Future Use Architecture: Connecting housing policy, housing typology, and resource use for housing in Canada

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This study investigates the potential of residential building material stock in Canadian cities to address Canada's housing and retrofitting needs. We introduce the concept of Future-Use Architecture (FUA) within a Circular Economy (CE) design approach. Cities are significant contributors to a nation's material resource use, but they are also banks of materials. In alignment with Canadian government policies and projections, the study addresses the imperative of retrofitting 600,000 homes annually until 2040 and meeting the demand for 2.3 million new homes between 2021 and 2030. FUA involves incorporating recovered materials into new building designs and the early integration of end-of-life building strategies, such as design for disassembly. This approach encompasses a comprehensive evaluation of urban building material stocks and the development of reuse and recycling strategies.

This paper builds on prior work by the authors that investigated the potential carbon emission reductions through material recovery in Canadian housing stocks. Taking this as a starting point, it links this knowledge to current government policies for renovating and building new housing in Canada by 2040. The findings highlight the substantial quantities of building materials embedded in our structures and the considerable potential for reducing environmental impacts, such as carbon emissions, through adopting the Future-Use Architecture (FUA) approach. However, it becomes apparent that substantial shifts in both material supply and construction practices within Canada are imperative to fully unlock the potential of FUA and efficiently utilize the materials stored in our buildings.

> (...) "is well known that personal identity resides in memory and that the annulment of this faculty constitutes idiocy (...)"
>
> —Jorge Luis Borges, History of Eternity

INTRODUCTION

As Jorge Luis Borges eloquently conveyed in his renowned essay, removing a person's memory results in the loss of their identity, leaving only foolish behavior in its wake. Similarly, memory is central to our understanding as individuals and in the context of cities, buildings, and materials. Identifying this memory is particularly evident when examining the cultural heritage of cities and buildings. In the case of materials, their value is primarily rooted in their environmental and social memory and is harder to recognize at first sight. However, acknowledging and respecting buildings and materials' memory should be crucial for building industry stakeholders, preventing engagement in proven inefficient linear models of demolishing and landfilling. The building material memory encapsulates attributes such as embodied energy, water usage, carbon footprint, and the labor invested in their production. The central idea lies in the recognition that by recognizing this environmental and social memory, we can reshape the way we design our buildings. This allows for the reuse and recycling of components and materials.

The potential to reduce and avoid embodied carbon is greatest during the early planning and design phases. Future use architectural (FUA) design involves considering the end of life of the building during the early design phase. This shift in thinking requires a consideration of the material and construction ecologies of a building including how early design choices have repercussions on the ability to re-use or recycle materials later on. Circular economy (CE) can assist in such thinking as it aims to eliminate waste and pollution, circulate products and materials, and regenerate nature through design. This paper studies such thinking at a macro-scale to understand if a circular approach to design and retrofit of housing can mitigate climate change effects.

In line with this notion and as a prerequisite for comprehending the potential for a CE within Canadian cities, it is essential first to grasp the composition of the current building stock. Hence, this paper builds upon the authors' prior research involving a life cycle assessment (LCA) of residential buildings in five major Canadian cities (Montreal, Toronto, Vancouver, Edmonton, and Winnipeg)[1], collectively constituting 36% of the country's dwellings,[2,3,4,5,6] which, in turn, represent over one-third of Canada's housing building material stock. Recovering materials from these buildings can circumvent carbon-intensive extraction processes of non-renewable resources by repurposing them as "raw" materials for new products or after minor cleaning and maintenance, enabling reuse, a vital manufacturing role not fully developed.

Future scenarios for material stock in Canada are analyzed concerning the government's projections to retrofit 600,000 homes yearly until 2040[7] and address the demand for 2.3 million new homes between 2021-2030.[8] Finally, the study highlights the building industry's challenges in transitioning to a circular market. Reclaimed materials can reduce carbon emissions, but market and policy changes are required to meet the increasing demand for building materials. Policymakers can use this research to develop circular strategies that promote sustainability, reduce carbon emissions, and contribute to Canada's 2050 net-zero emissions goal.

CANADA BUILDING STOCK

Canada possesses an extensive inventory of buildings, necessitating substantial endeavours for retrofitting existing structures to attain decarbonization objectives.[7] Currently, the retrofitting mainly focuses on operative energy and is well described in the 2030 Emissions Reduction Plan. This plan outlines existing efforts and new measures to cut emissions across the entire economy. The goal is to achieve a 40-45% reduction below 2005 levels by 2030 and progress toward net-zero emissions by 2050. In the plan, the potential for significant carbon emissions reduction through the use of repurposed materials due to embodied carbon, is hardly mentioned.

Notably, about three-quarters of Canadian homeowners have plans for at least one home renovation in the coming year.[9] This is reflected in the major investment in renovation of over CAD $84 million) in 2022 compared to new construction investments of almost CAD 110 million.[10] Therefore, it is important not only to reduce a home's operational energy but also to minimize embodied energy by utilizing repurposed materials and designing for future use are integral components of this equation.

According to Statistics Canada's 2022 data, the total number of dwelling units in Canada stood at approximately 16.5 million. This figure comprises 8.6 million single houses and 5.8 million apartment buildings, among other typologies.[10] For this study, the geographical distribution of these dwellings was determined by integrating housing archetypes with a Geographic Information System (GIS), using open data collected in a prior study.[1] Finally, this paper delves into the feasibility of FUA and a CE approach, which involves prolonging the lifespan of buildings and employing selective deconstruction to achieve the goal of retrofitting across Canada's urban housing stock. In particular, the research focuses on five cities concerning the potential for the housing stock to be maintained via the conservation of the bank of materials embedded in the current housing stock.

CITIES, MATERIAL STOCK AND URBAN MINING

The environmental and social costs of building materials[11] have led to increased research on urban mining[12,13,14] and landfill mining.[15] This has become a central issue for future sustainability. Material recovery from existing buildings, known as urban mining, has significant potential to reduce carbon emissions.[16] The construction industry plays a crucial role, and the European Union has highlighted the importance of addressing construction and demolition waste (C&DW). However, construction industry stakeholders often overlook these waste streams, resulting in low recycling rates and environmental consequences.[17] In this sense, it is central to generate data related to flows and stocks of materials at national and regional level and in addition, to identify the possible economic benefits for each material.[18]

Research into construction-focused urban mining has demonstrated considerable promise and advance. A study in Singapore found that annual urban mining efforts could yield enough materials to construct over 6,000 low-cost houses[19]. In various cities, concrete consistently emerges as the primary building material by weight.[20] For instance, in the Netherlands, concrete, brick, or asphalt accounts for 90% of the weight of Construction and Demolition Waste (C&DW), with plastics, wood, and metals making up the remaining 10%.[21] A similar trend is observed in Canada, where concrete, aggregates, and brick dominate the total material stock of buildings.[22,23] This observation highlights the importance of exploring recycling and valorization methods for these materials, as current efforts often focus on metals due to their high recycling value, which may not be the case for non-metallic minerals in urban mining. In the case of Canada, there are still barriers to address in relation to recovering and reusing materials, both technically and economically.[24,25]

In contrast to urban mining, which primarily focuses on maximizing the resource and economic value of urban waste streams[12], FUA intentionally designs buildings for material recovery. FUA involves identifying materials suitable for a second life, specifying when and how they can be reused, and designating materials for disposal. While urban mining is a strategy for the current state, FUA should be integrated into new design practices that should include a technological and detailed estimation of the future stock, with clearly established circularity indicators[26], but for the future scenario. Both approaches have significant implications for potential savings in embodied carbon emissions.

METHODOLOGY

In applying the FUA concept within Canadian cities, the methodology comprises a structured approach consisting of three core steps, as illustrated in Figure 1. The initial step involves calculating the mass of materials for each of the six housing archetypes in every one of the five analyzed cities. This database is a fundamental tool for identifying the volume of available materials, categorized by archetype and vintage, within these urban areas. The second step entails scaling up the analysis from individual buildings to the city level. This process uses a

GIS dataset from five Canadian cities where the archetype and year of the residential building are presented. A more detailed explanation of this method is outlined elsewhere.[1] As a result, the total material quantities for each archetype and vintage are determined, now represented on a city-wide scale. Recognizing the inherent uncertainties associated with the first two steps and their respective data sources, it is essential to regard the city material stock values as preliminary estimates rather than definitive figures.

ARCHETYPE-SPECIFIC MATERIAL MASS CALCULATION

To establish the housing archetypes, we built upon prior research conducted by the authors[1] as our starting point. Subsequently, in defining these archetypes, our methodology relies on data sourced from Statistics Canada's census.[27] As a result, we have identified six primary archetypes for this study, which include: single detached, semi-detached, row house, duplex, and apartment buildings with fewer than five stories, along with apartment buildings with five or more stories. In addition, each archetype was segmented into four vintages. A 'vintage' denotes an archetype variation that aligns with a specific time frame and city, which entails distinct structural systems and materials. The four defined vintages are: A:1800-1920; B:1920-1950; C:1950-1980; D:1980-2022. Note that the vintage years group might vary in years, but they are very similar.

Once the archetypes and vintages were identified, the methodology involved developing a Building Information Modeling (BIM) for each housing variation. Subsequently, the BIM software generated a Bill of Material for each variation, and the materials were categorized according to established construction standards. [28] This classification organized the materials into seven construction subgroups: Concrete, Masonry, Metals, Wood, Plastics and Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes. However, since this classification allowed for potential material mixtures, an additional step was taken to further categorize the materials into 21 distinct categories, as detailed in Figure 1. This process enabled the determination of the weight of each building variation distributed among these 21 specific materials.

CITY-LEVEL AGGREGATION

For extrapolating the building values to a city level, first, the number of buildings of each type and vintage in each city was calculated. This information was taken from a previous study[1] that utilized GIS Data sourced from city and federal agencies and that assigned a dwelling census code, to each archetype. This approach allows for counting the number of each archetype and vintage in each city, providing valuable information for quantifying the total material stock under each archetype by city. Hence, the number of houses of each archetype and vintage per city were defined.

After identifying the number of buildings by archetypes and vintage per city, for practical purposes, the material composition of the archetypical house was multiplied per the total number of buildings of that archetype and vintage for each city. As a result, the total material mass for the residential building stock is determined. In the concluding phase, to assess the building stock's capacity to meet future demands, each material was categorized into a particular layer: space plan, skin, or structure. A designated usage period was assigned to each layer, with 15 years for the space plan, 50 years for the skin, and 100 years for the structure, following guidelines from.[29] It's important to note that this step entails certain assumptions and generalizations. For example, despite some wood being used for floors, it is uniformly categorized as part of the structure. Finally, per each city, it is possible to identify the material stock organized according to the previously described 21 materials or by building layer.

The FUA concept presents the benefit of reusing and recycling materials, which can potentially substitute primary materials, avoiding the corresponding impacts from extraction, transportation, and primary manufacturing. However, not all materials can be replaced in a one-to-one manner, as some undergo downcycling, and there are instances where recycling technology is

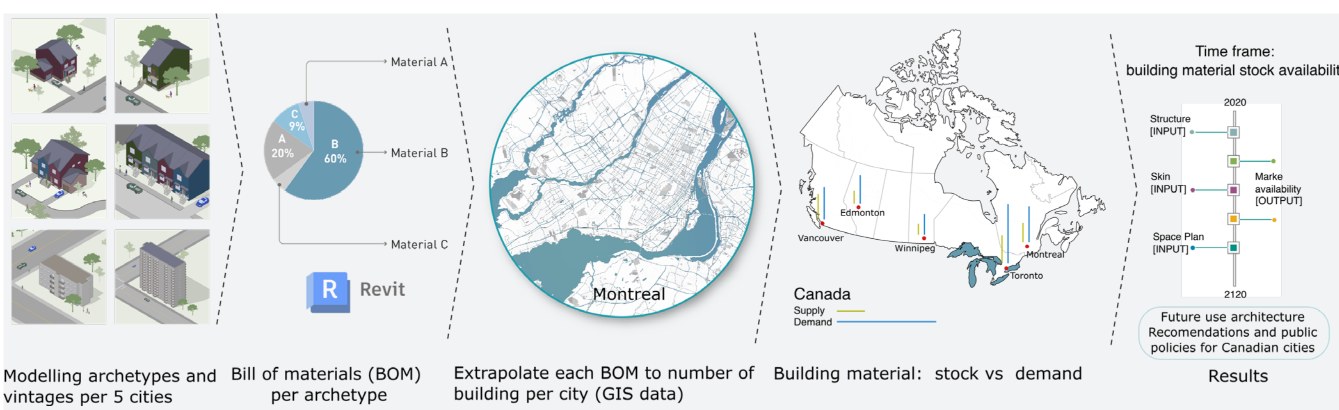

Figure 1. Methodological diagram. Image courtesy of authors.

either unavailable or materials were not initially designed for recycling. The material stock calculation incorporates a recyclability percentage and a quality ratio to tackle this challenge. Comprehensive insights into this proxy calculation are available in a previous study.[30]

MATERIAL AVAILABILITY ASSESSMENT

The final step is identifying the potential of the five cities' material building stock to address the retrofitting and housing demand and the possible implications concerning environmental impacts (GHE, water use and fossil use) that could represent the repurpose and reuse of this material. Therefore, in this phase, it is central to establish the year of material availability, the year of demand for new materials, along with the required quantity, while also considering potential environmental implications.

For identifying the material availability in relation to a time frame, i.e., when the material will be available for a second service, the material building stock is grouped in relation to the four previously defined vintages. The initial date of each vintage group serves as the initial reference point. Then, the lifespan of each building layer is applied to estimate when materials from each layer may become available. For instance, if a building was constructed in 1930, it is categorized within the 1920-1950 vintage. It is assumed that in 1970 (after 50 years), the building's skin underwent renovation, resulting in the disposal of the previous materials. Following this, it is anticipated that in 2020 (after 100 years), both the structure and skin will require replacement. This approach enables the identification of the quantity of each material that could potentially be repurposed for a second life in each future decade. Furthermore, it facilitates the identification of specific aspects of the building that can be retained, such as retrofit possibilities. For example, while the structure may be preserved in a particular vintage of housing, the façade might require replacement.

To estimate material demand, government projections were considered. The process began with the creation of an average building profile, considering all six archetypes, and determining its material composition based on the most recent vintage (D, 1980-2022). It was assumed that the material proportions in new constructions would mirror those of the vintage D category. This 'average house' was then multiplied by 2.3 million to approximate the required material for new constructions. For retrofitting, a total of 4.8 million cases were projected for 2030. In retrofit scenarios, the focus was on the space plan and skin layers, with a presumed 50% renewal ratio or material change for these cases.

Concerning materials' environmental impacts, reuse and recycling proxies were computed using the GaBi LCA software. It's worth noting that these environmental impact proxies were initially calculated in a prior study, which considers the loss of material in the process for both proxies as outlined here.[30] However, we utilized the EN15804+A1 (i.e. the Environmental Product Declaration (EPD) standard) for this research, excluding the Biogenic Life Cycle Impact Assessment (LCIA). These proxies were subsequently applied to estimate the greenhouse gas (GHG) emissions (in kg CO2 eq) for three end-of-life scenarios: selective deconstruction, recycling, and landfill disposal. This entailed multiplying the total material mass at the city level by each proxy, allowing us to calculate both the environmental impacts and the potential reduction in GHG emissions associated with material stock reuse and selective deconstruction in Canadian housing. Lastly, the study acknowledges uncertainties when scaling the material composition from housing level to city, since GIS databases are still limited. The total sample consists of 1'180,810 housing buildings. From this total, 267,046 housing are located in Montreal, 311,263 in Toronto, 86,622 in Vancouver, 290,462 in Edmonton, and 225,417 in Winnipeg. Despite these limitations, the results can be used for scenario analysis and to estimate future stock developments, particularly in the context of resource efficiency and CE policies. As an example, to show the potential of FUA design, a building stock material flow diagram is presented in *Potential to address housing demand* section.

RESULTS AND DISCUSSION

This section provides a comprehensive presentation of the results obtained through each method. Additionally, in each section in a subsequent paragraph, an in-depth analysis and discussion of these results is presented, delving into their broader implications. The analysis primarily centers on understanding the practical consequences of the findings and identifying potential solutions, including policy-oriented recommendations.

MATERIAL MASS BY ARCHETYPES

As a result of the material mass calculations for each building variation, Figure 2 presents the material composition of each archetype for the four assigned vintages at the national level. There is a significant increase in the use of concrete and a decrease in other materials like stucco or concrete blocks. This shift is attributed to changes in construction systems over time. Additionally, the material use intensity notably increases with the introduction of archetypes 5 and 6. Archetypes that rely less on high embodied carbon materials, such as concrete, primarily use wood as a structural system, often in combination with concrete. It's important to note that while some materials may not be as significant in terms of mass, they have substantial environmental impacts (metals and some plastics). Thus, it is crucial to emphasize their potential for reuse and recycling.

These findings emphasize the significance of continuing legislative developments that harmonize with the ever-changing material landscape stock. Such alignment can empower local governments to strategically plan for infrastructure and enact legislation accordingly. For instance, neighborhoods predominantly featuring apartment buildings (types 5 and 6) should consider the inclusion of recycling and reuse centers dedicated to the treatment of concrete, brick, and steel. Furthermore, when looking at past building stock, the results highlight the

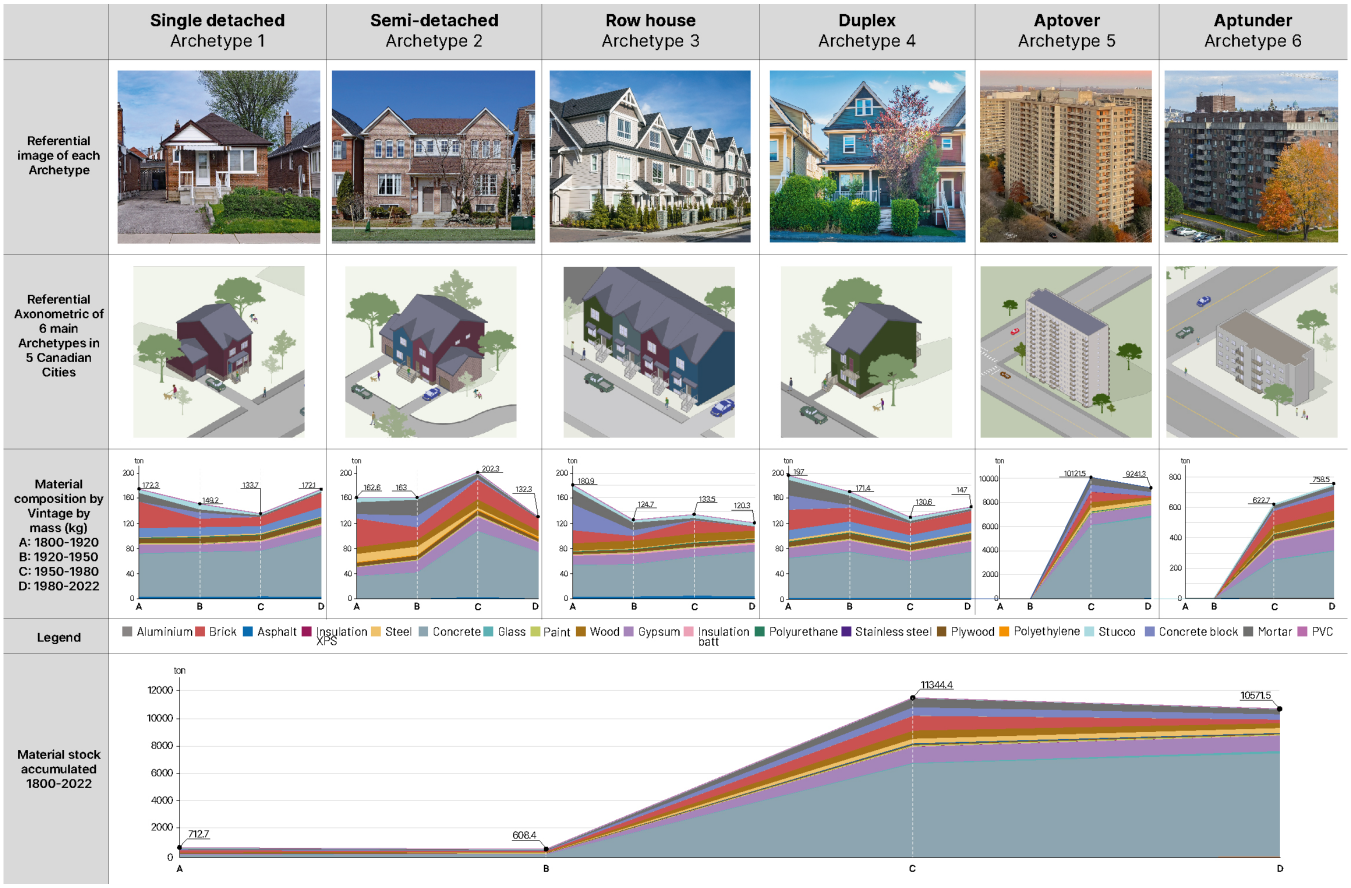

Figure 2. The average material composition of Canadian cities' residential buildings by archetype and vintage. Each archetype has a different scale, and the total accumulated material stock is presented at the bottom.

potential for constructing cities where materials with high embodied carbon are utilized with reduced intensity. Notably, despite minor variations, there are substantial commonalities in building composition among cities and regions.

POTENTIAL MATERIAL MASS FOR SECOND LIFE

The analysis of building material stock by mass reserved for potential secondary use reveals a notable uptrend in material intensity over time. This can be primarily attributed to the prevalent use of concrete and steel in Canadian city construction. Also, the introduction and continual development of apartment buildings, which heavily rely on concrete and steel, contributed to this growth (figure 3).

Concerning the potential material stock measured by mass, the initial analysis highlights concrete as the most abundant material, with an astounding total of 195 Megatons (Mt) across all cities. Brick accounts for 36 Mt, and gypsum amounts to 34 Mt. This underscores the substantial presence of non-metal minerals, constituting 77.6% of the total material stock in Canadian cities. When we examine the layers, it becomes evident that the structure layer is a significant contributor, representing 75% of the overall building material stock, while the skin layer constitutes 12% of the total, with brick veneer being the most predominant material. It is essential to mention that wood and plywood represent around 8.7%, and that steel and aluminum are 2% and 0.3% of the total potential material for secondary use, respectively.

In previous periods, a linear approach and disposal of materials can be inferred, especially for the space plan and skin layers in vintages A, B, and C. For instance, in buildings from vintage group A (i.e., 1800-1920) that are usable in the present, it is clear that the longevity of the space plan and skin layers surpasses the typical usage expectations. The skin is generally designed to last a maximum of 50 years, while the space plan is expected to endure for 25 years. This suggests extensive retrofitting in these buildings, including structural reinforcement or repairs, multiple skin layer renovations, and numerous alterations to the space plan. Thus, materials replaced during these retrofit activities should not be considered part of the city's building material stock; instead, they are likely to have been repurposed or disposed of in landfills, as shown in Figure 4, for the case of Montreal. Some non-reusable materials, such as stucco, polyurethane, and paint, which might contain lead, formaldehyde or asbestos, are considered toxic materials that often end up in landfills or incinerated.[31] In these cases, there could be implemented a chemical solution to separate toxics, so that they are not released over time

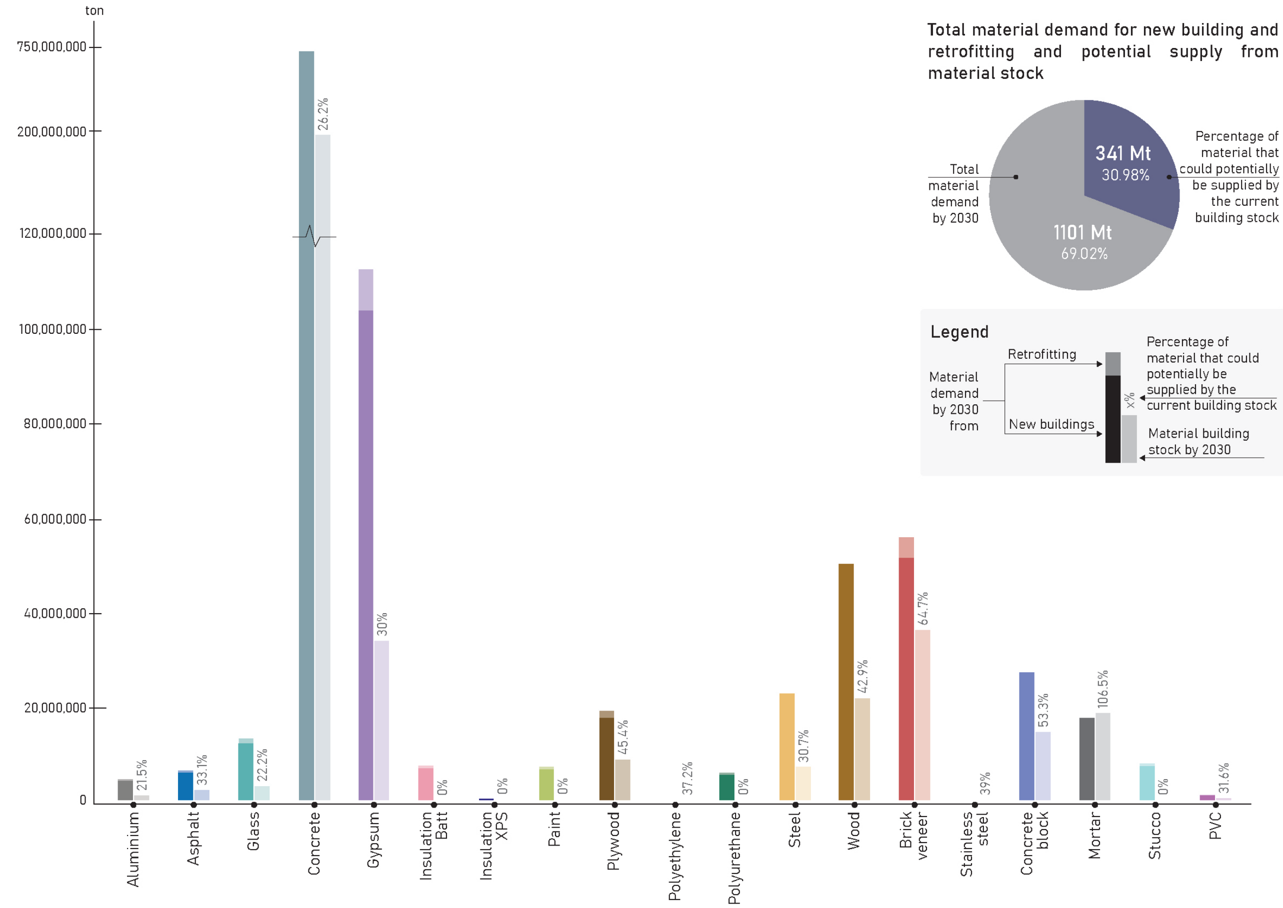

Figure 3. Potential material stock by material (mass) and projected material demand by 2030. The first bar represents the projected total material demand by 2030 at the country level, categorized by material. The second bar indicates the potential percentage of material that could be sourced from the existing material stock. Image courtesy of authors.

avoiding environmental impacts or promote their separation in hazardous waste landfills.[32]

POTENTIAL TO ADDRESS HOUSING DEMAND

The total material demand for 2030 is 1101 Mt, considering the new buildings and the retrofitting of each Canadian city (refer to the *Material Availability Assessment* section for the calculation). The assessment of materials potentially available, from the existing building stock, considers each material's reusability and recycling proxies. This evaluation considers the current housing structures in Canada to determine their potential for a second use. Comparing these building stocks to the national material demand for 2030, it manifests that implementing FUA available materials, focusing on reusing and repurposing materials, can fulfill approximately 30.98% of the demand, as shown in Figure 3. This translates to an average of 822,000 housing units that could be met through the use of second-life materials. It's important to note that these numbers vary depending on the material type. For example, second-use plywood could meet the demand for 1.1 million housing units, concrete blocks for 1.2 million, and brick for 1.6 million dwellings. Note that this projection addressing the demand is not considering the lifespan of each layer.

When analyzing Montreal as an example, in terms of material availability, starting from 2022 as our reference point, it can be noticed that by 2030, a portion of materials within the skin and space plan layers will require renovation (figure 4).[25] This means that approximately 3.48 Mt of materials going out from those layers can potentially re-enter the market for repurposed or second-use materials. Looking ahead, by 2050, the materials from the structure layer from vintages C (1950-1980) will become available, representing a substantial input of 96.3 Mt of building materials.

POTENTIAL CARBON SAVINGS AND POLICIES

The evaluation of material stock and the associated carbon savings for meeting the 2030 housing targets by repurposing existing materials has been conducted at the national level (figure 5). As mentioned earlier, our findings indicate that the cumulative national building stock could potentially fulfill approximately 31% of the new material demand for new construction and retrofitting. To analyze these outcomes comprehensively, the research explores two distinct paths: Path 1: Primary Resource Use (PRU), and Path 2: FUA each encompassing three scenarios

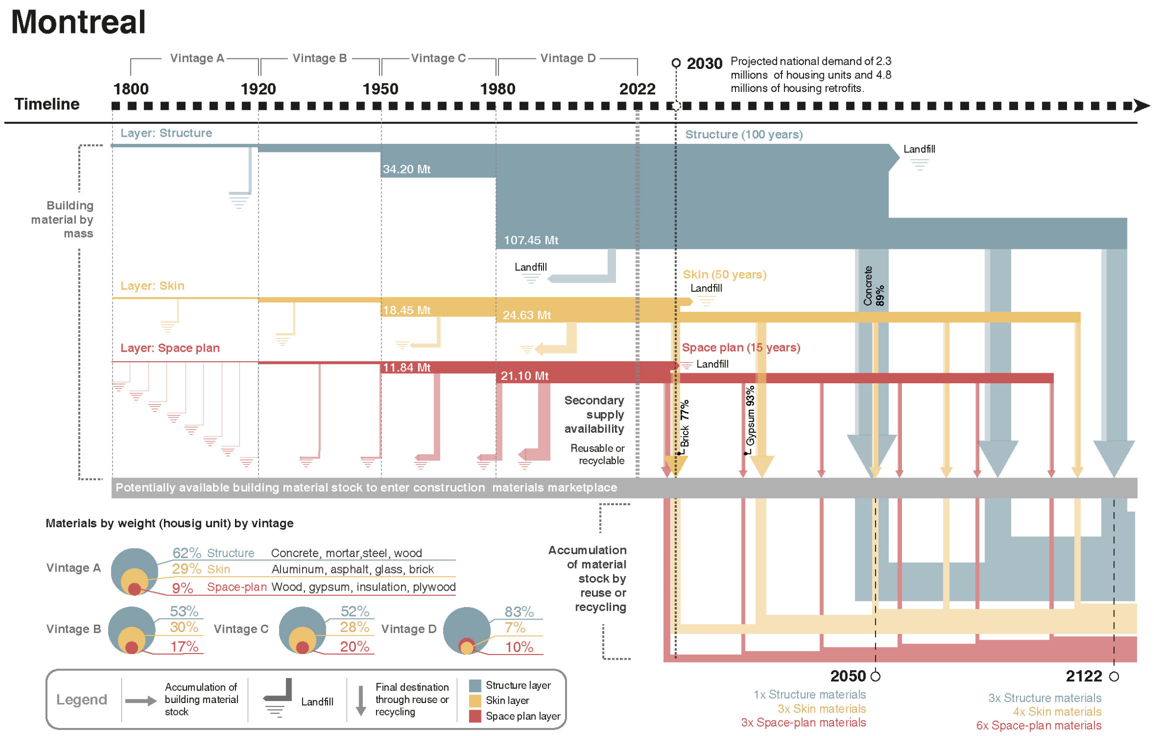

Figure 4. Syncing material cycles in Montreal – a new supply and demand model. Proposing a new circular model for CRD material management. The quantity and timeframes of material availability are shown. Image courtesy of authors.

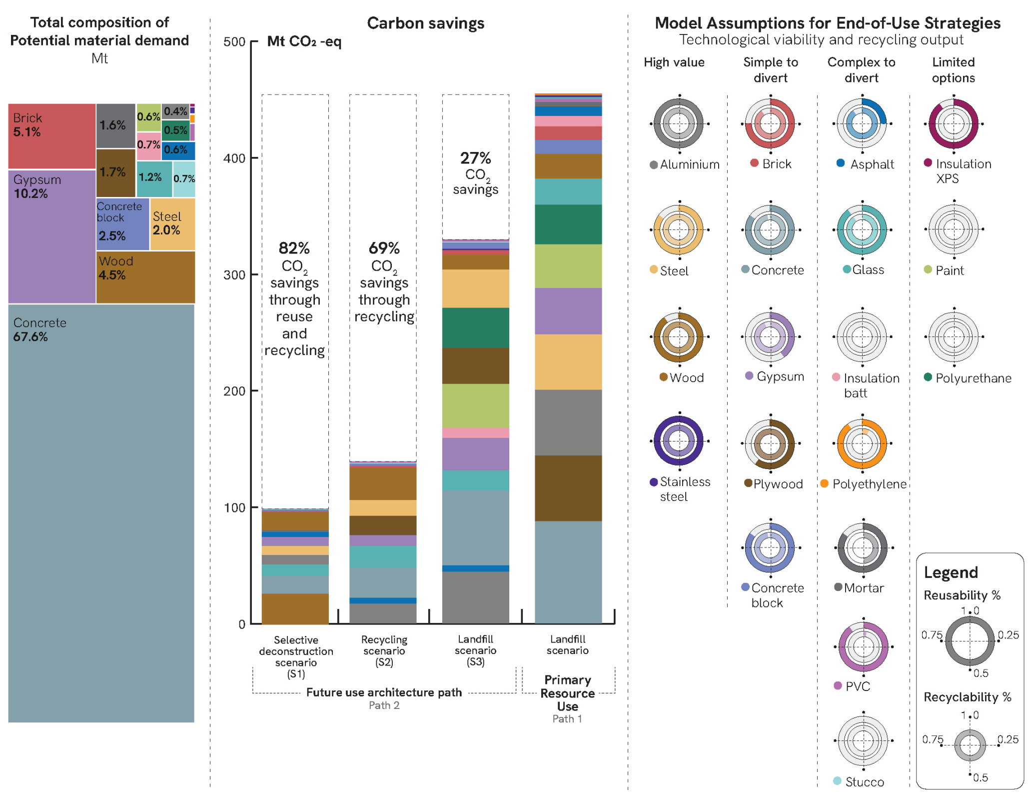

Figure 5. Results of Life Cycle Assessment (LCA) showing the potential carbon savings resulting from using circular scenarios across Canada's housing sector. Image courtesy of authors.

S1: Selective deconstruction; S2: Recycling; S3: Landfill disposal. There are two key differences between the two paths related to both the origin and the end-of-life treatment of materials for new construction and retrofitting. In Path 1 (PRU), 100% of materials are virgin and sourced from linear processes, such as extraction. In contrast, Path 2 (FUA) integrates 31% of materials recovered from the existing building stock (presumed to undergo recycling or reuse), with the remaining portion assumed to be virgin material. Concerning the end-of-life stage, Path 1 disposes of all materials in a landfill. Conversely, Path 2 (FUA) offers three potential scenarios for the end-of-life: Selective deconstruction (S1), Recycling (S2), and Landfill disposal (S3).

Hence, In Path 1: PRU, the material building stock is not utilized. In contrast, Path 2: FUA, involves the use of the recovered materials (building stock) to address the housing demand and retrofitting. In both cases, to compute end-of-use emissions (in kg-CO2-eq), Life Cycle Impact Assessment (LCIA) proxies were introduced for each material, as detailed in *Material Availability Assessment* section.

The results demonstrate significant savings compared to the landfill scenario for Path 1, considered the worst-case scenario. Path 2 (FUA) showcases a remarkable 82% reduction in S1, 69% in S2, and 27% in S3.

To achieve these savings, policies must be taken, such as tax benefits for adopting selective deconstruction during demolitions or renovations. This involves proper sorting of materials for enhanced reuse and recycling, ensuring high-quality material recovery, as implemented in Denmark, Finland, and Sweden through legal regulations.[33]

Additionally, governments should actively advocate for the utilization of recycled aggregates, sourced from Construction and Demolition (CRD) waste, over virgin aggregates by offering favorable financing rates. In case of using virgin aggregates, increase the taxes to improve environmental programs regarding CRD waste. The United Kingdom serves as an exemplar in this regard, showcasing the highest utilization of secondary aggregates within the European construction industry.[34]

The UN advocates financial incentives to create marketplaces for reusable materials, which facilitate the dismantling, storing, preparation, and maintenance of recovered materials for resale. In recycling, encourage the competition of secondary markets, ensuring their quality and constructive standards required, thus improving their acceptance in the construction sector.[11]

CONCLUSION

We have identified the number of materials available in Canada's housing stock. We demonstrate the potential carbon savings if this material is reused and recycled rather than going to landfill, which could reach 85% in the best-case scenario. This also involves the amount of material extraction that could be avoided if a selective demolition approach to Canada's housing stock is followed. Through understanding this data on an urban scale, we aim to demonstrate the carbon-saving potential of a CE in Canada's housing stock but also the potential for much of the life cycles of these materials to be extended in preserving the architecture. This FUA design approach has significance in helping city governments to understand the potential of CE in reducing waste and avoiding unnecessary raw material extraction. It also acts as evidence for these governments to promote policies on circularity, including incentives for material reuse marketplaces and more advanced recycling, as well as the retrofitting of existing buildings. In addition to these measures, promoting the standardization of construction materials facilitates interchangeability and ease of reuse in new construction projects. The standardization method allows easier disassembly and reuse, which is crucial to promote selective deconstruction scenario.

The research findings concerning material stock and availability in time hold great importance in promoting CE). Urban stakeholders, including designers, will be able to gain insights into the availability of materials and relate this information with renovation or replacement plans at the building or city level.

The results of this research highlight the importance of integrating FUA into the CE model, which will contribute to optimizing urban resource management and minimizing the use of virgin materials. However, to use these potential material stocks, it is necessary to promote policies, market development and technical manuals for reusing and recycling materials, especially the non-metallic mineral base materials. Finally, the research advocates for the utilization of building materials stock by adopting the FUA approach for cities' future projects. FUA is a developing field of study that delivers positive environmental outcomes and will encourage collaboration between government agencies, construction companies, and waste management to create a holistic approach to reuse and recycling potential.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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