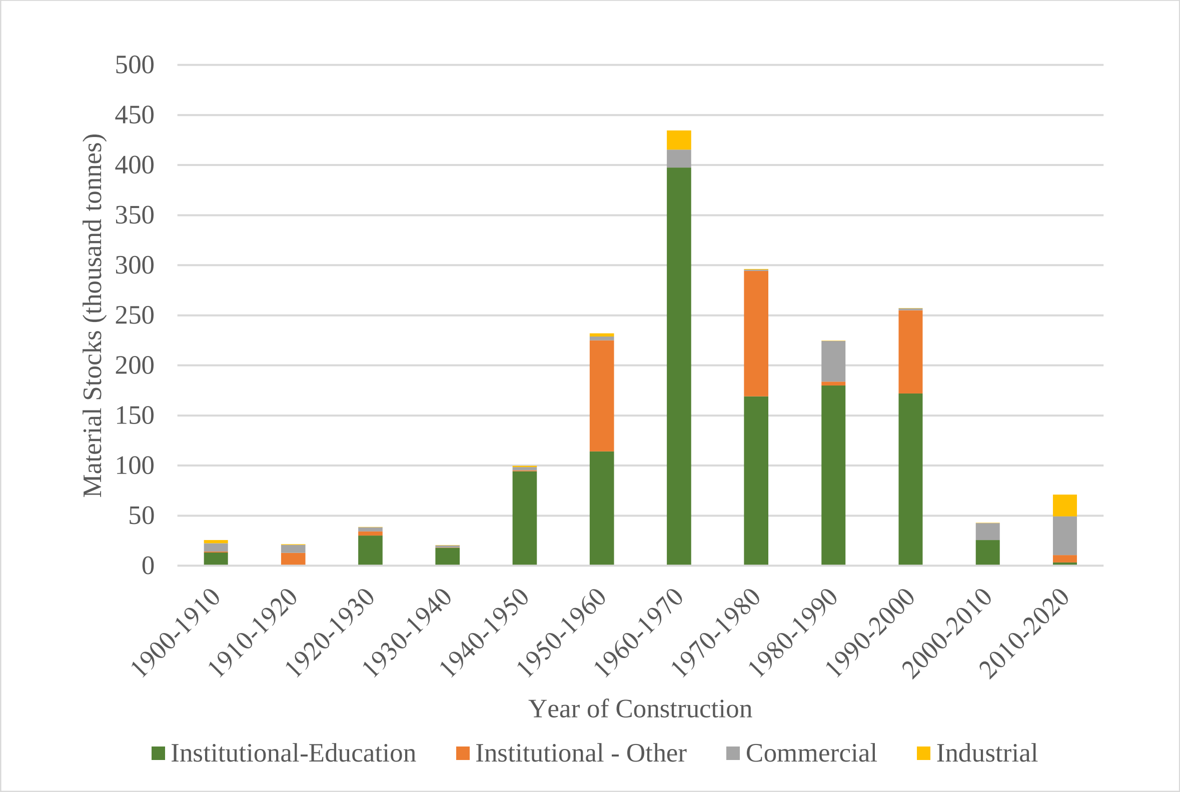


Figure 3.6: *Material Stocks over time in 10-year periods for the City of Kitchener. This graph shows the other top four service classes in the City of Kitchener and the year they were constructed as well as how many in-use material stocks were added at the time.*

3.5 Discussion

The following section is a discussion of the results from the MS analysis and services within the City of Kitchener and what it means in a city context. This section includes what the accumulated stocks and their associated services mean and potentially why these results are occurring as well as limitations and future work. For further discussion of what this research means in a broader context and how it compares to other similar studies, see Chapter 5.

3.5.1 Material Stocks and Associated Services

Kitchener had a total of 29,000 kilo tonnes of material equivalent to 125 t/capita. In terms of individual materials, concrete made up the largest share at 68%, aggregate at 18%, and brick at 12%. In terms of the volume of materials timber and steel accounted for about 1% of total mass, but timber was almost 10 times the volume at 514 m^3, equating to 4% of gross material volume. Even though there is a larger mass of steel present in the city, there is an even larger volume of timber. From an environmental perspective, timber is more voluminous and thus requires better collection and handling (Bohne, Brattebo, & Bergsdal, 2008). This volume increase impacts management of construction waste as this increased volume of timber has a larger impact at the end of the building life cycle.

Building stocks provide essential services that societies rely on to improve social and economic conditions. Therefore, the units of service from building stocks can indicate levels of human development and be a benchmark for future developments in countries and cities (Lanau et al., 2019). For the City of Kitchener, the top five service categories account for 94.7% of the total material stock. The residential class was the highest making up 71% of total materials at 89 t/capita. Other service categories include institutional-education at 7.3% and 9.1 t/capita, commercial at 7.1% and 8.9 t/capita, institutional-other (government buildings, nursing homes, etc.) at 4.7% and 5.8 t/capita, and industrial at 4.6% and 5.7 t/capita. Knowledge of these material stocks at a point in time uncovers the amount of essential services which societies rely on, however, changes in these services can occur as cities and countries move through development transitions (Haberl et al., 2019). A planner at the City of Kitchener eluded that some of the industry and industrial buildings previously used in Kitchener is shifting to China as manufacturing is cheaper. This shift results in a reduction of industrial building needs and therefore a change in development trajectories but leaves the building stock. The importance of planning sustainably comes through in developmental transitions in which Kitchener is potentially shifting from an industrialized society to a more service driven society in which facilities for education, healthcare, entertainment, communication networks, environmental management and housing will be needed for the future.

The challenge becomes meeting these societal demands without the historical correlation of high resource use (Haberl et al., 2019).

This study is novel for Canada, as well as for North America, as it is the first material stock account considering a bottom-up approach in a North American study area. The material intensities derived in this study can be utilized for similar study sites within Canada and Northern U.S. by utilizing the descriptions of the buildings in Appendix C.4 and applying the typologies to other sites. For future studies within the City of Kitchener, some of the typologies might change overtime as the building code changes. Kitchener is a city boundary within the tri-cities and is quite developed, therefore, any large future development plans will shift towards increasing population density by building ‘upwards’ and not ‘outwards’. This will affect the material accounts in the future, since these will likely be steel framed concrete buildings. Planning for these development changes requires an understanding of the services required for future populations, by shifting to a pathway of infrastructure use that will be more environmentally friendly and sustainable. It is recommended that planners use this approach to increase awareness of energy and recycling of building materials in the shift of populations towards urban centres.

3.5.2 Spatial Distributions of Stocks and Services

Examining the spatial distribution of stocks further, it was noted that a large portion of stocks are located in downtown Kitchener, where a higher density of buildings (e.g., high rises) are located. Construction development is on-going, as town homes have been replaced by large storey apartment buildings. These buildings are largely for residential use with shops located on the first level and are often retrofitted with large concrete raft slabs and underground parking. This results in a dense cluster of high-rises located along main bus routes and roadways, and areas where services are easily accessible.

From a service perspective, different spatial patterns are evident for different residential classes. The top four occurring classes were mapped in Figure 3.4 and show residential, education, industrial and commercial classes. The residential class is spread throughout the city and shows a neighbourhood pattern where single family and town homes are located throughout the city. Industrial and commercial areas are quite prevalent along major roadways, and not many residential homes occur in these corridors. Industrial services show a large stretch of industry along Highway 7 and a large industrial park in the middle south-west called the Trillium Industrial Park.

Commercial areas tend to occur along these highway corridors with recurring pockets located throughout neighbourhoods. Education tends to be quite spread out in terms of distribution throughout the city, which is expected, since individual schools tend to service different neighbourhoods. In understanding the spatial dynamics of services, the city can continue mapping them over time to determine whether there is any expansion or shifts in certain services, which may help planners to make more informed decisions about where to locate new subdivisions or commercial areas.

3.5.3 Limitations and Future Studies

As discussed in the methodology, building footprint data for the attribute of year of construction is missing for a large number of buildings, specifically in non-residential categories. When examining material stocks over time, it would be more efficient to examine changes on a year-to-year basis, but many years between 1900 and 2000 had incomplete information. Studies providing material stock accounts over the years contribute further to socioeconomic metabolism allowing a more in-depth understanding in the flow fluctuations of materials over time and why they occur. For example, Cheng et al. (2018) conducted a study in Taipei City and found that in 1990 to 2014 there was a doubling of total material stock accumulation. Examining these material stocks spatially can help determine where old building clusters exist and enhance the efficiency of predicting future end-of-building life cycle waste flows (Cheng et al., 2018; Stephen & Athanassiadis, 2018). For the City of Kitchener, it is difficult to conduct an accurate study to examine which year the stocks were accumulated, since there is substantial missing information. From the results obtained a boom in construction occurred from 1960-1970. A large proportion of this increase were educational buildings which could be because of the demand for educational services for the ‘baby boomer’ generation. However, this was only a subset of 23% of overall buildings so it is hard to determine if this is what truly occurred or if it was over a larger period of population growth from the 1960-2000 where building construction year was not previously recorded.

In terms of the material intensities, the assumption is that most of the buildings within each occupancy class have the same typologies. This is not always the case, since some homes are constructed differently and can have variable typologies, such as different height basements, roof lines, or exterior building composition. Most experts concluded that it was very difficult to provide an accurate prediction of the distribution of different material typologies as they had done a variety of work throughout both of their career lifetimes. Therefore, the distributions are estimated quite broadly with a recognized assumption, and it is important to note that building styles and technology change over time influencing construction styles. For future studies, fieldwork can be conducted to obtain a sample estimation to confirm expert estimates. Future calculations in the amount of MS and providing information on the availability of urban resources will help policy makers and planners understand future supplies that can be used for recycling or re-building purposes.

Chapter 4: Thesis Discussion and Conclusions

4.1 Discussion

This section concludes the thesis with a discussion of the key results from both island and city contexts, and how they fit within previous material stock-service research. Recommendations of applying this research are discussed, as well as future directions for work related to material stocks and services.

4.1.1 Island and City Contexts

The integrated nature of the United Nations Sustainable Development Goals (SDGs) plays a role in linking local ambitions with global goals (UNDP, 2018). Taking into consideration the United Nations 2030 Agenda for Sustainable Development, a central focus is making progress in each of the SDGs (United Nations, 2019). These goals can be considered in various contexts and bridges the gap between nations and cities to make battling the effects of climate change and the push for more sustainable development, global issues. Goal 9 of the SDG's is 'Industry, Innovation and Infrastructure' to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation (United Nations, 2019). Goal 11 is 'Sustainable Cities and Communities' in which cities and human settlements are inclusive, safe, resilient and sustainable (United Nations, 2019). Goal 12 is 'Responsible Consumption and Production' in which sustainable consumption and production patterns are understood and improved (United Nations, 2019). The aforementioned SDGs can be applied to both case studies of Grenada and the City of Kitchener and within the context of this research. Although one case study focuses on a SIDS environment and the other in a North American city context, both system boundaries are important to understand in tackling the global SDGs. This study bridges the gap between both geographic study areas and shows why both study sites are important to achieving the global SDGs.

It is important to discuss the application of this research and proposed methodology within different geographic contexts throughout the world. Chapter 2 provided a comprehensive account of material stocks and services within an island context. The Caribbean is a large tourist hotspot and infrastructure relating to tourism is quite high at 15.9 t/capita. Therefore, building infrastructure and existing material stocks are not only driven by the local economy, but also by foreign visitors entering the country. Due to the SDGs being a global issue, discussing the island context in Chapter 2 is important, but it is also important to consider how this compares to other geographic areas. Chapter 3 explores material stocks and services within a North American city context, where there is an observed increasing shift of residential populations into city and built-up areas. Combining these two chapters, helps to provide a more comprehensive understanding of the relationships between material stocks and the services they provide, which contributes to socioeconomic metabolism research.

4.1.2 Material Stock Accounting

Grenada's final MS in buildings is estimated to be 132 t/capita in 2014. The City of Kitchener's final MS in buildings is estimated at 125 t/capita. The global average for total stock is estimated at 115 t/capita, which puts both Grenada and the City of Kitchener above these global figures (Krausmann et al., 2017a). Since Kitchener is located in a climate zone that experiences four seasons, more building materials are required for withstanding freeze-thaw weather patterns and for keeping homes insulated. However, Kitchener has a slightly lower per capita estimate compared to Grenada due to a greater number of apartment buildings and a higher population density. Much of the building infrastructure in Grenada supports their 'floating population' (i.e., visitors and tourists), as previously discussed in Section 2.4.1, and therefore there is an increase in per capita estimate of material stocks due to this population. Some buildings within Kitchener could be identified as being built for a floating population, since populations between the tri-cities (Waterloo, Kitchener, Cambridge) mix throughout the day. Students live in Kitchener but go to school in Waterloo, large industrial areas in Kitchener provide a place of work for some of the population that resides outside of Kitchener, and people commute in for work and social events. Looking into the services that are utilized and how the buildings' function can help answer and understand these complex interactions. A novel contribution of this research is how it marks a start to understanding how societies interact with their built environment and how demands coincide with how buildings function, especially in the case of infrastructure use.

Various studies have explored the residential housing stock, but not necessarily the stock as a whole (domestic and non-domestic buildings). Categorizing building services into different categories allows various services to be compared on a per capita basis and the potential to identify which countries have higher stock estimates and why this might be. Table 4.1 and Figure 4.1 compare the residential material stock between four countries and three cities, GDP per capita (for the country), country happiness index, and the source of the study. Previous research has shown that Singapore, Germany and Chiclayo in Peru have relatively low material stock accounts per capita at 28.8 t/capita, 45.7 t/capita, and 47 t/capita, respectively (Arora et al., 2019; Mesta et al., 2018; Ortlepp et al., 2016). The highest account of MS is in Vienna, Austria at 139 t/capita, however, the study considers a large number of other building materials including ceramics, glass, plastics, and gypsum, which were not considered in this study (Kleemann et al., 2016). MS for Kitchener, Grenada, and Japan fall in the middle range at 89 t/capita, 93 t/capita and 74 t/capita, respectively (Tanikawa et al., 2015).

Table 4.1: *Residential building material stock, GDP, and Country happiness per capita from this research and previous studies.*

City/Country	Material Stocks-Residential (per capita)	GDP indicator per capita (Helliwell et al., 2018)	Country Happiness Index (Helliwell et al., 2018)	Source
Vienna, Austria	139	10.74	7.14	(Kleemann et al., 2016)
Japan	74	10.58	5.92	(Tanikawa et al., 2015)
Singapore	28.8	11.36	6.34	(Arora et al., 2019)
Germany	45.7	10.73	6.97	(Ortlepp et al., 2016)
Kitchener, Canada	89	10.70	7.33	Current Study
Grenada	93.4	N/A	N/A	Current Study
Chiclayo, Peru	47	9.43	5.66	(Mesta et al., 2018)

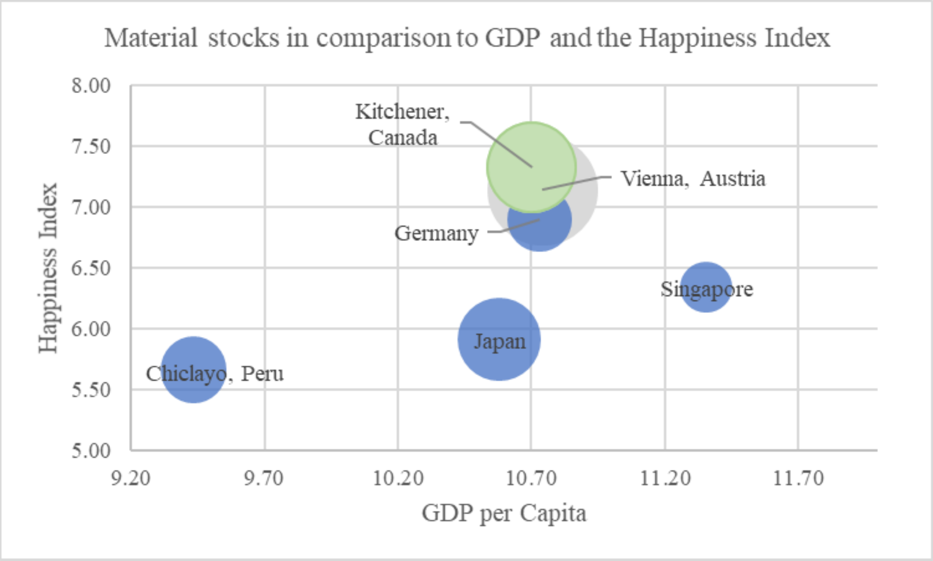


Figure 4.1: *Material stock bubble graph showing highest material stock as proportional circles in comparison to GDP and the Happiness Index.*

Material stocks can also be compared to the happiness index to assess whether having more materials, which typically translates into more living space, can have an influence on people's happiness. The *World Happiness Report* conducted by Helliwell, Layard and Sachs (2018), takes into account GDP per capita, social support, life expectancy, freedom to make life choices, generosity, perceptions of corruption and dystopia as factors of happiness. Each of these indices are measured together to derive an index of happiness. The report only measured 156 countries, which included the larger populated Carribbean Community (CARICOM) islands like Trinidad and Tobago but not smaller islands such as Grenada, Antigua & Barbuda, Saint Lucia and others (Helliwell et al., 2018). Therefore, only material stocks per capita were displayed in Table 5.1 for Grenada. Kitchener located in Canada - a country rated 9th in the world for level of happiness - has one of the higher per capita material consumption rates and was average in terms of GDP per capita (Helliwell et al., 2018). Singapore, which is a small island state has the lowest residential stock with the highest GDP per capita and was in the middle of the happiness score for the countries studied. In comparison to similar studies done on material stocks, Singapore has a population density of more that 7,700 people per km^2, making Singapore one of the worlds' highest in terms of population density (Arora, 2019). This affects the material account, but not GDP, which is highest. Therefore, the amount of material per capita is not always reflected by the highest GDP rate. This also only takes into account residential homes and therefore industrial, commercial, and other services are not considered. More research is required to understand these dynamics and how material consumption is influenced by GDP, not only the residential stock but other services. Looking at material consumption and stocks from a service perspective will help further uncover these relationships to work towards a balance of material consumption, happiness, and economic growth.

4.1.3 Recommendations

The following section outlines recommendations for policy makers and stakeholders on how this research can be applied to use material stock accounting as a way of managing future resources. Recommendations made are generalized and thus can be applied to other similar study sites.

4.1.3.1 Island Context

SIDS lack of diversification in economic activities and degree of isolation make them ideal testbeds for sustainable development and disaster risk management practices. Using this research for informing disaster risk management, as well as preparing for shifts in the economy will help planners and policy makers in moving forward with dealing with risks and damage due to climate change.

- Potential impacts from natural hazards and disasters require planning and assessing the vulnerabilities. This research can help to inform how many critical services will be exposed to sea level rise or various natural disaster events. Utilizing the material stock accounts per individual buildings, disaster risk planners will be able to conduct various scenarios including number of building materials that will be affected if a natural disaster were to occur, as well as the location. The use of the data produced in this research provides an approach to accounting disaster risk that has not yet been implemented in policy or disaster planning.
- Conducting material stock analysis in the future should be done with more accurate height information as assumptions in material stock accounting can underestimate or overestimate material stocks. This can affect waste management and disaster risk planning as outlined in Section 2.4.1. It is recommended that Grenada invest in processing their LIDAR information for accurate height data as well as implementing a data sharing program for researchers, which in turn can provide the processed information to associated Ministries.
- Understanding GDP shifts in island economies and the building and materials that come along with that is an important step in moving towards an economic society in which other services can dominate or be shifted to more sustainable locations. This means identifying the function of buildings through services. This study provides a new perspective when considering how materials are distributed in societies. The spatial approach allows researchers and planners to see not only how much, but where these services are distributed, both on a small scale as well as a country-wide scale. Being able to identify where and how much of these critical services are located can help leverage the stock and shift towards a more sustainable building functions and longevity. This could mean shifting resorts and tourism hotspots away from the coast, and away from

areas where they are already largely present. This could potentially be done for St. George’s University as new programs and any need for new campus buildings could be moved to other parts of the island to reduce vulnerability as a large amount of tourism and education stock is located in the Southwestern part of the island.

4.1.3.2 City Context

A city can be viewed as a local entity effecting the environment around it. Bai (2007) argues that as populations increase, environmental problems of cities have grown beyond city limits. As more than half of the world’s population lives in urban areas, cities have become a forefront for sustainable practices (Bai, 2007; Clark, 2003). This research was conducted to contribute towards a better understanding of the current state of material stocks and their relationship to key services. The following list summarizes potential recommendations from this research:

- For potential policies of managing building stocks for the City of Kitchener, this material stock analysis will allow the city to better quantify recycled building material as well as buildings that can be transitioned for other services. Utilizing the calculated material stocks bottom-up methodology can help answer questions such as: how much can be re-used? what amount is being moved to the landfill? and what are the amounts of individual materials? For example, the City of Kitchener has an application status for demolition control, where planners manage homes that are to be demolished. Most of these demolitions are single dwelling homes that are being demolished for development of multiple resident infrastructure, utilizing the material stock account provides the material composition knowledge of these buildings.
- Currently only 6% of materials are being circulated back into buildings (Haas, Krausmann, Wiedenhofer, & Heinz, 2015). Policies can be implemented into *LEED (Leadership in Energy and Environmental Design)* certifications with the aim of improving recycling of building materials and setting a standard for new buildings to have a certain percentage of recycled materials. Outdated and unused parts of the building stock as well as vacant buildings can also be used for potential adaptation measures in finding new services for these buildings to fulfill (Haberl et al., 2019; Huuhka & Lahdensivu, 2016). Instead of demolishing old buildings, retrofitting them to new standards and new purposes can result in a longer building life cycle.

4.1.4 Future Work

In terms of material inputs and increasing global domestic material consumption, more research is required to understand the socio-economic transitions that regions undergo and the influences that result in increased consumption (Fischer-Kowalski, 2011). Further understanding is necessary to explore how GDP and population changes can affect inflows of stocks, as well as affluence and other variables including: technology, politics, energy usage, social services, demographics, and trade information (Fischer-Kowalski, 2011; Fishman et al., 2014; Wang et al., 2018). To understand the interlinkages of all these variables involves exploring inputs and outputs over-time to examine if any of the aforementioned influences may affect flows of materials into a system, resulting in stocks (Aksozen, Hassler, & Kohler, 2017). A large number of studies are conducted for residential classes only, and although this is arguably the largest sink of MS, it does not provide information on other non-residential MS. Bridging the gap by breaking down MS into services can help compare them to socioeconomic indicators like population, affluence, and other variables aforementioned to see if there are correlations. Defining correlations will help further inform socio-economic metabolism and to predict what transitions will occur in the future, and how to plan appropriately for these transitions to reduce consumption.

Uncertainties in accounting for material stocks over time is apparent in the renovation and adaptations of new buildings, where stocks are only accounted for in the first stages of construction (Ravetz, 2008). Long-term changes in buildings will require maintenance and refurbishment of existing buildings, indicating that renovation will become the dominating activity of the built environment (Kohler & Hassler, 2002; Sartori, Bergsdal, Muller & Brattebo, 2008). However, renovations are hard to monitor as household renovations do not require a building permit unless something changes structurally. Using a spatial and GIS approach will enable better management of large-scale changes and estimates of building stocks, as building types change and small buildings are demolished to incorporate multiple residential dwellings (Kavgic et al., 2010; Meinel, Hecht, & Herold, 2009). GIS has a role in managing these materials and compositions of individual materials over-time. This also includes employing building information modelling through computer-aided software such as AutoCAD where quick calculations of building composition can be made (Wong & Zhou, 2015). Utilizing GIS in a 4D approach by incorporating length, width, height and time, will provide more accurate accounts of material stocks, especially when identifying construction and buildings services over time (Kumar, Sachdeva, & Kaushik, 2007). New technologies like CAD drawings and LIDAR data will help mitigate assumptions in material stock research and open avenues of accounting over time through record of more in-depth attributes such as year of construction and accurate height information.

Along with enhanced understanding of the socio-economic metabolism of material flows and consumption, it is also important to consider energy flows and consumption. Future studies could implement the methodology implemented in this thesis to exploring patterns of energy consumption (instead of material stocks) for individual homes, as well as energy requirements of certain services. A study conducted by Dall'O, Galante and Torri (2012) utilized the spatial building information, building typology, and energy usage, to find where energy consumption was high in the Lombardy region of Italy. Similar research was conducted by Fabbri, Zuppiroli, and Ambrogio (2012), on heritage buildings in Italy in order to examine their energy usages. The research was conducted for various time stamps and found that heritage homes take up larger amounts of energy than new dwellings (Fabbri et al., 2012). Utilizing this type of methodology for energy flows and consumption will help to inform homeowners of their energy usage patterns and allow policy makers to allocate funding for promoting more energy efficient homes. Article 9 of the European Directive 31 outlines that by the end of 2020, all new buildings will achieve close to zero-energy, as well as reducing greenhouse gas emissions from the construction sector by 20% within the EU (Dall'O et al., 2012; European Parliament, 2010). Regarding existing buildings, this is a large undertaking. The methodology outlined within this research can help to provide a framework for future bottom-up studies and how different service sectors perform not only from a material consumption perspective, but also other aspects of socio-economic metabolism such as energy consumption.

4.2 Conclusion

This thesis presented a novel study, which identified why services are important in relation to material stocks. This was also the first bottom-up material stock account conducted in a North American context. The research described throughout this thesis provides a methodological approach that can be applied in both a small island developing context, as well as a city context. It also contributes to a database of ongoing metabolism studies. Various studies have improved the knowledge of stock accumulation and prospective modelling can now help to anticipate what material stocks will be under different future conditions and scenarios. This involves divulging further into services and in-use resources that can be driven by various factors, such as GDP, affluence, and material consumption. The results of this study supports the need for continuous monitoring of material stocks in relation to services for policy makers to better understand material fluxes both spatially and temporally.

In order to further breakdown the socio-economic metabolism of islands and cities and to understand the fluxes that these systems go through, more research is required to enhance understanding of other aspects of metabolism. Future improvements regarding socio-economic metabolism include monitoring not only buildings, but also other inputs such as energy and road materials. Regarding the availability of GIS data, both study areas can improve continuous monitoring of material stocks and keeping up-to-date records of constructed buildings, including the year of construction and physical building footprint attributes. This would allow for improved material stock estimates that could be monitored over time. Combining the results of this research with information about demolition activities and potential climate events will allow cities and islands to plan for the outflow of materials, sustainable development, and future development trajectories.

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Appendices A. Supplementary Information for Introduction to Thesis

A.1 Semi-Structured Interview for Material Stock Accounting

These interview questions are to serve as a research method for collecting data to help inform research for a master's thesis. The thesis seeks to explore a material stock analysis within the small island country of Grenada and a generalizability study applied to the City of Kitchener to examine potential socio-economic drivers of these spatial patterns of stock accumulation. There are certain services provided by the material building stock that can possibly be explained by socio-economic drivers. Mapping these services will help provide an overview of hotspots of material stocks as well as where there are vulnerabilities of stock loss due to climate change or deteriorating buildings.

Material stock and flow analysis is an analytical tool to better understand current material cycles in the built environment. This can be from a global material stock and flow analysis of one material, to a local scale of multiple, materials, such as the urban building stock (Gloser et al., 2013). This includes studying the material intensities that buildings are currently composed of such as concrete, steel, brick or wood (Marcellus-Zamora, 2015). Material flows are simply the flows of these materials in and out of the system. Quantifying these resources and knowing the socio-economic system can help when it comes to extraction of primary resources, and help to decouple the socio-economic system which drives these material flows.

Q. Introduction to material stock and flows

Do you know of any internal studies where material stocks and flows are being conducted?

Are there any material accounts for each building for example if there is building permit data, does the island/city calculate the amount of material that is to be built and the size of the buildings?

Do you have any data pertaining to building permits. If so, where would this be located? Can it be obtained for free?

Do you know overall where materials are sourced from? Where do the majority of material come from (local or imported) Do they have an idea of the approximate proportion that is local vs imported?

Q. Construction and building material intensities

It is important to obtain data of material intensities to give a more accurate representation of how much materials are in the built environment. The main materials that I will be conducting are wood, concrete, aggregates, and brick. - Do you know if there is any data available like this?- Do you know who would have this type of information?

- Are there any types of main construction materials used on the island that I did not mention, if so what are they?
- How much concrete, brick, wood, or aggregates would be used for each floor of said apartment/condo building? Do you have this type of information? If not, then who possibly would?
- Do you have an idea of the proportions of materials? Or which material would hold the majority?

Q. Wood

- How much wood is being used for building purposes?
- Where is the wood obtained? If it is from international sources, where does it typically come from?
- Do you have any data on the amount of wood?
- Have you seen any future changes or predictions in the amount of construction materials, for example, would you say there is less or more wood being used for new buildings?
- Do you think climate change or future sustainable development has anything to do with increases or decreases in wood? If so, why?

Q. Concrete

- How much concrete would be used in a residential building? How much concrete would be used on a base of an apartment building? How much aggregate goes into concrete?
- How much concrete is being used for building purposes? What building typology (for example, industrial residential, etc.) is concrete the most prevalent?
- Where is the concrete obtained? If it is from international sources, where does it typically come from?
- Do you have any data on the amount of concrete?
- Have you seen any future changes or predictions in the amount of construction materials, for example, would you say there is less concrete being used for new buildings?
- Do you think climate change or future sustainable development has any impacts on increases or decreases in concrete? If so, why?

Q. Brick

- How much brick would be used in a residential building? How much brick would be used on a base of an apartment building?
- How much brick is being used for building purposes? What building typology (for example, industrial residential, etc.) is brick the most prevalent?
- Where is the brick obtained? If it is from international sources, where does it typically come from?
- Do you have any data on the amount of brick?
- Have you seen any future changes or predictions in the amount of construction materials, for example, would you say there is less or more brick being used for new buildings?
- Do you think climate change or future sustainable development has any impact on increases or decreases in brick? If so, why?

Q. Aggregate

- How much aggregate would be used in a residential building?
- How much aggregate would be used on a basement/foundation of an apartment building?
- How much aggregate is being used for building purposes vs roads? What building typology (for example, industrial residential, etc.) is aggreage the most prevalent?
- Is the amount of aggregate directly correlated with the amount of concrete?
- Where is the aggregate obtained? If it is from international sources, where does it typically come from?
- Do you have any data on the amount of aggregate used in a structure? in a road network?

- Have you seen any future changes or predictions in the amount of construction materials, for example, would you say there is less or more aggregate being used for new buildings?
- Do you think climate change or future sustainable development has any impact on increases or decreases in aggregates? If so, why?

Q. Recycling Building Materials

- How much gravel and grounded down material is from recycling? How much do you get trucked from gravel pits?
- Who gets the money from recycled materials/who sells it and who buys it on the island/city?
- Is there even a plan in place for recycling building materials after a major disaster or new renovation?
- What is the quantity of concrete, steel, timber or aggregates that can be recycled vs those that have to be thrown out?
- Is there any data on recycled amount of buildings? Would a developer be more likely to have this information?

Q. GIS Infrastructure

- Do you have any GIS data pertaining to building footprints, building size, type of building?
- Do you have any GIS data pertaining to building records, or year when buildings were constructed?
- Do you have any height information such as DEM's, DSMs that are of a good resolution?
- Are there any other GIS contacts that you can refer me too, that will help complete any additional information?

Q. Services that Buildings provide

Q. Tourism

- What is the future of tourism in Grenada? Is it ecotourism, starting to move away from the coast?
- Is there a plan in place for sea level rise? How much will this affect the existing stock?
- How many people do you have coming into the resort in one given year? How about 2014? Do you have demographics on that? Statistics of the customer base?
- How many people come into the cruise port? Which companies are serviced at the cruise port and where are they from? Do you have statistics on this?
- What contractors are on the island? What contractor did your resort hire? What developer? (Management portion)
- Are there plans for expansion?
- What do you do to ensure your buildings do not get affected by hurricanes or significant weather events?
- Who did you consider as a major contractor for any renovations ? Who else did they consider? Are they different then other resorts, or the same?
- Who owns the resort is it someone local? Where does the investment for new infrastructure come from? Foreign or local?

Q. Policies and Future Directions of Development

- Would planning department adopt sustainable policies if there was a monetary value associated with recycled materials? Ie. is there any plan in place to calculate how much recycled materials are worth?
- Would developers/contractors be more likely to recycle if there was a monetary value associated with demolished materials?
- Is there any policies in place for sustainable development pertaining to recycling of building materials?
- Who gets the money from recycling these building materials?
- What policies are in place to obtain a building permit?
- Is there any restrictions in place around the coastal areas? Ie. you have to build x amount from a shoreline?

Q. Urban Planning

- What are the future development plans on the island/within the city and projected growth?
- Where on the island/city are the future planning zones and the most projected growth?
- What kind of services will these developments require? i.e. commercial, residential, tourist, institutional, agricultural, industrial?
- Which types of services are prioritized?

A.2 Recruitment Letter Used in Contacting Potential Interviewees

The following outlines the letter format used in contacting potential interviewees.

“

Hello,

My name is Kristen de Kroon and I am a master’s student working under the supervisions of Dr. Su-Yin Tan in the Applied Geomatics Research Laboratory in the Geography and Environmental Management Department at the University of Waterloo, Canada. I am contacting you because I am looking to gain expert local knowledge on Grenada, specifically from an amount of building material in the built environment, which can also be referred to as building material stock. Any data and information gained will be used for my master’s thesis research study. I believe your knowledge and understanding of construction and planning in Grenada will help inform the study and provide valuable information.

Participation in this study is in the form of a semi-structured interview in person that should only take up to one hour of your time or longer if required and you are available. These interview questions will serve as a research method for collecting data to help inform/explore a material building stock analysis within Grenada. There are certain services that these building stocks provide such as tourism, education, health, well-being, residential and more. Through mapping these services, we can see where vulnerabilities in building stocks are located if a natural disaster were to occur or a building were to deteriorate.

Some example questions include:

- Do you have any data pertaining to building permits?
- The main materials that I will be conducting research on are wood, concrete, aggregates and brick- Do you know if there is any data available like this? Are there any types of main construction materials used on the island that I did not mention? If so, what are they?

- Do you have an idea of the proportions of materials? Or which material would hold the majority of construction materials?

If you are interested in participating in an interview, your input could be very valuable to the research. Please e-mail if you are interested, and I will follow up with an e-mail to make an appointment time that will fit in your schedule.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee."

Appendices B. Supplementary Information for the Case-Study of Grenada

B.1 Data Sources and Associated Metadata

Table B.1: *Data sources and metadata for case-study in Grenada*

Source	Description	Data type(s)	Resolution	Details	Units	Date
Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers	Airports	GIS Layer	n.g.	Vector		2016
	Hurricane shelters	GIS Layer	n.g.	Vector		2016
	Quarries and waste disposal sites	GIS Layer	n.g.	Vector		2016
	Parish boundaries	GIS Layer	n.g.	Vector; shows boundaries		current
	Demographic data	GIS Layer	Census enumeration districts	Vector; population	# people	per last census - 2011
	Road network	GIS Layer	n.g.	Vector; classified as main, secondary or tertiary roads		Jan 01 2014 - Dec 31 2015
	Population per building	GIS Layer	n.g.	Vector; shape area, use type, building pop	avg # people	Jan 01 2014 - Jan 01 2015
	Census enumeration districts	GIS Layer	n.g.	Vector; shows boundaries		current
	Buildings (new)	GIS Layer	n.g.	Vector; includes use type info		Jan 01 2014 - Jan 01 2015
	Land use	GIS Layer	n.g.	Raster; 19 use types	GRAY_INDEX	Jan 01 2014 - Jan 10 2015
	Households by parish	Data table	Parish		# of households, % of country's households,	1981, 1991, 2001, 2011

Grenada census					mean occupancy	
	Type of dwelling unit	Data table	Parish	11 types	# and % of parish households	2001, 2011
	Population density	Data table	Parish		persons/sq km	2001, 2011
	Dwelling area	Data table	National		# and % of sampled households	1998, 2008
	Number of floors	Data table	National		# and % of sampled households	1998, 2008
	Outer walls	Data table	National	Material	# and % of sampled households	1998, 2008
	Material of floor	Data table	National		# and % of sampled households	1998, 2008
	Roofing material	Data table	National		# and % of sampled households	1998, 2008
Grenada Physical Planning Unit and Grenada Department of Agriculture, Forestry and Fisheries	Building application information	Data table	Town	Details sq. footage and building use-type		Jan 2008 - Sept 2017
	Land-cover map					1982, 2000, 2001, 2009

B.2 Semi-Structured Interview List of Interviewees

Table B.2: *Job description of interviewee and information they provided.*

Job Description	Information they provided and other comments
Local Contractor	Completed the semi-structured interview on types of materials and new construction.
Managing Director of Engineering Firm	Completed the semi-structured interview on types of materials and new construction.
Building Technology Professor	Completed the semi-structured interview on types of material and new construction, as well as if there are any retrofitting for more resilient structures.
Senior Planning Officer	Completed the semi-structured interview on types of materials and new construction.
Land Use Officer	Completed the semi-structured interview on types of materials and land-use.
GIS Professional	Completed the semi-structure interview on GIS, materials and tourism.
Director of Operations at a Resort	Completed part of the semi-structured interview on tourism perspectives and if they are seeing any changes or an increase of visitors or new construction.
Resort Manager	Completed part of the semi-structured interview on tourism perspectives and if they are seeing any changes or an increase of visitors or new construction.
Resort Manager	Completed part of the semi-structured interview on tourism perspectives and if they are seeing any changes or an increase of visitors or new construction.
Resort Manager	Completed part of the semi-structured interview on tourism perspectives and if they are seeing any changes or an increase of visitors or new construction.

B.3 Building Heights Calculated Using Basic Trigonometry Formula

In order to conduct building height estimates in the field, a clinometer was used to measure the angle of the slope. Using basic trigonometry the height of buildings were calculated from the angle of the slope using the distance away from the building. 64 sample sites were taken with this method.

- The distance away from the building was calculated by counting out steps and multiplying the size of the step by the amount of steps taken. This was taken from heel to toe to be as accurate as possible each step.
- The angle
- The eye height at which the clinometer was measured was 160 cm therefore, that was added to each calculated measurement.
- This gives an overall count of building height.

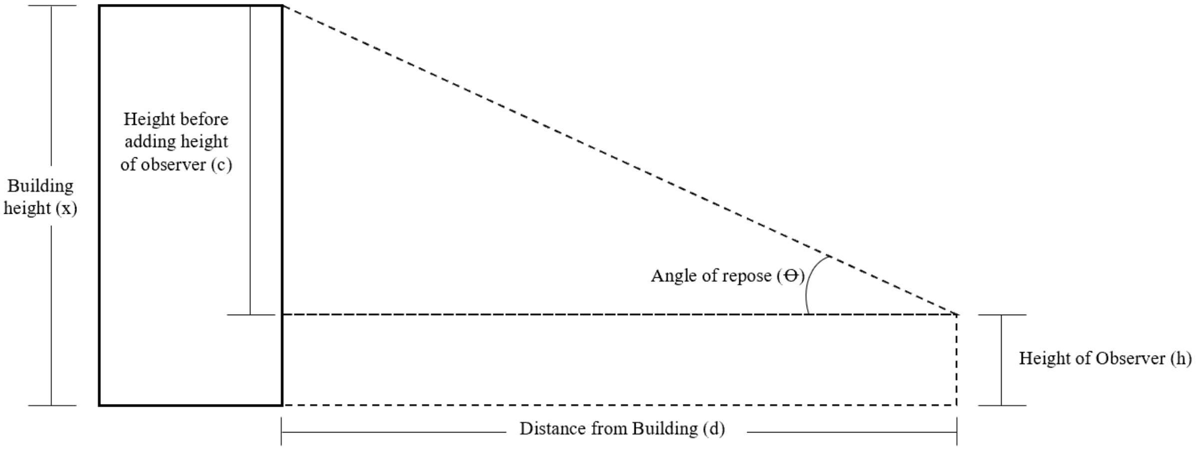


Figure B.1: Diagram of calculation for heights calculated through fieldwork.

This was the formula calculated for the height of each of the buildings collected through fieldwork:

x = (tan (angle (θ)) = Building height before height of observer (c)/distance from building (d)) + height of observer (h)

$x = (\tan(\theta) = c/d) + h$

$x = (\tan(\theta) * d = c) + h$

$x = (c + h)$

B.4 Grenada’s Material Intensity Typologies Used to Calculate Material Stocks

Table B.3: *Material intensity typologies used as a representative set of building construction styles in Grenada. Unit: kg/m*^{2} *(Symmes et al., 2019).*

	Aggregate	Timber	Concrete	Steel	Relevant occupancy classes
Concrete Structure type 1					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential-area single-family dwelling
Foundation - Pad footings	45	0	45	1	
Foundation - Posts	0	0	300	5	
Floors	0	0	450	10	
Walls	0	0	520	1	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	10	
Total	**45**	**40**	**1315**	**27**	
Concrete Structure type 2					Church/Chapel; Educational campus building; Standalone elementary/ secondary school; Minor hospital/Health center; Government office; Commercial; Urban-area mixed commercial; Industrial; Urban-area commercial/dwelling mix; Urban-area single-family dwelling; High density-area apartment; Low density-area apartment; Rural-area single-family dwelling; Residential area single-family dwelling; Small hotel cottage/villa; Recreational/community center; Seaport; Bus terminal
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	520	1	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	10	
Total	**159**	**40**	**1645**	**36**	
Timber Structure					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential area single-family dwelling
Foundation - Pad footings	45	0	45	1	
Foundation - Posts	0	0	300	5	
Floors	0	0	0	20	
Walls	0	50	0	0	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	10	
Total	**45**	**90**	**345**	**36**	
Concrete/Timber Mix Structure					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential area single-family dwelling
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	50	0	0	

Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	10	
Total	**159**	**90**	**1125**	**35**	
Steel Structure					Industrial
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	520	145	
Roof - Frame	0	0	0	145	
Roof - Covering	0	0	0	10	
Total	**159**	**0**	**1645**	**325**	
Brick Historical Structure					Cathedral; Historic building
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	0	20	
Walls	0	50	0	0	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	0	
Total	**159**	**90**	**675**	**35**	
Reinforced Concrete Structure					Major hospital; Large multi-unit hotel building; Stadium; Airport
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	0	145	
Roof	0	0	0	10	
Total	**159**	**0**	**1125**	**180**	

B.5 Confusion Matrix for All Occupancy Classes from Fieldwork

	110	111	112	120	121	122	123	132	140	210	214	220	241	242	310	322	330	331	340	411	412	520	542	530	610	723	811
110 - Church / Religious place	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
111- Cathedral	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112- Church	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120 - School / Education Centre	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	2	0	0	2	0	0	1	0	0	0	0	0
121 - Educational Campus Building	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
122 - Stand alone public / secondary school	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123 - Day care centre	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
132 - Minor hospital / health centre building	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
140 - Government Office	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
210 - Commercial	0	0	0	0	0	1	0	0	0	9	0	4	1	0	0	0	26	0	8	0	0	0	0	0	7	0	0
214 - Gas Station/Repair/Specialties	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
220 - Urban-area mixed commercial	0	0	0	0	0	0	0	0	0	3	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
241 - Urban-area commercial / dwelling mix	0	0	0	0	0	0	0	0	0	1	0	12	5	0	2	0	0	0	1	0	0	0	0	0	2	0	0
242 - Rural / residential-area commercial / dwelling mix	0	0	0	0	0	0	0	0	0	4	0	1	0	0	0	0	9	0	2	0	0	0	0	0	0	0	0
310 - Urban-area single-family dwelling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
322 - Low density apartment building	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
330 - Rural-area single-family dwelling	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	154	0	0	0	0	0	0	0	0	0	0
331 - Detached Garage	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	6	0	2	0	0	0	0	0	0	0	0
340 - Residential-area single-family dwelling	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0	4	222	0	115	2	6	0	0	0	0	0	0
411 - Large multi-unit hotel building	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6	0	0	0	0	0	0
412 - Small hotel cottage / villa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
520 - Recreational Centre	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
542 - Museum	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
530 - Historic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
610 - Seaport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
723 - Warehouse	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
811 - Farm Building	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure B.2: *Confusion matrix for all occupancy classes from fieldwork, evaluating fieldwork values vs Symmes et al. (2019) assumed values.*

Appendices C. Supplementary Information for the City of Kitchener Study

C.1 Data Sources

Table C.1: *Data and metadata for geodatabase for the case-study of Kitchener*

Data Layer	Description	Source	Year	Data Type	Extent/Scale	Attributes
Building Footprints	Building footprints drawn from aerial imagery, building surveys or site plans	City of Kitchener: Kitchener GeoHub	2016	Vector: Polygon	Kitchener Boundary	Category, city facility, location, area, status, fire information
Kitchener Boundary	City of Kitchener municipal boundary	City of Kitchener: Kitchener GeoHub	2015	Vector: Polygon	Kitchener Boundary	Area, municipality
Planning Intensification Area	Planning intensification areas within the City of Kitchener	City of Kitchener: Kitchener GeoHub	2016	Vector: Polygon	Kitchener Boundary	Status, category, name, intensificationID
Ward 2016	Political boundary representing each of the wards within the municipality of Kitchener.	City of Kitchener: Kitchener GeoHub	2016	Vector: Polygon	Kitchener Boundary	Councillor, name, councillor bio, email, fax, home, shape area
LIDAR SWOOP 2015 DSM Data	South Western Ontario ortho-imagery project.	Ontario Ministry of Natural Resources	2015	Raster	Kitchener Boundary	Digital surface information in metres
DEM Data	DEM data collected from points (processed LIDAR)	City of Kitchener: Kitchener GeoHub	2015	Vector: Points extracted from LIDAR	Processed to the Kitchener Boundary	Digital elevation information in metres
DTM Model	DTM model collected from points (processed LIDAR)	City of Kitchener: Kitchener GeoHub	2015	Vector: Points extracted from LIDAR	Processed to the Kitchener Boundary	Digital terrain information in metres
Application Status Report Demolition Control	Demolition control applications submitted by users, identifies what the project is and how large, address as well as ward information	City of Kitchener: Kitchener GeoHub	2016	Table	Kitchener Boundary	Location, description of demolition, application request
Planning Community 2016	Planning communities within the City of Kitchener	City of Kitchener:	2016	Vector: Polygon	Kitchener Boundary	Building inspector, fire inspector,

		Kitchener GeoHub				urban designer, area, census ID

C.2 Semi-Structured Interview List of Interviewees

Table C.2: *Job description of interviewee and information they provided.*

Job Description	Information they provided and other comments
Local Contractor	Full Semi-structured interview on material intensities and typologies.
Construction Foreman	Conducted the distribution of material typologies per occupancy class (Table 9).
Operations Manager – Construction Company	Conducted the distribution of material typologies per occupancy class (Table 9). Full semi-structured interview.
Planner	Full semi-structured interview. Mostly on planning and what is currently happening in Kitchener.
Sales Representative for Construction company	Semi-structured interview on upcoming large developments for their firm.

C.3 Final Material Intensities Summarized in kg/m^2

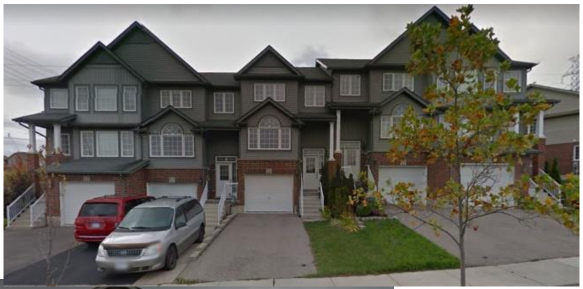
Table C.3: *Final material intensities summarized within each building occupancy class converted to kg/m^2*

(kg/m^2)	**Aggregate**	**Concrete**	**Timber**	**Steel**	**Masonry (Brick)**
Foundation with reinforced concrete					
Total a. (brick exterior)	310.5	609.4	19.9	4.42	312.9
Total b. (vinyl exterior)	310.5	609.4	19.9	4.42	-
Foundation without reinforced concrete					
Total a. (brick exterior)	310.5	609.4	19.9	-	312.9
Total b. (vinyl exterior)	310.5	609.4	19.9	-	-
Concrete Structure 1					
Total	347.52	1,648.7	-	21.1	-
Total a. (brick exterior)	347.52	1,648.7	-	21.1	353.4
Concrete Structure 2					
Total	347.5	928.8	11.94	19.32	-

Total a. (brick exterior)	347.5	928.8	11.94	19.32	353.4
Concrete Structure - Steel Reinforced					
Total	-	1,564.8	-	22.5	-
Steel Structure - Steel Walls					
Total	-	479.3	-	28.7	-
Steel Structure - Precast					
Total	-	222.47	-	40.04	-

C.4 Material Intensity: Building Typology Examples of each Distribution of Material Intensity

Residential Homes: 1. Foundation with reinforced concrete, 2. Foundation without reinforced concrete: Residential homes with concrete structure basements, timber framed, timber framed roof, different exterior wall materials. A. Stucco, B. Brick C. Wood Siding



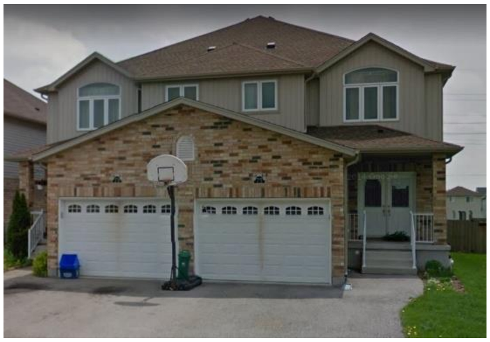


Figure C.1: *Photo examples of the building typology classes: Foundation with reinforced concrete and foundation without reinforced concrete.*

3. Concrete Structure 1: A concrete structure typically under 4 storeys or 12 metres, Concrete block with a concrete roof and Stucco or block exterior no basement just slab on grade. Typically, commercial, etc

Figure C.2: *Photo examples of the building typology classes: Concrete Structure 1*

4. Concrete Structure 2: *Concrete Structure a.* A concrete structure typically under 4 storeys or 12 metres, concrete block walls (fire walls) /timber frame with a timber roof, stucco or block wall exterior. *Concrete Structure 2b. Brick exterior*

Figure C.3: *Photo examples of the building typology classes: Concrete Structure 2*

5. Concrete Structure - Steel reinforced: Typically, higher than 4 storeys or 12 metres and therefore reinforced. High-rises.

Figure C.4: *Photo examples of the building typology class: Concrete Structure-Steel reinforced.*

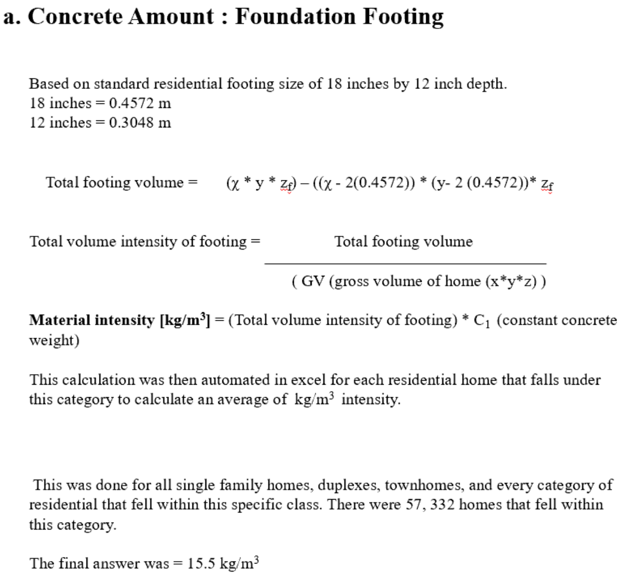
6. Steel Structure – Concrete Foundation: Typically, industrial warehouses and 1 or 2 storeys. Large

Figure C.5: *Photo examples of the building typology class: Steel structure – Concrete Foundation.*

C.5 Calculations Used when Creating the Material Intensity Estimates

Table C.4: *Constants used for calculating mass of each individual material. These masses were added all together to equate total material tonnes.*

Constant	Value	Source
C_1 (concrete constant weight)	2400 kg/m^3	(Calc Hub, 2019)
T_1 (Wood/Timber constant weight)	540 kg/m^3	Based on average of Spruce, Fir and Pine (Roof Online, 2019)
S_1 (Steel constant weight)	7900 kg/m^3	(Block Layer, 2019)
A_1 (Aggregate constant weight)	1600 kg/m^3	(Vulcan Materials Company, 2013)
B_1 (Brick constant weight)	1922 kg/m^3	(SI Metric, 2016)



a. Concrete Amount : Foundation Footing

Based on standard residential footing size of 18 inches by 12 inch depth.
18 inches = 0.4572 m
12 inches = 0.3048 m

Total footing volume = $(\chi * y * z_f) - ((\chi - 2(0.4572)) * (y- 2 (0.4572))* z_f$

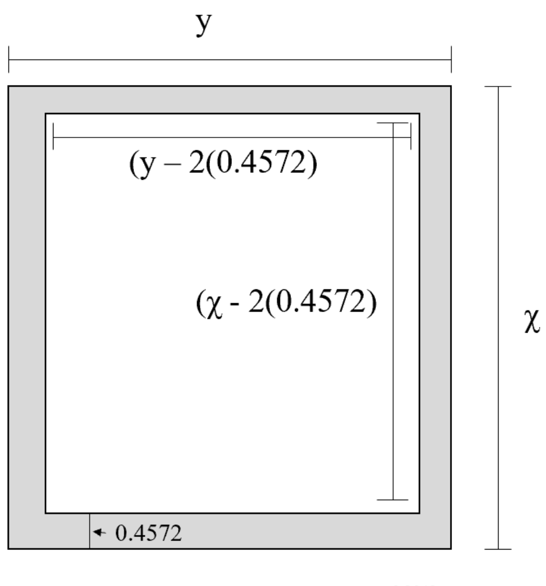
$$\text{Total volume intensity of footing} = \frac{\text{Total footing volume}}{\text{(GV (gross volume of home (x*y*z))}}$$

Material intensity [kg/m^3] = (Total volume intensity of footing) * C_1 (constant concrete weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

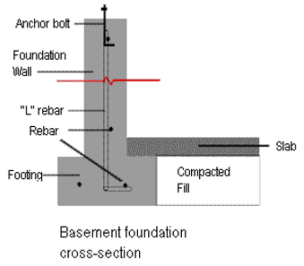
This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

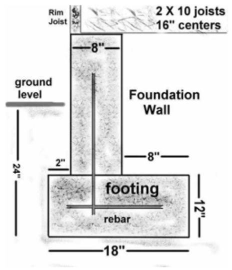
The final answer was = 15.5 kg/m^3



z_f (elevation of footing) = 0.3048
z = total height of building

b. Concrete Amount : Foundation Slab





Based on standard slab above compact fill which is typically 4 inches.
z_{slab} 4 inches = 0.1016 m

- Source: Expert and online construction sites

Total compact fill volume = $(\chi * y * z_{slab})$

$$\text{Total volume intensity of compact fill for foundation} = \frac{\text{Total compact fill volume}}{(\text{ GV (gross volume of home } (x*y*z)\text{)})}$$

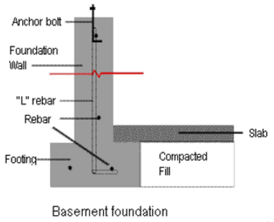
Material intensity [kg/m^3] = (Total volume intensity of compact fill) * A_1 (constant aggregate weight)

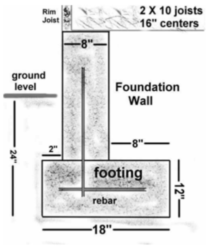
This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

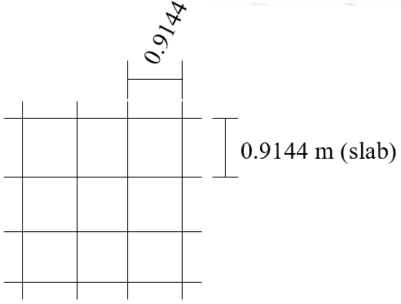
This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer was = 29.86 kg/m^3

c. Steel Amount : Foundation - Slab







Based on standard residential rebar size of ½ inch (#4 rebar).
- Can be placed every 36 inches if in a concrete slab (in any direction)
- 36 inches = 0.9144
- ½ inch = 0.0127

- Source: https://www.hunker.com/12003229/rebar-requirements-in-concrete-wall-construction, and expert

Total volume intensity of rebar for slab =

$$\frac{(((\text{ Width}/0.9144) *(\text{ Length} * 0.0127 * 0.0127) + ((\text{Length}/0.9144) * (\text{Width} * 0.0127 * 0.0127)}{(\text{ GV (gross volume of home } (x*y*z)\text{)})}$$

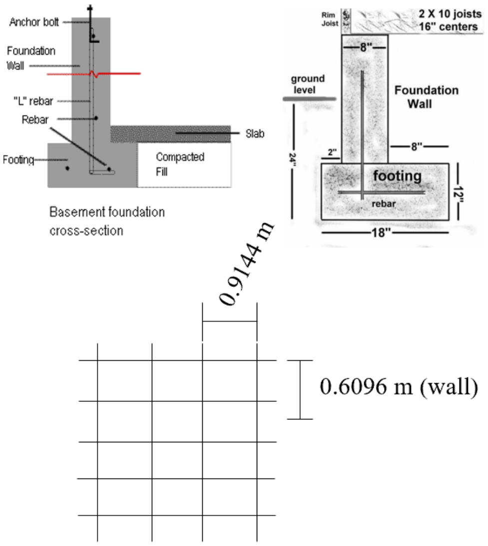
Material intensity [kg/m^3] = (Total volume intensity of footing) * S_1 (constant steel weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer for Foundation slab was = 0.34 kg/m^3

d. Steel Amount : Foundation - Wall



Basement foundation cross-section

Based on standard residential rebar size of ½ inch (#4 rebar).

- Rebar is placed every 24 inches horizontally and 36 inches vertically if in a wall.
- 36 inches = 0.9144
- 24 inches = 0.6096
- ½ inch = 0.0127
- 10 ft (average height of concrete basement wall) = 3.048

- Source: https://www.hunker.com/12003229/rebar-requirements-in-concrete-wall-construction, and expert

Total volume intensity of rebar for wall =

$$\frac{\left((((3.048/0.6096) * \text{Length}) * 0.0127) + (((3.048/0.6096) * \text{Width}) * 0.0127) + (((\text{Length}/0.9144) * 3.048) * 0.0127) + (((\text{Width}/0.9144) * 3.048) * 0.0127)) \right) * 2}{(\text{ GV (gross volume of home } (x*y*z)\text{)}}$$

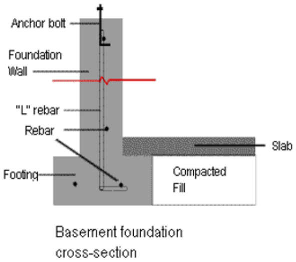
Material intensity [kg/m^3] = (Total volume intensity of footing) * S_1 (constant steel weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

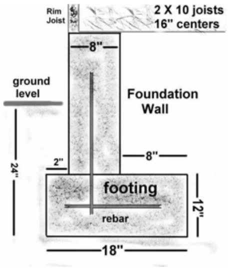
This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer for Basement wall was = 0.51 kg/m^3

e. Aggregate Amount : Foundation



Basement foundation cross-section



Based on standard residential compacted fill underneath a residential slab.
z_c 12 inches = 0.3048 m

- Source: Expert and online construction sites

Total compact fill volume = (χ * y * z_c)

Total volume intensity of compact fill for foundation = $\dfrac{\text{Total compact fill volume}}{(\text{ GV (gross volume of home } (x*y*z)\text{)}}$

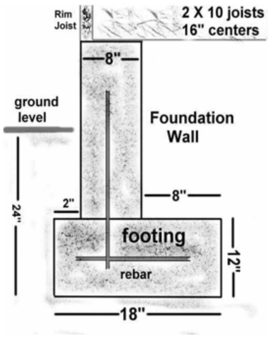
Material intensity [kg/m^3] = (Total volume intensity of compact fill) * A_1 (constant aggregate weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer was = 59.71 kg/m^3

f. Concrete : Foundation/Basement Wall



Based on standard forming a typical residential basement wall is 8 inch thick concrete.
z_{wall} 8 inches = 0.2032 m
$Height_{basement}$ = 3.048 m

- Source: Expert and online construction sites

Total wall volume of concrete = $(2\,(\chi * 3.048 * z_{wall})) + (2\,(y * 3.048 * z_{wall}))$

$$\text{Total volume intensity} = \frac{\text{Total wall volume of concrete}}{(\text{ GV (gross volume of home } (x*y*z)))}$$

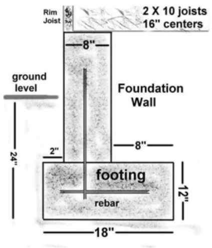
Material intensity [kg/m^3] = (Total volume intensity of compact fill) * C_1 (constant concrete weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer was = 71.84 kg/m^3

h. Timber: Wall Frames



Based on standard residential placement of 2x4 floor joists every 16 inches.

- 16 inches = 0.4064
- 2 inch = 0.0127
- 4 inches = 0.254

Plywood surround

- 3/8 inch plywood = 0.0056

- Source: https://www.hunker.com/12003229/rebar-requirements-in-concrete-wall-construction, and expert

Total volume intensity of timber for wall studs =

$$\frac{(\,((Length/0.4064) * (Height * 0.0127 * 0.254)) + ((Width/0.40664) * (Height * 0.0127 * 0.254))\,) * 2}{(\text{ GV (gross volume of home } (x*y*z)))}$$

Total volume intensity of outside sheathing walls =

$$\frac{(Height * Length * 0.0056) + (Height * Width * 0.0056) * 2}{(\text{ GV (gross volume of home } (x*y*z)))}$$

Material intensity [kg/m^3] = (Total volume intensity) * T_1 (constant timber weight)

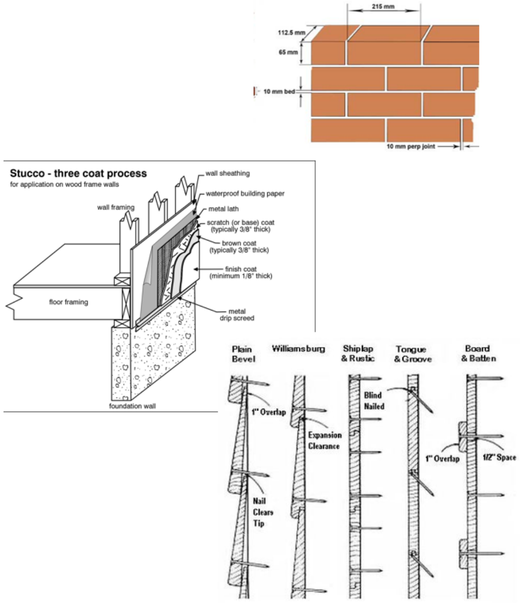
This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer for Timber in walls was: Total: 2.04 kg/m^3

Wall studs : 1.2 kg/m^3
Sheathing walls: 0.84kg/m^3

i. Exterior wall materials
(Brick, Wood Siding or Concrete/Stucco



Different type of exterior wall material thickness:
Thickness of Wood siding: - ½ inch = 0.0127 m
Thickness of Stucco – ½ inch = 0.0127 m
Thickness of Brick – = 0.1125 metres

- Source: https://www.hunker.com/12003229/rebar-requirements-in-concrete-wall-construction, and expert

Brick: Total volume intensity of outside wall material =

(Height * Length *0.1125) + (Height* Width * 0.1125) *2
(GV (gross volume of home (x*y*z))

Stucco:

(Height * Length *0.0127) + (Height* Width * 0.0127) *2
(GV (gross volume of home (x*y*z))

Wood Siding:

(Height * Length *0.0127) + (Height* Width * 0.0127) *2
(GV (gross volume of home (x*y*z))

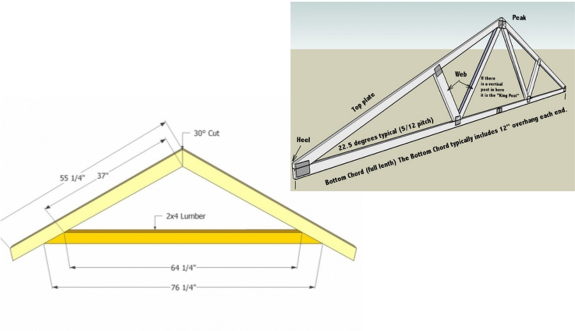
Material intensity [kg/m^3] = (Total volume intensity) * $_1$ (constant weight)

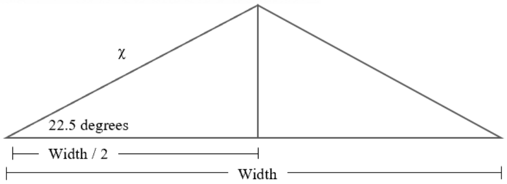
This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer for Timber in walls was: Wood Siding: 1.91 kg/m^3
Brick: 60.17 kg/m^3
Concrete/Stucco: 8.48 kg/m^3

j. Timber: Roof Frames and Sheathing





To calculate x = width (or adjacent angle)/ cosine (22.5)

Based on standard residential placement of 1 truss every 16 inches.
Assumption of 22.5 degree angles and 2 x 6 for base and top plates running to peak. Did not consider 2x4 in middle as different trussing forms.

- 16 inches = 0.4064
- 2 inch = 0.0127
- 6 inches = 0.1524

Plywood sheathing
- 3/8 inch plywood = 0.0056

- Source: https://www.hunker.com/13402536/what-is-the-standard-spacing-of-a-roof-rafter, and expert

Total number of trusses needed = (Length/0.4064)
Total length of top plate= (2 ((Width/2)/ cos (22.5))

Total volume of roof frame = ((Length/0.4064) * ((Width * 0.0127*0.1524) + (Length of top plate*0.0127 * 0.1524))

(GV (gross volume of home (x*y*z))

Total sheathing volume = (Length of top plate (new width) * Length of building * 0.0056)

(GV (gross volume of home (x*y*z))

Material intensity [kg/m^3] = (Total volume intensity) * T_1 (constant timber weight)

This calculation was then automated in excel for each residential home that falls under this category to calculate an average of kg/m^3 intensity.

This was done for all single family homes, duplexes, townhomes, and every category of residential that fell within this specific class. There were 57, 332 homes that fell within this category.

The final answer for Timber in roof sheathing was = 0.4 kg/m^3
roof frames was = 0.66 kg/m^3

C.6 Monte-Carlo Code Used for Assigning Material Stocks to Material Intensity Class Distributions

```
##Set working directory
Setwd(working directory file)

#Create new distribution and random generation for whichever service class distribution
#Import csv of all buildings and their associated attributes
df <- read.csv("Service.csv", header = TRUE, dec = ".")

#Create results table to output all the final counts after Monte Carlo completes with each individual
material assigned and the sum of these materials
results <- data.frame()
x <- c("K_MSAggSum", "K_MSTimberSum", "K_MSConcSum", "MSSteSum",
"K_MSBrickSum", "K_TotalMSSum" )

##LOOP START## (Counter is any number of iterations you want to run)
counter <- 1000000
# repeat{
for (i in 1:counter){

  #Distribution of Material Intensities, creates randomizer to assign values that then appends into
the material intensities
  y <- sample(LETTERS[1:4],291,replace=TRUE, prob = c(0.25,0.25, 0.25,0.25))
  df$Index <- y

  #Define df$Index and corresponding material stock values
  df$MIAgg12 <- ifelse(df$Index =="A", 0.11584, ifelse(df$Index == "B", 0.11584,
ifelse(df$Index == "C", 0.11584, 0.11584)))
  df$MITimber <- ifelse(df$Index == "A", 0.00, ifelse(df$Index == "B", 0.0, ifelse(df$Index ==
"C", 0.00398, 0.00398)))
  df$MIConc12 <- ifelse(df$Index == "A", 0.54955, ifelse(df$Index == "B", 0.54955,
ifelse(df$Index == "C", 0.30961, 0.30961)))
  df$MISteel1 <- ifelse(df$Index == "A", 0.00703, ifelse(df$Index == "B", 0.00703,
ifelse(df$Index == "C", 0.00644, 0.00644)))
  df$MIBrick <- ifelse(df$Index == "A", 0.11780, ifelse(df$Index == "B", 0.0, ifelse(df$Index ==
"C", 0.1178, 0.0)))

  #Define the total Material Stock per Material Category:
  #with respect to each individual Building footprint and their associated gross volume
  df$MSAgg <- df$MIAgg12 * df$GV_GrossVol
  df$MSTimber<- df$MITimber * df$GV_GrossVol
```

```
  df$MSConc <- df$MIConc12* df$GV_GrossVol
  df$MSSteel<- df$MISteel1* df$GV_GrossVol
  df$MSBrick<- df$MIBrick* df$GV_GrossVol

  #Calculate the total Material stock for the individual Building footprint
  df$TotalMS = df$MSAgg + df$MSTimber + df$MSConc + df$MSSteel + df$MSBrick

  #Sum columns of calculated values from iteration
  dfout <- data.frame(ncol=5,nrow=counter)
  colnames <- x
  dfout$K_MSAggSum <- sum(df$MSAgg)
  dfout$K_MSTimberSum <- sum(df$MSTimber)
  dfout$K_MSConcSum <- sum(df$MSConc)
  dfout$K_MSSteSum <- sum(df$MSSteel)
  dfout$K_MSBrickSum <- sum(df$MSBrick)
  dfout$K_TotalMSSum <- sum(df$TotalMS)
  results <- rbind(results, dfout)
  ##LOOP END##
}
write.csv(results, "Mixed_Use_MS_Final.csv")
#END SCRIPT#
```

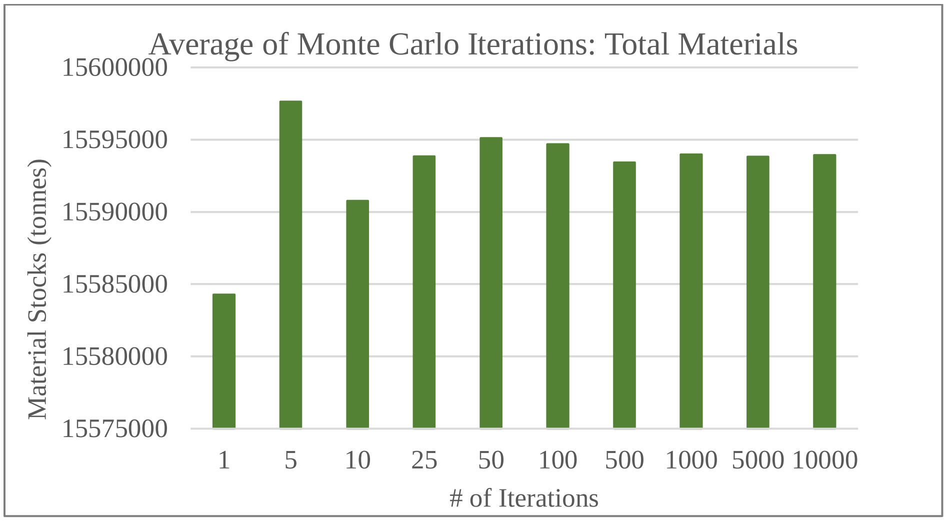


Figure C.6: *Monte Carlo results of total material calculations for the residential building class. From this you can see that after about 5000-1000 iterations it starts to flatten out.*

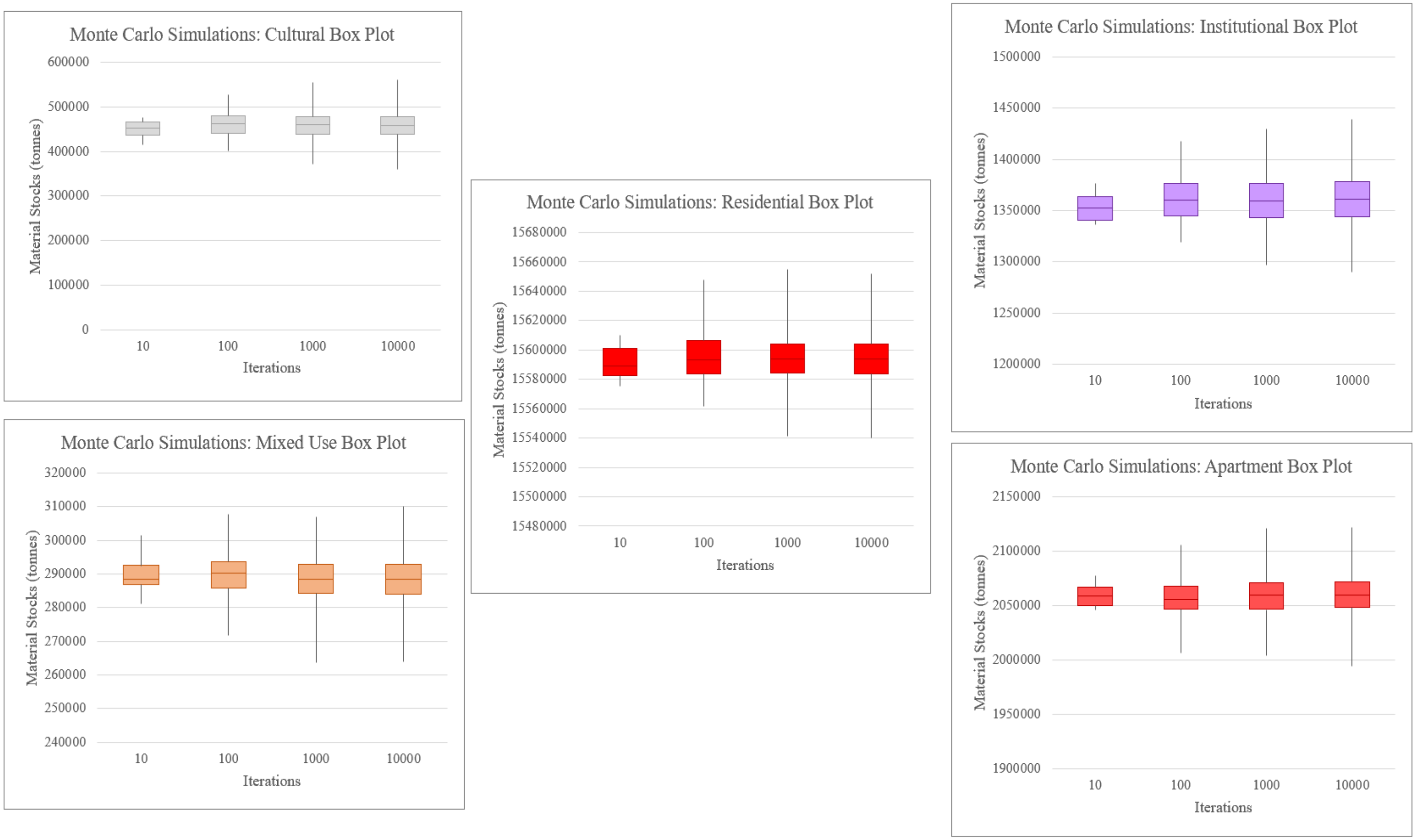


Figure C.7: *Monte-Carlo simulations box plots for each distribution that was not 100%, showing at 10,000 iterations quite a lot of variability still between the quartiles, therefore, median was chose as the best representation for calculating the material intensities.*