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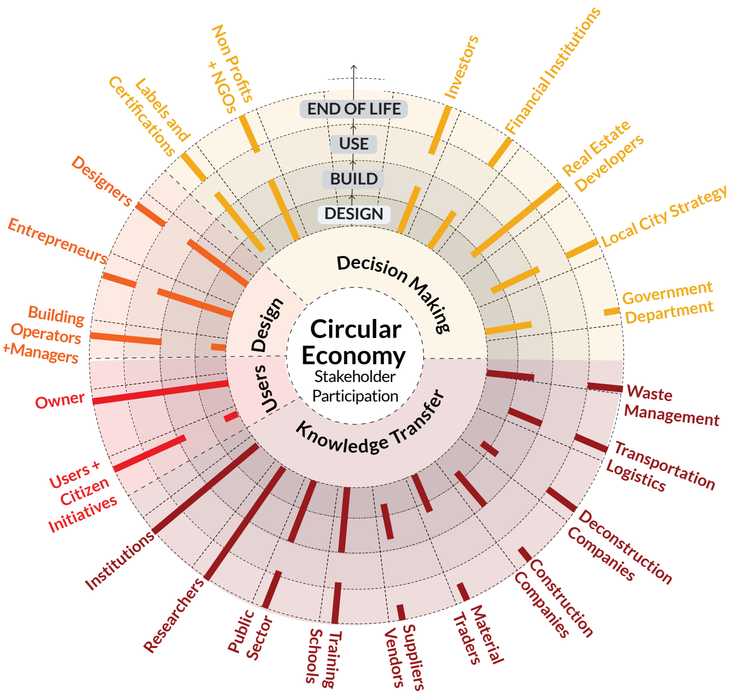
Data Visualization for a Circular Economy: Designing a Web Application for Sustainable Housing



An impediment to effective Circular Economy (CE) implementation in residential buildings is the lack of standardized building data to represent a building's life cycle, from material sourcing to end-of-use apparatus. This paper presents an overarching methodological approach for creating a circular web application named Data Homebase (DHB). DHB integrates housing data into Housing Passports (HPs), visualizing calculations of estimated energy use, carbon emissions, and affordability building indexes. Using data-driven narratives, DHB outlines a building's degree of circularity and potential for improved environmental outcomes via circular strategies. The passport system and data-based approach provide a once-missing portal entry for housing stakeholders seeking actionable circularity measurements. This research contributes to the long-term elucidation of key decision-making processes for homebuilding within a comprehensive tool to achieve a far-reaching CE.

Keywords: Circular Economy, Data Visualization, Affordable Housing, LCA, Urban Energy Modeling, GIS

Introduction

Currently, in Canada, as in many countries worldwide, housing supply is a fundamental challenge (CMHC 2022). There are two key housing supply challenges: (1) affordability and (2) environmental sustainability. In Canada, there is an affordability challenge. On average, Canadians spend almost 46% of their gross annual income on housing, which is well above the 30% defined affordable housing rate (Statistics Canada 2022a; Omololu 2022). In terms of sustainability, as governments work to achieve the Paris Agreement goals, there is a push to reduce GHG emissions and waste associated with buildings, such as Vancouver's zero emission building plan (City of Vancouver 2017, 2020a) and Montreal's recent mandate for the disclosure of GHG emissions from buildings which includes dwellings (Ville de Montreal 2022a). Hence our primary research questions are—how can a Circular Economy (CE) support the building of affordable and sustainable housing? More specifically, how can a CE be encouraged by making building stakeholders more informed?

A CE approach can offer a pathway to sustainable and affordable housing by (1) keeping buildings in use, (2) reducing waste and costs of new housing construction, and (3), at the end of a building cycle, revealing its materials as untapped resources rather than waste. Figure 1 depicts a circular housing model shift compared to the current linear economy. Studies indicate that establishing a CE in the housing sector requires robust, standardized data about material, energy, building composition, and affordability to ensure coordination between all realms of sustainability (Heinrich and Lang 2019; Keena and Dyson 2020). However, building data is fragmented and scattered, making evidence-based decision-making difficult (Pagoropoulos, Pigosso and McAloone 2017; Gupta et al. 2019). Emerging research highlights that material passports (i.e., digital descriptions of material characteristics) can offer a methodology and data structure for standardization (Benachio et al. 2020; Heinrich and Lang 2019).

Context

Figure 2 depicts the changing roles of housing stakeholders from linear to circular practices of the economy (McKinsey Global Institute 2017). This research aims to standardize housing data, making it easily accessible to building sector stakeholders, policymakers, and financial actors to facilitate this transition. This service is done through what we coin Housing Passports (HP), which are standardized digital descriptions of residential building characteristics, including materials, composition, energy consumption information, carbon footprint, and affordability. The HP differs from past attempts at organizing housing information by including, in a highly detailed and easily accessible fashion, circular implementation, financing, economic considerations, policy, and social life cycle information all in one place.

In developing the HP characterization, several frameworks that have striven to create a standardization method for describing buildings, materials, and building retrofits were studied (Société d'Habitation du Québec 2017; Heinrich and Lang 2019; Kurkowska et al. 2017; Global Alliance for Buildings and Construction 2021; Buildings Performance Institute 2017). A review of these initiatives highlights that they vary substantially with different focuses across different aspects of life cycle activities, e.g., focusing solely on energy, materials, or renovation roadmaps. There is a paucity of passports that include affordability metrics or other data categories which would meet the needs of the diverse group which encompasses building sector stakeholders. Hence, building upon these references, the HP is significant in offering a new standardization format that goes beyond the basic building and material characteristics and enriches them with context-related attributes, as explained in the Methodology section.

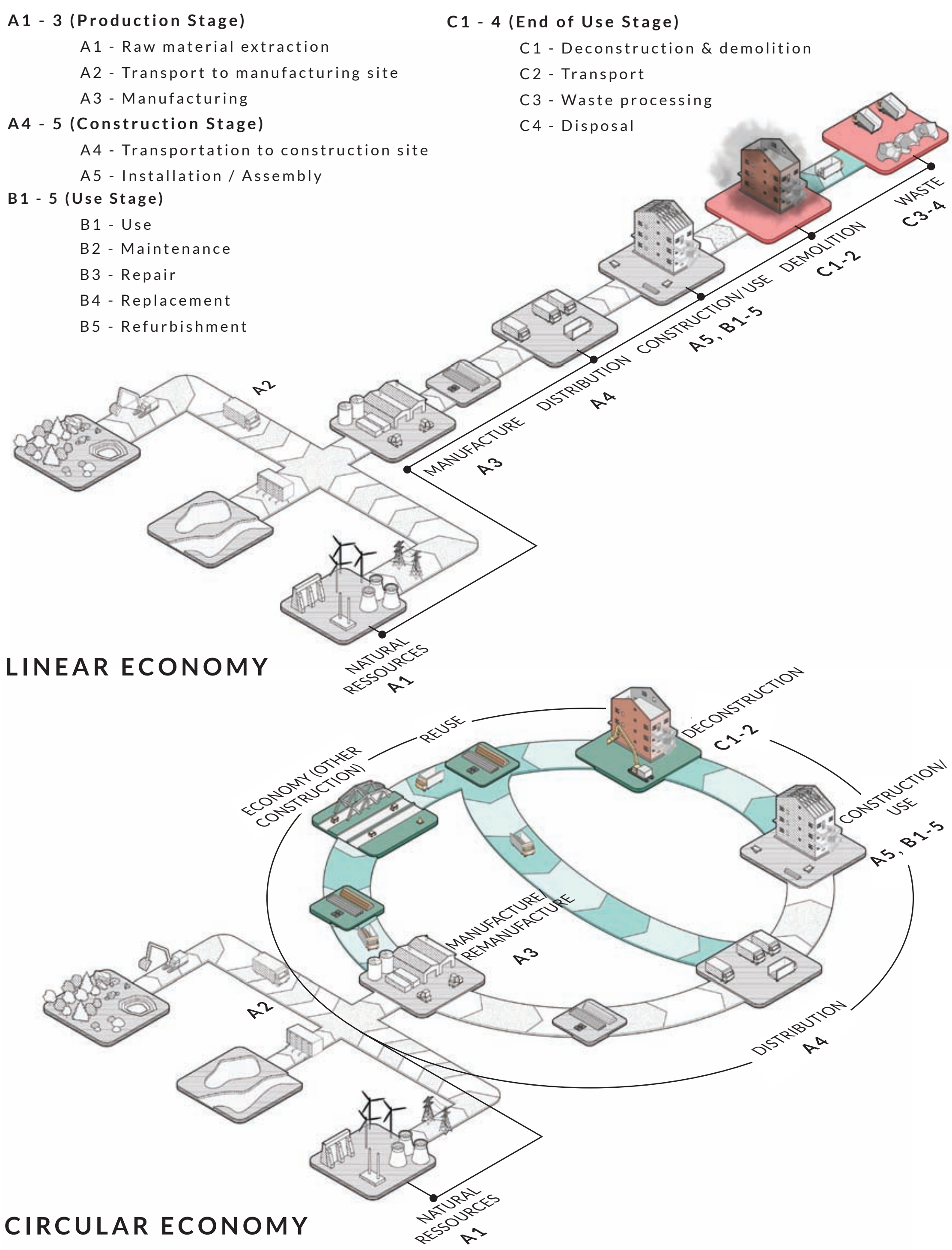
This paper introduces a new web application and CE framework named Data Homebase (DHB), which generates and visualizes digital HPs and delivers an accessible and searchable web-based interface to navigate them. HPs visualized in DHB identify and showcase the value of housing (i.e., its materials, products, and components) for present use, reuse, and recovery. HPs aim to be significantly relevant to housing stakeholders making CE decisions. While the DHB web application has four main features (HP map, HP toolkit, material passport, and case studies), this paper will focus primarily on the first feature of DHB. This HP map geolocates HPs on a given city map, as this is the feature of the DHB on which the following components are built. The following sections will explain how the DHB application creates an overarching framework to tackle energy use, carbon life cycle emissions, and affordability within a CE. This initial version of DHB focuses on Canadian cities. Still, it is designed to be widely applicable to the emerging global field of circularity in the built environment.

Methodology

Several methods are involved in developing the new DHB web application of standardized HPs, as illustrated in Figure 3: (1) HP characterization; (2) data collection and data mapping; (3) data generation, visualization modeling and data analysis: energy, carbon, affordability; (4) data visualization and designing data-driven narratives. It is important to note that a vital back-end component of the DHB involves data integration and encoding knowledge via semantic linking and machine learning activities. However, these are deemed outside the scope of this paper, which focuses on the new data generation and visualized results and their potential impact in fostering a CE in housing.

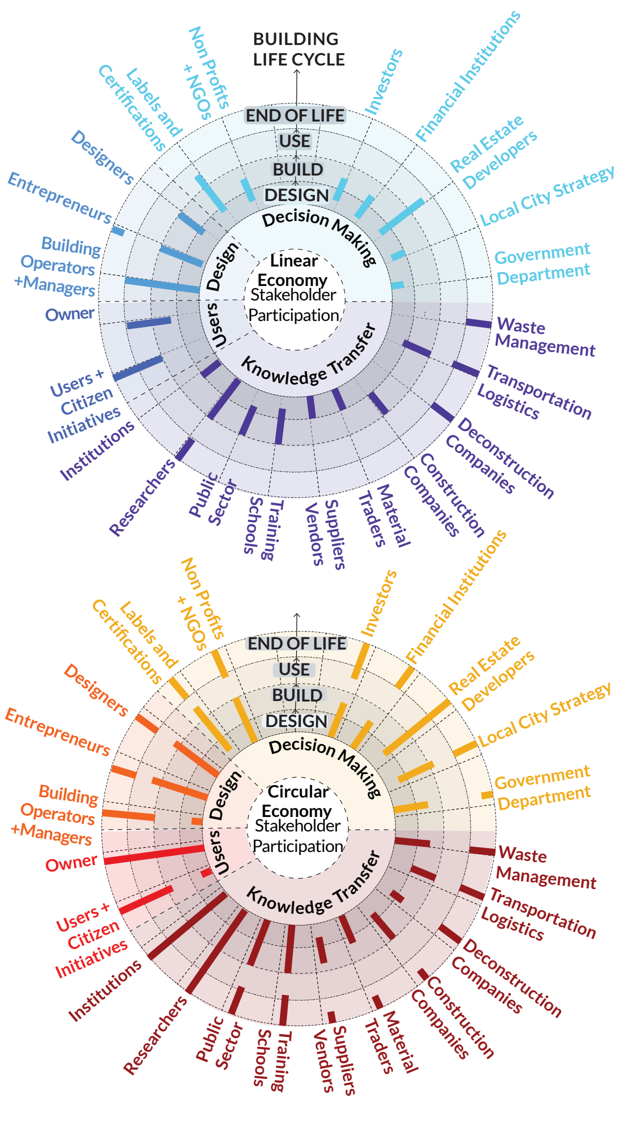
Method 1: HP Characterization—Choosing the Appropriate Categories for the HP and Defining the Building and Material Characteristics of an HP

Standardization of housing data via the HP was achieved by defining a set of housing categories (divided into buildings and materials). Within each category is an assigned group of characteristics that define attributes of that category, as illustrated in Figure 4. As explained above, HP builds upon prior passports and aims to supersede them by offering context-specific data categories, as shown in Figures 5 and 6. Indeed, context-related characteristics are vital to the DHB, including demographics,



◁ Opening figure. The changing role of stakeholders in a circular economy. (Credit: Authors for all figures)

△ Figure 1. How the building process shifts from a linear economy to a circular economy by taking a life cycle approach.

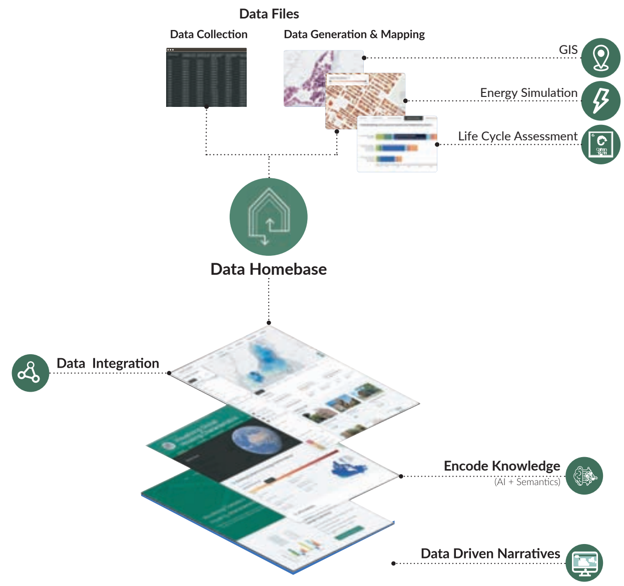


△ Figure 2. The changing role of stakeholders from a linear to a circular economy.

climate, macroeconomics, affordability indexes, and contributions to the UN Sustainable Development Goals (SDG) attributes (Figure 5). These characteristics offering context are then visualized and explained using easily accessible data-driven narratives, as illustrated in Figures 5 and 6. Offering region-specific data provides a well-rounded picture of housing supply type to reflect the diverse realities of people living in Canada.

Method 2: Data Collection and Data Mapping of HP Characteristics of Housing Stock

HP data was collected and mapped to Canadian housing stock across five major cities in Canada to test and showcase the HP standardization; Montreal, Vancouver, Toronto, Edmonton, and Winnipeg. As described below, residential archetypes and a Geographic Information System (GIS) model were developed to achieve this.



△ Figure 3. Designing data-driven narratives to tackle the global challenge of sustainable housing: diagramming the research methodology in developing the DHB web application. Methods include: (1) housing data collection; (2) data generation and mapping (i.e., generating GIS maps, building energy use simulation, and life cycle assessment (LCA) for the carbon footprint of housing); and (3) visualizing via data-driven narratives the integrated HP data for easy access by a broad range of housing stakeholders to foster circularity.

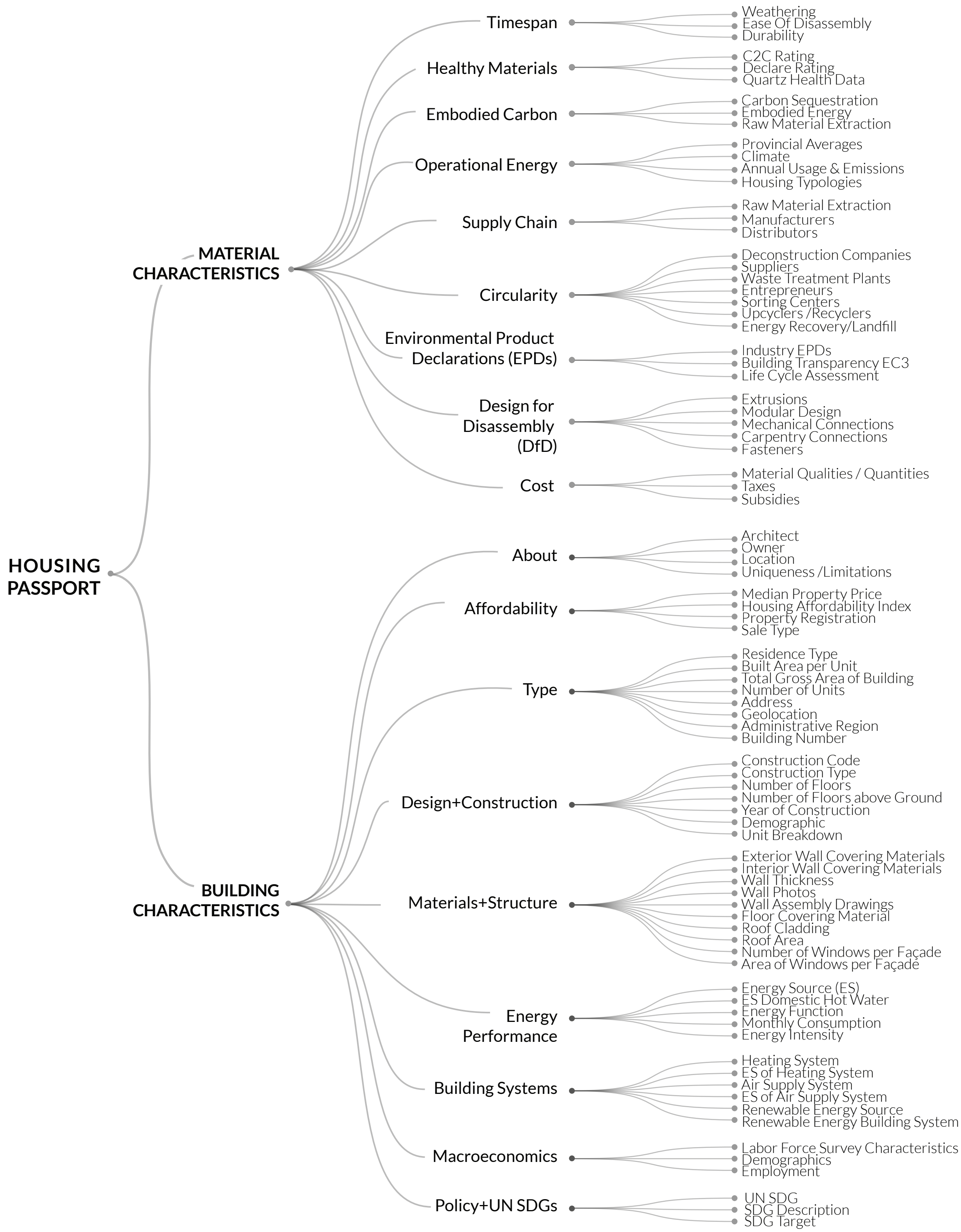
Designing the HP Map Using Archetypes and Geographic Information System (GIS)

A housing archetype corresponds to the typical features of a residential building, such as the number of stories and units, as well as being attached to or detached from the surrounding buildings. While case studies or building surveys are more specific, archetypes enable the analysis of entire neighborhoods and cities while reflecting individual buildings in the data set. This section will define the archetypes used and the architectural design selection, and pinpoint shifts in residential construction methods based on the housing vintage. It will then explain how the archetypes were integrated into a GIS model.

Six major housing archetypes are characterized based on dwelling classifications defined by Statistics Canada (2017) census data. Dwelling census codes were assigned to each archetype classification. This feature allowed for mapping the archetypes to specific locations in the GIS map, as described below, where the census code information was also used.

The six archetypes DHB uses include single detached, semi-detached, row house, duplex, apartment buildings with fewer than five storeys, and apartment buildings with five or more storeys. Statistics Canada also includes movable dwellings; however, since mobile homes and portable dwellings did not make up a significant part of the housing stock, they were excluded from the archetypes, although they could be added in the future.

Next, we selected architectural design drawings based on the archetype categories. Drawings came from previous studies



△ Figure 4. Data-tree visualization of the HP characterization including the building and material characteristics. Note: this paper focuses primarily on the building characteristics.

by the authors and the literature on Canadian housing typologies (Friedman 2001; Friedman, 2007; Debicka and Friedman 2009; CMHC 2013; Keena and Friedman 2022). Since the single detached house had the most variation, many designs were selected, such as the two-storey, the two-storey with a garage, the wartime 1.5-storey, and the one-storey house of the mid-twentieth century. In some cases, the design of the house varied from city to city. For example, Ergun (Ergun and Gorgolewski 2015; Ergun 2014) identified the 1.5-storey detached house as a Toronto housing archetype in the postwar period. The triplex, classified as code 6 by the census categories, is an archetype unique to Montreal. Many of the designs feature a gabled roof and a basement. Each archetypal category was further divided into different vintages. A "vintage" is a version of an archetype that corresponds to a particular period and city, as well as the construction assembly types, and structure used.

Using the collected architectural drawing information, building information modeling (BIM) models of housing archetypes using Autodesk Revit were generated, including variations associated with their vintages, construction types, and Canadian city location, as in Figure 7.

Integrating the Housing Archetypes Building Information Modeling (BIM) with a Geographic Information System (GIS) Platform

The proposed methodological framework integrates GIS-based urban building modeling with BIM of housing archetypes. As illustrated in Figure 8, open data representing geometric and nongeometric building stock characteristics, such as building footprints, addresses, and property tax records, are collected from city and federal agencies (Statistics Canada 2022b; City of Vancouver 2020; Ville de Montreal 2022b; Toronto 2023; City of Winnipeg 2023; Edmonton 2019). The GIS platform is then developed to process and standardize the collected urban building data. As described above, each archetype is assigned a dwelling census code. Using identical census codes for the residential buildings in the GIS model and the archetypes allowed the archetype metrics to be assigned to a specific geolocated house. Thereby, we enhanced the archetype information to provide more specificity on individual geolocated housing by using the GIS model to define the exact footprint and height of each building (i.e., using shape file information) and its vintage and construction type (i.e., based on its year of construction). With this information, each geolocated residence had a customized archetype that defined its scenario. In this way (as explained in "Method 3," below) the existing housing stock in a city is more accurately defined, thereby providing a complete picture of the "bank" of valuable materials available in a city, neighborhood, or specific building, and its potential for recovery. This step is crucial in facilitating data-driven decision-making for a CE.

Method 3: Data Generation via Modeling and Data Analysis: Energy, Carbon, Affordability

Using the collected data on existing Canadian housing stock mapped via GIS and the BIM models of the archetypical housing, we ran a series of analyses for three key metrics: energy performance, carbon footprint, and affordability, as described below.

Simulating Energy Use

The housing stock operational energy is simulated using a physics-based energy simulation approach using the urban GIS models, archetype BIMs, and urban building energy models (UBEMs). The energy performance of archetypes was analyzed at an urban scale by assigning archetypes to the GIS model of the city. The urban GIS models provide the standardized geometric and nongeometric characteristics of residential buildings required for UBEMs. BIM models encapsulate the material specification and assemblies, essential features required to create the energy templates of Canadian housing archetypes. The urban GIS models and archetype energy templates are combined to produce UBEMs of housing stocks in different Canadian cities. Urban Modeling Interface (UMI) application (Ang et al. 2022; Reinhart and Davila 2016) was used to analyze the energy performance of archetypes at the urban scale. UMI is a Rhino plugin and a file type that is comprised of three main components: an epw file with the weather data, a json file with the building templates, and a 3dm file with the geometry of the urban model. Therefore, three files are needed to transition from a GIS shapefile to a UMI bundle: the weather data, the template library, and the GIS file as a zip file. The UBEMs are run by the UMI application using the Energy Plus solver to calculate the operational energy of housing stocks.

The epw file containing the weather data can be downloaded from EnergyPlus according to the location of the energy model. The template library for Montreal was created in Rhino, using the existing materials and schedules for energy consumption of a residential building adapted from Davila, Reinhart, and Bemis (2016) Boston Template Library. While the UBEM online toolkit (UBEM.IO n.d.) can join the files into a UMI file, limitations include the maximum file size. An alternative to the UBEM toolkit is downloading the UMI Python script from GitHub. A Bayesian method is applied to calibrate the UBEMs (Sokol, Davila and Reinhart 2017). The simulation outputs are then integrated with the GIS platform implemented with the energy rating system to standardize the visualization of housing performance. It was necessary to reference the data frame containing the GIS dataset and the IDs in the UMI database, both of which are contained in the UMI file bundle, to assign building templates based on the archetype code of each building in the GIS model. The energy simulations in UMI provide data for the energy loads (i.e., heating, cooling, lighting, equipment, domestic hot water, and window radiation) of each building for every month of the year. Such a method has not been applied to the Canadian context at the grand scale we present here. Furthermore, the visualization of such data has not been made easily accessible. Our novel data visualization techniques aim to make this energy data more user-friendly, offering a solid contribution to UBEM methods.

Analyzing Carbon Footprint with Life Cycle Assessment (LCA)

A comparative LCA of the archetypes was conducted to understand: 1) the carbon emissions associated with the existing linear life cycle scope of Canadian housing from the cradle to the grave, and 2) the potential carbon savings associated with a circular cradle-to-cradle life cycle scope. Typically, the life cycle of a building is made up of five stages: A1–A3

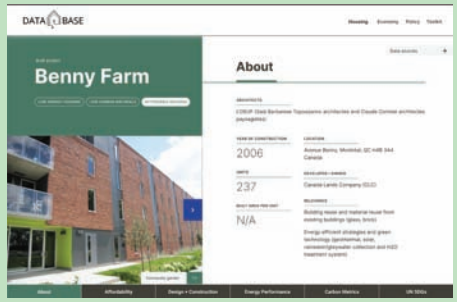
A

HP BUILDING CHARACTERISTICS

HP Category Description | **Design of Data Driven Narratives**

ABOUT

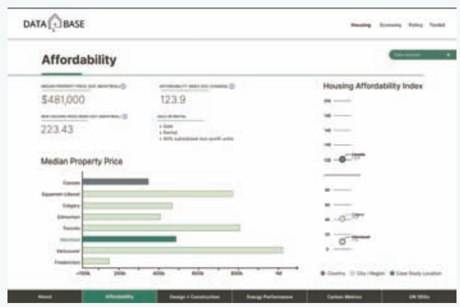
ABOUT: On selecting a built housing or demonstration project, the user's first view is the About section. This is an introductory category giving a general overview of the case study selected by presenting highlights of information from the other categories. Along with various images of the project, the information found is the name of the project, its location, the architects involved, the managing body, the year of construction, number of units, built area perunit, its limitations and ranking as well as its uniqueness and relevance CE.



TYPE, SIZE, LOCATION & CLIMATE: Data found here includes residence type, the total gross area of the building, the number of units, the built area per unit, the area of living space per unit, the area of common areas, the geo-location, administrative region, and the Köppen Climate classification. Using interactive data visualizations we highlight benchmarks, e.g., comparing total gross area of the chosen case study to that of the average for a building in that region.

AFFORDABILITY

COST: This category offers data related to the median property price, housing affordability index, new housing price index in reference to the case study location. It highlights the need for affordability and the regions which need it most by comparing location-based data to one another. It showcases our data and metadata annotation which provide context. The power of the back end semantic representation is exposed on the web pages, by hovering above various data a definition of that concept appears via a tooltip.



MACROECONOMIC: contextualizes the housing data. The information shown includes inflation, average mortgage interest rates, and labor force survey at the federal, provincial and/or city level.

DESIGN & CONSTRUCTION

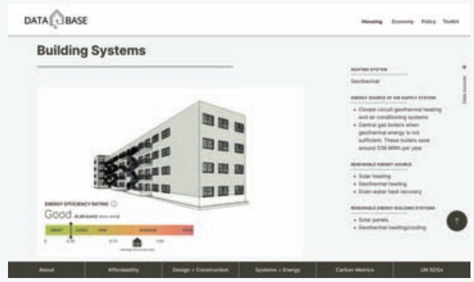
DESIGN & CONSTRUCTION: characteristics include construction type, construction code, supply type, year of construction, number of floors, number of bedrooms. The featured scatter-plot maps all case studies according to the year of construction, the number of floors and/or carbon footprint; the potential for end-of-use disassembly, based on the materials each project utilizes, is indicated by the size of the dot. Users can easily compare the environmental impacts of the selected case study against all other housing in the database.

MATERIALS & STRUCTURE: Characteristics include exterior wall type, interior wall type, floor type, window type, roof type data, structural system, embodied energy and embodied carbon of materials. This category links to the Materials web page. See Figure 6 for more details on the Materials page.

△▷ Figure 5. A description and data-driven narrative view of the HP building categories and associated characteristics, (a) covering affordability, design, and construction, (b) covering energy performance, carbon metrics, UN sustainable goals, and best practices.

ENERGY PERFORMANCE

ENERGY RATING: Here a user can navigate detailed information which relates to primary energy sources for energy use, the energy function, monthly consumption (if monthly consumption data e.g., billing info. is not available, a 3D Building Information Model (BIM) model of the house is used to calculate the operational energy) monthly production (if any), energy use intensity (EUI) GJ/m^2. The EUI is used to calculate an energy efficiency rating as a benchmarking device.



BUILDING SYSTEMS: describes the mechanical composition of the selected case study. Details include the housing heating system and its energy source, the type of air vent system, the air supply system energy source and the type of renewable energy systems utilized by the project (if any).

CARBON METRICS

CARBON RATING: Detailed information which relates to the embodied carbon emissions associated with the selected housing based on its materials and energy life cycle impacts. A 3D BIM model of the house is used to run a Life Cycle Analysis (LCA) to calculate the environmental impacts broken down by total, life cycle stage and building components. This is navigated by the user via interactive data visualizations. The model is used to calculate an embodied energy rating used as a benchmarking instrument.

UN SUSTAINABLE DEVELOPMENT GOALS (SDGs)

UN SDGs: contextualization of the home by mapping it to the UN SDGs. The users can understand how the case study reaches certain targets and indicators while also pin-pointing which targets, and more generally UN SDGs, could potentially be reached by tackling specific areas from the data seen in the previous categories.

BEST PRACTICES

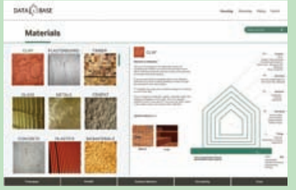
BEST PRACTICES: presents final remarks which pertain to the entire case study, highlighting certain qualities of the project which either needs attention to reach affordability and sustainability, or excels in reaching them. In both cases, CE approaches tailored to the case study are suggested, giving users the tools to understand and apply CE thinking.

HP MATERIAL CHARACTERISTICS

HP Category Description | **Design of Data Driven Narratives**

TIMESPAN

TIMESPAN: Service life of material and where it is used in the building. E.g., 'site' materials such as those used in foundations have +100 years timespan, whereas materials used in 'partitions' within the building have a much shorter time span of 10 - 15 years. In considering circular business models which could re-manufacture or upcycle these materials, understanding the timespan for the material is important.



HEALTH

HEALTH: The Health characteristics display the health hazards associated with the material selected based on the Quartz open database. A user can also navigate to the sites of other material health rating systems such as Cradle to Cradle rating and the DECLARE rating.

EMBODIED CARBON

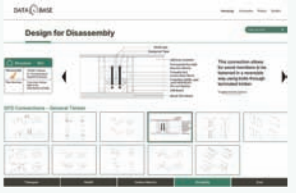
ENVIRONMENTAL PRODUCT DECLARATIONS (EPDs): The EPDs panel allows users to browse through Canadian manufacturer's EPDs. The international EPD system is a global program for environmental declarations. EPDs present transparent, verified and comparable information about the environmental impacts of materials and products across their life cycle.

EMBODIED CARBON and EMBODIED ENERGY: This category presents the embodied carbon and embodied energy of a range of construction materials through interactive data visualizations.

CIRCULARITY

SUPPLY CHAIN: Mapping the raw material source, manufacturers, suppliers, sorting centers and reuse centers. The address and precise location of each manufacturer is also shown as a helpful resource for users to consult. Choosing the 'Circularity' filter highlights on the map areas where materials can be recycled, reused, re-manufactured, sold for reuse (i.e., sorting centers, recycling centers, upcycling retailers).

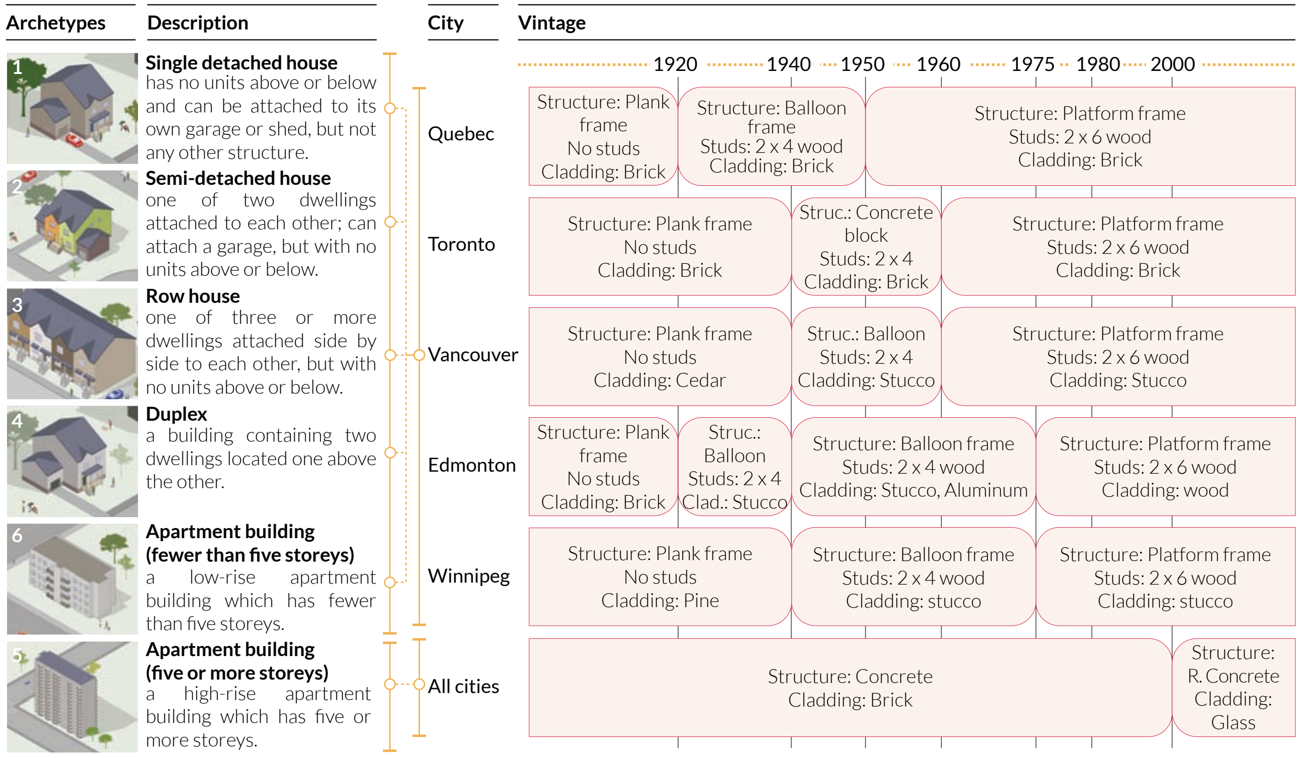
DESIGN FOR DISASSEMBLY: The Design for Disassembly (DfD) panel presents a bank of construction details that showcase DfD options per material type. These construction details are based on an extensive literature review of circular DfD construction details from around the world. These have been revised to be relevant to the Canadian construction industry.



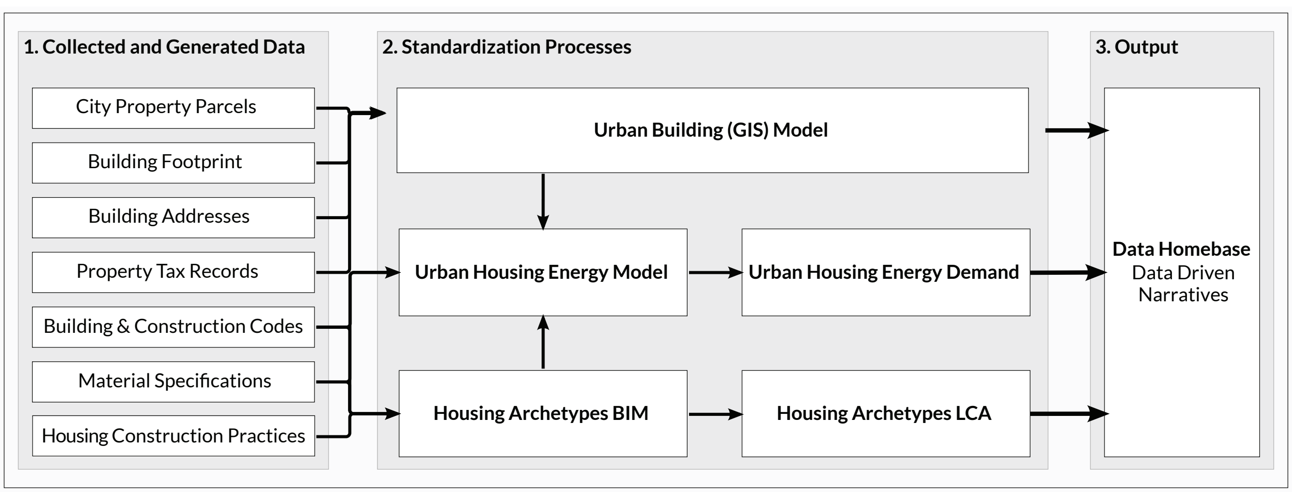
COST

COST: This category identifies estimates of the cost difference between the use of a new or virgin material vs a re-used, upcycled or recycled material. Sources of pricing data is displayed for each material type based on Canadian sources.

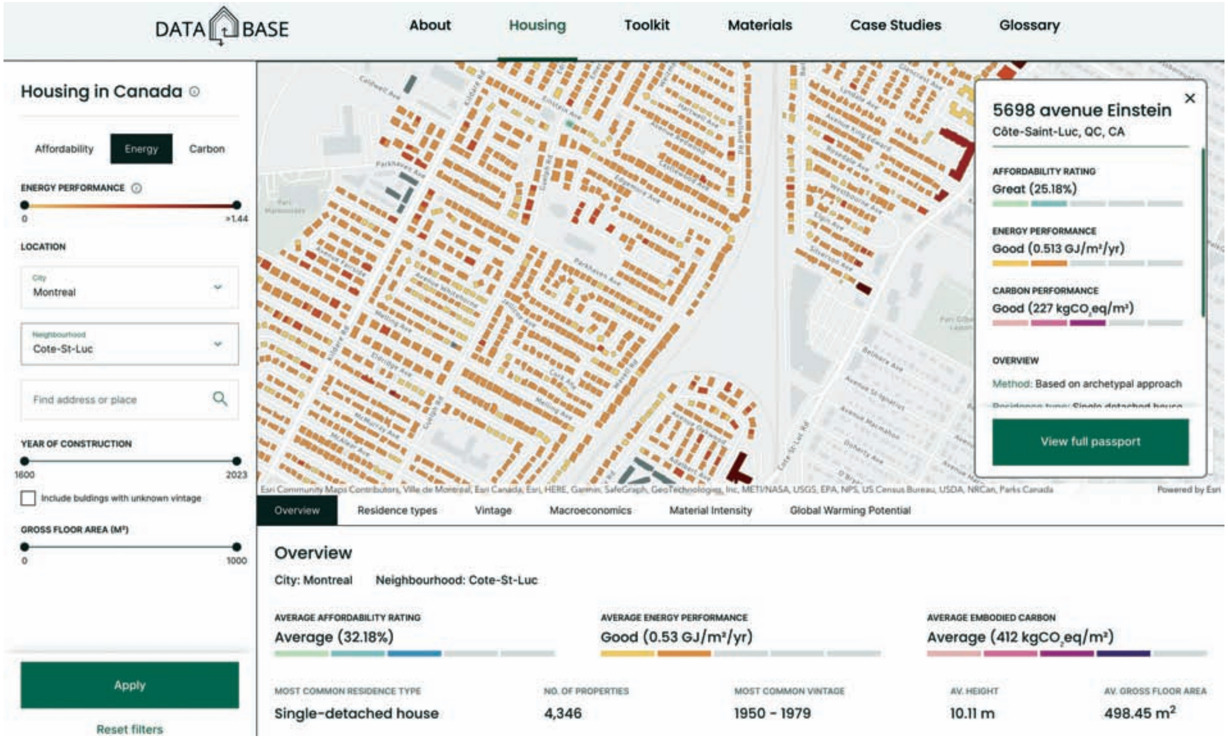
△ Figure 6. A description and data-driven narrative view of the HP material categories and associated characteristics.



△ Figure 7. Canadian housing archetypes and their codes, definitions, and vintages for five major cities.



△ Figure 8. DHB dataflow architecture.



△ Figure 9. Map search function on the "Housing" page of the software showing the various filtering methods.

Production, A4-A5 Construction, B1–B5 Use Stage, C1–C4 End of Use Stage, and Module D, which represents benefits beyond the system boundary. For the HPs of defined archetypes, the life cycle was analyzed from the cradle to the grave, which includes extraction up to disposal. Still, we also show the potential carbon savings of a cradle-to-cradle approach if reuse and recycling are incorporated at the end-of-use phase. It's important to point out that the carbon footprint values shown in DHB focus on materials only; hence, we do not include the operational energy as shown in the energy ratings aspect of DHB. Future iterations may incorporate energy use into the carbon metrics to provide a whole-housing lifecycle impact assessment.

The life cycle impacts of housing archetypes are calculated using an LCA plugin to the BIM model Tally (Tally 2022). A bill of materials (BOM) is identified using the BIM model. Tally organizes the model by elements (doors, walls, floors, etc.) to facilitate assigning materials from its database to each. Material data sources include Thinkstep's Life Cycle Inventory (LCI) integrated within the Tally system and the Carbon Leadership Forum's EC3 software allowing us to use Environmental Product Declaration (EPD) data specific to Canadian and North American material manufacturing of products where available. Three scenarios are considered using the LCA model: (1) landfill, assuming all demolished materials go to landfill (a linear economy approach); (2) recycling, assuming all materials that can viably be recycled are and (3) reuse and selective deconstruction, assuming all materials that can be are reused are and those that cannot are recycled. Assuming these three scenarios, whose LCA methodology is outlined in greater detail elsewhere (Keena et al. 2023; Keena, Rondinel-Oviedo, and Demaël 2022; Keena and Rondinel-Oviedo, 2022) we can project the potential environmental impact at the city, neighborhood, and building scale of shifting towards a CE where materials are reused rather than turned to waste.

The LCA results also provide the material intensities associated with a residential building. Life cycle environmental impacts of archetypes are reported regarding global warming potential (GWP) measure in CO2eq, a key indicator of carbon footprints. Archetypes' carbon footprints are also reported for different building life cycle stages, including production, construction, use (i.e., maintenance), and end-of-life, as illustrated in Figure 13c in the Results section. The resulting LCA model allows for estimating the reduction in embodied carbon emissions of a housing archetype by recycling and reusing materials as major end-of-use scenarios for a CE. The carbon emissions and material intensities of archetypes for different life cycle scenarios serve as inputs for the urban GIS models to estimate the carbon footprint of the housing stock. This input allows policymakers, for example, to estimate potential carbon savings by implementing a circular approach to building material reuse and recycling at a city or neighborhood scale.

Affordability Analysis

Affordability Index and Affordability Ratings are used to calculate the portion of disposable income that a household can spend on housing-related expenses and the share of income that a household would put towards housing-related expenses, namely mortgage payments and utility fees. DHB ranks the affordability rating from 0 (very affordable) to more than 80 (not affordable). The affordability index acts as a macroeconomic indicator, while the affordability rating is building specific.

As seen in Equation 1, the affordability index formula derived from the Bank of Canada (2022) is:

(1) $$C = [R/[(1-(1+R)^{(-N)})]]*M + U$$

Where: C = Quarterly housing-related costs; R = Effective mortgage rate (weighted average of discounted one-, three-, and five-year fixed rate mortgages and the discounted variable-rate mortgage)—we assume a five percent interest rate (R = 0.05); N = Number of monthly payments (assumed to be 300 over 25 years); M = Total value of the mortgage, where we assume a 95 percent loan-to-value ratio, so that M = (0.95) P (where P = six-month moving average of the Multiple Listing Service average resale prices); U = Utility fees, based on the consumer price index for water, fuel, and electricity. Use the average level of spending on utilities by homeowners for their principal accommodation from the 2011 Survey of Household Spending (Statistics Canada 2017).

Data for the affordability index comes from the Canadian Rental Housing Index (Canadian Housing Index 2023). The utility fee numbers come from Census Canada (Statistics Canada 2017), giving the monthly expenses on the building, which is then compared to the median income spent on housing as a percentage. At the Census Metropolitan Area (CMA) and neighborhood level, P is the median value of all dwellings within a region, as Statistics Canada for 2021 reported. By contrast, in our calculations for the affordability rating, P is the assessed value of the building, as reported by municipal tax offices. We use the median value of dwellings per Dissemination Area (DA) for cities that do not release tax assessment data. This input gives the monthly expenses on the building, which can then be compared to the median income in the area to get the amount of the median income spent on housing as a percentage.

The denominator for C is the national disposable average household income divided by the number of households in Canada, provided by the Bank of Canada using data reflective of National Income and Expenditure Accounts. While their denominator reflects disposable income nationally, we do not assume that relevant income figures are identical in cities across Canada. Therefore, in our affordability indices at the CMA and neighborhood level and the affordability rating at the building level, we substituted this denominator with income data from Statistics Canada that reflect the same geographic scale. Finally, this affordability analysis is embedded in our GIS model.

To meet environmental targets, "green" and "circular" financing is becoming more commonplace, in which financial institutions use energy and carbon performance indicators to evaluate climate change-induced risk by assessing how climate responsive a new development or existing property is before offering to fund (United Nations Environment Program n.d.; Covered Bond & Mortgage Council 2020). Hence, measuring affordability alongside energy and carbon metrics is deemed timely in fostering circular financing strategies.

Method 4: Visualizing the HP Data via Data-Driven Narratives

We have developed novel visualization components in DHB to deliver clear and accessible data-driven narratives of HPs, as illustrated in Figures 5 and 6. Methods involved designing webpage mock-ups with data visualizations and user experience (UX) design methods implemented to create the web application data-driven narrative front-end, as illustrated in Figure 10.

Interactive Data Visualization

A central goal of DHB is to provide detailed housing data to a range of stakeholders in a way that conveys information clearly through interactive data visualization. Data-driven narratives of HPs are accessed via a single website, allowing exploration at an overview level via the HP map or by drilling down into the data if more detail is sought, e.g., the digital HP report and access to data sources. Such navigation is made possible using interactive data visualization (Segel and Heer 2010; Keena and Dyson 2017; Keena, Etman, and Dyson 2020).

Some prominent interactive data visualization in DHB includes the means of exploration on the HP map (Figure 9). The map functions as a filtering method to search through various housing and contains additional information about affordability, energy performance, and embodied carbon, all in color-coded scales (Figure 10). This map allows users to compare these factors between cities, neighborhoods, and individual homes depending on the map's zoom level. The overview panel under the map works with a user's map selection to provide additional information on aspects such as archetypes, vintages, macroeconomics, material intensity, and global warming potential of housing for the selected location.

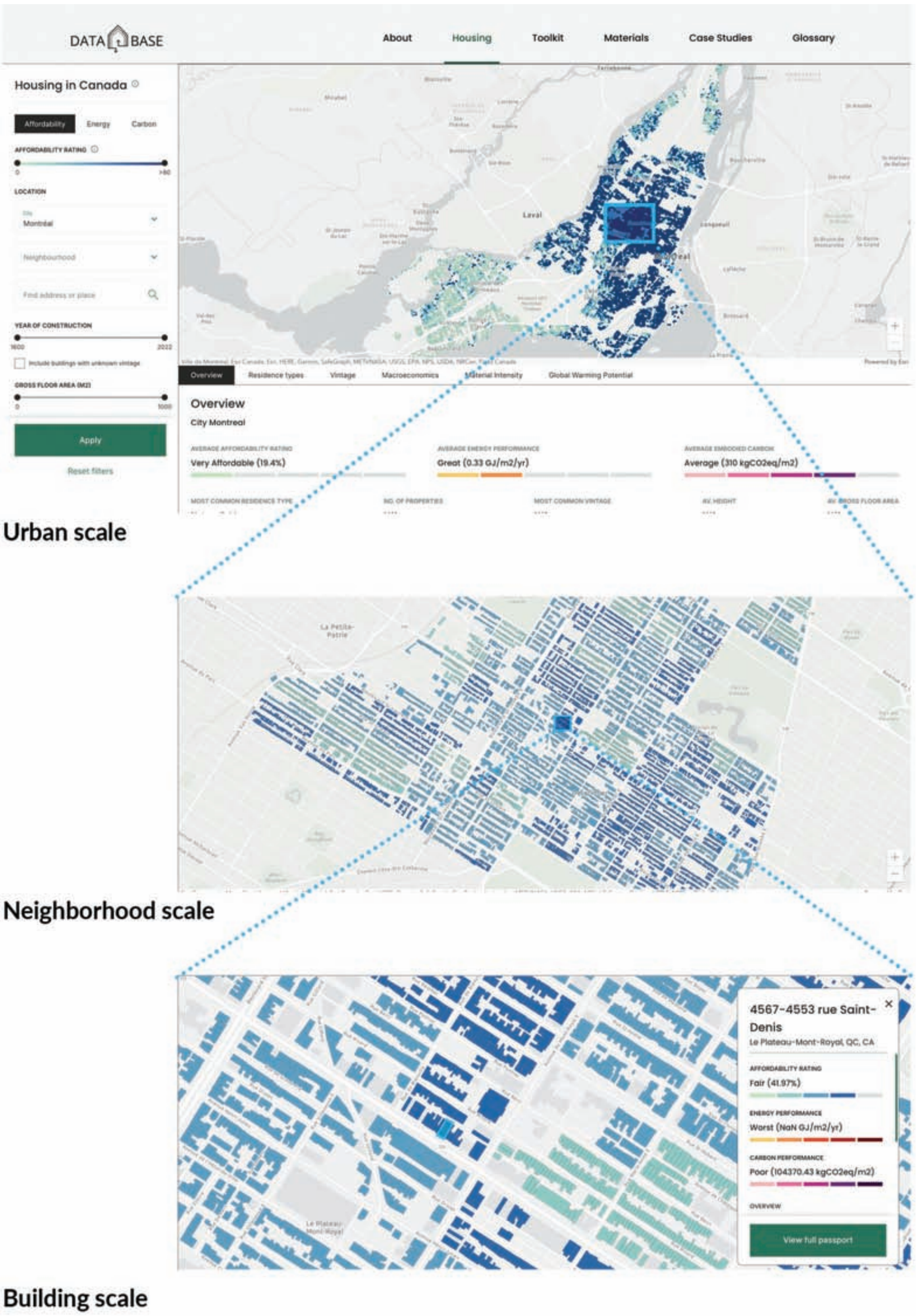
Results and Contributions

This section outlines the results of testing and validation of the methodology.

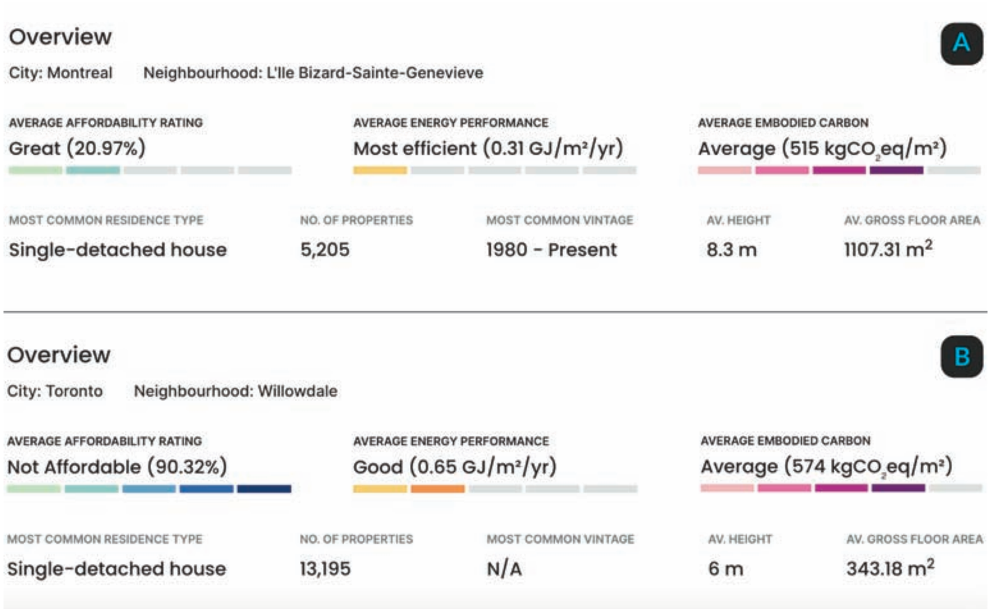
HP Map: A Multiscalar Approach to Visualizing Housing Data

DHB facilitates multiscalar visualization of urban housing stock characteristics at the different granularity and aggregation levels, namely urban scale, neighborhood scale, and individual building scale as shown in Figure 11. At the urban scale, Figure 10 shows a view from the HP map of the affordability, energy performance, and carbon footprint visualized for the housing stock in Montreal, one of the Canadian cities included in DHB. At the neighborhood scale, the platform also enables contextualizing characteristics of the associated residential buildings. Figure 12 displays examples of housing stock characteristics (e.g., most common residence type, average affordability, average energy use rating, average carbon footprint, most common vintage, number of properties, etc.) in two neighborhoods located in two different Canadian cities. DHB, hence, helps stakeholders make informed decisions relevant to a circular housing supply chain.

△ Figure 10. Introducing DHB web application: a view of the homepage (top). Color coded scales coordinate to the data displayed on the map: affordability blue-green scale; energy red-yellow scale; carbon purple-pink scale (bottom).



△ Figure 11. The housing map shown in three scales: urban, neighborhood, and building scale.



◁ Figure 12. Examples of housing stock characteristics visualized for two different Canadian cities and neighborhoods including (a) Montreal, L'Île-Bizard–Sainte-Geneviève, and (b) Toronto, Willowdale.

Carbon Footprint Analysis: Overview of Material Intensity and Global Warming Potential

DHB provides a carbon rating system that enables standardized visualization of embodied carbon emissions associated with city and neighborhood residential buildings. The intensities of different building materials offered by the housing stock are also visualized at neighborhood or city scales. Based on this integrated approach, the platform can identify the housing archetypes contributing to a low carbon footprint. The platform also facilitates comparing the potential contribution of recycling and reusing housing stock materials to help stakeholders foster a CE (Figure 13c). For example, in the case of Montreal's row houses, recycling materials can contribute to a 53% saving in carbon emissions, and reusing materials with a selective deconstruction approach (i.e., combining reuse and recycling) can lead to 70% savings in emissions compared to landfilling those materials at the building's end-of-use phase.

DHB makes two key contributions to a multiscalar understanding of housing stock: facilitating future reuse economies and building scale reports. It generates new knowledge at the city scale, the neighborhood scale, and the individual housing scale regarding which residence types in Canadian building stock are 1) the most affordable, 2) contain the lowest carbon footprint, and 3) use the least operational energy.

Facilitating Future Reuse Economies

One can also learn which housing vintage is most dominant in a city or neighborhood via the Overview panel under the HP map, as shown in Figure 10, with a detailed view in Figure 13. This feature is significant, as to facilitate a CE city planners, designers, and housing stakeholders need to understand when certain housing stock needs to be renovated or replaced. Using DHB's 'material intensity' and 'global warming potential' views, those users can understand what materials are available in that vintage housing type to plan a material reuse or recycling program at a city or neighborhood scale. Reuse of building materials is only viable if there is a supply of secondary materials available when new construction or retrofit is being planned.

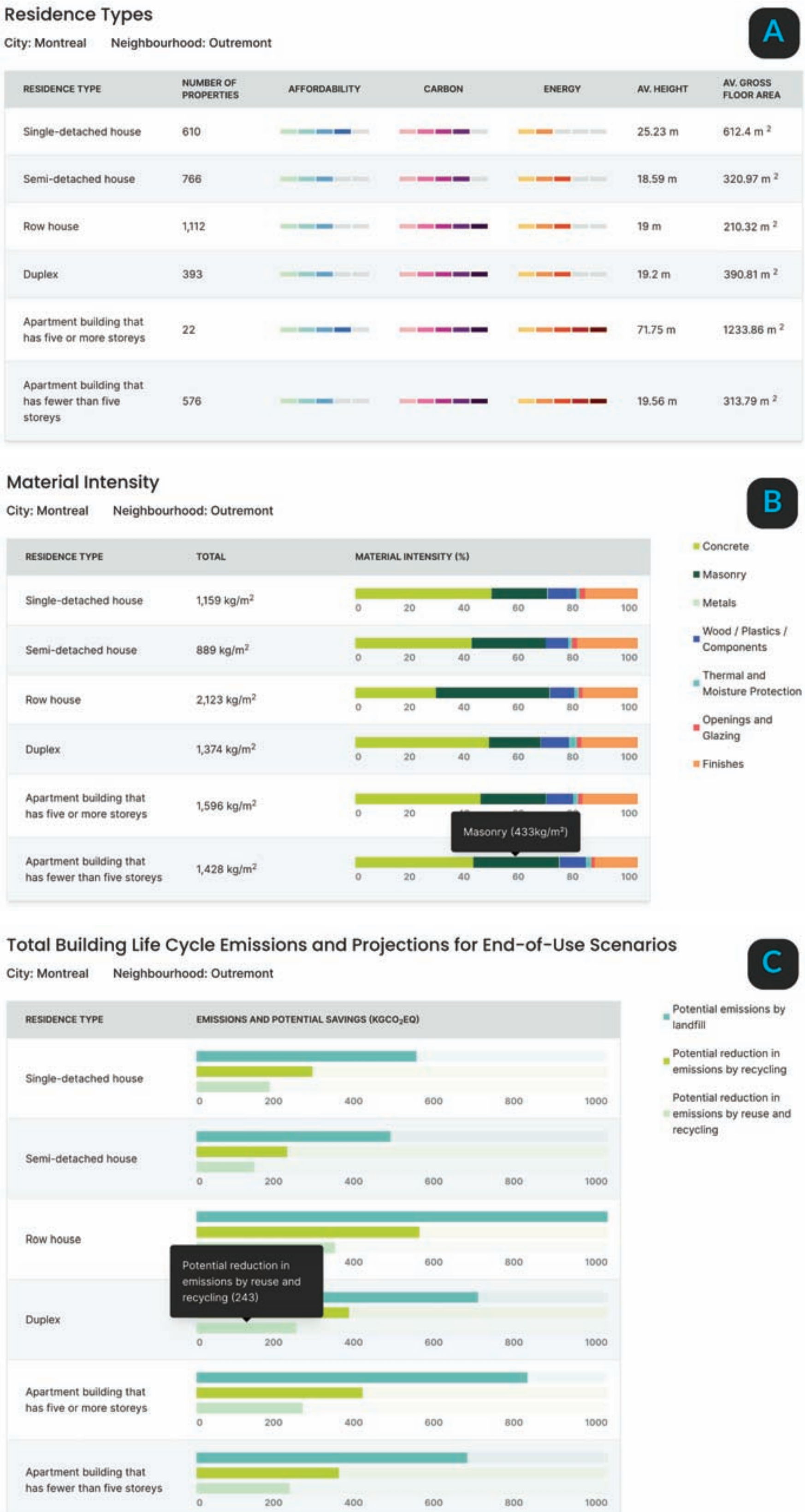
Building Scale—HP Digital Report

At the scale of an individual residence, the resultant HP detailed web page or digital report in Figure 14 presents the affordability measurements, building systems and energy performance, design and construction, carbon performance, and relevant contributions to associated UN SDGs.

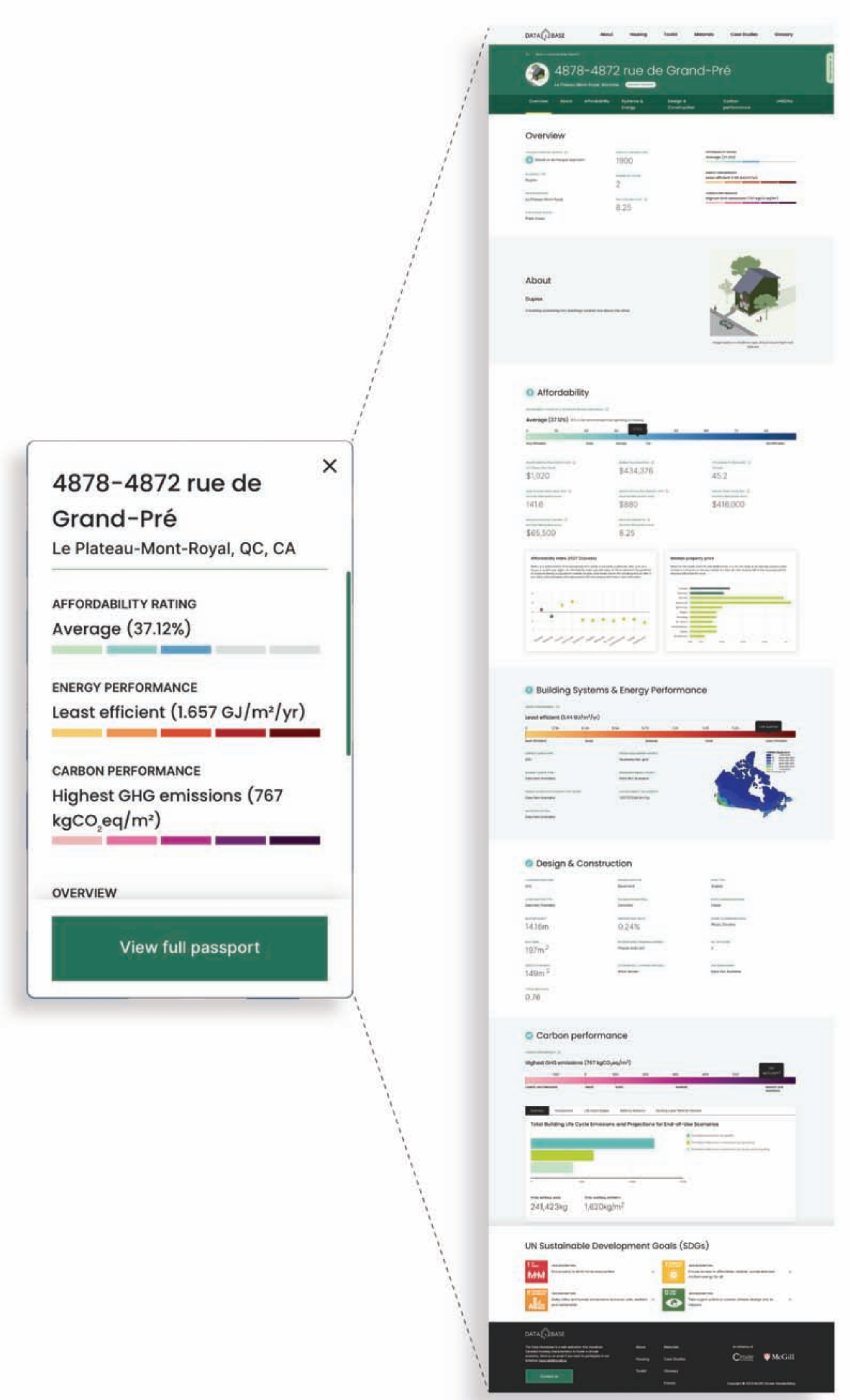
Discussion

The HP and DHB is the first attempt at providing a one-portal entry where building stakeholders can simultaneously gain access to affordability, carbon, and energy housing data instead of seeking this information from disparate sources. To the best of the authors' knowledge, it is the first time a user can gain quantitative information on the carbon footprint of Canadian housing, including the potential reduction in carbon emissions associated with reusing and recycling the existing "bank of materials" embodied in those houses. In this way, DHB can highlight the value of recovering building materials at the scale of Canadian housing and help policymakers and designers to understand the carbon savings associated with viewing these materials as untapped resources.

Mortgage affordability calculators, material passports, carbon emission calculators, and building renovation passports provide valuable information about a building's sustainability to homeowners, contractors, and architects; however, a successful CE approach to the building requires simultaneous consideration of these combined metrics. Hence, the significance of the DHB lies in its integration of essential building characteristics of a highly detailed nature in one easily accessible platform. However, to foster a CE in the building and



◁ Figure 13: Visualizing the materials most available in the housing stock at neighborhood level to encourage the reuse marketplace. (a) Neighborhood level housing stock characteristics; (b) material intensities of the neighborhood archetypes; (c) GHG emissions of the existing housing and the potential carbon savings associated with recycling and reuse.



◁ Figure 14: Housing Passport (HP) Digital Report: At the scale of an individual residence, the resultant HP presents a detailed standardized digital description of a home's characteristics.

construction sector, many factors will need to be considered beyond solely the visualization of information—for example, making reuse accessible, meeting the demand for materials with reuse supply, the cost and logistics of developing reuse marketplaces, etc.

In other words, providing circular, affordable, and sustainable housing is a grand challenge. DHB alone is not going to solve this problem. However, it offers a significant step forward in filling an existing knowledge gap that impedes a CE in housing. Our analysis of the housing industry revealed that decision-making was often siloed and did not consider the full spectrum of a building's life from conception to end-of-use. With DHB, we have created a forum to access and share data to foster truly circular thinking.

Conclusion: Moving Forward with DHB

It is important to point out that DHB intends to provide an initial multiscalar view of housing stock from the city to the neighborhood to the building scale. DHB is an entry point for decision-makers. By design, it uses heterogeneous data (including census, analyzed, and simulated data) to provide the widest possible multiscalar housing information. From that starting point, decision-makers (architects, financial institutes, and retrofit developers) would then progress to a more local, granular analysis, such as an onsite building survey. This step is important to highlight, as we do not want the web application to provide misleading information or overclaim its information capability. As is pointed out in Method 4 on "data-driven narratives," interactive data visualization techniques have been used to make the user aware of this limitation of the tool. For example, tooltips, information icons, and 'data sources' links throughout the tool explain to the user how the data was accessed or generated. In addition, a link to a set of peer-reviewed publications will be provided in the Glossary section of the tool, allowing a user to delve deep into the methodologies used to provide each data set.

The plan to scale up the DHB project is underway, testing and amending the web application's functionality through a pilot project toward an imminent launch of this open-source application. Future research will outline how incorporating a robust collection of exemplars of international CE case studies in the HP database, each with an HP, provides precedents for achieving circularity. HPs of these case studies highlight how specific circular design strategies have led to excellent energy, carbon, and affordability metrics ratings. Furthermore, a toolkit for users to generate their housing passports is being developed in future versions. Transitioning towards a CE future will require the participation of multiple housing stakeholders, and the DHB tool aims to facilitate this journey via a one-portal entry for standardized housing-related knowledge.

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Data Statement

Data are available on request from authors.

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