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Multiscale pattern analysis of building replacements in Zurich from 2000 to 2019

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Multiscale pattern analysis of building replacements in Zurich from 2000 to 2019

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Abstract. Building replacement (BR) – i.e., the demolition of existing structures and subsequent construction of new buildings on the same site – is often understood as a necessary urban planning strategy despite significant environmental implications regarding solid waste generation, raw material depletion, and embodied greenhouse gas emissions. Besides, BR may also be considered an effective form of urban mining. Yet it has not been adequately studied in academic literature. Current studies often adopt a simplified 'black box' approach that overlooks the intricate internal mechanisms and fails to capture the interconnected material flows within the building stock. To address these gaps, this paper utilizes descriptive statistics and bipartite graph analysis to examine the transformation patterns of BR across three spatial scales in the city of Zurich. The analysis encompasses 1,018 replacement projects involving 6,115 building units from 2000 to 2019. By comparing the characteristics of demolished and newly constructed groups, the study reveals insights into the dynamic nature of BR. From a broader perspective, the combination of the various heterogeneous BR-related findings in this paper highlights the need to evaluate the application of circular economy principles to large building stocks with a more nuanced understanding of building stock dynamics over time.

1. Introduction

Building replacement (BR) refers to existing buildings being demolished and replaced by new ones that are locally and temporarily connected. In Europe, BR has emerged as a prominent strategy for addressing the changing spatial demands of existing building stocks because of its efficiency in managing operational energy efficiency issues for the aging building stock [1,2], in promoting sustainable land use and city densification [3,4], in offering greater flexibility for accommodating the built environment to constantly updated ways of living and production [2,4], and in supporting periodical demands of real-estate investment, material manufacturing, and construction activities [1]. However, promoting BR without considering its potential negative consequences may lead to an undesirable shift in pollution due to the significant solid waste, considerable non-renewable resource consumption, and substantial greenhouse gas emissions associated with demolishing old buildings and constructing new ones [5,6]. Therefore, a comprehensive understanding of BR dynamics is essential for effective decision-making and trade-offs between multiple dimensions, particularly for integrating circular economy (CE) principles at large urban scales.

1.1. Bigraph patterns of BR

From the perspective of urban mining, BR stands out significantly compared to studies that solely focus on the material dynamics of demolition or new construction in the building stock. Its uniqueness stems from its ability to connect the end-of-life of buildings with the start-of-life of other facilities in the closest occasion and moment, generating and linking output and input material flows simultaneously. Mathematically, the relationship between the entities from two sets with different properties can be described by a bipartite graph or bigraph. Consequently, in this paper, the patterns associated with BR are formulated by such bigraphs, with two sets of nodes representing features of either old or new buildings, and edges connecting these sets representing the shifts in quality and quantity brought about by BR. Analyzing these bigraph patterns in BR offers valuable insights into identifying opportunities for circular material flows of CE, such as salvaging materials or designing buildings that facilitate future disassembly and reuse.

1.2. Multiscale perspective of BR
Despite BR's potential as an effective urban metabolism (UM) practice, it has been overlooked. Its understanding is limited to using a simplified linear input-output model operating as a 'black box' [7,8]. The few studies [9] of BR currently available restrict their discussion to averaged values at the city scale. However, city-level averages cannot grasp the specific patterns and internal mechanisms characterizing each BR project at a more detailed scale, e.g., for understanding shifts of functional use, room dimensions, or material use within same BR projects. From Moreover, from a design system viewpoint, macroscopic urban observations are inadequate for guiding project- or building-level design decisions and requirements. Thus, it is crucial to comprehend the patterns of BR from a multiscale perspective.

1.3. Research scope
The greater city of Zurich is chosen as a case study due to the prevalence of BR as a strategy for its urban development. The exhaustion of accessible building land reserves within the city boundary in the 1990s [10], followed by re-urbanization [11] and rapid population growth [12] at the turn of the 21st century, brought about a notable emergence of BR in Zurich. In 2015, seven percent of the city's population lived in replacement buildings [13]. This phenomenon was particularly significant in Zurich.

In essence, the primary research question this study addresses is, "How can a comprehensive understanding of the dynamics involved in BR be derived, and how can these dynamics be effectively managed to enhance decision-making and trade-off processes?" Accordingly, this paper aims to elucidate the intricate process of BR through a comprehensive multi-scale analysis, spanning from city-wide perspectives to individual plot and unit details. This research reveals two key insights:

First, the city-level analysis emphasizes the role of BR in the city's non-renewable resource consumption, demonstrating the need for a holistic evaluation system in urban decision-making.
Second, employing a bigraph analysis on plot and unit levels elucidates distinctions among different segments, informing more precise circular economy applications through detailed scenario targeting.

2. Data and method
2.1. Data
This research uses datasets aggregated from statistical offices, municipal records, and cadastral GIS. The primary source encompasses 1,018 valid replacement projects involving 3,359 demolished and 2,756 newly constructed building units collected between 2000 and 2019. Each project may involve the demolition or construction of multiple building units. Consequently, a data structure resembling a tree-like hierarchy is formulated, following a bottom-up recursive approach from the unit level to the plot level and eventually to the city level. To enhance data accessibility, building functional types are uniformly categorized into nine basic categories, further classified into residential (R) and non-residential (NR) super-categories (Table 1) per federal-level recording standards outlined in [14]. The pertinent attributes include the functionality (use category), the state of existing or demolished, and the building volume, ensuring a statistical completeness rate exceeding 90%.

2.2. Methodology
The multiscale analysis proceeds progressively from city to plot and unit scales. The urban level is examined to encompass the entire building stock involved in BR, while the project and unit levels focus on specific elements. Bigraph patterns of BR are derived by comparing the characteristics of demolished

and newly constructed groups across scales, primarily considering changes in functionality (use category) and size (volume). Proportionality, net value, and replacement rate mathematical methods summarize the quantitative comparative results. The replacement rate, which represents the ratio of new construction to demolition [9,15], offers a more intuitive means of comparing larger values. Comparative relationships between the old and new groups at each scale are established as follows.

City-scale analysis. This level mainly concerns embodied flow impacts of BR in total city building stocks, pertinent inventory changes by functionality, and urban density changes caused by BR.

Plot-scale analysis. At the plot scale, it is essential to consider the functional shifts within each project, which may consist of multiple units with different use categories. Super-categories are used to generalize the primary function of a project. Residential (R) and non-residential (NR) classification is determined empirically, using a 60% residential volume share as division bounds, based on 140 projects with precisely 60% residential volume share pre- or post-replacement. Consequently, a project's functional shift is defined as the transition between R and NR, leading to four distinct functional shift types in bigraph patterns: R to R, NR to R, NR to NR, and R to NR.

Unit-scale analysis. Distinguishing the plot scale and establishing a one-to-one correspondence between demolished and newly constructed units is challenging due to inconsistent numbers within the same project. However, these buildings are typically grouped for cohesive planning, dismantling, design, and construction. Therefore, it is assumed that each demolished unit has a shifting relationship with all new units within a project. A directed complete bipartite graph mathematically represents this shift relation. Upon this model, the bigraph patterns of units in terms of functional and size changes are examined. Since each unit is assigned a specific essential category (excluding 'unknown' due to its small proportion), 64 shift types in bigraph patterns at the unit scale are formulated. The quantity of demolition and new construction assigned to each edge vertex represents the quantitative characteristic.

Table 1. Use category classification.

Super-Categories	Basic-Categories	Abbr.	Basic-Categories	Abbr.
Residential buildings (R)	Single-residential buildings	SNR	Multi-residential buildings	SNR
Non-residential buildings (NR)	Hotel & catering	HAC	Industrial & warehouse	IND
	Office & commercial buildings	OFC	Community & cultural & education & health buildings	CEH
	Garage	GAR	Special public service buildings	SPS
	Unknown	N/A		

3. Results

Results at the city scale show collective shifts aroused by BR analysis in the Zurich building stock. In contrast, bigraph patterns of functional and volumetric shifts are presented at the lower scales.

3.1. Inventory shift at the city scale

Figure 1 provides the collective change of material flows associated with BR in the Zurich building inventory. Between 2000 and 2019, 3,359 building units in Zurich were demolished through BR, resulting in a decreased volumetric displacement of about 8.7×10^6 m^3, and replaced with 2,756 new units, totaling an increased volumetric displacement of 21.3×10^6 m^3. Over this period, an apparent densification of the BR's inventory is observed, with a collective volumetric expansion rate of 2.44. As the total number of units decreased, the replacement rate of 0.82 new units for every demolished unit resulted in a more pronounced impact on the individual unit size enlargement through BR.

Notably, demolitions through BR accounted for a substantial proportion of the total city-recorded demolitions, representing 56.3% of the total volume. New constructions through BR constituted 10.7% of all registered constructions or 11.7% of the existing built stock (Figure 1b).

By use category, more information can be explored about the material flow changes. In absolute terms, the most dismantled volume originates from office and multi-residential buildings, followed by industrial ones. At the same time, the reasonably significant growth of new construction concerns multi-residential and office buildings (Figure 1.d). The absolute volume displacement of the other categories in demolition or new construction appears insignificant compared to the most significant category, likely due to their relatively low share in the city's building stock. (Figure 1e). Upon reviewing the existing inventory of each use category, it becomes evident that BR has significantly impacted demolition and new construction for nearly every category (Figure 1c).

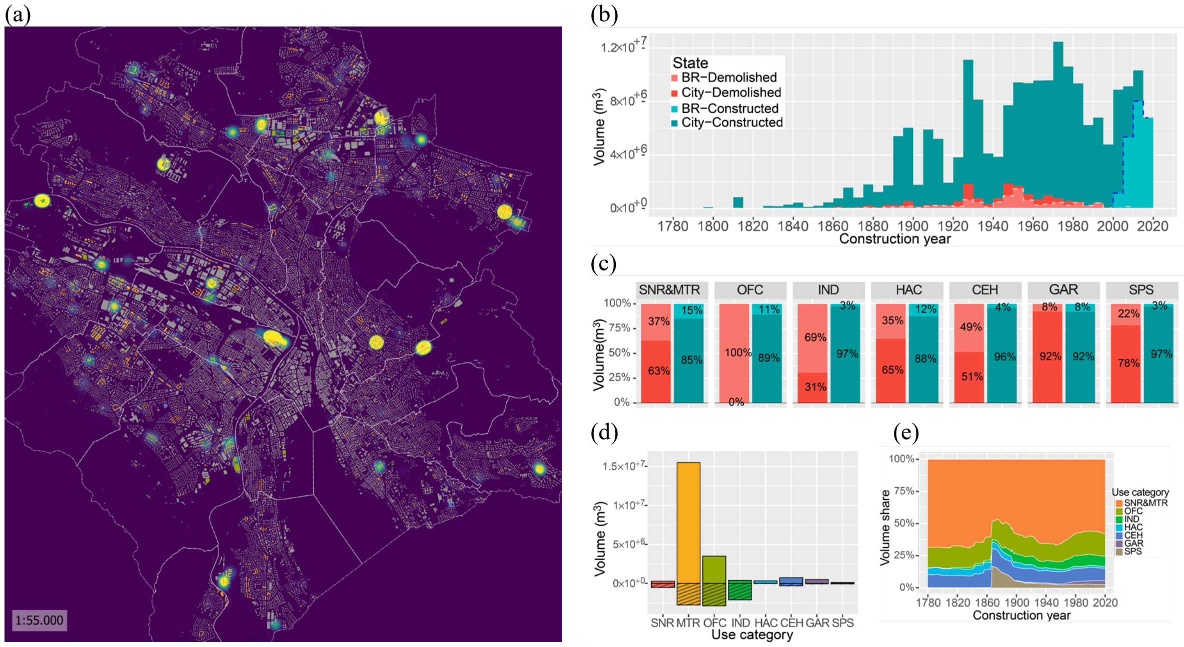

Figure 1. Patterns of BR from 2000 to 2019 at the city scale. (a) Yellow dots highlight the location of BR buildings in Zurich from 2000 to 2019 with a high volumetric replacement rate. (b) Volume of recorded demolished and existing buildings by construction year. (c) Volume share of BR in city demolished and existing stock by use category. (d) Quantity of BR's new construction and demolition by use category. (e) Share of each use category in existing city building stock by year.

3.2. Bigraph patterns of BR at the plot scale

Table 2 presents the results of the bigraph patterns of functional and volumetric shifts at the plot scale. Firstly, more than half of the projects are classified as RtoR. Another 22% of the projects fall under the NRtoR flow category, with 174 being not of residential use before demolition. Thirdly, most new non-residential projects replace former non-residential plots, as seen in the NRtoNR flow category. Conversely, RtoNR projects are rare, indicating that the need to clear residential areas for public infrastructure is not common. The first three functional shift flows account for nearly equal shares of the volumetric displacements in BR's demolition and new construction.

Table 2. Statistical summary of the four project functional shift types.

project functional shift types	volume share of living space in demolished buildings in a project	volume share of living space in newly constructed buildings within a project	# of projects	total volume share in BR demolition	total volume share in BR new construction
RtoR	>= 60%	>= 60%	636	35%	39%
NRtoR	< 60%	>= 60%	229	36%	33%
NRtoNR	< 60%	< 60%	129	28%	26%
RtoNR	>= 60%	< 60%	24	1%	2%
		total	1,018	100%	100%

Figure 2 displays essential differences in volumetric replacement rates observed across project functional shift types in BR. While BR has been shown to increase urban density collectively, certain projects exhibit a decrease in volume. The most common shift flow is RtoR, with most projects showing mild volume enlargement in the 1 to 3 times range. On the other hand, projects originating from the NR condition exhibit a wider range of replacement rates and are the primary contributor to shrinkage. The distribution peaks of project shift variants vary in descending order from NRtoNR to NRtoR, and RtoR, with RtoNR flows being excluded due to their insignificant share. It is worth noting that extreme shifts expanding by more than ten times are rare. The median, mean, and volume-weighted mean of the volumetric replacement rate for projects are found to be 2.72, 3.64, and 2.44, respectively, suggesting that the larger volume projects have a lower replacement rate in the overall group.

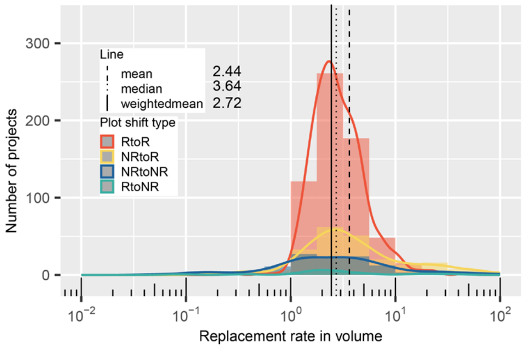

Figure 2. Histograms and kernel density estimations of the number of projects concerning project replacement rate in volume by project functional shift type. Replacement rate expressed logarithmically. Three central tendencies of project replacement rates are marked: solid, dashed, and dotted black lines indicate volume-weighted mean, mean, and median and the corresponding values are labeled in order from top to down.

3.3. Bigraph patterns of BR at the unit scale

This subsection provides more granular bigraph patterns of functional and volumetric shifts at the building unit scale. Figure 3 shows that the RtoR and NRtoR functional shift flows are primarily converted to new multi-residential and originated mainly from old multi-residential, industrial, office, and single-residential, accounting for respective 30%, 20%, 16%, and 5% of BR's demolished volumetric displacement. NRtoNR flows are mainly presented as taking over former office or industrial space to place new office buildings at the unit scale, involving 10% and 4% of BR's deconstructed volume, respectively. Other sporadic variations in unit functional shifts occur due to the relatively lower representation of certain categories in the city's building stock (such as gastronomy) or with the functional alignment of a building being influenced more by external factors such as the surrounding urban context and property ownership than by personal preference or choice.

The higher volumetric replacement rates are mainly concentrated in the unit shift types that concern special public service, followed by single-residential and industrial. Significantly, the former two are the categories with the smallest size in demolition, and industrial is also with a low building height, implying a more significant potential for heightening. For most other unit shift types, 1-4 times volume growth is dominant.

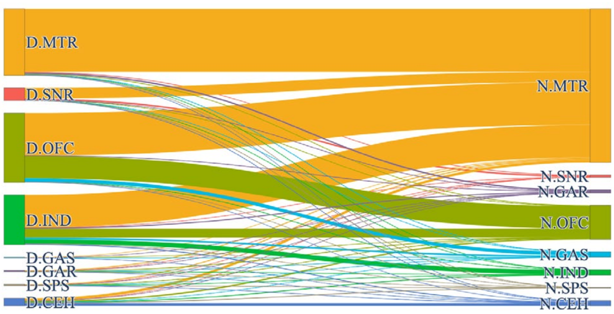

Figure 3. Bigraph patterns of BR in functional shifts at the unit scale. Left is the share of the involved demolition volume by each use category. Right is the share of involved new construction volume by each use category. Prefixes D and N denote demolished and newly constructed buildings, respectively.

4. Conclusion and future work

This paper has analyzed key features of building replacement in the city of Zurich over the past 20 years. Results at the city level underscore the significant impact of BR on non-renewable resource consumption within the city's inventory, particularly in terms of generating waste from deconstruction. Consequently, establishing a comprehensive evaluation system is crucial, offering insights into prospecting, mitigating, and managing material flows as integral components of urban decision-making. The bigraph analysis of patterns from demolition to new construction in BR considers an increase of granularity from plot to unit scale. The lower scale reveals heterogeneity among the refined segments. Therefore, adopting a multiscale perspective when analyzing the outcomes of BR's bigraph patterns provides more targeted scenarios and specific conditions for future discussions on the application of circular economy principles through or despite BR. For future research, we aim to enhance this multiscale bigraph model by expanding the existing framework to incorporate more detailed scales and complex building attributes. Since a significant portion of the relevant information is often absent from databases and instead recorded in drawings, our future work will employ a bottom-up approach to information development.

The methodology employed in this study holds potential for investigating additional urban building stocks related to BR, thereby prompting a reassessment of material flows and environmental repercussions associated with BR practices.

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References
[1] Binz A and Fregnan F 2002 *Rebuilding instead of renovation? Neubauen statt Sanieren?* (Switzerland)
[2] Schürt A, von Bodelschwingh A, Pietschmann H and Schmidt K B 2012 *Möglichkeiten und Grenzen des Ersatzneubaus als Beitrag zu Energieeinsparung und Klimaschutz bei Wohngebäuden* (Berlin: Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR))
[3] Barthel S, Isendahl C, Vis B N, Drescher A, Evans D L and van Timmeren A 2019 Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System *The Anthropocene Review* **6** 71–97
[4] Cadosch S, Bächtold H-G, Kessler T, Nicolai B, Schwalfenberg C, Kämpfen B, Sonderegger A, Solt J, Lokai T, Ammann T and Binz A 2015 *SIA-Tagung «Ersatzneubau I Erneuerung, Entscheidungskriterien»* (Bern)
[5] Bilsen V, Kretz D, Padilla P, van Acoleyen M, van Ostaeyen J, Izdebska O, Hansen M, Bergmans J and Szuppinger P 2018 *Development and implementation of initiatives fostering investment and innovation in construction and demolition waste recycling infrastructure* (Brussels: European Commission)
[6] International Energy Agency P 2019 *Material Efficiency in Clean Energy Transitions* (Paris)
[7] Athanassiadis A, Crawford R H and Bouillard P 2015 Overcoming the "black box" approach of urban metabolism *Living and Learning: Research for a Better Built Environment, Proceedings of 49th International Conference of the Architectural Science Association* pp 547–56
[8] Huang Q, Zheng X, Liu F, Hu Y and Zuo Y 2018 Dynamic analysis method to open the "black box" of urban metabolism *Resour Conserv Recycl* **139** 377–86
[9] Huuhka S and Kolkwitz M 2021 Stocks and flows of buildings: Analysis of existing, demolished, and constructed buildings in Tampere, Finland, 2000–2018 *Journal of Industrial Ecology* **25** 948–60
[10] Rey U 2015 *Zurich Baut Sich Neu - Ersatzneubauprojekte 2004 – 2015* (Zurich)
[11] Lerch M 2022 *Urban sprawl and the changing geography of mortality in Switzerland 1966-2018* (Lausanne)
[12] Rosin K 2022 *Stadt Zürich: Bevölkerungshöchststand übertroffen* (Zurich)
[13] Rey U and Brenner M 2016 *Bauliche Erneuerung in Zahlen-Erneuerung von Whonbauten in der Stadt Zurich 2000-2015* (Zurich: Statistik Stadt Zurich)
[14] Eidgenössisches Gebäude- und Wohnungsregister 2018 *Merkmalskatalog* (Switzerland)
[15] Huuhka S and Lahdensivu J 2016 Statistical and geographical study on demolished buildings *Building Research and Information* **44** 73–96