RESEARCH AND ANALYSIS

Stocks and flows of buildings
Analysis of existing, demolished, and constructed buildings in Tampere, Finland, 2000–2018

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Abstract
Research has identified cities as potential urban mines for recovering secondary construction materials. Studies typically focus on stocks or flows of bulk materials on high abstraction levels. To enable a shift of focus toward higher levels of circular economy, such as waste minimization, there is a need for a more detailed understanding of the dynamics that contribute to the waste flows, building replacement in particular. This paper examines the characteristics and location of the stocks and flows of buildings, both residential and non-residential, in the city of Tampere, Finland, over the last 20 years. Statistical and geographical analyses are performed on the building stock, new construction, and demolition in Tampere to unveil patterns pertaining to stock change and building replacement. The study shows that these patterns vary significantly between buildings of different function. Spatially confined redevelopment areas within the city structure, that is, brownfields and grayfields, whose industrial and commercial functions yield to housing and mixed residential–commercial use, make up major arenas for replacement. Policy-making should acknowledge that urban planning stirs these waste flows and incorporate their conscious prevention and management on its agenda.

KEYWORDS
buildings, cities, industrial ecology, material flow analysis (MFA), urban metabolism, urban planning

1 | INTRODUCTION

Societies are growing more interested in the circularity of production and consumption for sustainability reasons. Construction is one of the sectors to consume the most virgin raw materials (Bourguignon & Orenius, 2018) and to produce the most waste (European Commission, 2019). Consequently, building stocks are attracting attention as potential deposits for secondary resources, typically understood as secondary raw materials. Extraction from these “urban mines” is considered to be more environmentally friendly than the extraction of virgin resources.

Most of the urban mining research focuses on bulk materials (Lanau et al., 2019), but the secondary resources embedded in building stocks can in fact take up many forms and scales. Huuhka and Vestergaard (2019) have conceptualized them against the hierarchy of circular economy (CE), echoing the EU waste hierarchy (European Union, 2008). As these hierarchies prioritize life-cycle extension and waste prevention, the first and
foremost resources are the buildings themselves and the spaces they encompass, inviting life-cycle extension and adaptation. The relocation of buildings or the reuse of components is promoted as the second-best option. If none of the above are feasible, recycling or recovery of materials or substances should be prioritized over energy recovery or disposal (HuuHka & Vestergaard, 2019). This hierarchy underlies the research interests of the current paper.

In practice, the available options are connected to the type of obsolescence behind the demolition. Literature distinguishes at least four types of obsolescence: technical, functional, economic, and context related (Thomsen & van der Flier, 2011). Buildings whose obsolescence is not technical show a higher potential for life-cycle extension and component reuse. Functional obsolescence may be tackled with adaptation or adaptive reuse, economic obsolescence with renovation, extension, or downsizing, and context-related obsolescence with relocation, in particular if the structure permits deconstruction and reassembly. Only buildings whose fabric is seriously degraded (i.e., buildings that suffer from serious technical obsolescence) may not have other options available for them but recycling. For others, however, higher-level options should be sought.

2 | RESEARCH DESIGN

2.1 | Methodological background

Comprehensive reviews have been presented for the different approaches to mapping the contents of urban mines (Augiseau & Barles, 2017; Gö swein, Silvestre, Habert, & Freire, 2019; Lanau et al., 2019). Many studies investigating these stocks, for example, Cheng, Hsu, Li, and Ma (2018), Heeren and Hellweg (2018), Kleemann, Lederer, Rechberger, and Fellner (2017), Lanau and Liu (2020), and Tanikawa and Hashimoto (2009), take advantage of geographical information systems (GIS), helping to identify the specific location of the secondary resource in the urban structure. The so-called 4D-GIS includes the temporal dimension, enabling the identification of the material potentially leaving the stock (Tanikawa & Hashimoto, 2009). In the GIS-based approaches, data specifying the type and location of the building, such as cadaster maps, are associated with material intensity coefficients (MICs) (sometimes titled “material composition indicators” or MCIs) considered representative of the type and age cohort of a building (Augiseau & Barles, 2017; Gö swein et al., 2019; Lanau et al., 2019). This follows from the strong focus on bulk materials (cf. Lanau et al., 2019), rather than other types of secondary resources, for example, whole buildings or spaces.

2.2 | Purpose of the current study

The current study takes the first step toward reviewing the secondary resources in the city of Tampere, Finland. With circa 235,000 residents, Tampere is the third largest Finnish city. The research analyzes, characterizes, and compares the construction and demolition patterns of buildings with the help of GIS. The aim is to steer away from the bulk material quantification and to introduce the higher levels of the CE hierarchy, especially the possibility to avoid waste creation through life-cycle extension, into the secondary resource stock and flow research. A detailed analysis of demolished buildings is also provided, contributing to the evidence base on end-of-life buildings, which remains an underdeveloped area of research (cf., Kohler, Steadman, & Hassler, 2009).

Apart from the unique access to the dataset, the novelty of the work lies in the holistic approach to analyzing inflow and outflow patterns of buildings in one city and transferring these findings into a detailed geographical study about the replacement of buildings. By exploring the inter-relation between demolition and construction based on building size, function and location, the dynamics driving changes in the building stock that result in virgin and waste material flows are scrutinized. The emerging understanding creates preconditions for avoiding demolition and waste and managing material flows more consciously in urban planning policies and practices in future.

2.3 | Method

The basic approach may be described as bottom-up material stock and flow analysis (cf., Augiseau & Barles, 2017; Lanau et al., 2019). In the study, it takes the form of quantitative and qualitative analyses of existing buildings (stock), new buildings (input), and demolished buildings (output), considering the locations, functions, sizes, and materials of the buildings. The units used for the quantitative examination are the number of buildings and their gross floor area (m²)¹. Whenever the current study uses m², it refers to the gross floor area of buildings. According to Lanau et al. (2019), this kind of a study can be considered a form of material stock and flow analysis even if it does not encompass a quantification of the bulk materials. The current study cannot quantify the materials because MICs have not been calculated for the Finnish building stock (Pusu et al., 2020). In the study’s data, the main material of the load-bearing frame has been recorded and is investigated as a proxy indicator for the material content.

¹ By definition, the floor area of “normal” floors, measured along the outer surface of exterior walls, as well as any area in attics or basements containing spaces intended to be used for the main function of the building (Statistics Finland, n.d.).
The study is based on a static building stock approach. However, the investigation looks at the incoming part (new buildings) and exiting part (demolished buildings) of the stock annually for the years 2000–2018. This way, the static approach leads to a retrospective dynamic flow analysis (cf., Lanau et al., 2019). Apart from the more complex data processing, described later and in Supporting Information S1, the procedures largely follow those used by Huuhka and Lahdensivu (2016) and consist of descriptive statistics. In practice, data of individual buildings is aggregated to categories, such as building types, for which simple measures of central tendency, such as average size or average age, are calculated. However, emphasis is given to a more detailed geographical examination. In the analysis, the raw data, which is in point form, is transferred to a grid of 250 m by 250 m. This is a standard way of presentation for GIS data, which enables showing volumes; examining more than one variable at a time, and overcoming issues related to overlapping of points. The underlying city development is interpreted qualitatively with the help of maps and planning documents, taking also advantage of the researchers’ local knowledge of the areas highlighted by the analysis (their usage; their status as city development areas or brownfields, etc.). It is an iterative process where the researcher has fluctuated between interpreting the point data, the grid data, and maps and urban plans.

2.4 Data processing

The data was provided by the city of Tampere. The raw data consists of two datasets: (1) an extract of the national Building and Dwelling Register (BDR), maintained by the Finnish Population Register Center, and; (2) a similar extract out of the register maintained locally in Tampere by the municipality. Both data cover existing buildings in Tampere in 2018 and buildings that have been demolished in the past. In theory, the registers should contain the same buildings, even if they are managed by two different bodies. The basic attributes are also the same, the most important of which for the current study are the coordinates, building type, year of construction, gross floor area, main construction material, and the demolition year. An English-language list of all attributes has been given in, for example, Huuhka (2016a). However, in addition to buildings, the local data contains structures, which are not recorded in the BDR.

In principle, the registers should be relatively reliable in terms of demolished buildings. This is because the buildings on the registers influence the real estate taxing of the land owner. So, land owners have an economic incentive to have nonexistent buildings removed from the registers. There are, however, shortcomings in both datasets and discrepancies between them. Generally, the data for residential buildings (holiday cottages excluded) is more complete than for non-residential buildings (NRB), and the data for existing buildings is more complete than for demolished buildings. The registers are also the more complete the newer, larger, and more prominent (prestigious or centrally located) the buildings are. They are quite complete for residential, public, and commercial buildings, and less complete for agricultural buildings, holiday cottages, and utility buildings. The final data used in the study was a result of matching, combining, and eliminating the records from both datasets. The details of the process are given in the Supporting Information, but in outline the procedure is as follows.

For the examination period, the BDR contained 2,841 and the local data 4,758 records for demolition. The local data was selected as the starting point, since only it encompassed the coordinates, which enable locating the demolished building geographically within the city. Records identified as structures were removed from the data. Then, the merger with the BDR was performed to transfer missing attribute data. The final number of records for demolished buildings landed at 3,134. Of these, 1,954 records lacked the information on the floor area; these were mainly utility and agricultural buildings but also holiday cottages. The missing data was compensated with the average of the building type in question, calculated from the part of the data that contained this information. Similar difficulties occurred in the datasets for the existing buildings. In their case, a comparison of completeness of information between the datasets was conducted on building type group level (see later). The BDR was found to be more complete, so missing information was transferred into it from the local dataset. The final number for the records on existing buildings was 43,637. The extent of the compensation is described in the Supporting Information.

The datasets cover 74 different building types, identified by a three-digit building type code. To make the data more easily approachable, the 74 building types were categorized into 13 building type groups (Table 1) and further into residential buildings (RB) and NRB. The details can be found in the Supporting Information. In most analyses, this paper uses the building type groups. The more detailed building types were only used in very specific analyses, for example, for studying the replacement of buildings in a detailed geographical level. RB/NRB are used for providing a rough overview before diving deeper into the building type groups or to portray a distinct phenomenon. For the sake of conciseness, the paper refers to the building type groups also as “building types.” In terms of materials, the main material of the structural frame has been recorded, and five options have been provided (wood/concrete/steel/bricks/other).

Once the national and local datasets were merged, annual stocks, inflows (new constructions), and outflows (demolitions) for the examination period, 2000–2018, were extracted from the harmonized dataset with set operations described in the Supporting Information. Annual new constructions were identified based on the construction date and demolitions based on the demolition date. Annual stocks until the year 2000 were reverse engineered from the 2018 stock by removing the past inflows and adding outflows (see Supporting Information). Then, the number of buildings in any stocks, inflows, or outflows could be counted and the gross floor area quantified with the following Equation (1):
TABLE 1 Building type groups’ (hereafter: Building types’) relation to RB and NRB

| Main group                        | Building type group                      |
|-----------------------------------|------------------------------------------|
| Residential buildings (RB)        | Detached houses                          |
|                                   | Row houses                               |
|                                   | Blocks of flats                          |
|                                   | Holiday cottages                         |
| Non-residential buildings (NRB)   | Dormitories                              |
|                                   | Utility buildings                         |
|                                   | Commercial and office buildings           |
|                                   | Public buildings                          |
|                                   | Warehouses                                |
|                                   | Industrial buildings                      |
|                                   | Agricultural buildings                    |
|                                   | Transport buildings                       |
|                                   | Other buildings                           |

\[
GFA = \sum_{b=018,f,13,m=1}^{b=2018,f=13,m=5} GFA_{b,f,m},
\]

where GFA is the gross floor area \([m^2]\), \(b\) is the construction year, \(f\) is the building type, and \(m\) is the main material of the structural frame.

2.5 Uncertainties of the data

Due to the compensatory measures to complete the data, the results can be considered the more reliable the higher the aggregate level is. This is particularly true for old, small, and numerous buildings, such as utility buildings. As these types of buildings are of a rather uniform size though, compensating for the floor area brings about less uncertainty than for larger and more prominent buildings, such as commercial buildings, for which fewer buildings of a greater size variation contribute to the compensatory average. Then again, the larger and more prestigious the building, the more reliable the data is at the building level, and the less need for compensation in the first place. Consequently, the data is more reliable where a lot of buildings are agglomerated (urban centers) and less reliable where buildings are sparse (the rural area). This suits the current study, as its interest lies on stocks rather than on individual buildings.

Moreover, examining the main material of the frame as a proxy indicator for material composition has obvious limitations, as buildings withhold multiple materials. The indicator can be considered fairly reliable for concrete-framed buildings, since studies show that they are up to 90—95% concrete in terms of weight (Perälä & Koski, 2009; Schiller et al., 2018). The indicator can be less reliable for wood- and steel-framed buildings, whose mass may also be dominated by the concrete from the building’s foundation (Schiller et al., 2018).

3 RESULTS

3.1 Overview

Tampere building stock in 2018 is 43,637 buildings with 19,040,046 m². There are approximately 81 m² of stock per resident. Having gained circa 40,000 people since 2000 (Statistics Finland, 2018), Tampere is a growing city—so 8,317 buildings with 4,431,604 m² have been built after 2000. Simultaneously, 3,134 buildings with 1,054,061 m² have been demolished. This equals to an annual average of 438 new buildings or 233,242 m² and 165 demolished buildings or 55,477 m².

62% of the new construction was net addition to the building stock if calculated based on the number of buildings. When calculated based on the buildings’ floor area, 76% of the new construction was net addition. Correspondingly, the proportion of new construction “replacing” existing stock, that is, the replacement rate, was either 38% (number of buildings) or 24% (floor area). The replacement rate for Tampere is clearly larger than for the whole of Finland, whose respective rates are 22% and 12% (Huuhka & Lahdensivu, 2016). Fast growth, which Tampere has experienced, has
been identified by Thomsen, Schultmann, and Kohler (2011) as a characteristic situation where demolitions occur. Because the city is delimited by lakes and neighboring municipalities, the pressure to grow manifests itself partly as stock replacement.

The annual demolition rate of floor area was on average 0.32% of the stock. This makes Tampere demolition rate double compared to the whole of Finland (cf., Huuhka & Lahdensivu, 2016). There is a major difference between the rates for RB and NRB: the former was on average 0.05% whereas the latter was 0.68%, that is, more than 13-fold. The Tampere RB demolition rate is in the same scale as in other West and North European countries (cf., van der Flier & Thomsen, 2009). Previous research (e.g., Bradley & Kohler, 2007; Huuhka & Lahdensivu, 2016) has identified that the rates for NRB tend to be larger than for RB, but in Tampere, the phenomenon is more intense.

3.2 Spatial occurrence

Figure 1 (top left) presents how the existing stock situates in the city. Figure 1 shows how the new constructions (top right) and demolitions (bottom left) situate, as well as where they overlap (bottom right). From the building stock, two distinct, dense areas can be identified. The first one is the Tampere city center that comprises of a large variety of compact building typologies. The backbone of the city center is a 19th century grid-like street plan, in which the buildings lie. The oldest buildings date back to the 1880s, but many have been replaced in the course of the 20th century, resulting in a building stock of mixed ages, uses, and architectural styles. As Tampere was founded as an industrial city, complexes of brick-built factory buildings from different eras are also characteristic to the city center. Most of the remaining ones have been converted to other uses. The second area, to the south-east of the city center, is the satellite town Hervanta. It started developing in the 1970s, when a technical university and mass housing in prefabricated concrete was built there. Infill construction has emerged in Hervanta in the 21st century, which can be also seen in Figure 1 (top right).
The map on building replacement (Figure 1 bottom right) draws together the new constructions (Figure 1 top right) and demolitions (Figure 1 bottom left) to identify areas where the phenomena overlap (stock replacement areas) and where one dominates over the other. The areas with mainly new construction are most often greenfield developments at the edges of the city or densification areas of an existing urban fabric, such as the city center or Hervanta. In few cases it was identified that the ostensible new construction areas from early 2000s are in fact replacement areas where the land use is changing from industrial to residential. However, the demolition took place in the 1990s, that is, before the examination period. The demolition-dominated areas are mostly brownfields and grayfields. Some of them are waiting to be turned into residential and mixed residential–commercial districts in near future. In other cases, demolition was stirred by traffic developments, especially noticeable along the railway and newly developed streets in the city center. However, in most demolition-dominated areas, the phenomenon is too diverse to identify an obvious pattern. It takes place here and there seemingly spontaneously, without a connection to any larger re-zoning or redevelopment project. In all, almost half of the demolition occurred in clusters and half of it was sprawled over the city.

3.3 | Replacement patterns

The areas where construction and demolition overlap (Figure 1 bottom left purple squares) were analyzed in detail to identify where they merely coincide and where stock replacement actually takes place. Attention was given to geographically contained replacement areas (circled locations). These turned out to be brownfields and grayfields, whose transformation fell within the examined period. Note that it is not possible to differentiate these clusters simply by looking at Figure 1. They were analyzed by identifying the exact locations of demolition and construction on the plot level and by investigating their occurrence in time.

Three areas, named in Figure 1 (bottom left), were selected to showcase typical replacement patterns in more detail. Zooming in, it can be observed that these areas also encompass distinct points of construction, demolition, and replacement. Figure 2 shows Kalevanrinne, which is a prime example of a grayfield turned into a residentially dominated mixed district. Härmälä shows a high level of demolition for industrial and commercial buildings that, due to a new masterplan, were replaced with dense housing. This development has started slightly before the examination period and is still to be completed. The third area, Kaukajärvi, used to be a low-density mixed residential–commercial area that was drastically densified. These examples reflect the overall replacement trends in Tampere. In total, more than 75% of demolished floor area in the replacement areas originated from industrial or commercial buildings. New construction that replaced them consisted characteristically of high-density housing.
3.4 Building types

After the spatial findings, the paper scrutinizes the findings from quantitative analyses of the statistical data, formed by aggregating the data on individual buildings. In terms of the number of buildings, detached houses and utility buildings prevail for both new constructions and demolitions. However, from the spatial analysis it can be concluded that their new construction on greenfields dominates over their replacement. In terms of demolition, their spatial patterns are of the sprawling type.

When the phenomena are measured in floor area, blocks of flats clearly dominate the new construction, and demolition focuses on industrial, warehouse, and commercial buildings, in this order (Figure 3). The finding echoes the spatial findings on replacement patterns. The replacement rate for building types, calculated based on their floor area (also given in Figure 3), vary from 2% for blocks of flats to 340% for agricultural buildings, the latter meaning that 3.4 times as much agricultural floor area was demolished as was built. The differences between the building types presumably reflect societal structural changes, such as agriculture and industrial production as decreasing means of livelihood, and urban restructuring, for example, production and logistics (warehouses) moving to more affordable and/or better-connected areas in surrounding municipalities.

When new constructions and demolitions of building types are investigated in time, it can be observed that the formed curves are more constant in the case of small and numerous buildings, such as houses, holiday cottages, or utility buildings, and more varied and random for NRB, which are large, and so a small number of buildings can change the patterns quite drastically. This echoes the spatial findings regarding dispersed and centralized demolition patterns, characteristic to the building types. The clearest patterns over time could be observed for residential, public, and commercial space, whose overall construction clearly exceeded demolition during the two decades. For blocks of flats and commercial space, both construction and demolition remained relatively constant the whole time, whereas the construction of floor area in detached houses, row houses, and holiday cottages showed a descending trend, even if still way above the demolition line. Inversely to the aforementioned building types, the demolition of agricultural space prevailed constantly over its construction, and demolition even increased in relation to new construction toward the end of the period. For warehouse, utility, and industrial space, the patterns changed during the two decades: construction prevailed first but was overtaken by demolition; more pronouncedly for warehouse and utility space than for industrial space. Figure 4 shows the fundamental basic difference in stock change for RB and NRB.

3.5 Building size and age

The average size of a demolished building was 336 m$^2$ and is 545 m$^2$ for a new building, equaling to an increase of 62% in the average area. Apart from two exceptions (row houses and utility buildings), growth in average area can be observed in almost all building types: doubling (public buildings detached houses, holiday cottages) and more than tripling (blocks of flats, commercial, and office buildings) is typical. Notably, there is no significant change of average size for warehouses and industrial buildings. So, the building size does not seem to be a significant driver for their demolition, but the question is likely more about functional requirements or spatial reorganization of the functions in the city.

The average age of existing buildings is 44 years, whereas the average age of demolished buildings was 50 years sharp. The average ages of demolished buildings by building types are given as a part of Figure 5 and in the Supporting Information. The highest average ages go to RB: blocks of flats (65 years) and detached houses (64 years), which make up only 8% of the demolished floor area. With row houses (33 years) as an exception,
### 3.6 Construction materials

As explained under the research design, due to the lack of MICs, a combination of the main construction material of the structural frame and the floor area of the building are looked at as a proxy indicator for the material composition. Alas, half of the demolished buildings lack the material information, as do some new and existing buildings, but to a lesser extent. Assuming that their material distribution follows that of the buildings for which the information is known within the building types, an estimation of the relation between waste and virgin materials can be given (Figure 6).

The material composition of the demolished and existing buildings differs from that of the new buildings: the use of bricks as a structural material has yielded to concrete, the use of steel has increased, and the use of timber has decreased. The discrepancy between the waste and virgin materials is more relevant if the means of utilization is reuse or recycling and less relevant if buildings are converted to new uses. On the other hand, buildings can be constructed out of more than one material, so the current dominance of concrete is not be taken as inevitable.

Reviewing the average ages of the floor areas built in given construction materials gives a different angle to the issue. Steel buildings are on average the youngest at the time of demolition (23 years), followed by concrete buildings (36 years), brick buildings (49 years) and, lastly, timber buildings (54 years). This reflects the construction traditions: the older the demolished building is, the more likely it has been made of the traditional local materials, that is, bricks or timber. An important lesson to be learned though is that the use of the building and the area (especially when it comes to commercial and industrial functions, whether these are individual buildings or grayfields and brownfields ingrown into the city structure) seem more decisive for the buildings’ actualized lifespan than the durability of the structural material. This draws attention to the fact that building types that are known to be relatively short lived are nevertheless built with carbon-intensive materials that have potential for much longer technical lifespans. To this end, it is disconcerting that in the newer building stock, the use of wood as a structural material has yielded to concrete and steel. This may also reflect the increased size of buildings, as wood has traditionally been conceived as a material for small-scale construction. Since the 1990s, though, advances in timber engineering have increasingly challenged this thinking.
In terms of demolition, this study’s findings from Tampere resonate with previous research from Finland and elsewhere. For instance, Huuhka and Lahdensivu (2016) found that in terms of floor area, three-fourths of demolition in Finland is directed at NRB. In Tampere, the situation is the same. Also, both this study and Huuhka (2016b) found that the average age of a demolished building is only 50 years, and NRB are as a rule even younger at the time of demolition. Moreover, their demolition rate is manifold in comparison to RB. These findings underscore the importance of NRB over RB for building stock research, in particular for studying phenomena where end-of-life buildings are a major factor, such as material flows or stock dynamics (cf. Bradley & Kohler, 2007; Kohler et al., 2009; Thomsen et al., 2011).

The results also reinforce existing theories on building mortality, such as the notions that it varies significantly between building types, in particular between RB and NRB (cf., Bradley & Kohler, 2007), and in time and between buildings constructed in different decades (cf., Johnstone, 1993).
Acquiring novel empirical evidence, which this study does, is important for developing models predicting stock dynamics in future, such as Bradley and Kohler (2007), as the modeling is underlain by assumptions, which this kind of evidence can confirm or contradict.

The empirical findings can also contribute to theories of building obsolescence, such as that of Thomsen and van der Flier (2011). Based on the one hand on the notably short average ages of the demolished buildings made out of durable materials and the locations of the redeveloped brownfields and grayfields in the city structure on the other hand, it does not seem plausible that the redevelopments would primarily be driven by the technical obsolescence of the buildings. This resonates with Thomsen and van der Flier’s (2011) theory in that exogenous (context-related) factors seem to be more decisive for demolition than endogenous (building-related) factors, such as age or physical condition.

4.2 Methodological implications

In terms of studying the dynamics of urban stocks, the domino effects of land use changes present a specific research challenge. When a brownfield or grayfield is redeveloped, its former industrial or commercial function yields to a novel one (usually residential). The phenomenon taking place inside the redevelopment area can be scrutinized, as portrayed in the paper. However, the previous functions might already have spread out to (multiple) other locations, do so as a result of the redevelopment, or do not relocate at all due to a diminished need.

It is very hard to trace this kind of patterns, in particular the domino effects where the relocation or a function induces new construction in one place and demolition or replacement in another, with the current methodologies and data. Apart from three particular instances, specific time-bound relations (chain reactions) could not be identified from within Tampere for most building types simply by examining the statistical data on demolitions and new constructions over time. It is possible that some functions were relocated to other municipalities of the region and therefore are not visible in the data. This calls for broader spatial boundaries from future research, given that data is available, and tracing spatial changes in time.
When it comes to the materials in the stock, the current paper’s approach is not perfect due to the lack of MICs. Buildings of different type with different structural solutions will have differing material intensities: hall buildings with long-spanning pre-stressed structures (industrial buildings, big-box stores, warehouses) will be less material intensive per square meter than room-based buildings (apartments, offices, classrooms) based on a massive structure. Furthermore, the area-based quantification undoubtedly overemphasizes the shares of lightweight materials, such as wood, in comparison to a mass-based quantification (cf., Schiller et al., 2018). Then again, the buildings made of “unknown” materials are more likely to be on the small side, and small buildings are usually made of wood, so the method may also underestimate the quantities for timber. The development of proper MICs remains a task for future research.

4.3 Practical implications

The study identified two distinctive demolition patterns: clustering and dispersed demolition. They have differing implications for prospecting, mitigating, and managing the material flows as a part of urban policy-making. Even though the study’s methodology does not predict the future, an important take-away is that the material flows from the geographically contained areas are a result of urban planning decisions made years earlier. The inflows and outflows of buildings and, consequently, materials do not come of the blue but are underlain by zoning decisions, such as greenfield, brownfield, and grayfield developments, which are introduced into the planning system (regional and local master plans) even decades earlier.

Even though researchers (e.g., Baccini & Brunner, 2012; Oswald, Michaeli, & Baccini, 2003) have proposed that the material flows should be consciously managed and even designed, the urban metabolism arising from urban redevelopment is not currently considered as a part of city planning. Proactive material flow management should be inserted into these processes in the future. This would already have a major impact on the demolition outflows, as half of all demolished floor area was found to be located in clear geographical clusters, the other half being more spread out. The dispersed demolition is perhaps not as easily addressable, as it is more ad hoc and not centrally planned for. Steering it might require activating other urban policy-making instruments, such as economic incentives for proprietors who choose conservation and extension over demolition and new construction.

In terms of prospecting, the estimates for clustering demolition could easily be drawn from planning documents ahead of time, whereas mathematical models are more appropriate for predicting ad hoc demolition. Obviously, the buildings comprising the data of the current study are already demolished and therefore beyond life-cycle extension. Nevertheless, studying their patterns can help to make more informed choices in the future. The kind of data on demolished buildings, which this study used, is generally not readily available in many contexts (Thomsen & van der Flier, 2011). However, if the effort to identify the buildings to be demolished is made proactively, as an operational part of urban planning, the necessary data can be compiled from building owners’ archives and by studying the buildings directly, while they are still in existence. This includes identifying the highest potentials for the obsolete buildings and helping them to reach that, be it repair, relocation, reuse, or recycling. Based on the results of the current study, the possibilities for the adaptive reuse and relocation of NRB, as well as the reuse of their building parts, would deserve much more attention.

5 Conclusion

The current paper investigated the inflows, stocks, and outflows of buildings, both residential and non-residential, in the Finnish city of Tampere, over the course of two decades. In all, the demolitions could theoretically have catered for one-fourth of the new construction, if fully capitalized on through waste minimization (renovation instead of demolition), reuse or recycling. In particular if the buildings were preserved, not only would a respective amount of waste have been avoided, but also the extraction of a corresponding amount of new materials.

Due to the lack of MICs for the Finnish stock, the study was unable to explicitly quantify the amount of waste and virgin materials that could have been avoided. Developing MICs manually, without the help of automatic data processing, is labor-intensive, especially given the multitude of building cohorts examined in the current study. So, future research should take on a machine learning-based approach to ease and speed up the development of MICs. Moreover, not only bulk materials but also building components and spaces deserve to be quantified in future, to highlight the potential for component reuse and building reuse.

To give truly informed estimates about the refurbishment, renovation, and adaptive reuse potentials of buildings, though, their physical condition, spatial structure, and structural capacity should be studied individually, and alternative city development scenarios should be developed to the ones that were implemented. Such an exercise is work intensive, and as the buildings studied in the current paper are factually already demolished, it would have a limited relevance. To avoid wastage in the future, the conclusion is that urban planning needs to urgently adopt a more proactive role in the sustainable management of material resources embedded in existing building stocks.

The study also shows that carbon-intensive materials, such as concrete or steel, are not only used in long-lived structures, but also in buildings with inherently short functional lifespans. Much better discretion is needed in the use of these materials in building construction. At the very
minimum, such structures should be designed for disassembly. As urban planning sets the border conditions for construction, it should also address the responsible use of materials more explicitly when planning for functions that are known to be short lived.

To prepare for the adoption of a more resource-conscious urban planning, it would benefit to study the replacement phenomenon at a more detailed level (plot level) as well as in geographically larger areas (entire regions). This could help to create a more complete picture of the replacement phenomenon, which is a domino effect of functions yielding to others while typically also increasing the urban density. A better understanding of these dynamics is needed to truly address the potential for waste avoidance through life-cycle extension on the stock scale.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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