Material flows from buildings

A comparison of patterns in two Finnish cities

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Abstract

In the circular economy, building stocks are valuable urban mines of secondary resources and reserves of space whose utilization has the potential to substitute for virgin resources. The purpose of this study is to compare patterns in construction (inflows) and demolition (outflows) and how they shaped the building stock in two Finnish cities, Vantaa and Tampere between 2000 and 2018. By attributing flows to distinct urban development patterns (such as greenfield, replacement, infill, etc.) and investigating population and labour force structure, the goal is to recognize differences and similarities between the case studies. In doing so, the aim is to understand how a comparative approach may help to identify drivers and patterns in the building stock dynamics of the two cities which further aids the development of a circular building stock management. The methodological foundation for this research is Urban Metabolism in form of Material Flow Analysis with a focus on the product i.e., building level but also space as a service provided by buildings. Tampere and Vantaa are the third and fourth largest cities in Finland, with a population of circa 230,000 each. Despite their similar sizes, differences in their geographical properties, contexts, and roles in Finland make them interesting targets for comparative research.

The results show that growth in population and labour force led to a substantial increase in both cities' building stocks. While Vantaa's more rural character allowed a higher amount of sprawl by loose-built housing typologies, geographical restrictions and the already dense building stock in Tampere often led to more compact housing and an overall higher amount of demolition in relation to construction. The development of both non-residential building stocks shows a clear tendency towards typologies that support respective economic operations. Alas, material intensity coefficients, which would enable quantifying the material and CO2 impacts of these developments, do not yet exist for Finnish building typologies. Nevertheless, this study's findings provide a preliminary understanding of how different mechanisms of urban development, such as construction and demolition, shape environmental strains and support the development of pinpoint circular strategies.

Keywords: circular economy; comparative research; building stock dynamics; material flow analysis; sustainable cities

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Introduction

As a consequence of a reduction in operational energy, the embodied energy of buildings has gained increased significance in their overall life cycle (Azari and Abbasabadi, 2018). The growing awareness of the embodied environmental burden not only in the form of energy consumption but also resource exploitation and carbon emissions in the built environment (Huang et al., 2018) has led to research increasingly aiming to identify more sustainable practices. Circular economy (CE) offers promising strategies whose aims are to maintain material and preferably product values indefinitely. Cities are both large material sinks in the form of buildings and hotspots for construction and demolition activities which makes urban areas important targets for CE research to reach global climate goals (Joensuu et al., 2020). In conceptualizing the streams and quantities of material and waste flows, Wolman (1965) is often cited as the founder of the term Urban Metabolism (UM). Similar to biological metabolism, UM is defined as the in- and outflows of materials and energy, their respective stocks in addition to the internal processes which generate and shape them (Baccini and Brunner, 2012, 30).

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Originally, UM research focused on quantifying stocks and flows of, inter alia, materials (Kennedy et al., 2011). Since then, however, research techniques and objectives have evolved significantly (Fu et al., 2022) and spatial, temporal, and material scales show great variety (Lanau et al., 2019). Today, Material Flow Analysis (MFA) and – as further specified by Tanikawa and Hashimoto (2009) – Material Stock Analysis (MSA) stand out as the most commonly used analysis tool to study anthropogenic stocks (Lanau et al., 2019). MFA and MSA are systematic assessments of materials (i.e., substances and goods) in form of inputs, outputs, and stock of processes within a city or other system (Brunner and Rechberger, 2004, 3). Geographical Information Systems (GIS) allow spatial analysis of data and are often used in combination with MFA and MSA (Göswein et al., 2019; Guo and Huang, 2019). Methodologically, research can be roughly divided into top-down or bottom-up (Augiseau and Barles, 2017; Chen and Graedel, 2015; Müller et al., 2014). In the top-down approach, a building stock is defined as the sum of annual net additions in form of inflows minus outflows whereas in the bottom-up approach, a building stock is aggregated from different sub-categories which often makes it more laborious to study but allows to get a better picture of its composition. The choice of an appropriate research approach, however, is often driven by the availability of adequate data and the geographical scope of the study (Beloin-Saint-Pierre et al., 2017; Göswein et al., 2019; Lanau et al., 2019; Tanikawa et al., 2015). Despite a considerable number of reviews attempting to classify approaches used in stock (and flow) research in recent years it is difficult to find a consensus on precise definitions (Wiedenhofer et al., 2019), and recommendations to implement CE strategies based on this research remain scarce (Wuyts et al., 2022).

Inconsistencies in data availability and quality are to some extent responsible for both the variety in methodological approaches and gaps in current research. In their analyses of building stock studies, Lanau et al. (2019) and Röck et al. (2021) criticise the underrepresentation of non-residential buildings (NRBs). Fu et al. (2022) and Lanau et al. (2019) highlight how few building and material stock studies have a higher spatial resolution than the country level whereas Athanassiadis et al. (2015), Göswein et al. (2019) and Lanau et al. (2019) critique the lack in temporally dynamic approaches. Today, one of the most precarious shortcomings is, however, the predominantly descriptive nature of research (Li and Kwan, 2018) in which socioeconomic and human drivers and patterns of stocks and flows are rarely uncovered (Athanassiadis et al., 2015; Lanau et al., 2019; Zhang, 2013).

The goal of this research is to engage with the aforementioned research gaps by applying different methods parallelly on two case studies. In using a comparative approach, it is possible to study discrepancies and similarities of the two cases. The results are expected to benefit the qualitative assessment of the cities' UM and to support in identifying the potential for implementing more circular building stock management strategies. The accompanying research questions are as follows:

How did the building stocks of two similar-sized cities – Tampere and Vantaa – evolve in time and space in conjunction with the development in population and labour force?

In what way do the findings from each of the case studies differ from one another?

How can a comparative approach support identifying context-specific drivers and patterns in the building stock dynamics and how can they help in defining CE strategies?

The targets of this research are the existing building stocks and flows in the form of construction and demolition of the two Finnish cities Tampere and Vantaa between 2000 and 2018. The developments of each of the building stocks get further compared to the development in population and employed labour force which is based on the theory of socio-economic metabolism (Fishman et al., 2015; Tanikawa et al., 2015) in which demographic and economic factors are expected to have a considerable influence on flows and the accumulation of stocks. The chosen approaches can be considered a form of MFA and material stock analysis (MSA) even though the materials from these flows do not get explicitly quantified. Apart from the lack of material indicators for the Finnish building stock (Pesu et al., 2020) addressing stocks and flows on the product, i.e. building level has advantages. Firstly, applying CE hierarchically onto the built environment means prioritizing buildings and their maintenance which enables more resource- and energy-efficient strategies compared to the reuse and recycling of materials. Secondly, goods are logically connected to metabolic processes which are driven by a human need (Baccini and Brunner, 2012, 85). Because of the changes in human demands, new models such as in the business or the housing sectors emerge which drives building stocks to evolve. The study of spatial, temporal, demographic, and economic impacts on the stock developments, therefore, can be expected to give deeper insights into drivers beyond a merely descriptive approach.

Method & Material

Advances in Research Designs

To overcome most prominent research gaps, scholars have developed recommendations and novel study designs that give new directions for future UM, building stock, and flow research. In contrast to a top-down approach, a bottom-up approach is characterized by its highly disaggregated data and fine results which aid in developing CE strategies (Mohammadiziazi and Bilec, 2022). When seeking for spatially dynamic results, Göswein et al. (2019) recommend the joint use of MFA and GIS. Both Li et al. (2022) and Reimer and Kral (2020) used spatiotemporal approaches based on archival maps and geospatial data to quantify the historic development of building stocks of two cities. In conjunction with classifying the municipalities of Sweden by settlement types and demography, Gontia et al. (2020) studied the spatiotemporal characteristics of the national residential building stock. Based on the principles of socioeconomic metabolism, Fishman et al. (2015) and Tanikawa et al. (2015) linked demographic and economic activities with the development of the Japanese building stock in order to identify causes and drivers for stock accumulation.

Method

The analysis in this research paper is a synthesis and comparison of the previously conducted standalone studies of Tampere (Huuhka and Kolkwitz, 2021) and Vantaa (Kolkwitz et al., 2023). In general terms, the research methods applied to parallelly studying both case studies' UM can be described as a bottom-up MFA for inflows (construction) and outflows (demolition) as well as a MSA applied to the building stocks. Unlike in conventional stock and flow research, targets of this qualitative and quantitative analysis are buildings on the product level by number of buildings and size in gross floor area (GFA). Building locations were studied with the help of GIS programs QGIS and MapInfo. On an urban scale, building data was combined into a grid with a 250-metre-wide mesh to get an overview of the spatial distribution while more specific findings were made on neighbourhood, plot, and building scales often in combination with aerial photographs. The studied time frame is between 2000 and 2018. With help of spatial and temporal attributes, the data was studied based on a spatiotemporal approach as specified in Kolkwitz et al. (2023) which allows identifying patterns in urban development such as infill, greenfield, shrinkage, and replacement. Infill describes construction which coincides with an existing part of the building stock whereas greenfield development in this paper is referred to as construction in an area free from buildings such as forest or agricultural land and potentially also urban green space. Demolition is defined as shrinkage if no construction follows afterwards. Replacement on the other hand, is defined as demolition followed by construction.

Due to minor shortcomings in the data and for reasons of harmonization, the methods underwent some changes and were partially expanded compared to the approaches in the aforementioned studies. The spatiotemporal analysis is largely based on the study of clusters with high building density on a neighbourhood level while city-wide findings from Huuhka and Kolkwitz (2021) and Kolkwitz et al. (2023) aided in their interpretation. A cluster is defined by buildings that are located on the same or adjacent plots or in the same neighbourhood in case construction or demolition activities correlate temporally or if the activities targeted specific types of buildings. The sum of built or demolished GFA must exceed 50,000 m^2 or 20,000 m^2 respectively to be classified as a cluster. As the most impactful methodological addition compared to the individual studies, this research includes an examination of the development of population and employed labour force and their correlation with the building stock development.

Material

The primary research data in this study encompasses building and plot data. In both Tampere and Vantaa, building data consists of two parts, existing buildings in 2018 and buildings demolished between 2000 and 2018. For Tampere, the raw data was provided by the city of Tampere and consists of two sets: firstly, an extract from the national Building and Dwelling Register (BDR) and secondly, an extract from the locally maintained register in Tampere. Both sources of data were compared, merged, and compensated for errors (for a comprehensive explanation see Huuhka and Kolkwitz (2021) which eventually resulted in 43,637 records of existing and 3,134 records of demolished buildings. In Vantaa, data was retrieved from the City of Vantaa and after some minor corrections (for further explanation see Supplemental Figure S1 in Kolkwitz et al. (2023), it contains 39,348 records of existing and 3,543 records of demolished buildings.

The building datasets of Tampere and Vantaa cover over 100 attributes of which the following are used in this study. Firstly, the functions of buildings are described in over 75 building types (BTs). In general, they are roughly divided into residential buildings (RB), and non-residential buildings (NRB) and further into 13 building type groups (BTG). Huuhka and Kolkwitz (2021) and Kolkwitz et al. (2023) give a comprehensive overview of their categorization. Secondly, the units of quantity are number of buildings or GFA in m^2. Thirdly, each building record contains information on year of construction and, in the case of demolished buildings, year of demolition. Finally, coordinates aided in studying the building's location.

The plot data used for the spatiotemporal analysis in Tampere was provided by the city of Tampere and contains detailed information on the plot structure of the city in 2018. Plot data in Vantaa of early 2020 was retrieved from the National Land Survey of Finland (n.d.). Aerial photographs were used to verify findings and to compensate for potential errors due to changes in the plot structure. In Tampere, aerial photographs from 1995 and 2018 were retrieved from open standards data source Geoserver (n.d.). Aerial photographs of Vantaa were retrieved for the years 1998 and 2017 from Helsinki Region Infoshare (n.d.). In addition to the building and plot data, statistical data for demographic and economic development was retrieved. Data for the population development between 2000 and 2018 was derived from Statistics Finland (2022a) and data for the population projection until 2040 was retrieved from Statistics Finland (2021). For the development of employed labour force data was collected from two sources which distinguish between total employed labour force within a municipality (Statistics Finland, 2022b) and those employed within but living elsewhere (Statistics Finland, 2022c).

Case Studies

Tampere and Vantaa are the third and fourth largest cities in Finland, however, they are positioned in quite different contexts (Figure 1a). Tampere is an inland city situated about 180 km to the North of the capital. It is the main city of the region and has no competing hotspots in its immediate vicinity. Vantaa is part of the metropolitan region of Helsinki on the South coast of Finland. The Helsinki capital region has a population of 1.4 M. In the Tampere region, it is only 400,000. In terms of city population, however, Tampere and Vantaa are of similar size and their different positions make it interesting to compare the dynamics within their building stocks.

By the numbers of the employed labour force, Tampere and Vantaa are almost equal (Table 1). However, of the employed labour force living in Vantaa, less than half also work in Vantaa, whereas almost 80% of the employed labour force living in Tampere also work in Tampere. The high rate of commuters in Vantaa seems to reflect a less centralized job market within the larger Helsinki metropolitan area.

Despite the labour forces' similar overall sizes and relatively even shares among secondary production (18.5% in Tampere and 21.5% in Vantaa) and service economy (80% in Tampere and 77.5% in Vantaa), the work sectors of both municipalities have noteworthy differences. With over 23,000 employed, Vantaa's wholesale and retail trade sector is almost twice as big as in Tampere. Around 19,000 in Vantaa are employed in transportation and storage which clearly reveals the important role of the airport for the local job sector. Tampere on the other hand, has a stronger information and communication sector as well as professional, scientific, and technical activities. Also, employment in education, human health, and social work activities are at the forefront in Tampere which altogether reflects the importance of the university for medical and technical education and consequentially for the city's economic activities.

The municipality of Tampere (Figure 1b) has a land area of 525 km^2 (MML, 2022) which stretches along the eastern shore of Lake Näsijärvi and north of Lake Pyhäjärvi. While a large part of the land to the North is rural and sparsely populated, the urban area is mostly located on a comparatively small amount of land between the two lakes and its municipal boundaries. These spatial circumstances limit Tampere's urban centre to a relatively narrow area. The consequential limitations imposed on the city's expandability have resulted in numerous modifications to the lake shoreline throughout the city's history. With 238 km^2, Vantaa's land area as seen in Figure 1c is approx. half the size of Tampere (MML, 2022). The Helsinki airport is the country's most important airport located centrally in Vantaa which makes the city an important transit area. Vantaa is interspersed with infrastructural axes and junctions such as the Helsinki ring road, train lines, and motorways connecting the South with the North.

Over 95% of Tampere's existing building stock is located within a radius of approximately 10 km from the city centre. For this reason, the focus of the spatial study rests on the South of Tampere which narrows the studied area down to a size which is notably smaller compared to the studied area in Vantaa. Comparing the study areas as of 2018 (Figure 1), Tampere has an average plot density of built-up plots (combined building GFA in m^2 divided by plot size in m^2) ca. 50% higher than Vantaa. Given the higher growth rate in Vantaa, this gap was most likely even more pronounced in 2000.

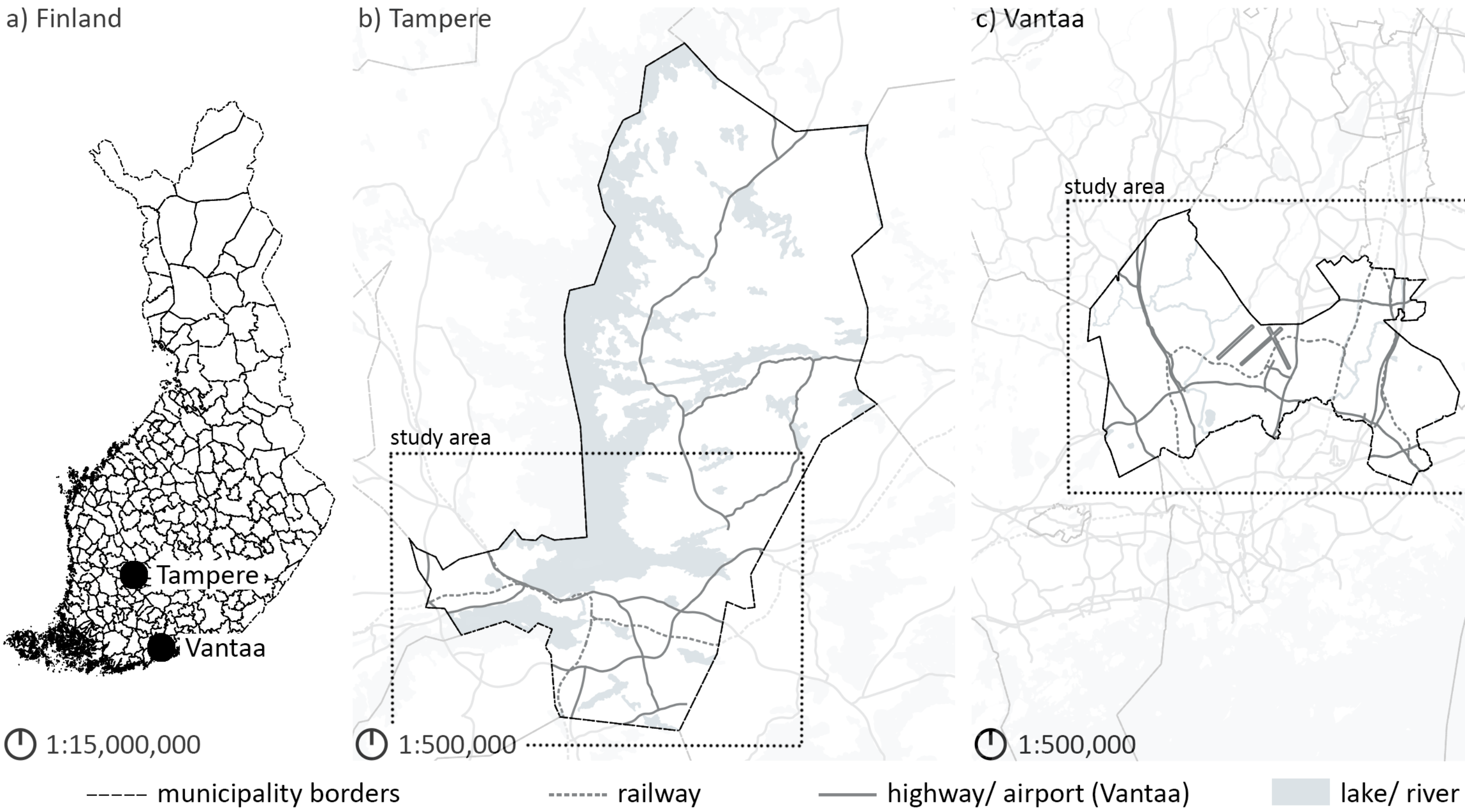

Figure 1. Maps of a) the locations of Tampere and Vantaa in Finland, b) Tampere, and c) Vantaa including municipality borders, bodies of water, and main infrastructure

Statistical Results

Overview

Table 1 provides a first overview of findings for building stock development, construction, and demolition, their respective numbers and totalled size. Over the examination period, Tampere's building stock has grown by 13% in number of buildings and 22% in GFA. In Vantaa, the increase has been 29% and 41% respectively. These numbers reflect the overall population growth (Statistics Finland, 2022a) and increase in employed labour force (Statistics Finland, 2022c, 2022b) in both municipalities which are both notably lower in Tampere (+20% and +24% respectively) than in Vantaa (+28% and +36%). The more rapid growth of Vantaa, therefore, reflects the overall higher net growth of its building stock.

The more rapid growth of Vantaa's population, therefore reflects the overall higher net growth of its building stock.

In both municipalities, over 3,000 buildings were demolished. This was to be expected, as Vantaa also built more than Tampere, and demolition in Finland has previously shown a connection with new construction (cf. Huuhka and Lahdensivu, 2016). Conversely, though, the amount of demolished GFA was greater in Tampere than in Vantaa.

Table 1. Building stock 2000–2018, construction and demolition 2000–2018, population 2000–2018, and employed labour force 2000–2018

	Tampere	*Vantaa*	*Difference*
Building stock 2000, pcs	38,950	31,020	7,930
Building stock 2018, pcs	43,637	39,348	4,289
New buildings, pcs	8,317	12,304	-3,987
Demolished buildings, pcs	3,134	3,543	-409
Building stock 2000, m^2	15,662,503	13,157,435	2,505,068
Building stock 2018, m^2	19,040,046	18,557,756	482,290
New buildings, m^2	4,431,604	6,288,806	-1,857,202
Demolished buildings, m^2	1,054,061	910,588	143,473
Population 2000	195,468	178,471	16,997
Population 2018	235,239	228,166	7,073
Employed labour force 2000	102,650	89,249	13,401
Employed labour force 2018	127,750	121,149	6,601

The fact that demolished buildings are clearly smaller than existing or new ones seems to reflect the ongoing densification to accommodate the growth in population and labour force.

Buildings demolished in Vantaa are on average older (58 years) than those in Tampere (50 years). In addition to the higher number of new buildings in Vantaa, this has led to an overall younger building stock in Vantaa with an average age of only 36 years in 2018, compared to Tampere with 44 years. These numbers seem to reflect Tampere's longer urban history and that the city's oldest part of the building stock may be protected today.

Interestingly, the average size of existing buildings and the average size of new buildings are almost equal within but differ between the two cities. The sizes are, in a respective order, 553 m^2 and 545 m^2 for Tampere and 472 m^2 and 511 m^2 for Vantaa. In both cases, demolished buildings are on average clearly smaller: 336 m^2 in Tampere and 257 m^2 in Vantaa. The fact that demolished buildings are clearly smaller than existing or new ones seems to reflect the ongoing densification, in both cities to different degrees, to accommodate the growth in population and labour force.

Construction

Construction of RBs outweighs construction of NRBs in both cases. In Tampere, 65% of total built GFA are RBs. In Vantaa, this share is 55%. Figure 2 shows the five most built BTs in Tampere and Vantaa. In both cases, blocks of flats are by far the most built BT followed by one dwelling houses. While their share of new construction is 10% in Tampere and 14% in Vantaa, the total amount is around twice as much in Vantaa than in Tampere.

Besides the differences in new construction of RBs, the most notable deviation in new construction can be observed for warehouses whose share of total construction in Vantaa is significantly higher than in Tampere where warehouses were hardly built at all. On top of that, newly built warehouses in Vantaa are on average more than three times larger than warehouses built in Tampere. This clearly reflects the importance of retail, transport, and warehousing for Vantaa's labour market.

Overall, the types of newly built BTs in Tampere suggest a housing- and service-oriented building stock development which is most likely a response to the municipality's growth in population and labour force. The overall faster growth in labour force in Vantaa on the other hand, coincides with an overall higher construction rate of NRBs including office buildings and aforementioned warehouses. Unlike in Tampere, transport buildings such as public transport stations and terminals, vehicle depots, and car parks make up a notable share of total construction in Vantaa. This development reflects the overall higher share of commuters in its labour force and the city's role as the country's most important infrastructural node. Furthermore, the higher rate of construction of one dwelling houses in Vantaa is in line with previous research (Gontia et al., 2020) that found a correlation between municipalities with many outbound commuters and the building stock's proportion of single-family houses.

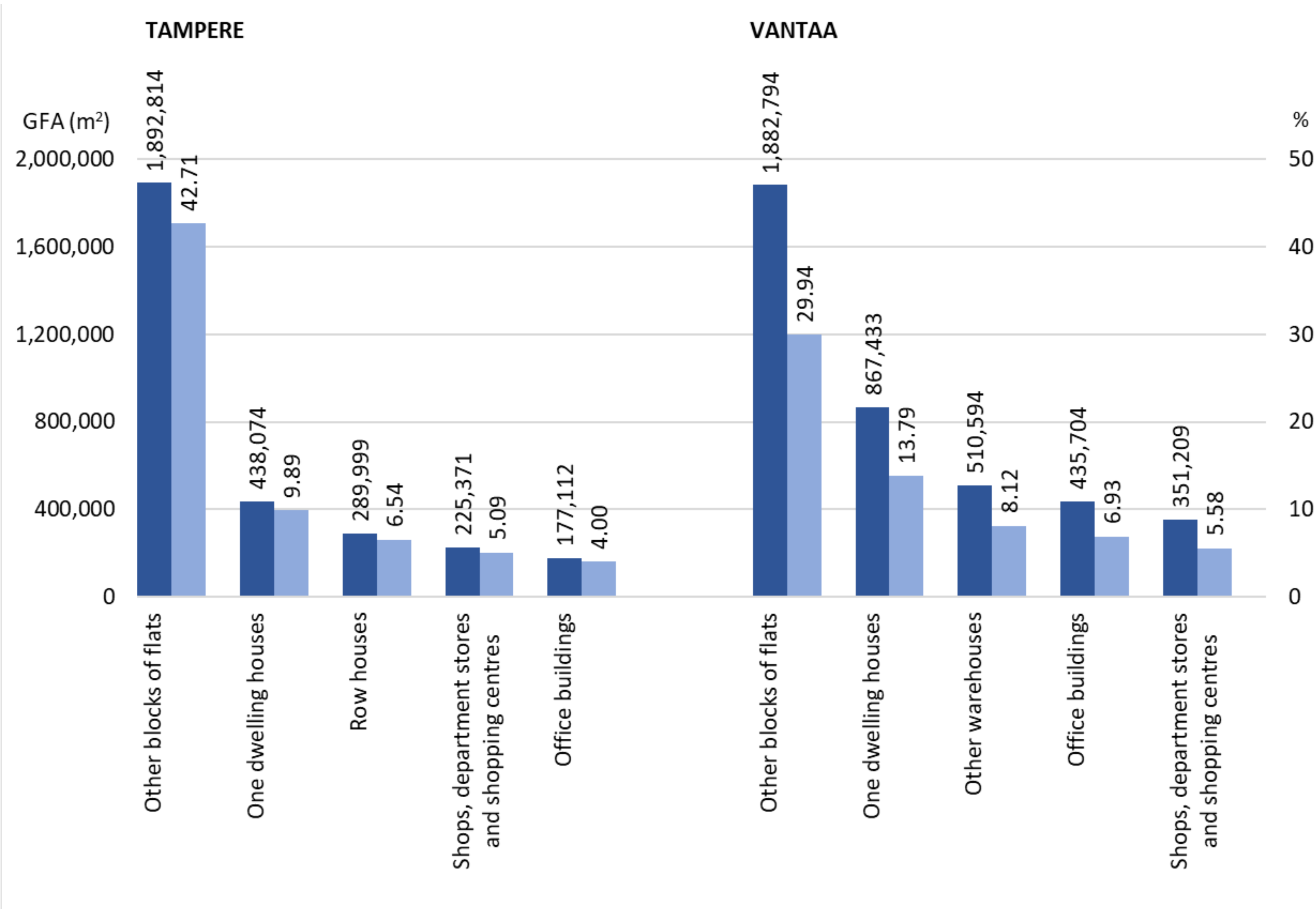

Figure 2. Top 5 most built building types (BTs) in Tampere and Vantaa 2000 - 2018. The dark blue colour indicates the built gross floor area (GFA) and the light blue colour indicates its share in percent of the total built GFA.

Demolition

In contrast to new construction, demolition of NRBs is clearly dominant with shares of 91% in Tampere and 82% in Vantaa of their respective total values. The most demolished BTGs in Tampere are industrial buildings (20%), warehouses (18%), and commercial and office buildings (14%) while warehouses (18%), transport buildings (14%), and industrial buildings (14%) are the three most demolished BTGs in Vantaa.

Compared to construction, demolition is spread across a wider range of different BTs and there is no single type that clearly sticks out in either Tampere or Vantaa. Figure 3 presents a comparison of the 10 most demolished BTs in Tampere and Vantaa which sum up to almost 75% of the overall demolition volume in each of the municipalities. Considering the importance of transportation and storage for the labour market in Vantaa, the large-scale demolition of warehouses may be surprising but might as well be the result of rezoning. With 20% of total demolition, industrial buildings in Tampere are the only BTG with a higher share. Bearing in mind the city’s industrial history, this seems to reflect an ongoing shift in its labour market towards a more service-oriented economy.

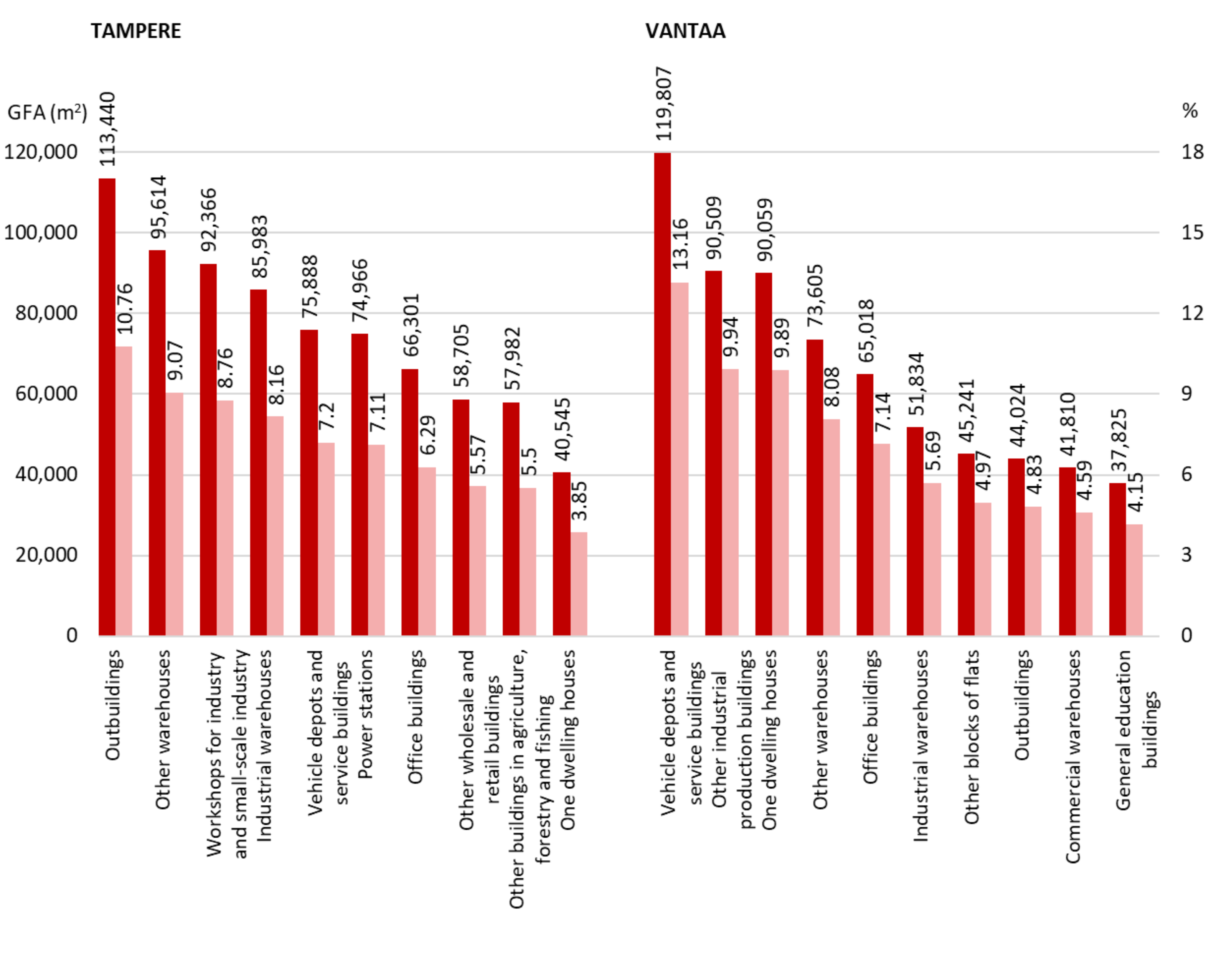

Figure 3. Top 10 most demolished building types (BTs) in Tampere and Vantaa 2000 - 2018. The dark red colour indicates the demolished gross floor area (GFA) and the light red colour indicates its share in percent of the total demolished GFA.

In most of the cases, demolished BTs are smaller than construction of the same type. Of those buildings listed in Figure 3, however, there are some exceptions to this rule like demolished other warehouses or vehicle depots and service buildings in Tampere which are notably larger than built ones. In Tampere, this seems to be another indicator for the shift in its economic structure and hence, less space allocated to such buildings. In Vantaa, the average size of demolished and built vehicle depots and service buildings is almost equal which might indicate a relocation pattern for these BTs.

The overall higher average age of demolished buildings in Vantaa shows that demolition has targeted an older part of the building stock than in Tampere. In Vantaa, demolished one dwelling houses, outbuildings, sauna buildings, and holiday cottages make almost 75% of the total number of demolished buildings. Their high age greatly raised the overall average age of demolished buildings. On the other hand, these BTs comprise only around one fifth of total demolished GFA which means they have a comparably small impact on the outflows of building GFA yet a significant impact on the overall average age of demolished buildings.

Non-residential buildings such as commercial and office buildings, warehouses, industrial buildings, and public buildings were demolished at a much younger age and make almost three fourths and over two thirds of demolished GFA in Tampere and Vantaa respectively.

Overall, NRBs were demolished at a much younger age than RBs which is in line with previous nation-wide research (Huuhka and Lahdensivu, 2016). In both Tampere and Vantaa, commercial and office buildings, warehouses, industrial buildings, and public buildings are among the five most demolished BTGs that make almost three fourths and over two thirds of demolished GFA respectively. Their respective combined average age at the time of demolition is 43 and 38 years which is significantly below the overall average. In consideration of being the second most demolished BTG in Tampere and most demolished one in Vantaa in combination with the average age at the time of demolition, warehouses clearly stick out with 34 years in Tampere and 37 years in Vantaa.

Evolution of the Building Stock Composition

While the overall net growth of Vantaa's building stock in GFA is almost twice the amount in Tampere, growth rates vary at times significantly between RBs, NRBs, and among the different BTGs and BTs. Figure 4 shows how the building stocks in Tampere and Vantaa have evolved by their composition of BTGs from 2000 to 2018.

The shares of RBs and NRBs in Tampere's building stock of 2000 are 55% and 45% respectively which is close to the ratio in Vantaa of 54% and 46%. Disproportionate growth between RB and NRBs in the two building stocks resulted in a slightly more pronounced gap. In 2018, 60% of existing buildings in Tampere are RBs, in Vantaa 56% are RBs. Especially in Tampere, this overall trend towards housing can be observed throughout the whole building stock. With only minor exceptions, the shares in the building stock of all non-residential BTGs have declined from 2000 to 2018. The opposite can be observed for RBs and especially blocks of flats whose share has increased to as much as 39% of the total existing building stock in 2018. Findings in Vantaa are slightly more diverse. While the share of industrial buildings has shrunk by almost 3%, the share of commercial and office buildings has increased by 2%. In Vantaa, the share of blocks of flats in the existing building stock has grown slightly during the studied period to approximately 29.5%. Overall, it seems that the development in population and labour force coincides with the development in both building stock compositions. A more proportionate growth in population and labour force in Vantaa reflects a more balanced increase in both RBs and NRBs. In Tampere, the disproportionately high population growth compared to the growth of labour force has led to a building stock composition which is slightly more lopsided towards RBs.

The overall net growth of both building stocks can be largely attributed to an increase of the RB stock by 32% in Tampere and even 46% in Vantaa. In Tampere's case, the growth of the NRB stock (8%), however, has a much smaller impact on the overall stock growth than in Vantaa (35%). With minor exceptions, all BTGs of both building stocks have experienced a net increase. For NRBs the net increase is lower due to the rather moderate amount of construction and higher amount of demolition compared to RBs. The only exception in both cases are industrial buildings almost stagnating between 2000 and 2018 which reflects the overall shift in profession away from industry which can also be observed in the small share of employed labour force in manufacturing professions in 2018.

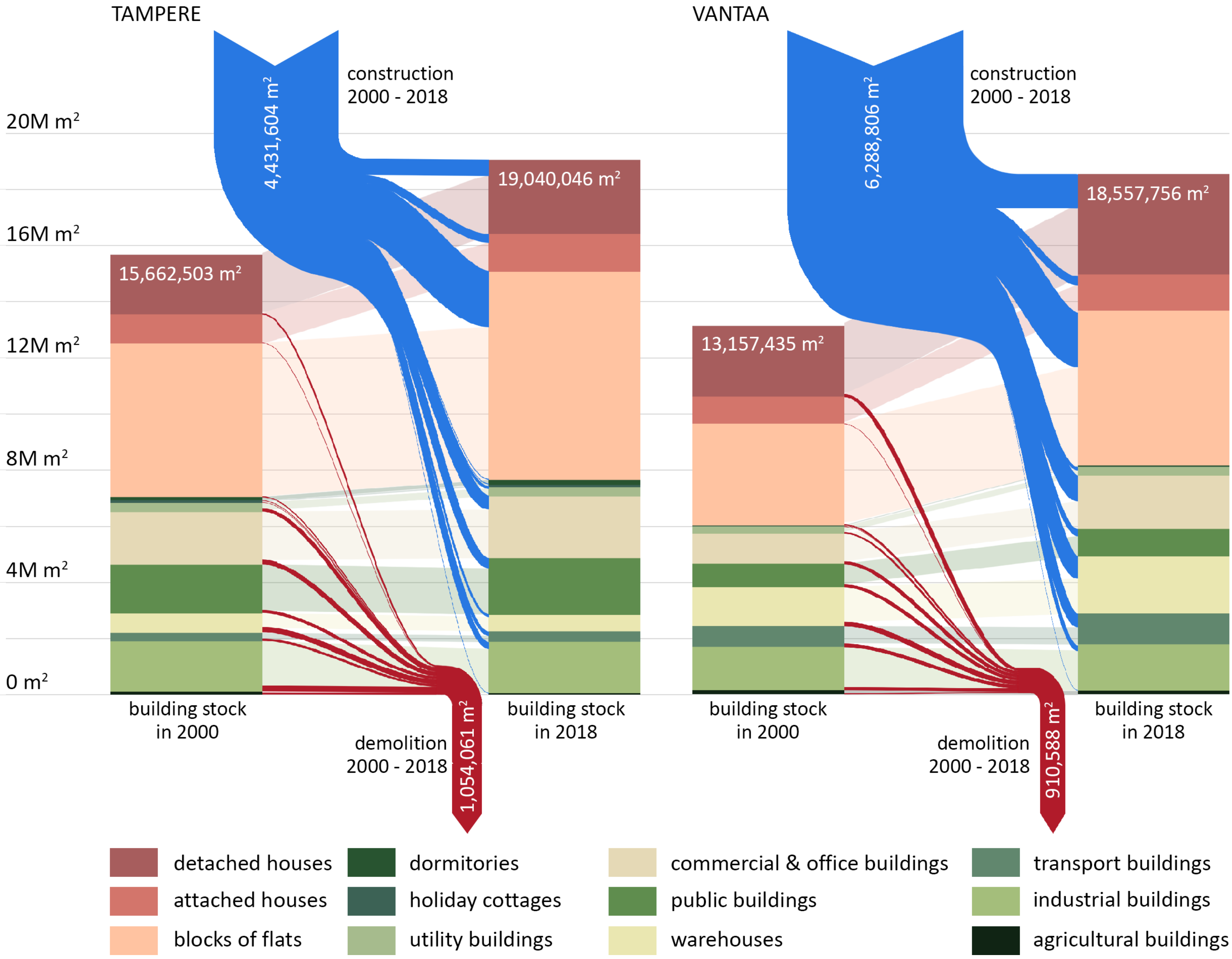

Figure 4. Evolution of the building stock composition in Tampere and Vantaa from 2000 to 2018.

Figure 5 shows the development of the average size per BTG in Tampere and Vantaa from 2000 to 2018. Overall, the average size of buildings in Vantaa has grown much faster than in Tampere which is another sign for an increasingly dense building stock. The average sizes and their development between 2000 and 2018 for RBs are almost identical in Tampere and Vantaa. Findings for NRBs show the most noteworthy discrepancies between the two cities. While the average sizes of commercial and office buildings increase the most in both municipalities, the increase in Vantaa is ca. three times the increase in Tampere. In both cases, this change is mainly due to the construction of very large shops, department stores, and shopping centres while in Vantaa, demolition of smaller buildings of this type further accelerated this phenomenon. The average size of public buildings in Tampere is significantly above respective BTG in Vantaa which is mainly due to very large university and hospital buildings in Tampere. The larger size of transport buildings in Vantaa on the other hand, can be attributed mainly to its airport function, related labour market, and its role as an infrastructural hub.

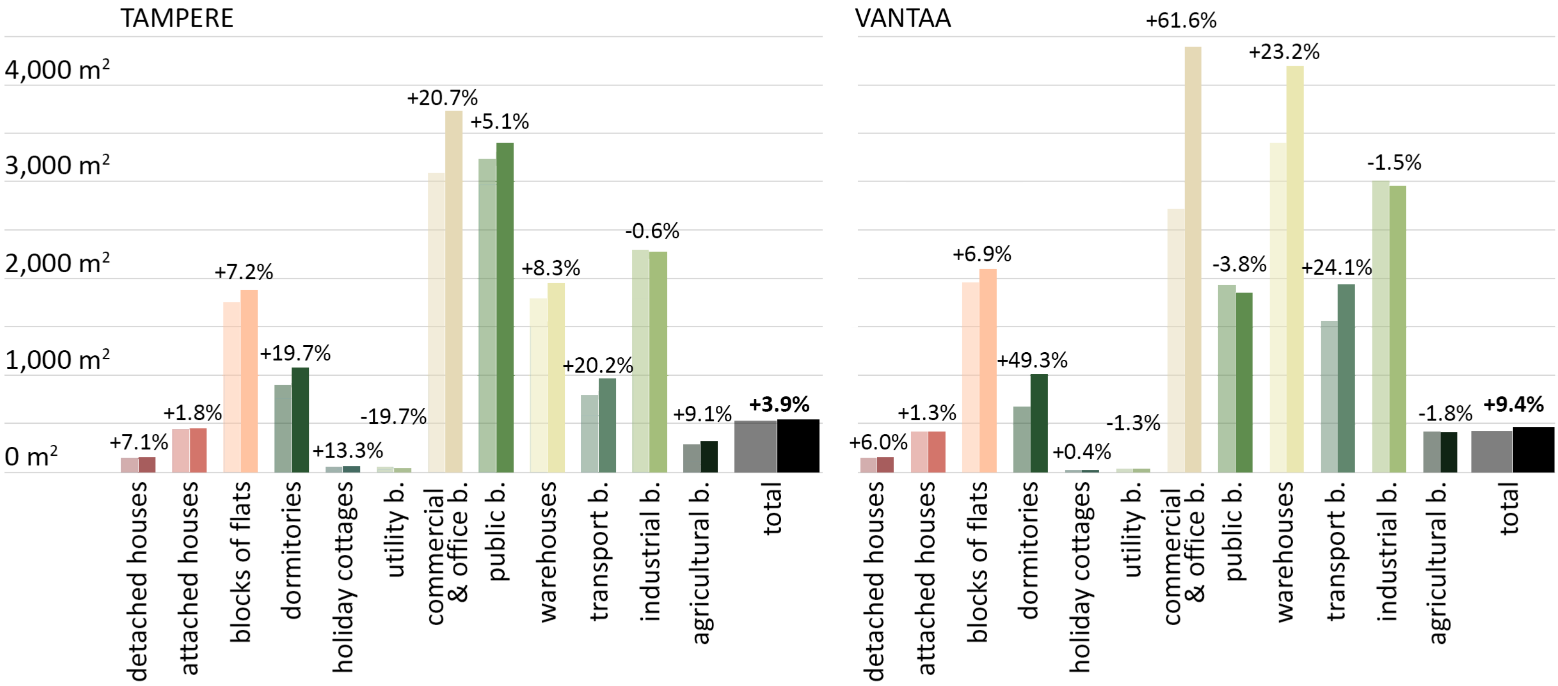

Figure 5. Evolution of the average size per BTG in Tampere and Vantaa from 2000 to 2018. The lighter coloured bar indicates the value in 2000 and the darker colour in 2018. The percentage above the bars indicates the change from 2000 to 2018.

Spatial Findings

Overview

The two areas with the densest building stock in Tampere in 2018 are the city centre and the satellite town Hervanta (Figure 6a). The city centre contains the majority of the municipality's oldest building stock with its characteristic former industrially used buildings made of red brick and residential art-nouveau-style or modernist buildings. Hervanta on the other hand, was established as a university campus and grew to one of the densest areas in Tampere which reflects the university's social and economic status within the city. Vantaa's building stock in 2018 is less concentrated and densely built clusters can be found in areas like Tikkurila, Myyrmäki, Martinlaakso, and Kartanonkoski (Figure 6b). In 1946, Tikkurila became the administrative centre of Vantaa. Myyrmäki, however, is the most populous district in Vantaa and hence, often considered to be the rival centre to Tikkurila. Building stocks in Tikkurila and Myyrmäki have evolved alongside train stations. In Tikkurila, the longer history of its railway and accompanying loosely built housing stock has led to the replacement of many historic buildings especially when urbanization and hence, densification gained momentum in the 1970s and 1980s. The opening of the Myyrmäki railway station on the other hand, has resulted in booming housing construction in the 1970s from primarily greenfield.

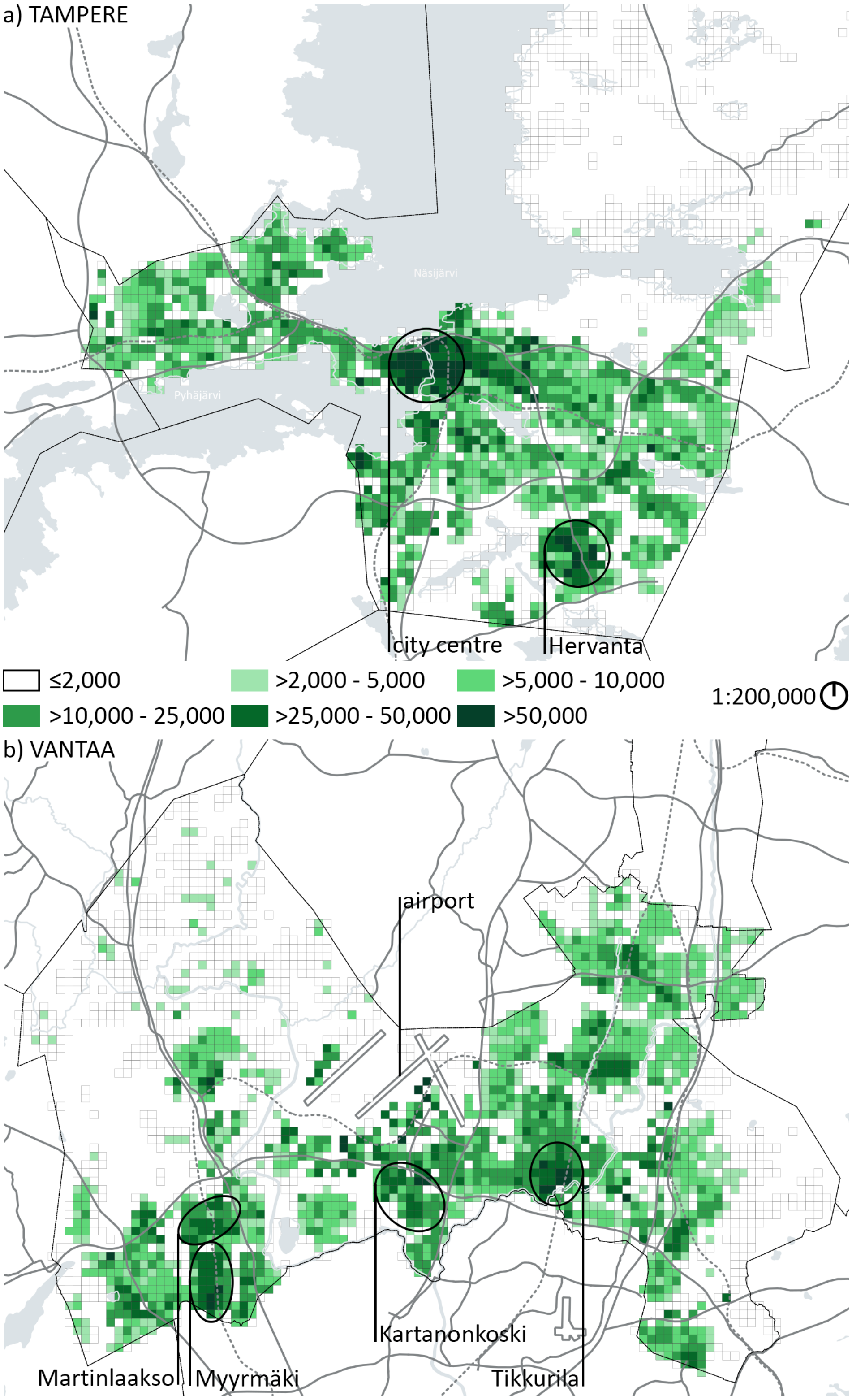

Figure 6: Spatial distribution of existing building stock in 2018: a) Tampere; b) Vantaa. The colours indicate the amount of combined GFA of all buildings located within each square. Most important clusters circled and named.

Clusters

Construction

In total, 2.3M m^2 GFA of construction in Tampere and 3M m^2 in Vantaa are located in clusters which is around half of total construction in both cases.

In Tampere and Vantaa, blocks of flats are the predominantly built BTG in construction clusters. In both municipalities, around two thirds of the total GFA of built blocks of flats are located in clusters which reflects the population growth in both municipalities and a tendency towards a denser building and especially housing stock. Detached and attached houses are significantly less often found in construction clusters which can be attributed to the BTG's loose granularity.

With over 425,000 m^2, commercial and office buildings make the second largest share of construction in clusters in Tampere. In Vantaa, almost 575,000 m^2 of warehouses and over 500,000 m^2 of commercial and office buildings were built in clusters. The large occurrences of warehouses and transport buildings in Vantaa's construction clusters further reveals economic differences such as the more pronounced transportation and storage sector.

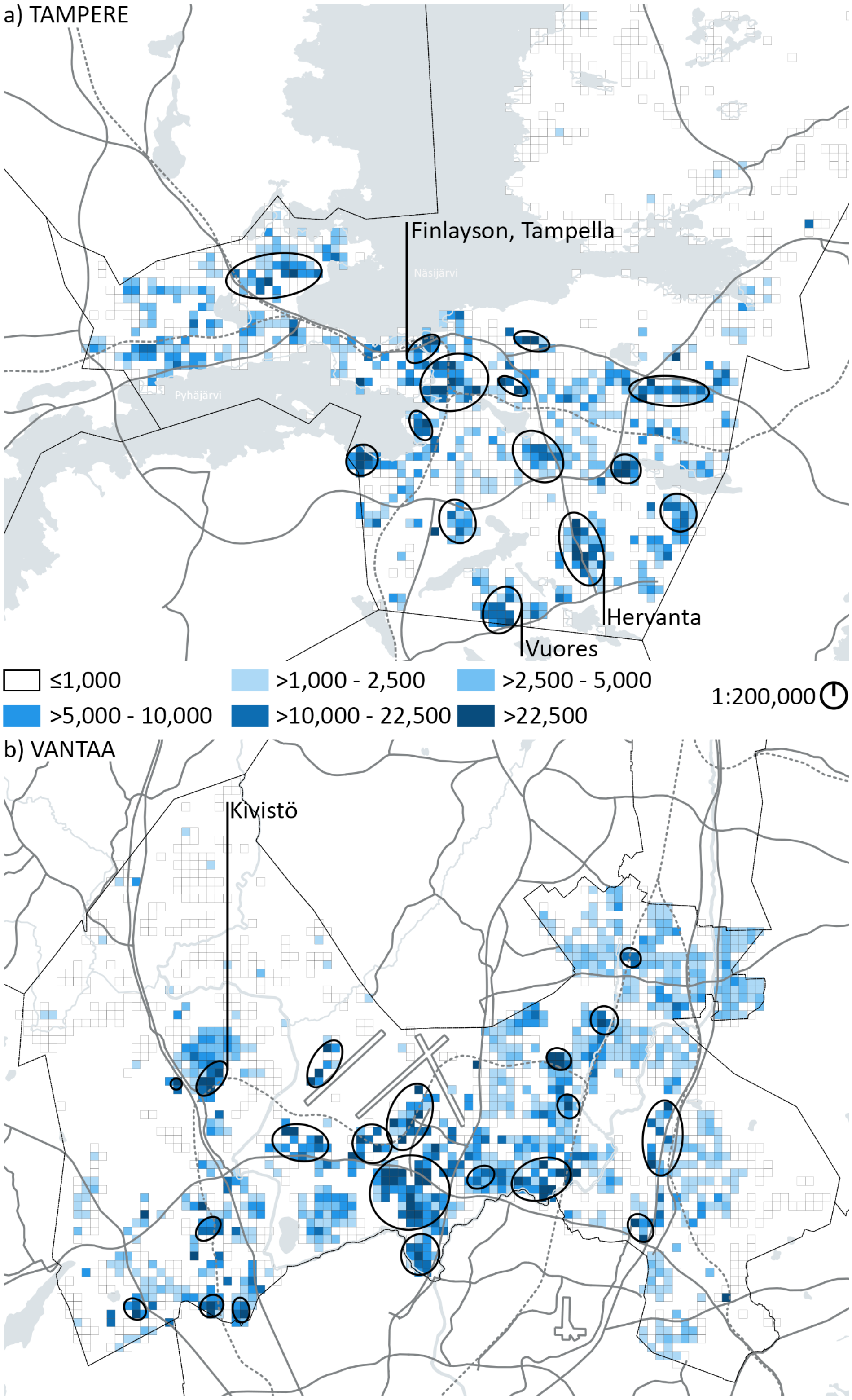

Figure 7. Spatial distribution of construction between 2000 and 2018: a) Tampere; b) Vantaa. The colours indicate the amount of combined GFA of all buildings built within each square. All clusters are circled.

Infill

Clusters where infill is the most dominant pattern are hardly existent. In Tampere, infill development mainly occurred in Hervanta (Figure 7a) in form of either blocks of flats, commercial and office or public buildings. In Vantaa, there is no

Given the comparably high density in Tampere, the seeming absence of infill development comes with some surprise as it can be considered a feasible development pattern in already dense urban environments.

construction cluster which is predominantly infill, however, replacement is often accompanied with infill development. These areas are dominated by the construction of blocks of flats.

Given the comparably high density in Tampere, the seeming absence of infill development comes with some surprise as it can be considered a feasible development pattern in already dense urban environments. On the other hand, cluster analysis may have some limitations to identifying infill as it might be a more spread-out and therefore less visible phenomenon in this type of study.

Greenfield

Greenfield clusters contain approx. 19% of total new construction in Tampere and 13% in Vantaa. In almost half of the cases in both Tampere and Vantaa, predominantly greenfield clusters have a noteworthy share of replacement development within them which is often due to predominantly greenfield clusters overlapping with existing buildings.

In Tampere, greenfield clusters are dominated by RBs and only rarely mixed with non-residential functions. With approx. 400,000 m^2, blocks of flats have by far the highest share of new construction in Tampere's greenfield clusters. The share between RBs and NRBs in Vantaa's greenfield clusters is more even whereas functions are hardly ever mixed within these cluster. Similar to findings in Tampere, blocks of flats are the most dominant building type in Vantaa's greenfield clusters.

Vuores in Tampere (Figure 7a and 8a) and Kivistö in Vantaa (Figure 7b and 8b) are typical examples of greenfield clusters. Vuores is a cluster comparably isolated from the existing building stock in Tampere. The greenfield cluster in Kivistö connects an already existing neighbourhood of detached houses to the newly established public railway station. In both clusters, the predominant BTG is blocks of flats. In Vuores other RBs such as attached and detaches houses sprawl from the cluster outwards.

The overall higher share of dense construction in form of clusters on former greenfield may indicate greenfield becoming an increasingly rare source for construction land in Tampere. Greenfield construction in Vantaa, however, less often forms clusters which might indicate a tendency towards more sprawl especially considering the high number of detached houses which, due to their low density, do not form clusters.

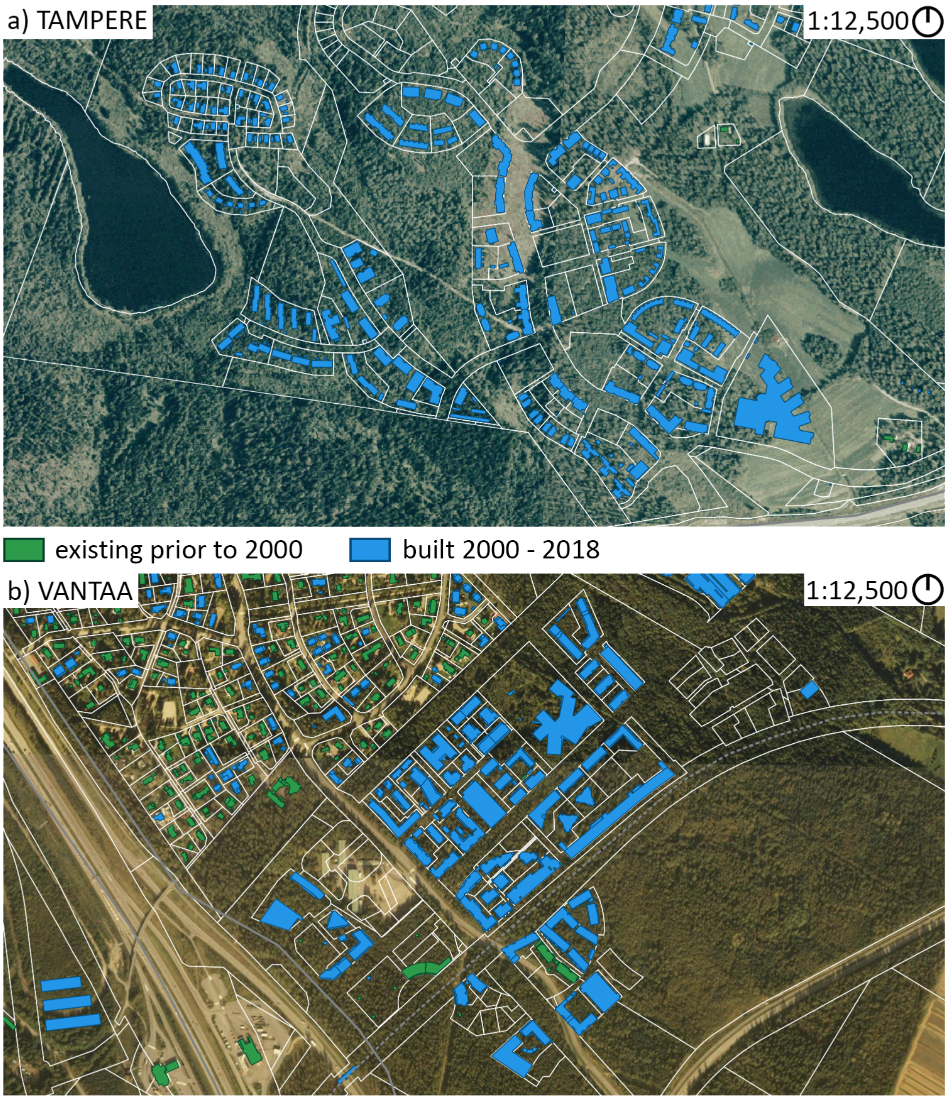

Figure 8. Greenfield construction clusters 2000 – 2018. a) Vuores in Tampere, aerial photograph from before construction in 1995; b) Kivistö in Vantaa, aerial photograph from before construction in 1998

Demolition

Demolition clusters contain around 30% of total demolished GFA in both Tampere and Vantaa. The overall small share of demolition in clusters reflects that demolition is a more spread-out phenomenon which can be seen in Figure 9.

The overall dominance of NRBs in demolition is even more pronounced in demolition clusters where NRBs make over 90% of demolished GFA. When it comes to the distribution among the specific BTGs, however, there is no one specific function that sticks out but a rather evenly tiered gradation among four to five BTGs that vary between Tampere and Vantaa. With over 105,000 m^2, warehouses are the most frequently demolished BTG in clusters in Tampere, followed by industrial buildings with around 90,000 m^2. In Vantaa, the most demolished BTGs in clusters are transport buildings with almost 100,000 m^2 followed by commercial and office buildings with ca. 65,000 m^2. In general, demolition clusters are a more diverse mix between functions compared to construction clusters.

In only few demolition clusters, shrinkage is a likely yet minor cause for demolition. In most of the cases, construction followed demolition leading to the assumption that replacement is the predominant spatiotemporal phenomenon in demolition clusters.

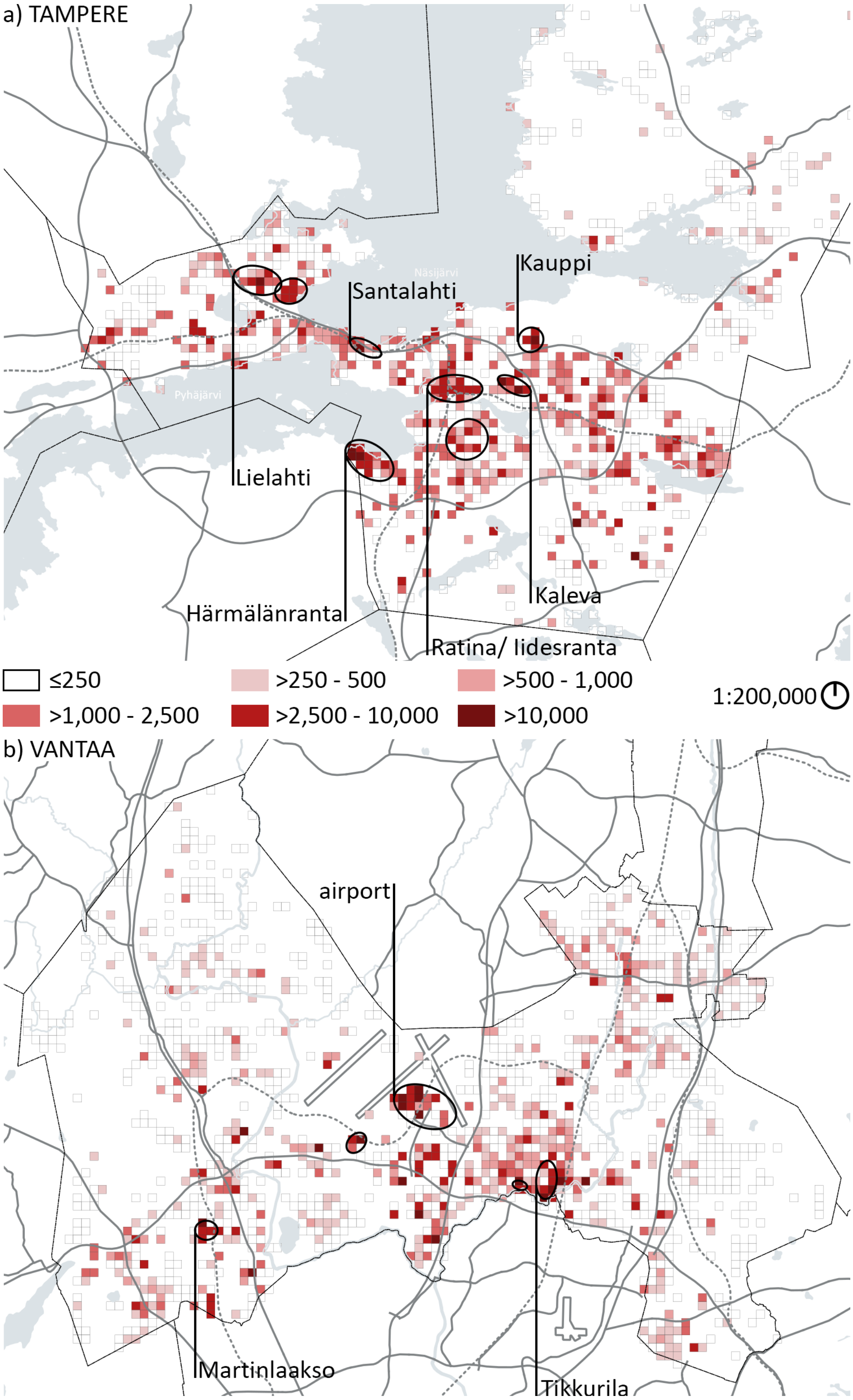

Figure 9: Spatial distribution of demolition between 2000 and 2018: a) Tampere; b) Vantaa. The colours indicate the amount of combined GFA of all buildings demolished within each square. All clusters are circled.

Shrinkage

In only two of the demolition clusters in Tampere and one in Vantaa, shrinkage is a likely yet minor cause for demolition. In most of the cases where demolition forms clusters, construction was followed either within or after the studied time period. In cases of actual shrinkage, this usually coincides with infrastructure development. The areas in Kauppi and Iidesranta (Figure 9a and 10a) in Tampere or the airport in Vantaa (Figure 9b and 10b) are examples where road construction or new space for parking cars and airplanes corelate with the demolition of existing buildings alongside building replacement. The fact that shrinkage hardly happens and demolition commonly being followed by either new construction or infrastructural development reflects the high costs of demolition and that it rarely occurs for no specific reason.

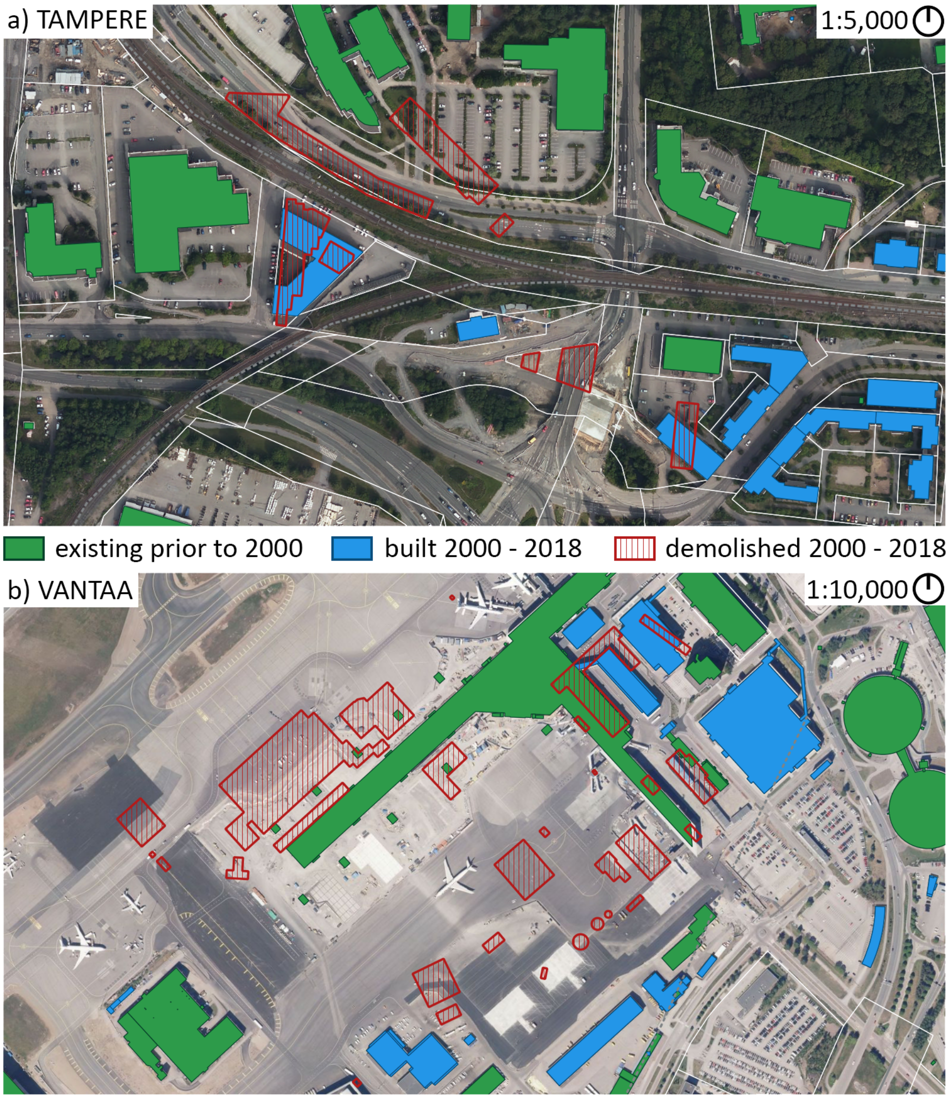

Figure 10. Shrinkage clusters and partially replacement 2000 – 2018. a) Iidesranta and Kalevanharju in Tampere, aerial photograph from 2018; b) Helsinki-Vantaa international airport, aerial photograph from 2017

Replacement

It was found that, in the majority of demolition clusters, construction clusters overlapped spatially in successive order. This allows to assume that replacement has been the predominant spatiotemporal phenomenon in these cases. In cases where demolition clusters do not coincide with construction within the studied time frame, it often occurred shortly after 2018.

In Tampere, over 1M m^2 GFA and in Vantaa even over 2M m^2 of construction in construction clusters were found to correlate with demolition. In both Tampere and Vantaa, especially construction clusters dominated by blocks of flats were found to coincide with demolition. Other BTGs built in such clusters are commercial and office buildings and in the case of Vantaa, warehouses and transport buildings.

Population growth in Tampere and Vantaa and hence, the increased demand for residential buildings seems to be one factor that increased the pressure especially onto the non-residential parts of the building stocks.

Since most of the demolition clusters in Tampere and all in Vantaa coincide with clusters of construction, almost all demolition clusters are simultaneously replacement clusters. Half of construction in replacement clusters are blocks of flats. In Tampere, the replacement clusters of Kaleva, Santalahti and Härmälänranta are examples where the construction of residential buildings followed the demolition of especially warehouses, industrial, commercial and office buildings. Figure 11a shows replacement that occurred in the Finlayson and Tampella area in central Tampere. Here, often historically valuable industrially used buildings were demolished to make way for the construction of blocks of flats. In Vantaa, replacement clusters such as in Tikkurila and Martinlaakso (Figure 11b) show a slightly different pattern where the construction of blocks of flats most often followed the demolition of commercial and office buildings but also industrial buildings, public buildings, and even blocks of flats. Population growth in Tampere and Vantaa and hence, the increased demand for RBs seem to be one factor that increased the pressure especially onto the non-residential parts of the building stocks. The specific BTGs that were demolished to be replaced with RBs, however, varied between Tampere and Vantaa which can be attributed to, inter alia, differences in their history, economic structures and hence, building stock composition.

Commercial and office buildings are another BTG whose construction often spatially coincided with demolition clusters. During the developments of the Ratina and Lielahti commercial areas in Tampere, a noteworthy amount of demolition of industrial, commercial, and office buildings and warehouses occurred. Another specific case is the development of the airport in Vantaa where the replacement of a substantial amount of transport buildings caused by an expansion of the airport coincides with a twofold increase in international passengers from 2000 to 2018 (Finavia, 2022).

Besides the overall dynamics in both building stocks, replacement was also found to be driven by multiple factors such as in the case of the renewal of hospital buildings in Kauppi, Tampere. In this case, the demolition of buildings can be explained with a need for larger and potentially more up-to-date medical facilities in this area which may be connected to the overall population growth and the hospital's connection with the university's expansion. Another factor may be the health and social services reform in Finland which restructured the country's health care organization. As a result, health care services tend to be more centralized which may have had an impact on the restructuring of Tampere's biggest hospital.

Overall, the average age of demolished buildings in replacement clusters is significantly below the total average ages. This seems to show that the replacement of buildings, especially NRBs, coincides with a shorter life span than buildings that were demolished outside replacement clusters.

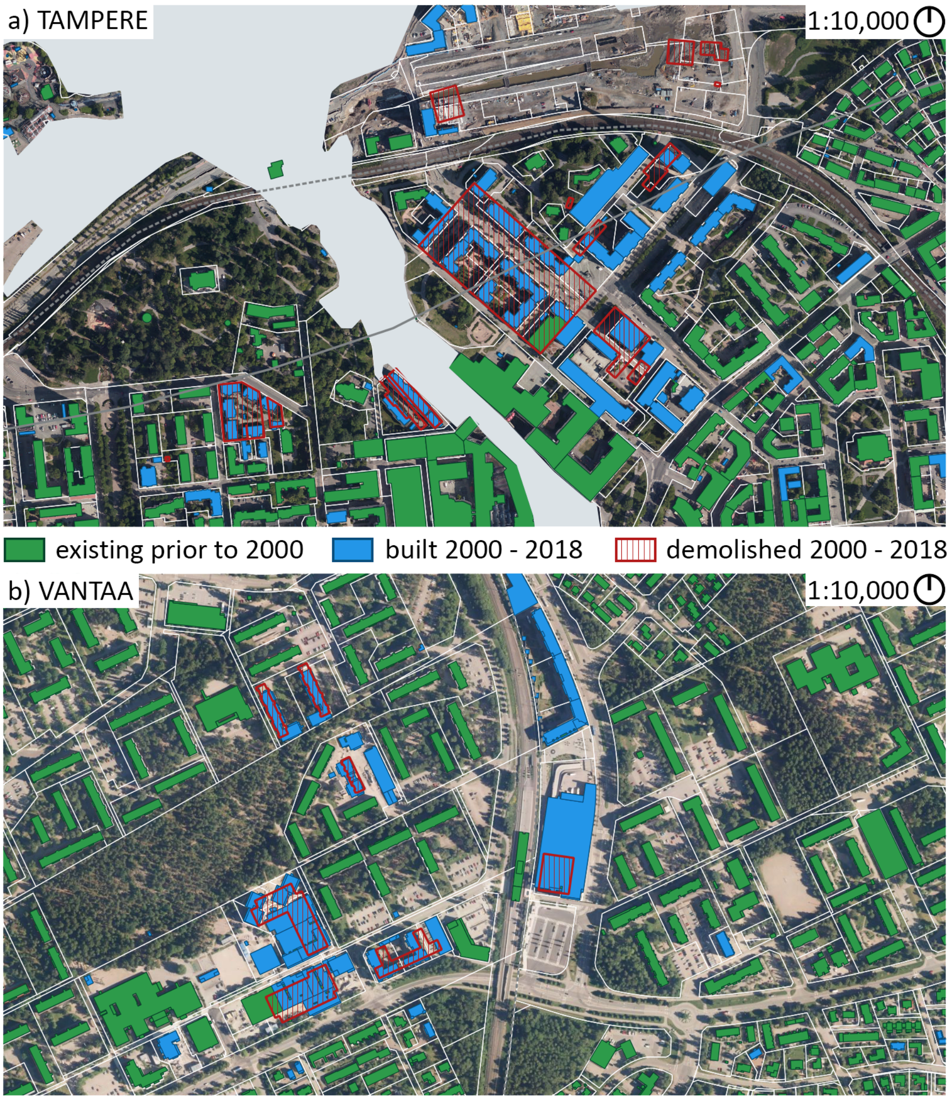

Figure 11. Replacement clusters 2000 – 2018. a) Finlayson and Tampella in the centre of Tampere, aerial photograph from 2018; b) Martinlaakso in Vantaa, aerial photograph from 2017.

Concluding Discussion

How building flows translate into material flows

In the context of UM research, the studied in- and outflows of buildings eventually result in material consequences in the form of demand for construction materials and disposal of demolition waste (cf. Schandl et al., 2020). To date, the lack of material indicators for the Finnish building stock prevents from making reliable estimates on the material stocks and streams associated with building stocks and flows in Tampere and Vantaa. Based on previously conducted studies, it can be estimated, however, that patterns of material streams differ from the patterns of flows of buildings due to discrepancies in the material intensities and qualities per building type. As an example, the construction of detached houses is significantly more material-intensive than the construction of an apartment (Hajer et al., 2014). Materials used in smaller buildings, especially in the Nordic countries, however, tend to be more often wood than in blocks of flats (Heeren and Fishman, 2019). The considerable quantity of newly built detached houses, especially in Vantaa, will therefore most likely be more visible in the overall material inflows, particularly for wood which is typically used in the building frame. Another example is warehouses which were found to be among the most frequently demolished BTGs in Tampere and Vantaa. Their open spaces and therefore, fewer interior walls and other building components will most likely translate into less voluminous outflows of construction materials than e.g., office buildings.

Impacts and drivers of building flows

Context-specific factors and consequentially different foci on building typologies result in qualitatively and quantitatively distinct material flows.

Overall, the discrepancies in how the building stocks in Tampere and Vantaa have evolved portray the context-specific factors and consequentially different foci on building typologies which in turn translate into qualitatively and quantitatively distinct material flows. As previously studied in other cases by Fishman et al. (2015) and Gontia et al. (2020), the demographic and economic developments in Tampere and Vantaa were found to correlate with growth in the building stock. Geographically, Tampere is bound to a narrower area which, in addition to a denser building stock, limits the city's opportunities for urban sprawl. The results are higher densification and in the case of RBs, a focus on more space-efficient housing typologies. Urban development in Vantaa, on the other hand, is less restricted by its geographical properties, administrative boundaries, or existing urban fabric. The high volume of built detached houses to accommodate the growing population, therefore, correlates with a higher level of sprawl of residential buildings and a less efficient use of residential building GFA.

In contrast to the RB stock, Schebek et al. (2017) found that a static observation of the NRB stock is no reliable indicator of the current employment situation in respective job sectors. This study shows how a comparative dynamic approach for building stock development in relation to the development of population and labour force can give meaningful insights into the dynamics within both the residential and non-residential components of a building stock. The net addition of e.g. warehouses and transportation buildings to Vantaa's building stock reflects the municipality's labour market and the importance of transportation and storage within it. The large volumes of demolition in the course of this development, however, shows that NRBs are more likely to be subject to renewal or relocation following e.g. the rezoning of commercially used areas into housing like Härmäläranta in Tampere or Tikkurila in Vantaa. The development of the hospital area in Kauppi, Tampere is another example of net growth following noteworthy demolition activities where besides the city's economic structure, changes in the legislation contributed to this phenomenon.

The lack of material and environmental indicators for buildings in this study is a shortcoming that needs to be addressed in future studies. Nevertheless, this study gives first insights into drivers and patterns of building streams and paves the way for a deeper understanding of consequential material flows and both cities' metabolisms. Furthermore, their high outflow rates and spatiotemporal interrelationship with RBs provide evidence for the importance of accounting for NRBs in UM studies.

An estimate of the environmental impacts of material flows

This research shows the necessity of perceiving materials and the products they are embedded within as tightly interconnected. Demolishing a building determines the end-of-life of materials and vice versa, the construction of buildings kicks off a series of sourcing, transportation, manufacturing, and assembly processes. Construction materials entail a multitude of sustainability strains related to inter alia their sourcing, embodied emissions, and end-of-life-treatment. The mere volume of material streams is, therefore, no indicator of how sustainable a city's UM operates. Instead, it is important to be aware of the origin and processes entailed in material inflows and the consequences of outflows in addition to creating an understanding of the intermediate mechanisms behind the construction and demolition of buildings.

A future outlook on the building stocks' development

Findings in this research show how the overall building stock development is connected to macro-level internal and external factors driven by population growth and influenced by its economic structure, infrastructure development, building stock density, as well as national policy. According to the projected development in both municipalities by 2040, the municipalities' population will grow by similar factors as between 2000 and 2018 (Statistics Finland, 2021). The diversity of variables that impact how growth translates spatially and into building consequences makes predicting the future developments of Tampere and Vantaa and their respective building stocks a complex task. Based on previous patterns, however, there are a few general assumptions that can be made on potential future trends, especially for the RB stocks assuming no major shifts in construction and planning practices occur. The higher building stock density in Tampere will most likely lead to construction focusing on even more space-efficient typologies. In Vantaa, lower density, and more agricultural land close to building stock clusters will most likely result in more sprawl in the form of greenfield development than in Tampere.

The overall aim in a CE is to maintain material and product values and extending their life cycle to avoid waste and to reduce the use of virgin materials. In a metabolic system, this translates into cutting outflows to a minimum and utilizing their secondary resource potential to substitute for inflows.

In both cases, obsolete NRBs can be expected to get demolished to be replaced with housing. Causes and types of obsolescence are manifold (Thomsen and van der Flier, 2011) but findings in the study of replacement clusters and shifts in the economic structures suggest that e.g. smaller industrially used buildings in Tampere or commercial and office buildings in Vantaa might become threatened to get demolished also in the future.

Implementing Circular Economy planning strategies

To make full use of the secondary resource potential of existing buildings and to respond to the complexity of obsolescence, a wide portfolio of strategies is required which includes renovation, (energetic) retrofitting, rehabilitation, the reuse of components, and recycling (Shahi et al., 2020) as well as strengthening these by design (Timm et al., 2023). Given the focus of this paper, namely buildings as products, their function and size, implementations for future planning are narrowed down to fit this scope for both building stock treatment and new construction.

The overall aim of a CE is to maintain material and product values and extend their life cycle to avoid waste and to reduce the use of virgin materials. In a metabolic system, this translates into cutting outflows to a minimum and utilizing their secondary resource potential to substitute for inflows. The demolition of buildings and hence, the disposal of construction materials are, therefore, highly undesirable practices. Instead, the practice of highest priority would be not to build at all and to substitute spatial needs by utilizing existing space (Kuittinen, 2023; Sanchez and Haas, 2018) in the form of spatial and functional adaptation. The study of replacement shows that adapting originally non-residentially used spaces into RBs might have great potential to avoid their demolition and hence, to substitute for new construction. Given the growing average size of the studied building stocks and the predominantly smaller size of demolished buildings, spatial conversion in the form of adding spaces can be another form of utilizing smaller buildings' potential as a spatial resource. This concept applies particularly well to commercial and office buildings but also warehouses in Vantaa all of which were often replaced by the same BT of greater size. Overall, this study shows how urban development in built-up areas often comes with a notable amount of demolition which urges a shift – particularly given the increasing density in Tampere and Vantaa – in current planning and policymaking towards a building stock-centred approach.

Comparing the total numbers of demolition with construction in Tampere and Vantaa, the demolished GFA would theoretically substitute for one-fourth and one-seventh respectively of new construction. Construction, therefore, seems unavoidable, especially in a likely future scenario with notable population growth. The comparison between Tampere and Vantaa indicates, however, that the denser a building stock gets, the more demolition occurs in the cause of new construction. This further proves the relevance of applying CE strategies to existing building stocks but also new construction. Translating the principles of CE into design principles means to acknowledge the importance of a building's end of life during its original design phase. This further translates into enabling a building's ability for, inter alia, adaptive reuse in the form of e.g., functional change and spatial extension instead of getting demolished. In their case study, Kröhnert et al. (2022) identified a notable potential in saving embodied emissions and landfill waste by applying a flexible design. In Tampere and Vantaa, the predicted future growth in both RB stocks and continuous densification calls for rethinking the practice of greenfield sprawl and incorporating potential future development scenarios to avoid the replacement of unadaptable low-density housing typologies (see Newton et al., 2017). Furthermore, urban sprawl in the form of greenfield development is often more costly (Hamilton and Kellett, 2017), related infrastructure development is more material-intensive, and may pose a higher threat to local habitat (as in the case of Vuores, see Asikainen and Jokinen, 2009) than infill. Replacement, on the other hand, results in large amounts of demolition waste for the sake of renewal (Wang et al., 2019). The notable replacement of NRBs with RBs in the past gives incentives for applying a design for adaptive reuse, especially to commercial and office buildings as well as industrial buildings in Tampere and transport buildings in Vantaa to be transformed into housing. The spatial layout and structural properties of warehouses, on the other hand, make them unlikely to be adapted into housing. An approach that favours their disassembly, allocation, and reassembly, therefore, might be another suitable response to the common practice of rezoning commercial areas into housing.

Circular Economy in today's sustainability discourse

To ensure a truly sustainable development in building stock and flow management, the implementation of circular economy strategies requires efforts by stakeholders throughout the scales from macro such as policymaking, to micro, such as product manufacturing (Pomponi and Moncaster, 2017). This in turn means that neither architects nor urban planners alone can achieve such a transition. Furthermore, a fully sustainable built environment requires expansion from resource- and energy efficiency and to include social aspects, biodiversity, health, and more. Their inseparability and the urgency of addressing the climate crisis, however, make the implication of CE strategies a meaningful stepping stone to reach global sustainability goals.

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