Conceptualising an Urban Digital Twin Framework for Simulating the Impact of Household Consumption Choices on the Carbon Footprint of Urban Neighborhoods

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Abstract

This paper presents a concept and first glimpse at the development of an urban digital twin framework to estimate and forecast the carbon footprints of urban neighbourhoods, with a focus on household consumption choices, specifically in buildings, food, and transportation sectors, as key emission contributors. Despite constituting nearly three-quarters of global carbon emissions, the influence of household consumption choices on a region's carbon footprint is often neglected. While assessments at a regional or city scale may prove too broad for targeted mitigation strategies, estimating carbon emissions at the neighbourhood scale can foster sustainable and resilient urban areas. However, challenges arise in estimating emissions at this scale due to the availability of aggregated data, insufficient cross-sectoral data integration, and a lack of practical visualisation tools, causing policymakers to overlook the impact of household choices on neighbourhood carbon footprints. Therefore, the present article provides insights into the ongoing early-stage development of using urban digital twins to model, simulate, analyse, and visualise the impact of household consumption choices on neighbourhood-scale consumption-based carbon emissions. By exploring "what-if" scenarios, this research also seeks to forecast emission profiles based on how household consumption choices influence a neighbourhood's carbon emissions under future climatic and demographic conditions.

1. Introduction

It is widely recognised among domain experts and practitioners that traditional carbon accounting methods frequently neglect and insufficiently examine emissions from household consumption choices of goods and services. Despite constituting nearly three-quarters of global carbon emissions, the influence of these choices on a region's carbon footprint is often omitted, leading to an underestimated carbon emission profile (Ottelin et al., 2019). This perception highlights a gap in comprehensively addressing the entirety of carbon emissions within a region. However, regional or city-scale assessments can be too broad and lack integration of local socio-economic, demographic and land use parameters for implementing target-based mitigation strategies when examining the impact of household consumption choices on a region's emission profiles. This necessitates a shift towards neighbourhood-scale analyses driven by localised parameters. Unfortunately, estimating emissions at the neighbourhood scale encounters challenges due to the availability of aggregated data, lack of cross-sectoral data integration, and inadequate visualisation tools, causing policymakers to overlook the impact of household choices on neighbourhood carbon footprints (Chen et al., 2023). Consequently, there is a pressing need for improved neighbourhood-scale carbon emission estimation to enhance public policies, guide climate investments, and raise resident awareness about their household choices impacting the neighbourhood's carbon footprint.

Over the past decade, there has been a notable surge in Information and Communication Technology (ICT) utilisation to drive sustainable urban development. Integrating ICT hardware such as sensors, mobile phones, and satellite systems, as well as incorporating intelligent computer algorithms and geospatial software, has helped in novel digital and data-driven methodologies for urban studies and multi-criteria decision-making. Google, in 2018, released the Environmental Insights Explorer (EIE) tool to empower cities with comprehensive data and insights for informed decision-making on carbon emissions from buildings and transportation. Based on the CURB Tool: Climate Action for Urban Sustainability (The World Bank, 2019), EIE uses a combination of aggregated geodata sources, modelling techniques, overhead imagery and GIS visualisation tools for taking action toward a low-carbon future when aggregated to a city scale (Google, 2018). However, due to its reliance on overhead imagery and the aggregated nature of data sources, it fails to provide granular insights and target-based mitigation strategies at a city-district scale. On the other hand, the concept of Urban Digital Twins has emerged as a bright spot, presenting a transformative approach to tackle urban centres' complex challenges. Urban digital twins replicate a built environment's physical and dynamic aspects in a virtual space at a much more granular level than Google's EIE. These twins are created by collecting and integrating diverse data sources, including but not limited to geospatial data, sensor data, social data, and real-time information from various urban systems. They enable detailed, standardised, and granular representations of urban environments while facilitating cross-sectoral data integration, scenario modelling, and broader stakeholder engagement. These digital counterparts of urban areas empower citizens and decision-makers with valuable insights, enabling informed decisions on various urban issues. Therefore, by using urban digital twins, there is an opportunity to improve the accuracy, granularity, and understanding of carbon emissions at the neighbourhood scale.

Against this backdrop, the current research aims to advance our understanding of urban neighbourhood carbon footprints, focusing on buildings, food, and transportation as primary emission contributors and necessitating a cross-sectoral investigation. The present article seeks to achieve two key objectives: 1) to furnish a comprehensive overview of existing consumption-based carbon accounting approaches, therefore meticulously identifying key challenges faced by domain experts and practitioners in its estimation, and 2) to highlight the role of urban digital twins in sustainable urban development through the lens of urban carbon emissions and provide insights into the ongoing research, focusing on using urban digital twins as a framework to model, simulate, analyse and visualise the role of household consumption choices in estimating neighbourhood-scale consumption-based carbon emissions. By exploring "what-if" scenarios, this research also aims to analyse how household choices, such as changes in building set point temperature, dietary choices, food waste, and transportation mode, impact carbon emissions of their neighbourhood under future climatic and demographic conditions.

2. State of Art

2.1 Existing Consumption-Based Urban Carbon Accounting Approaches

Consumption-based carbon emissions play a pivotal role in comprehensively assessing the environmental impact of human activities. This field employs various methodologies to trace and quantify carbon emissions from consuming goods and services. Several methods are employed for consumption-based carbon accounting; a few commonly used methods are described below:

1. Input-Output Analysis (IOA): traces carbon emissions through goods and services production and supply chains. It utilises a comprehensive economic matrix to capture transactions between industries, applying emission coefficients to estimate the carbon footprint of each sector. While IOA provides a systematic view of entire supply chains, its reliance on aggregated data may mask variations at finer scales, hindering the identification of emission hotspots. Additionally, IOA cannot capture spatial and temporal dynamics within supply chains, limiting its adaptability to changing consumption patterns (Han et al., 2022).

2. Consumption-Based Emissions Factors (CBEFs): represent a simplified approach that utilises emission factors associated with specific goods and services to estimate consumption-based emissions. This method is less data-intensive and computationally complex than IOA but may have lower accuracy (St-Jacques et al., 2020).

3. Trade-Balance Method: typically uses international trade data to allocate emissions to a region based on their net imports or exports of embodied carbon in goods and services. However, challenges arise when applying it at very granular scales, such as neighbourhoods, due to data limitations and the complexity of modelling household consumption profiles (Clora and Yu, 2022).

4. Life Cycle Assessment (LCA): evaluates a product's or service's environmental impact across its entire life cycle. It encompasses raw material extraction, production, transportation, use, and disposal. LCA involves detailed energy consumption, emissions, and resource use assessments at each life cycle stage. LCA provides a holistic understanding of the environmental impact. However, it is resource-intensive and demands extensive data, making it challenging to conduct for every product or service. Moreover, incorporating dynamic consumer behaviours into LCA can be difficult, as it typically assumes static consumption patterns (Chau et al., 2015).

2.2 Key Challenges and Gaps

Urban areas are complex and challenging to quantify based on their carbon footprints. They are interconnected infrastructural, social, economic, cultural, and political systems with a continuous trade of goods and services with nearby regions. Traditionally, assessments of regions' carbon footprints have focused predominantly on their operational phases using a production-based emission approach with a minimum focus on the consumption side of goods and services (Dubois et al., 2019). This limited focus has resulted in underestimating the overall carbon footprint of urban areas. Despite the diverse approaches outlined in section 2.1 and the abundance of academic and commercial tools, databases, and inventories available in the market (The Global Covenant of Mayors for Climate and Energy (GCoM), together with Bloomberg Associates (BA) and the World Resources Institute (WRI), 2021), several criticisms persist regarding the efficacy of the consumption-based carbon accounting approach and paying less attention to household consumption profiles (Balouktsi, 2020) (Volden, J., 2018). Households are responsible for 65% of global carbon emissions, yet they are often overlooked while calculating the building's carbon footprint due to their complex, diverse, and interdisciplinary nature (Hong et al., 2017). A primary challenge lies in the aggregated nature of datasets, which underscores the requirement for more granular datasets to identify and visualise consumption-based emissions hotspots at a local scale (Chena et al., 2020). Moreover, there is widespread criticism regarding the absence of standardised data frameworks and visualisation capabilities. These tools frequently encounter challenges seamlessly integrating with local datasets, including demographics, land use, socio-economic parameters, and household consumption profiles, reducing their overall utility. Datasets about residents' preferences for set-point temperatures, electricity usage, food consumption, waste production, and modal choices are seldom available as open datasets at the household scale due to privacy. Disaggregating national data to local levels presents an opportunity to generate datasets that reflect consumption-based emissions at granular scales. However, the technical capability to produce disaggregated data often relies on census datasets and statistical models. This dependence results in a spatial gap, hindering the analysis and visualisation of carbon footprints at the local scale, such as in neighbourhoods (West et al., 2015). Moreover, the absence of a standardised urban data model that facilitates cross-sectoral data integration to examine the impact of household consumption choices on neighbourhood emission profiles intensifies this challenge (Sharifia et al., 2018). To summarise, the following are the five critical gaps frequently highlighted in the available literature:

1. Less attention paid towards household consumption profiles: household consumption choices and behaviour are often overlooked, resulting in underestimating carbon emissions.

2. Missing local parameters: lack of understanding of how local factors such as socio-economic parameters, demographics, and land use influence consumption-based emissions.

3. Aggregated data and quality: data on consumption patterns and subsequent estimates of carbon emissions are usually available at an aggregated national or regional scale.

4. Absence of a standardised data model: no standardised urban data model exists, which can help to understand the impact of household consumption choices on neighbourhood emission profiles and quantify consumption-based carbon emissions.

5. Lack of geo-toolsets for decision-makers: the aggregated nature of data availability restricts residents and decision-makers from identifying emissions hotspots and making target-based mitigation strategies.

2.3 Use of Urban Digital Twins in Sustainable Urban Development

The concept of a digital twin is not new and has been regularly used in different professions, such as automobiles, aeronautics and medical science. However, the term "urban digital twins" and its application in sustainable urban development gained significant attention alongside smart-sustainable city initiatives triggered by urbanisation and climate change issues (Ferré-Bigorra et al., 2022). Urban digital twins replicate both the physical and dynamic aspects of a built environment in a virtual space. This enables a holistic way to identify and prioritise opportunities and challenges leading to urban sustainability even at a local scale. Based on data-driven workflows, urban digital twins can also help predict future urban processes and built environments, irrespective of whether the counterpart already exists in the real world or will exist in the future, empowering collaborative decision-making for a more livable and resilient future. For example, to study the impact of population growth, migration patterns, economic potential and climate pressure on the housing supply and demand for the Plieningen district of Stuttgart in Germany, (Xu and Coors, 2012) extended the system dynamics-GIS integration with 3D visualisation of the building stock to perform sustainability assessment of urban residential building stock and its spatial distribution for current and future conditions based on sustainability indicators divided into four groups: environment, economics, housing and society. Helsinki's 3D department used the city's urban digital twin to develop the "Energy and Climate Atlas," focusing on various environmental-related aspects, including heating systems, refurbishments, energy certification, carbon emissions, wind simulation, electricity, district heating, water and solar energy potential (Ruohomäki et al., 2018). Zurich's urban digital twin evaluates environmental and energy efficiency, urban planning, and micro-climate simulation. The authors argue that integrating climate concerns into planning decisions using urban digital twin is now more feasible, allowing analysis and visualisation of the impact of new developments on climate-relevant factors like temperature, wind, air pollution and carbon emissions (Schrotter and Hürzeler, 2020). Vienna's urban digital twin, renamed "Urban Digital geoTwin," emphasises geodetic and geometric aspects, integrating data for use in diverse areas, including public participation, urban management, and a comprehensive climate strategy (Lehner and Dorffner, 2020). Similarly, many other EU and global cities have either developed or are developing their urban development and environmental strategy using urban digital twins (Caprari et al., 2022).

A common building block found in all the urban digital twins is the presence of a 3D city model developed for the whole city that is accessible online. 3D city models serve as a spatial framework that helps organise, integrate, and exchange diverse cross-sectoral datasets related to the built environment at multiple spatial-temporal scales across different toolsets, effectively closing data interoperability gaps (OGC, 2023). In the context of urban sustainability, urban digital twins powered by 3D city models can continuously monitor and analyse urban sprawls and carbon emission patterns, track progress towards carbon reduction goals, and inform sustainable urban planning decisions. Many urban digital twins are based on Open Geospatial Consortium (OGC) CityGML 3D city models. OGC CityGML is a standardised and open data model and exchange format that allows storing the topology, geometry, semantics, attributes and appearance of city objects in different levels of visual details (LoD). City objects in CityGML are defined as all the physical objects found in the real-world built environment. (Wysocki, O. and Schwab, B. and Willenborg, B., 2020) provides an extensive list of CityGML datasets openly distributed by many cities worldwide. Recent studies have shown the potential of using urban digital twins developed around CityGML to analyse and visualise critical issues in urban sustainability as compiled by (Biljecki et al., 2015). Currently, research is primarily focused on estimating neighbourhood-scale carbon footprints, particularly household activities contributing to three key emission sources: building energy consumption, food consumption and waste, and transportation behaviours. Therefore, the following paragraphs explain various studies that have leveraged CityGML 3D city models within these domains.

Since its first release of CityGML in 2008, many studies have frequently used CityGML for modelling, simulating, forecasting and visualising the building stock for its energy demand and potential. After its geometric and schematic validation (Coors et al., 2020), CityGML-based building models are used to extract data on the building volumes, thermal zones, building height, orientation, sun-exposed wall area, solar irradiation and combined with functional attributes on building function, year of construction to predict the energy demand for heating and/or cooling for different building typologies and renewable energy potentials. Different urban energy simulators like SimStadt (Nouvel et al., 2015), CitySimPro (Rosser et al., 2019), EnergyPlus (Holcik, P, 2017), and TEASER+ (Malhotra and Shamovich, 2019) use CityGML datasets as the basis for urban energy simulations. To study the environmental impact of carbon emissions from building stock, estimating energy demand is a fundamental and multi-faceted step in any building refurbishment project. (Eicker et al., 2018) utilised CityGML building models for the entire county of Ludwigsburg, Germany, to assess heating and electricity demands for each building in the current state and under "Medium" and "Advanced" refurbishment scenarios using SimStadt. Rooftop photovoltaic (PV) potential and carbon emissions were also analysed based on energy consumption and emission factors. On a city scale, (Shindo et al., 2022) utilised CityGML to study embodied carbon and renewable Energy in Tokyo. The study explores achieving carbon-neutral districts in Tokyo by 2050 using 3D CityGML. Analysing carbon emissions and reductions from buildings, it utilises the PLATEAU model along with the CityGML extension of sustainable urban planning (i-ur ADE) to simulate solar radiation on exterior walls or roofs. Photovoltaic power calculations, based on solar radiation results, reveal that wall-mounted PV contributes to reducing building carbon emissions during operation, similar to roof-mounted PV. For the city of Helsinki, using the city energy and climate atlas, (Rossknecht and Airaksinen, 2020) utilised CityGML with its building energy-specific extension of Energy ADE to provide energy-relevant information on individual buildings for more accurate heating energy demand simulation of Helsinki's building stock in different scenarios on the urban scale and calculate the heating-demand-saving potential, that can be achieved through renovations, on the building scale. Based on the energy demand for heating and information about the heating systems, the carbon emissions caused by heating were calculated. (Würstle, P., 2018) developed a prototype that allows altering the building set point temperature through a web-based application using CityGML and Energy ADE data model. The prototype was initially tested exclusively on public buildings, with the author arguing that acquiring datasets on set-point temperatures for private residential buildings posed a significant challenge. Subsequently, researchers have devised methods to predict building set-point temperatures by leveraging statistical datasets or smart thermostat data (Panchabikesan et al., 2021) (Gianniou et al., 2018). While similar studies are available at a regional or city scale, analysing refurbishment strategies by prioritising the local scale over the city scale is also essential. Local insights, socio-economic factors, and specific demographics significantly impact the success and effectiveness of refurbishment initiatives. Focusing on the unique characteristics of neighbourhoods or city districts allows for more tailored and impactful strategies.

In terms of the food sector, an international consortium of experts from urban design, sustainability, and geoinformatics collaboratively engineered a harmonised data model extension of CityGML called the CityGML Food-Water-Energy (FWE) ADE (Padsala et al., 2021b). This model was designed to facilitate urban simulations incorporating household consumption behaviours across the interconnected Food, Water, and Energy resources domains. The CityGML FWE ADE is still fresh and evolving with time. Studies have used FWE ADE to store inputs and outputs for many new bottom-up FWE nexus workflows such as biomass potential analysis (Bao et al., 2020a), bioenergy potential analysis (Bao et al., 2020b), building stock water demand (Bao et al., 2020c), food production and household food demand (Bao et al., 2021). Additionally, FWE ADE was deployed as a central data exchange platform to exchange data between SimStadt and a FWE land use simulator UD_InfraSim to simulate future biomass potential of a land-use scenario influenced by climate, population and urban development changes in Vienna (Padsala et al., 2021a). (Braun et al., 2021) identified new objects and attributes which can be a part of FWE ADE supporting circular economy workflows, such as energy recovery from food waste and water waste with a potential to extend it for storing carbon emissions stemming from household consumption of food type (plant-based or animal-based) and that from the transportation of food waste to the location of landfills.

In estimating emissions from transportation, (Ebrahim et al., 2021) developed a prototype platform to assess carbon emissions from building stock and vehicular traffic in the Stöckach neighbourhood of Stuttgart city. The carbon emissions from the building stock were computed by integrating CityGML datasets and the SimStadt simulation platform. The HERE traffic flow API was employed to calculate emissions from vehicular traffic, coupled with a modified version of the methodology outlined by (Cascetta et al., 2010). Key inputs for estimating carbon emissions from vehicular traffic included vehicle types, average speed, and segment length. While the authors acknowledged the challenges in obtaining such datasets, using statistical methods in conjunction with Origin and Destination datasets enables estimating vehicle types linked to individual buildings in the neighbourhood. Moreover, leveraging OpenStreetMap datasets or the Digital Landscape Model from the city of Stuttgart facilitates the identification of segment lengths for each road. The newer CityGML version 3 has enhanced the data model for transportation objects, improving its usability for traffic simulations, driving assistance systems, autonomous driving, and road and railway facility management (Kutzner et al., 2020). This has led to studies using CityGML 3 with the SUMO simulation engine, enabling more accurate traffic simulations and the development of advanced driving assistance systems (Beil et al., 2020). However, studies regarding utilising the CityGML data model for estimating carbon emissions from vehicular traffic based on household modal choices influenced by socio-economic parameters and landuse are currently lacking.

While isolated instances of academic research explore the use of urban digital twins for individual aspects such as urban energy simulation, simulation of food demand, or traffic simulation, comprehensive examples or use cases that encompass the quantification of carbon emissions from buildings, food, and the transportation sector while also incorporating household consumption choices on a neighbourhood scale is missing. Recognising and incorporating household behaviour into the simulation process is crucial for producing more accurate and realistic assessments of carbon emissions associated with energy usage in buildings, transportation choices, and consumption habits, which directly impact carbon emissions. This acknowledgement underscores the importance of considering human behaviour patterns as a key variable in carbon emission modelling efforts to improve the reliability and precision of emissions visualisation.

Another crucial application of urban digital twins in carbon accounting is through visualisation and engaging stakeholders. Urban digital twin platforms are virtual meeting points for multi-stakeholder engagement. Based on the purpose, an urban digital twin platform is generally an information-sharing platform (Würstle et al., 2021); a collaborative crowd-sensed platform to get information and feedback (Lieven, 2017) and/or a co-development platform for citizens and decision-makers such as architects, engineers, urban designers to simulate and test different scenarios (Schrotter and Hürzeler, 2020). Web globes and frameworks from Cesium visualise), Esri (ArcGIS JavaScript API), and Mapbox (Mapbox GL JS) are regularly used to develop digital twin platforms to interact and visualise large-scale 3D city models stored in OGC standards of 3D Tiles and i3S. (Würstle et al., 2020), (Santhanavanich et al., 2022) proposed an urban energy dashboard concept, leveraging diverse OGC standards. This innovative dashboard integrates

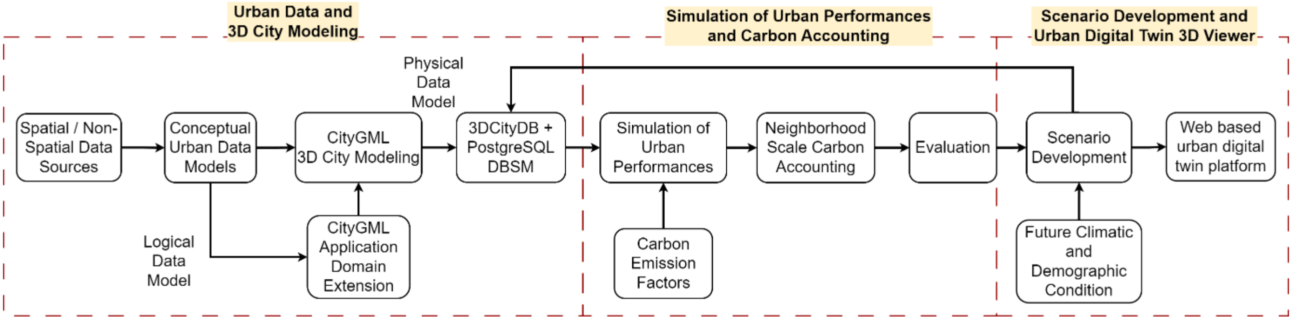

Figure 1. Overall methodology

CityGML 3D city models and utilises 3DTiles for web-based presentation. The application aims to deliver static and dynamic urban energy data to residents and city administration in a straightforward yet highly effective manner. However, the application solely exhibits heating energy demand values and real-time energy production data from photovoltaic rooftops. Notably, there is an absence of a Key Performance Indicators (KPIs) list and functionality to visualise what-if scenarios, which would otherwise assist households in understanding the impact of their choices on the carbon footprint of their neighbourhood. (Rossknecht and Airaksinen, 2020) (Köhler et al., 2021) in their web application based on CityGML models and 3D Tiles web format proposed functionality to visualise different what-if scenarios and integration of renewable energies, respectively. Notably, there is currently a distinct absence of web applications that comprehensively visualise carbon emission profiles at the neighbourhood level. These applications, capable of illustrating the influence of households' behaviour on building energy, food, and transportation, are yet to be developed or identified in the existing landscape.

3. Urban Digital Twin Framework for Household Carbon Footprints

Building on the above existing knowledge, this study wants to delve deeper into the carbon footprint of urban neighbourhoods. It pinpoints buildings, food, and transportation as key emitters, highlighting the need for a multi-faceted approach. Furthermore, by exploring different "what-if" scenarios, this research will examine how changes in household behaviour, such as adjusting home temperature settings, dietary choices, food waste reduction, and transportation mode selection, can influence neighbourhood emissions under projected climate and population changes. While doing so, the current research seeks to answer two overarching questions:

1. How can urban digital twins be effectively utilised to model, simulate, and assess the impact of household consumption choices on carbon emissions within urban neighbourhoods?
2. As climate change intensifies, how can we encourage residents to adopt sustainable behaviours like adjusting home temperatures, adopting plant-based diets, and choosing greener transportation options?

Fig. 1 shows an overall methodology proposed to achieve the above-mentioned research goals. For urban data and 3D city modelling, CityGML is used as the open and standardised data model to store and exchange digital 3D city models. However, despite the release of the latest CityGML version 3.0, the adoption in this work remains with version 2. This is primarily due to the limited software support available for the newest iteration while writing this article. The original data model of CityGML is further extended with new classes and attributes to store datasets on building set-point temperature, household dietary choices, food waste, land use, demographics, socio-economic parameters, household modal choices, origin-destination datasets, vehicle emission factors, amongst others. The framework of CityGML Food-Water-Energy Application Domain Extension fits well for this purpose, and it will be further developed because of its capabilities for storing different sector-specific datasets in a single cross-sectoral urban data model at different spatio-temporal resolutions (Padsala et al., 2021b). Datasets from publicly available literature, real estate cadastre maps, open data portals, and commercial geodata providers are used to enrich these data models. Different KPIs are identified to enhance the analysis and visualisation of consumption-based carbon emissions at the neighbourhood scale. For simulation purposes, SimStadt[1], a desktop-based urban simulation tool, is used due to its seamless compatibility with CityGML 3D city models. This compatibility also ensures a smooth integration of CityGML-stored urban data into the simulation and visualisation process. 3DCityDB [2], along with the PostgreSQL relational database, is used to manage and query the enriched CityGML datasets and simulation results effectively. New simulation workflows to estimate building-related energy demands based on household set-point temperature choices, food demands and generated food waste based on household dietary choices, emissions from transportation of food waste to landfill sites, and emissions due to residents' modal choices and mobility patterns are being developed to calculate identified KPIs based on the simulation results. For the transportation domain, agent-based models such as SUMO will be used to derive the residents' simulated origin and destination profiles and, subsequently, the chosen mode of transport by the residents and its related carbon emissions. Alternatively, a synthetic population model will be developed, i.e. without the traffic flow simulations. This should also give us a good insight into where people travel and estimate carbon emissions from their travelling pattern. For validation purposes, publicly available literature and measured datasets from municipalities will be used as benchmarks. Following validation and establishment of the base scenario, two scenarios will be formulated, drawing upon existing literature and futuristic urban concepts. Scenario A will include the projected climate profile for the year 2050, projected 2050 population density, the current choice of building set point temperatures, increase in private vehicles (75% gasoline/diesel

[1] https://simstadt.hft-stuttgart.de/
[2] https://www.3dcitydb.org/3dcitydb/

+ 25% electric), 1% annual retrofit rate of the existing building stock, forecasted dietary choices (plant and animal-based), and current carbon emission factor for district heating. Scenario B will include projected climate profile and population density for the year 2050, optimised building set point temperature, decrease in private vehicles (100% electric), 3% retrofit rate of existing building stock, etc., increase in plant-based food consumption, decrease in food waste, and forecasted carbon emission factors for district heating. Such scenarios will provide frameworks for examining the potential impacts of household choices on the neighbourhood's carbon footprint under future climatic and demographic conditions. All three scenarios' simulation outcomes will be integrated into the CityGML model for effective comparison and visualisation. Scenario ADE (Widl et al., 2018) will be evaluated and, if required, extended further for this purpose. A user-friendly web-based urban digital twin

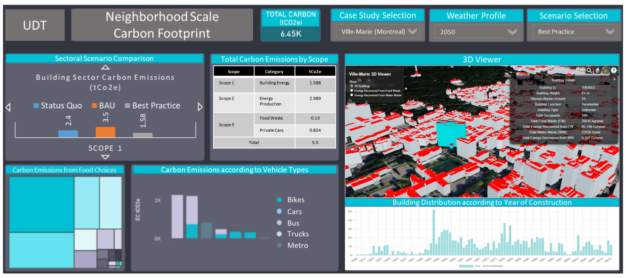

Figure 2. A mockup of web-based urban digital twin dashboard

dashboard, as shown in Fig. 2, is under development to facilitate effective comparison and visualisation of carbon emission profiles across all the scenarios using based KPIs and different carbon emissions profiles of the neighbourhood. The simulation outcomes from all three scenarios will be seamlessly integrated into the CityGML model. Subsequently, these results will be presented and navigated through the web-based urban digital twin dashboard. Such a platform will empower residents and stakeholders to make informed decisions towards sustainable future development. The web client uses open-source CesiumJS and ChartJS framework in the front end and the new generation of OGC APIs: 3D GeoVolumes, Features, and SensorThings in the back end (Santhanavanich et al., 2023). OGC API - 3D GeoVolumes will allow end-users to discover and access diverse 3D content from multiple providers, irrespective of its data format and distribution mechanism. In the context of this research, the CityGML 3D building model and the terrain model are pre-processed and converted into their streaming formats, 3DTiles *only geometry) and Quantised Mesh before hosting it as a service adhering to the OGC API 3D GeoVolumes specifications. For querying and visualisation of any 2D dataset, OGC API - Features will be used. In our scenarios, OGC API – Features handle data related to Points of Interest, land use, and various associated attributes, including socio-economic and demographics. A WFS service endpoint will retrieve simulation results across different scenarios stored in the database. For this purpose, the open-source WFS implementation of 3DCityDB will used. Attributes as part of the WFS endpoint will be integrated with the 3D city models on the client side. This will allow for the retrieval of geospatial data in real-time, enabling dynamic and up-to-date visualisation of simulation results within the urban digital twin dashboard application. To store measured temporal data such as from sensors or smart thermostats or interact with the time-series data associated with each building, OGC API - SensorThings will be used in its standardised service implementation.

Currently, the framework mentioned above will be evaluated in two neighbourhoods in the case study: Ville-Marie (Montreal, Canada) and Stöckach (Stuttgart, Germany). This dual-case approach is instrumental in gaining insights and comparing the urban performances of both cities. Ultimately, it will facilitate a comprehensive evaluation, identifying areas where cities can enhance their performances.

4. Conclusion

This research seeks methodological advancements in estimating neighbourhood carbon emissions using urban digital twins by integrating household consumption choices and localised socio-economic, demographic and land use parameters. Nevertheless, calculating carbon footprints at the neighbourhood level presents formidable challenges, primarily stemming from the reliance on aggregated national or regional data. Compounding this challenge is the absence of a standardised data model capable of harmonising the diverse elements essential for precise neighbourhood-scale carbon footprint estimation. Moreover, the limited integration with local datasets exacerbates this issue, hindering the accuracy and granularity of the assessments. Consequently, policymakers often miss capturing the impact of residents' choices on the carbon footprint of their neighbourhoods. Therefore, there is a significant need to estimate and forecast carbon emissions locally to fine-tune public policies and climate investments and foster general awareness among residents regarding the impact of their choices on the emissions profile of their neighbourhood.

By using urban digital twins, this study wants to look closely at how people in neighbourhoods use energy in buildings, what they eat, and how they get around. Subsequently, there is an opportunity to improve the accuracy, granularity, and effectiveness of emissions quantification and mitigation strategies at the neighbourhood scale. The production of dis-aggregated datasets at a building or a block scale (to avoid privacy issues) through simulation fills a crucial gap, identifying emissions hotspots and directing practical mitigation efforts. Through exploration of "what-if" scenarios, this research also aims to forecast emission profiles based on how changes in household consumption choices will impact neighbourhood's carbon emissions under future climatic and demographic conditions. Moreover, accessible geospatial data and a user-friendly visualisation dashboard will empower residents and provide a platform for policymakers to engage in creating integrated carbon mitigation strategies and fostering sustainable and resilient urban neighbourhoods. Ultimately, this research hopes to help local leaders and residents make better choices for the environment in their neighbourhoods in the future.

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