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Material Flows and Stocks in the Urban Building Sector: A Case Study from Vienna for the Years 1990–2015

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Abstract: Population growth in cities leads to high raw material consumption and greenhouse gas emissions. In temperate climates were heating of buildings is among the major contributors to greenhouse gases, thermal insulation of buildings became a standard in recent years. Both population growth and greenhouse gas mitigation may thus have some influence on the quantity and composition of building material stock in cities. By using the case study of Vienna, this influence is evaluated by calculating the stock of major building materials (concrete, bricks, mortar, and plaster, steel, wood, glass, mineral wool, and polystyrene) between the years 1990 and 2015. The results show a growth of the material stock from 274 kt in the year 1990 to 345 kt in the year 2015, resulting in a total increase of 26%. During the same period, the population grew by 22%. On a material level, the increase of thermal insulation materials like polystyrene and mineral wool by factors of 6.5 and 2.5 respectively were much higher than for other materials, indicating energy efficiency and greenhouse gas mitigation in the building construction sector. The displacement of brickwork by concrete as the most important construction material, however, is rather a response to population growth as concrete buildings can be raised faster. A question for the future is to which extent this change from brickwork to high carbon-intensive concrete countervails the achievements in greenhouse gas reduction by thermal insulation.

Keywords: material stocks; material flows; buildings; cities; material flow analysis; population growth; greenhouse gas emissions

1. Introduction

1.1. Background

Studies on the anthropogenic metabolism show that in highly urbanized societies, cities are the largest consumers of raw materials and the largest producers of waste and greenhouse gases (GHGs) [1–3]. In this metabolism, buildings play a particular role, as the raw materials used for their construction, the waste from their demolition and renovation, as well as the GHGs from their heating and cooling are responsible for the bulk of these resource consumptions and emissions from urban areas [4–6]. In countries with temperate and continental climates like Austria with long and cold winters, one major focus of sustainable urban development in the past and present is the reduction of GHGs from heating of buildings. The main reason therefore is that in 1990, which is the reference year for GHG reductions according to the Kyoto Protocol, heating of buildings was, at 17%, the second largest producer of GHG emissions in Austria, in the same range as transport and only topped by energy production and industries [7]. In the Austrian capital Vienna, buildings were the largest producer of GHG emissions in 1990 (29%). As a consequence, GHG mitigation policy in Vienna's building sector focused on a shift in energy carriers (oil to gas), district heating, and a reduction of heat demand [8]. The latter was achieved by higher thermal insulation standards for new buildings and renovation of old buildings with insulation materials and new windows. Even though a higher renovation rate of 3% of the not insulated building stock compared to the observed 1% is claimed to achieve GHG reduction targets [7], the success of these measures is undoubtable. While between 1990 and 2016, the overall GHG emissions in Austria remained at a stable level, the GHG emission reduction in the building sector was −37%. In Vienna, this decrease was even larger with −39%, making the building sector to be only responsible for 18% of GHG emissions in the city, compared to 29% in the year 1990 [9]. These figures are even more impressive when considering that the population of Vienna grew between 1991 and 2017 by 22%, from 1.56 to 1.87 million inhabitants [10]. Both the population growth as well as the GHG emission reduction policy had an impact on the consumption of raw materials and the composition of the material stock in buildings (e.g., a higher share of insulation materials), as well as on the production of waste (e.g. from demolishing old buildings and substituting them by new low-energy buildings). The question, however, is the size of this impact with respect to building material turnover (material inputs and outputs) and the subsequent building material stock of the main building and insulation materials, i.e., concrete, bricks, mortar, and plaster, steel, wood, glass, polystyrene, and mineral wool.

The present study aims to answer this question by determining the development of material flows and stocks of main building materials in the City of Vienna between 1990 and 2015.

1.2. *State of Research*

A number of studies investigated the material stock in buildings at different spatial levels [11], focusing on individual buildings [12,13], cities [14–17], regions [18], countries [19–23], and even country groups [24,25]. Most studies determine the building stock at a certain point of time, but not the dynamics over a longer time period [12,13,15,18,19,24]. Dynamics of the material stock in buildings for a certain time span are available at higher spatial scale [20,21,23,25] and to a lesser extent for cities. Of these, few are also retrospective [14,16,17], and an even fewer number links their analysis to GHG mitigation policy [26]. There is, however, no study that investigated the dynamics of the material stock in buildings in one of the EU's major cities (i.e., capitals and cities above 500,000 inhabitants), considering the response of the building construction sector in these cities to GHG mitigation policy and thus providing the base for projecting the status quo. By carrying out the case study at hand, this gap will be partially closed.

2. Materials and Methods

Material flow analysis (MFA) is used to determine material flows and stocks for buildings in Vienna. Therefore, a stock-flow model is designed, calculating the material stock in buildings for a certain year for which data was available (end of 2013). By using building-specific parameters available from statistics (gross volume GV and useable floor area UFA) and information about the generation of construction and demolition waste (CDW), the material stock of the other years can be calculated and the associated annual material flows of construction materials.

2.1. Material Flow Analysis

2.1.1. Background

A large number of studies on the materials flows and stocks in building sector have been performed, and many of these have used some form of material flow analysis (MFA) model to estimate the respective material flows [11,20,23,27,28]. For this reason, MFA is also used to develop, illustrate, and calculate the material flows and stocks in buildings in Vienna, using the MFA terms as described by Brunner and Rechberger (2016) [29]. Material in MFA is the umbrella term used for goods, sub-goods and substances. Sub-goods are components of goods (e.g., bricks in masonry work), while substances are chemical elements and compounds (e.g., aluminum in bricks). The spatial boundary of the MFA system refers to the city of Vienna, and the temporal boundary is one year as the MFA is carried out on an annual basis for subsequent years. Material flows m are given in mass per time unit (e.g., kg/y). For processes (e.g., transport, buildings) and systems (e.g., Vienna), the law of conservation of mass is applied, leading to Equation (1):

$$\sum m_{input} = \sum m_{output} \pm m_{stock} \quad (1)$$

where $\sum m_{input}$ is the total mass of input (material) flows m_{input}, $\sum m_{output}$ is the total mass of output flows m_{output} and m_{stock} represents the change in the material stock (net mass flow from or to a stock) located in a process or system.

The stock of a material m_{stock} (e.g., in kg) at time point t is determined either by building a time series of material flows m (Equation (2)), or by multiplying a counting unit representing the material i (e.g., volume) by a specific material intensity MI in the counting unit (e.g., kg/volume) at time point t (Equation (3)). The MIs used in this study refer to our previous work on buildings in Vienna [15].

$$m_{stock}(t) = \int_{t=0}^{t} \sum [m_{input}(t) - m_{output}(t)]dt + m_{stock}(t_0) \quad (2)$$

$$m_{stock}(t) = V(t) * MI \quad (3)$$

2.1.2. System under Investigation

The system investigated refers to buildings in the city of Vienna in the years 1990–2015 [15]. With respect to the building materials considered, a selection is made based on quantitative relevance and their direct and indirect impact on GHG emissions. Based on these restrictions, major building materials (concrete, bricks, mortar, and plaster, iron and steel, and wood) and insulation materials or other materials that have an impact on the energy demand of buildings (glass, mineral wool, and polystyrene) are considered. When talking about data and years, stock data always refers to a point of time, i.e., the status as of the last day of the regarding year (e.g., the stock in the year 1990 is by the 31 December of this year). Contrary to that, flows always refer to a time span (e.g., the material flow in the year 1991 are all materials moved between 1 January to 31 December 1991).

2.1.3. Overview on the Calculation Procedure

The calculation procedure follows a reverse MFA model. The reason for that is that for the year 2013, data on material stocks in the building sector is available [15]. Reverse in this sense means that starting from the year 2013, the material flows and stocks of the previous years back to the year 1990 are calculated. This is done by disaggregation of the material stock in the year 2013, using statistical data sets on the construction period of buildings, the development of the housing area of the population, and construction and demolition waste flows.

2.2. Calculation of the Material Stock in the Year 2013

The material stock of the selected materials i in buildings is calculated using the data from Kleemann et al. (2017a) [15], who determined this stock for different building categories j. These categories are distinguished with respect to their use (residential, commercial, industrial, and other buildings) and construction period (before 1919, 1919–1945, 1946–1980, 1981–2000, 2001–2015). This results in 20 building categories in total. In the approach of Kleemann et al. (2017a) [15], the material stock of buildings M was calculated after Equation (4) by multiplying the GV of each building category j (in m^3) in the year 2013 by the specific material intensity $MI_{GV,ij}$ (in kg/m^3) of each building category j and material i, and summing up all categories.

$$M_{ij} = \sum_{i=1}^{l} \sum_{j=1}^{m} MI_{GV,ij} \times GV_j \tag{4}$$

The GV data, available as GIS data set, came from different municipal departments of the City of Vienna, while the MI was determined based on the analysis of in total 66 buildings covering all 20 general building types identified by Kleemann et al. (2017a) existing. This corresponds to a sample size of 0.03% (considering that Vienna has in total 200,000 buildings) and about 3 buildings per building type. The methods used for the analysis comprised of solely analyzing plan documents (40 buildings), plan documents and sampling of buildings (14 buildings), as well as LCA inventories of new buildings (12 buildings). If for some building types no buildings (for sampling), plan documents, or LCA inventories were available, the mean value of other buildings in the same age category was used and crosschecked with literature data [15]. Even though the database developed by Kleemann et al. (2017a) as well as the calculation approach was well received in literature [30], it has a few shortcomings for the present work. In particular, the sampled buildings used for the specific material intensity MI for construction periods before 1981 were buildings which were demolished and thus were mostly not subject of prior renovation (i.e., thermal insulation and roof top extension). For this reason, they are hardly representative to the entire building stock in this construction period, and to apply Equation (4), the building categories j (of which there were 20 in the works of Kleemann et al., 2017a) have to be extended by subcategories, and the material intensities have to be adjusted. Furthermore, in order to calculate the development of the material stock and thus the material flow of buildings, a time series of the building stock is required. As such a time series is not available for the gross volume GV, but at least for residential buildings for another building specific indicator, namely the useable floor area UFA, the approach of Kleemann et al. (2017a) is adjusted and further developed, distinguishing between residential and other buildings.

2.3. Calculation of the Material Stocks and Flows for Residential Buildings 1990–2015

For residential buildings, a time series of the useable floor area can be derived from statistics. However, some adjustments are required, described in the first part of this subsection. In the second part, the conversion of the material intensity MI from gross volume to useable floor area is presented.

2.3.1. Development of the Useable Floor Area

The useable floor area UFA (*Nutzfläche* in German) is an indicator defined by Austrian and European Standards [31]. For residential buildings, the UFA is the area in m^2 of the apartments used for living. In multi-family dwellings, areas commonly used by all dwellers like hallways or basements, are excluded from the UFA. This is often not the case in single-family dwellings. Data on the UFA was taken from Statistic Austria's housing censuses of the years 1991, 2001, and 2011 [32–34] as presented in the online portal *Statcube* [35]. The censuses were carried out as surveys, and the data collected refers to the 31st of December of the previous year (e.g., 31 December 1990). The data, shown in Table 1, unveils that in the census 2001, the construction period was unclear for a total number of 64,867 units, which corresponds to about 7%. For this reason, only the census of the years 1991 and 2011 were used in this study.

Table 1. Housing statistics for Vienna from the census of the years 1991, 2001, and 2011: Number of units (apartments), useable floor area (UFA) in m^2 per unit, and UFA in m^2 total for each construction period.

Reference year	**Census year**	**Unit**	**Datasets per Construction Period of Units and UFA**								**Total**
			<1919	**1919–1945**	**1946–1960**	**1961–1980**	**1981–1990**	**1991–2000**	**2001–2015**	**No Data**	
1990	1991	**units**	321,750	101,411	114,770	235,224	79,936	-	-	-	853,091
2000	2001		309,416	97,256	113,336	233,054	72,326	20,490	-	64,867	910,745
2010	2011		317,803	99,561	114,911	233,016	72,037	71,565	74,947	-	983,840
1990	1991	*UFA* in m^2/unit	66	58	60	72	71	79	80		66
2010	2011		70	60	60	72	82	79	80		71
1990	1991	UFA_t in 10^6 m^2	21.260	5.855	6.829	16.980	5.698	-	-	-	56.622
2010	2011		22.275	5.973	6.889	16.818	5.910	5.647	6.030	-	69.541

In order to develop a time series for the UFA, the data from Table 1 has to be annually disaggregated. Furthermore, the renovation status as well as rooftop extensions of buildings have to be considered, as these influence the material intensity MI. This was done by dividing the regarding building categories which are subject to renovation and rooftop extension into subcategories, leading to in total ten categories and sub-categories for residential buildings (see Table 2).

Table 2. Categories *j* of residential buildings according to their construction period and renovation status.

j	**Building Category**	**Description**
1	Before 1919	Built before 1919, no thermal insulation and rooftop extension
2	Before 1919 renovated	Built before 1919 with some thermal insulation (walls, ceilings, windows)
3	Before 1919 rooftop	Rooftop extension constructed after 1990 on buildings built before 1919
4	1919–1945	Built 1919–1945, no thermal insulation (rooftop extension partly included in original design)
5	1919–1945 renovated	Built 1919–1945 with some thermal insulation (walls, ceilings, windows; rooftop extension partly included in the original design)
6	1919–1945 rooftop	Rooftop extension constructed after 1990 on buildings built 1919–1945 (only in buildings were not included in the original design)
7	1946–1980	Built 1946–1980, no thermal insulation (rooftop extension included in original design)
8	1946–1980 renovated	Built 1946–1980 with thermal insulation (rooftop extension included in original design)
9	1981–2000	Built 1981–2000 (thermal insulation and rooftop extension included in the original design)
10	2001–2015	Built 2001–2015 (thermal insulation and rooftop extension included in the original design)

To calculate the UFA of these categories and subcategories, Equation (5) was developed

$$UFA_t = UFA_0 + UFA_{new,0\text{-}t} + UFA_{rooftop,0\text{-}t} - UFA_{demolished,0\text{-}t} \tag{5}$$

where UFA_t is the usable floor area at time point t, UFA_0 is the usable floor area of the residential building stock at time point 0, which is the year 1990, $UFA_{new,0\text{-}t}$ is the newly built useable floor area during the time period 0 to t, $UFA_{rooftop,0\text{-}t}$ is the useable floor area of rooftop extensions constructed during the time period 0 to t, and $UFA_{demolished,0\text{-}t}$ is the useable floor area demolished during the during the time period 0 to t. UFA_t is available for the time points 0 (1990) and 20 (2010), based on the data from Statistics Austria shown in Table 1. For each time point in between and beyond, it must be calculated by building-up a time series for Equation (5). The corresponding formula is shown in Equation (6)

$$UFA_t = \int_{t=0}^{t=s} \left(UFA_0 + UFA_{new,0-s} + UFA_{rooftop,0-s} - UFA_{demolished,0-s} \right) dt \tag{6}$$

where the different UFA are calculated for time intervals from $t = 0$ to $t = s$.

UFA_0, which equals UFA_t for $t = 1990$, was taken from statistical data as shown in Table 1. This table also gives the UFA_t for the year $t = 2010$. $UFA_{new,0\text{-}t}$ was taken from statistical data on the annually constructed number of residential buildings [35]. This newly constructed useable floor area, however, is only relevant for the residential building categories 9 (constructed between 1981–2000) and 10 (constructed between 2001–2015) as shown in Table 2.

The useable floor area for rooftop extensions $UFA_{rooftop,0\text{-}t}$ constructed was calculated by multiplying the estimated number of rooftop extensions $k_{rooftop,0\text{-}t}$ by the average useable floor area of a rooftop extension $UFA_{rooftop,k}$ (see Equation (7)).

$$UFA_{rooftop,0\text{-}t} = UFA_{rooftop,k} \times k_{rooftop,0\text{-}t} \tag{7}$$

The annual number of rooftop extensions $k_{rooftop}$ was 360 per year between 1991 and 2000 [36] and around 400 per year between 2001 and 2015 [37]. The average useable floor area for a rooftop extension $UFA_{rooftop,k}$ and the share of rooftop extensions of each construction period was determined by screening the plan documents of 16 randomly selected rooftop extensions in Vienna. The plan documents of these rooftop extensions were retrieved from Municipal Authorities in Vienna. The result was an average $UFA_{rooftop,k}$ of 411 m^2 per rooftop extension. Eighty percent of rooftop extensions constructed between 1990 and 2015 were on buildings built before 1919, and 20% on buildings built between 1919 and 1945. For buildings built after that, the rooftop extension was part of the original design and thus not considered herein. This value was multiplied by the regarding number of rooftop extensions per year according to Equation (7) to determine the total useable floor area constructed in rooftop extensions between 1991 and 2015. For the calculating the annual development of the time series after Equation (6), the annual number of rooftop extensions for each time period ($k_{rooftop} = 360$ per year between 1991 and 2000 and $k_{rooftop} = 400$ per year between 2001 and 2015) was used (see Appendix A Table A1).

Due to the limited availability of statistical data, the useable floor area demolished $UFA_{demolished}$ was calculated by transforming Equation (5) to Equation (8) and using the UFA_t for the years 1990 and 2010 as a baseline, thus calculating in the first step the $UFA_{demolished}$ between 1990 ($t = 0$) and 2010 ($t = 20$).

$$UFA_{demolished,0\text{-}20} = UFA_0 + UFA_{new,0\text{-}20} + UFA_{rooftop,0\text{-}20} - UFA_{20} \tag{8}$$

Thereafter, it was possible to determine the total $UFA_{demolished}$ between 1990 and 2010. This amount was annually disaggregated. For the disaggregation, it was assumed that the annual demolition follows the amount of debris from buildings annually generated in Vienna between 1990 and 2010. The regarding data, which came from different municipal and national statistics, is presented in Appendix A (Table A2). The existing data gaps, namely missing data for selected years, were filled by linear interpolation.

For the demolished useable floor area in the year 2014, data from Kleemann et al. (2017b) [38] on the demolished gross volume shown in Table 3 was used and divided by a conversion factor which was calculated using the total gross volume GV and the useable floor area UFA (Equation (9)).

$$\text{Conversion Factor}_{GV/UFA} = GV/UFA \tag{9}$$

Table 3. Gross volume of the buildings stock in 2013 (GV_{2013}) and buildings demolished in 2014 in m^3.

Building Period	Residential	Commercial	Industrial	Other Buildings	Total
		Building stock in the end of 2013			
1800–1918	215,967,960	59,345,975	10,180,961	11,979,473	297,474,370
1919–1945	47,210,066	7,407,339	5,623,038	3,913,600	64,154,043
1945–1980	148,080,210	32,673,894	19,712,946	11,323,494	211,790,544
1981–2000	84,403,724	56,005,361	23,306,260	9,809,226	173,524,571
2001–2015	44,357,339	28,096,457	4,654,658	4,513,714	81,622,169
total	540,019,300	183,529,026	68,114,084	57,185,187	848,847,596
		Building stock demolished in 2014			
1800–1918	486,073	144,290	143,471	54,333	828,167
1919–1945	89,329	28,320	118,699	4856	241,193
1945–1980	158,951	291,442	314,555	13,788	778,737
1981–2000	33,374	500,245	72,719	23,287	629,625
2001–2015	5112	84,360	1219	1271	91,961
Total	797,471	1,075,265	685,844	204,636	2,763,216

The resulting conversion factors are 9.52 for buildings built before 1919, 7.85 for buildings built 1919–1945, 6.26 for 1946–1980, 7.31 for 1981–2000, and 5.68 for buildings built after 2000. By applying these conversion factors, the $UFA_{demolished}$ for the year 2014 was determined. The missing data, namely $UFA_{demolished}$ for the years 2011–2013 and the year 2015, was calculated by linear interpolation.

In order to also consider renovation with respect to the thermal insulation of buildings, the useable floor area UFA_t at time t had to be further disaggregated into the useable floor area of rooftop extensions $UFA_{rooftop,t}$, the useable floor area not renovated $UFA_{not\ renovated,t}$ and the useable floor area renovated $UFA_{renovated,t}$. As UFA$_t$ and $UFA_{rooftop,t}$ had already been calculated, only $UFA_{renovated,t}$ was missing. The data for determining the later came from the Municipal Department MA50, responsible for housing in Vienna [39]. The data was available as living units and useable floor area renovated per decade (1991–2000) and per year (2001–2015). Personal communication with MA 50 further revealed that there are two types of renovation with respect to thermal insulation, namely thermal insulation renovation only, and a total renovation. The first is valid for the construction period 1946–1980 and the second for the construction period before 1919, while buildings in the construction period 1919–1945 are renovated under both types (50% each). According to MA50, the renovated living units and thus useable floor area can be divided among the three construction periods proportionally, thus relative to the number of living units of each construction period in the year 1991 (which was 321,750 living units for the construction period before 1919; 101,411 living units for the construction period 1919–1945; and 235,224 living units for the construction period 1946–1980). The concluding useable floor area renovated is shown in Appendix A (Table A1).

2.3.2. Calculating Material Stocks and Flows Using the Material Intensity per Useable Floor Area

After calculating the useable floor area, the material intensity given in kg/m^3 gross volume (MI_{GV}) was converted into kg/m^2 useable floor area (MI_{UFA}). This was done by multiplying the MI_{GV} by the $CF_{GV/UFA}$ as determined after Equation (8). Before doing so, however, the data set for the MI_{GV} must be completed for the building period categories, which are renovated or contain a rooftop extension. For the buildings that underwent a renovation with respect to thermal insulation, it was assumed that the material intensity MI of the materials usually built in in thermal insulation renovations, namely styrofoam, mineral wool, and glass ($MI_{styrofoam}$, $MI_{mineral\ wool}$, and MI_{glass}) is similar to that of residential and commercial buildings built between 2001 and 2015. The material intensity of the other building materials (e.g., concrete, bricks) does usually not change during thermal insulation renovations. For rooftop extension, the material stock of 16 randomly selected roof top extensions were analyzed based on the construction documents (i.e., construction plans). With this completed data set, the material stock $M_{ij,t}$ in each year t considered as well as the annual material inputs and outputs are calculated, using Equation (10), which was derived from Equation (4). The corresponding data for the material intensities *MI* is presented in Appendix A, Table A3.

$$M_{ij,t} = \sum_{i=1}^{l} \sum_{j=1}^{m} MI_{UFA,ij} \times UFA_{j,t} \tag{10}$$

2.4. Material Stocks and Flows Calculation for Non-Residential Buildings

For non-residential buildings (commercial, industrial, and other buildings), no such information for a time series as the development of the useable floor area, was available. For this reason, the gross volume in the end of the year 2013 (GV_{2013}, see Table 3) was used as a base for calculation.

For the calculation of the development of the building stock of buildings built before 1980, Equation (11) was used. The gross volume demolished ($GV_{demolished}$) per year was estimated by using the gross volume of non-residential buildings demolished in the year 2014 (see Table 3) and directly relating it to the amount of debris and concrete waste generated per year (see Appendix A Table A1—Relative CDW generation using the year 2014 as reference), thereby assuming a constant share between the demolished gross volume of residential and non-residential buildings The gross volume was calculated on an annual basis, starting with the gross volume in the year 2013 taken from Kleemann et al. (2017a) [15] (see Table 3).

$$GV_{t-1} = GV_t + \int_{t-1}^{t} GV_{demolished} dt \tag{11}$$

For the calculation of the development of the building stock of non-residential buildings built after 1981, Equation (11) was used. The only difference to Equation (10) is that for the buildings of this category, not only the gross volume demolished, but also the gross volume annually added to the stock through construction ($GV_{constructed}$) must be considered. $GV_{demolished}$ was calculated by using the gross volume demolished in the year 2014 (see Table 3) and directly relating it to the amount of debris and concrete waste generated per year (see Appendix A Table A1—Relative CDW generation using the year 2014 as reference). The annual gross volume constructed after the year 1990 was calculated based on the total amount of the gross volume constructed for the regarding building period (1981–2000 and 2001–2013) and dividing it by the regarding time span (10 years for the first building period, i.e., 1991–2000; 13 years for the second building period, i.e., 2001–2013). The gross volume of each year was then calculated on an annual basis, starting with the gross volume in the year 2013 (see Table 3).

$$GV_t = GV_{t-1} - \int_{t-1}^{t} GV_{demolished} dt \tag{12}$$

Renovation is neither relevant for other buildings, nor for industrial buildings, but for commercial buildings built before 1981. The annual renovation rate based on the building stock in the year 1990 is assumed to be 1% per year [40].

Using then the approach of Kleemann et al. (2017a) [15], the thereafter calculated gross volumes were multiplied after Equation (4) by the material intensities shown in Appendix A (Table A3).

2.5. Overview of Assumptions

The methodology section shows that calculating the material stocks and flows for buildings is based on a number of assumptions. Table 4 provides an overview on these assumptions.

Table 4. Underlying main assumptions in the study at hand. CDW: construction and demolition waste.

Section	Parameter	Assumption	Potential Uncertainties
2.3	Rooftop extension $UFA_{rooftop}$	1. Rooftop extensions between 1990–2015 were only applied to buildings built before 1946. 2. Eighty percent of rooftop extensions were constructed on buildings of the building period category <1919, and the average size is 411 m^2 UFA. 3. The number of rooftop extensions constructed per year are uniformly distributed for the time spans 1990–2000 and 2001–2015.	1. Rooftop extensions on buildings built after 1946 2. Small sample size to determine average size of rooftop extensions and distribution between building period categories 3. Distribution of rooftop extensions
2.3	Demolishing $UFA_{demolished}$	4. The number and UFA of buildings demolished follows the generation of debris in CDW.	4. CDW generation data gaps and demolishing of concrete buildings
2.3	Renovation $UFA_{renovated}$	5. Distribution of renovation activities between different building period categories	5. Different distribution than assumed based on authorities
2.3	Material intensity MI	6. Material intensity of renovated buildings and rooftop extension	6. Assumption incorrect, small sample size rooftop extensions
2.4	Gross volume non-residential buildings GV	7. Demolishing of GV of non-residential buildings based on CDW debris data 8. Construction uniformly distributes, 1% renovation rate	7. Non-consideration of concrete buildings 8. Distribution of construction

3. Results and Discussion

The detailed results of the calculations, which are presented and discussed in the following subsections, can be found in tabular form in Appendix A (Tables A4–A8).

3.1. Building Material Inputs

The annual material input between 1991 and 2015 was in the range of 3000 to 5000 kt/y. This corresponds to 1.8–3.1 t/capita/y. This value is in the range of typical European cities [11]. Driven by the construction activity for residential buildings, the input was highest in the 1990s due to public housing programs and slowed down rapidly by the end of the decade due to much lower construction activity, while it increased again after the year 2010. The material inputs were dominated by concrete, followed by brickwork (bricks, mortar, and plaster) and steel, the latter mainly in association to reinforced concrete. Other materials (such as mineral wool or glass) show a more constant annual input, but at a significant lower rate compared to the prior mentioned (see Figures 1 and 2).

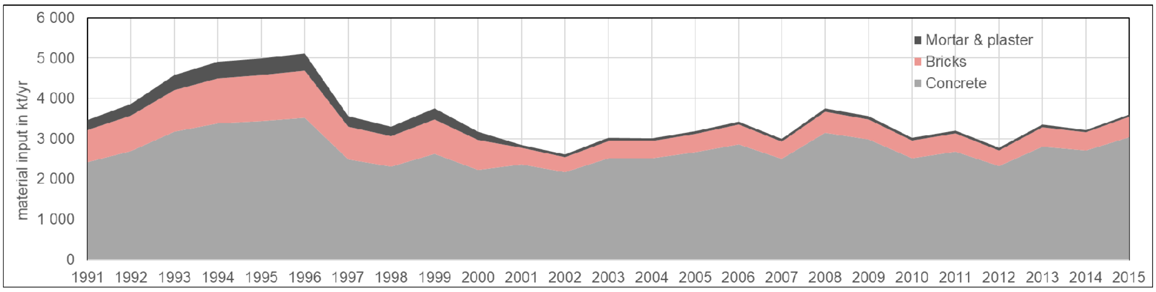

Figure 1. Material inputs in buildings in Vienna 1991–2015: concrete, bricks, mortar, and plaster.

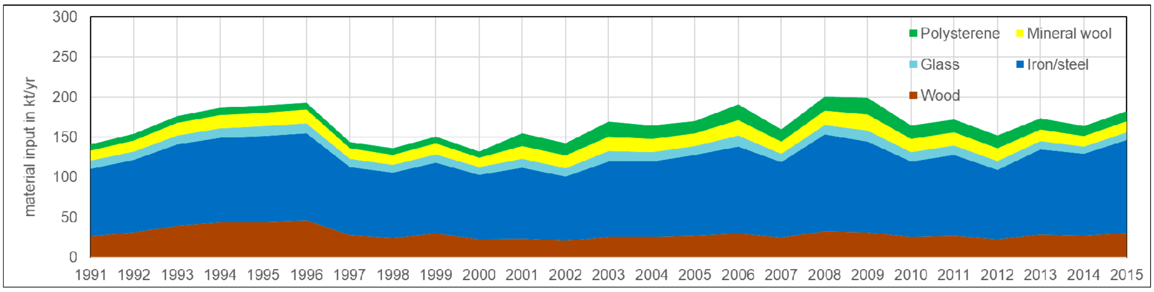

Figure 2. Material inputs in buildings in Vienna 1991–2015: polystyrene, mineral wool, glass, steel, and wood.

3.2. Building Material Outputs

On the output side, bricks were the most important material demolished, followed by concrete and mortar and plaster associated to brickwork. The material output from bricks and mortar and plaster increased gradually over time, while that of concrete only increased since the year 2000 (see Figure 3). Correspondingly, steel from reinforced concrete became an important construction and demolition waste (CDW) fraction, too (see Figure 4). Wood, another important CDW fraction, increased as well, particularly in association with brickwork. The reason for that is the high wood content in brick-based buildings [38].

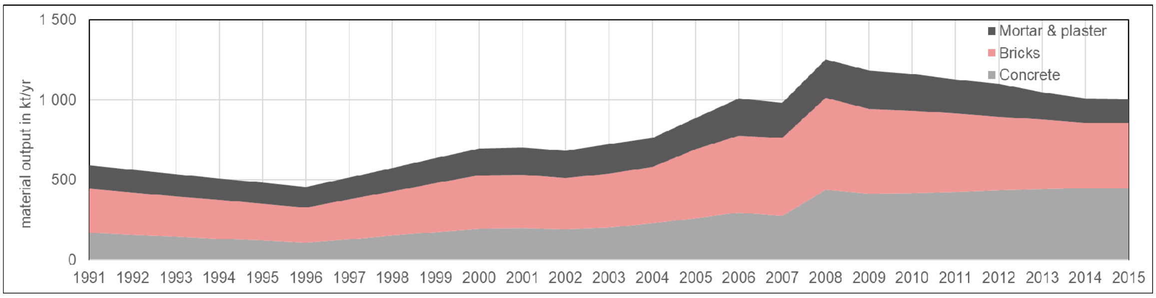

Figure 3. Material outputs of buildings in Vienna 1991–2015: concrete, bricks, mortar, and plaster.

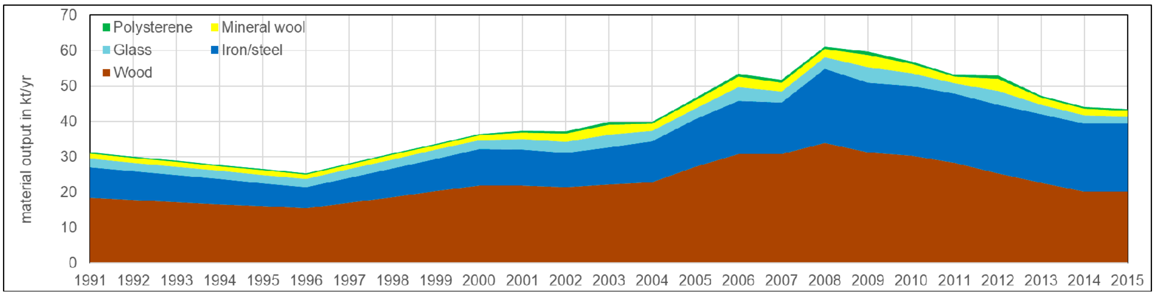

Figure 4. Material outputs of buildings in Vienna 1991–2015: polystyrene, mineral wool, glass, steel, and wood.

3.3. Building Material Stock Dynamics

The result of the material stock calculation is shown in Figure 5 and the subsequent tables. Between the years 1990 and 2015, the material stock increased from 274 to 345 million tons, corresponding to +26% over 25 years or 1% increase per year (see Table 5). This annual increase is higher than the 0.8% for the city center of Wakayama, Japan, between 1987 and 2004, or the 0.7% for Salford Quays, Manchester, UK, between 1990 and 2004 [16]. From a material perspective, concrete is mainly responsible for this growth, followed by bricks, and steel. The reason therefore is that old buildings demolished mainly consisted of brickwork, while newer buildings replacing the old ones are mainly consisting of concrete [15]. Concrete is used as it is superior to brickwork in terms of durability, stability, and construction time, which is particularly relevant when residential and commercial (including public) buildings have to be built for a growing population. This is contrary to the findings from Esche-sur-Alzette, Luxembourg, where a renaissance of brick-buildings was recorded in the 1990s [26].

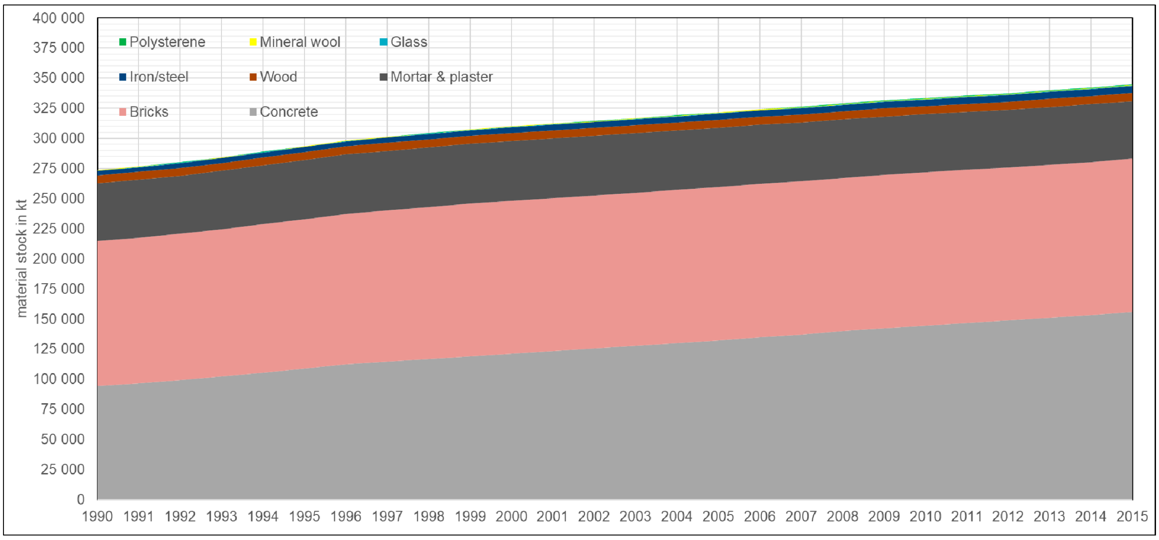

Figure 5. Development of the material stock in buildings in Vienna 1990–2015.

Table 5. Change in the composition of the building material stock between 1990 and 2015 in kt, t/cap, and %.

Material	1990	2000	2010	2015	1990	2000	2010	2015	1990	2000	2010	2015
	kt	kt	kt	kt	t/cap	t/cap	t/cap	t/cap	%	%	%	%
Concrete	94,483	121,264	144,566	155,895	63	77	85	85	35	39	43	45
Bricks	120,381	127,029	127,146	127,258	80	81	75	69	44	41	38	37
Mortar and plaster	47,969	49,704	48,374	47,810	32	32	28	26	18	16	15	14
Wood	6481	6638	6631	6650	4.3	4.2	3.9	3.6	2.4	2.1	2.0	1.9
Iron/steel	3780	4635	5478	5893	2.5	2.9	3.2	3.2	1.4	1.5	1.6	1.7
Glass	275	358	442	479	0.18	0.23	0.26	0.26	0.10	0.12	0.13	0.14
Mineral wool	236	366	514	578	0.16	0.23	0.30	0.31	0.09	0.12	0.15	0.17
Polystyrene	56	135	298	365	0.04	0.09	0.17	0.20	0.02	0.04	0.09	0.11
Total	273,662	310,128	333,449	344,928	182	197	196	187	100	100	100	100

From a pure quantitative perspective, other building materials do not contribute significantly to the stock increase. Having a look at the relative growth of each building material selectively as shown in Figure 6, however, it becomes clear that, even though having a little share in the overall material stock, the amount of insulation materials in buildings like polystyrene (increase by a factor of 6.5) and mineral wool ((increase by a factor of 2.5) increased at much higher rates if compared to the year 1990 (100%) than other construction materials. This indicates clearly the shift in building construction towards low energy buildings in times when Vienna introduced its first climate protection program [39]. While this shift has reportedly led to a reduction of greenhouse gas emissions in the building sector, the question is to which extend this reduction was rebound by using more CO_2 intensive concrete instead of less CO_2 intensive brickwork. One option to cope with that is the use of less CO_2 intensive building materials, like wood, brickwork, or even cements and concretes with lower embodied CO_2 emissions [41]. The latter can be achieved by lower clinker share in cement, alternative raw-mix for instance from the fine fraction of CDW debris, or recycling aggregate from CDW [42].

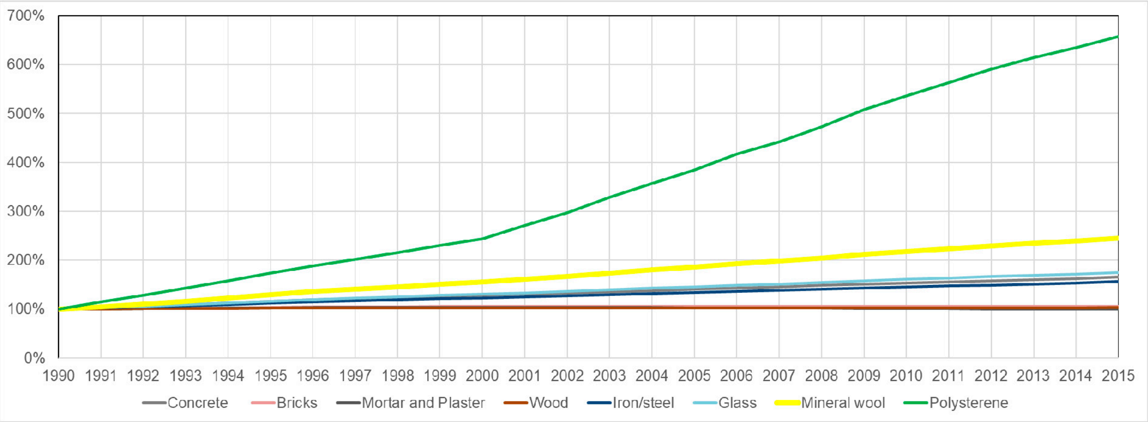

Figure 6. Index-based development of the material stock for each material based on the year 1990 (=100%).

With respect to the utilization, residential buildings is the one building category with the highest growth in absolute terms, particularly in the 1990s when a large number of residential buildings were constructed. In relative terms, the growth of commercial and other buildings was higher, while there is almost no overall growth in industrial buildings between 1990 and 2015, and even a decline in their material stock between 2000 and 2015 (Table 6).

Table 6. Change in the composition of the building material stock between 1990 and 2015 in kt and %.

Building Type	**1990**	**2000**	**2010**	**2015**	**1990**	**2000**	**2010**	**2015**
	kt	**kt**	**kt**	**kt**	**%**	**%**	**%**	**%**
Residential	180,064	198,917	216,255	225,824	66	64	65	65
Commercial	58,909	72,265	77,743	79,745	22	23	23	23
Industrial	20,758	22,982	22,361	21,738	8	7	7	6
Other buildings	13,931	15,965	17,090	17,621	5	5	5	5
Total	273,662	310,128	333,449	344,928	100	100	100	100

Besides the increase in the materials stock for building materials and buildings utilization, it is worth having a look of the material stock dynamics with respect to population growth. As shown in Figure 7, the material stock per capita increased in the 1990s, while it remained stable in the 2000s. After the year 2010, it decreased, as a consequence of the high population growth and the low construction activity between 1997 and 2010. This development is mainly driven by the residential building sector, as it corresponds to the development of the useable floor area, which was 38 m^2/capita in the year 1990, peaked at 41 m^2/capita in the year 2001, and decreased to 40 m^2/capita until the year 2015 [35]. This means that, while the overall material stock increased between 1990 and 2015 by 26%, the per capita material stock only increased by 5%. As the latter corresponds with the useable floor area of residential buildings that dominate the building stock, it can be concluded that in the 1990s, residential buildings were constructed for a stagnant population that used this activity to increase both, its useable floor area and thus its material stock. In the years after that, low construction activity in the residential sector together with high population growth lead to a phase of minor decoupling population with material consumption growth. This trend, even though desirable from a resource consumption perspective, lead to social impacts of questionable desirability, like steep increasing housing prices [43].

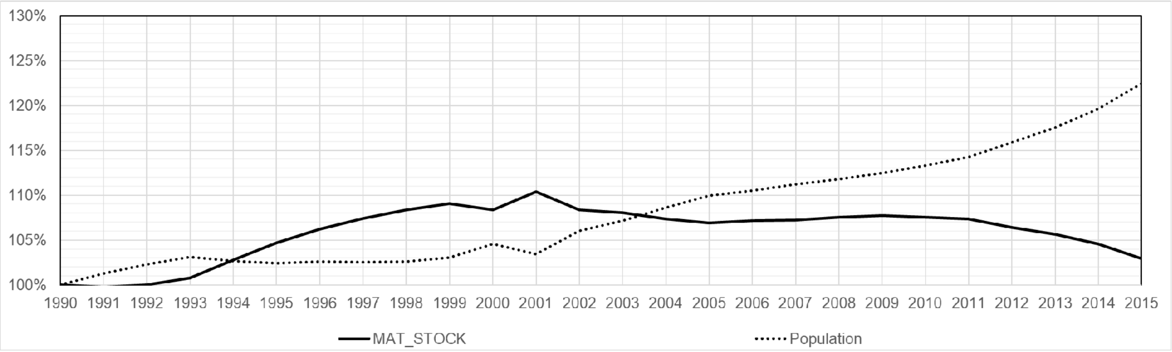

Figure 7. Index-based material stock and population development in Vienna between 1990 and 2015, based on the year 1990 (=100%).

4. Conclusions

The case study of the construction materials flows and stocks in the city of Vienna between 1990–2015 exemplarily showed some of the dynamics of modern European cities, even though these dynamics are not necessarily in line with initial hypothesis. With respect to the reaction of the construction sector and thus the construction material turnover, one might expect an increase in the material input and stock when population is increasing. However, the example of Vienna showed exactly the opposite trend, namely a strong increase when the population was declining in the 1990s, and a lower increase when the population was growing after the turn of the millennium. However, having a more detailed look also at the most recent statistical data on construction [19], it turns out that the construction sector only reacts to population growth after some time lag. The same was observed in the 1990s, even though the initial population growth in the beginning of this decade was much smaller than after the turn of the millennium. Contrary to that, the reaction to global warming by greenhouse gas mitigation manifested in the thermal insulation of buildings showed a more continuous trend. This has to do with a policy initiated in the 1990s by the climate action program [39] and continued by the Smart City Wien Framework Strategy that at the first time in the history of the city set some ambitious trans-sectoral targets for a sustainable urban future, amongst others by the reduction of greenhouse gas emissions, energy demand, and the consumption of raw materials in the building sector [44]. While some achievements were gained for the first of these objectives by the thermal insulation of buildings, the material stock is still growing, driven by the consumption of raw materials for building construction. Even though the per capita material stock in buildings decreased particularly in the years between 2010 and 2015, the question is not only if this is sufficient for the objectives of the Smart City Wien Framework Strategy, but also whether the causes for this decrease, namely a reduction of the useable floor area in residential buildings, is viable as a sole strategy. Of course, in the sense of sufficiency, a reduction of consumption of useable floor area can make sense, but in a city with a policy of pronounced social standards and equality like Vienna (which is also highlighted in its Smart City Wien Framework Strategy), this reduction must be distributed among as many individuals in society as possible. Thus, other options of resource conservation to reduce the growth of the material stock to a sustainable rate, like the avoidance of demolishing old but still livable buildings or enhanced recycling of construction and demolition waste, should be considered.

Author Contributions: J.L. developed the concept of the article, performed most of the calculations (unless stated otherwise) and wrote the article. A.G. carried out the GIS analysis for selecting the samples for determining the rooftop extensions, and proofread the document. U.M. contributed to the calculation of the effective floor areas and F.K. contributed to the calculation of the gross volume. C.S. coordinated the spatial planning calculations and J.F. reviewed the document. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Useable floor area UFA renovated according to construction period of renovated buildings.

	$\mathrm{UFA}_{\mathrm{demolished},t}$ [m^2/y]				$\mathrm{UFA}_{\mathrm{rooftop},t}$ [m^2/y]		$\mathrm{UFA}_{\mathrm{renovated},t}$ [m^2/y]			UFA_t [m^2]				
Year	**1946–1980**	**1919–1945**	**1946–1980**	**1981–2000**	**1800–1918**	**1800–1918**	**1946–1980**	**1919–1945**	**1946–1980**	**1946–1980**	**1919–1945**	**1946–1980**	**1981–2000**	**2001–2015**
1990										21,260,446	5,854,541	23,809,274	5,697,633	-
1991	60,046	20,492	4154		118,368	29,592	137,708	66,882	137,708	21,318,767	5,863,642	23,805,120	6,100,011	-
1992	58,102	19,828	4019		118,368	29,592	137,708	66,882	137,708	21,379,033	5,873,405	23,801,101	6,623,486	-
1993	56,158	19,165	3885		118,368	29,592	137,708	66,882	137,708	21,441,244	5,883,833	23,797,216	7,365,443	-
1994	54,213	18,501	3750		118,368	29,592	137,708	66,882	137,708	21,505,398	5,894,923	23,793,466	8,204,338	-
1995	52,269	17,838	3616		118,368	29,592	137,708	66,882	137,708	21,571,497	5,906,678	23,789,850	9,069,718	-
1996	50,325	17,174	3481		118,368	29,592	137,708	66,882	137,708	21,639,541	5,919,096	23,786,369	9,973,137	-
1997	55,651	18,992	3850		118,368	29,592	137,708	66,882	137,708	21,702,257	5,929,696	23,782,519	10,402,000	-
1998	60,978	20,810	4218		118,368	29,592	137,708	66,882	137,708	21,759,647	5,938,478	23,778,301	10,751,483	-
1999	66,305	22,628	4587		118,368	29,592	137,708	66,882	137,708	21,811,710	5,945,442	23,773,715	11,242,170	-
2000	71,632	24,445	4955		118,368	29,592	137,708	66,882	137,708	21,858,446	5,950,589	23,768,760	11,556,615	-
2001	72,296	24,672	5001		131,520	32,880	235,774	78,152	235,774	21,917,671	5,958,797	23,763,759	11,556,615	505,357
2002	72,960	24,899	5047		131,520	32,880	351,580	83,655	351,580	21,976,231	5,966,778	23,758,712	11,556,615	934,014
2003	73,624	25,125	5093		131,520	32,880	443,463	104,324	443,463	22,034,127	5,974,533	23,753,619	11,556,615	1,495,794
2004	74,288	25,352	5139		131,520	32,880	247,216	80,173	247,216	22,091,359	5,982,061	23,748,480	11,556,615	2,057,575
2005	92,583	31,596	6404		131,520	32,880	336,671	65,494	336,671	22,130,296	5,983,346	23,742,076	11,556,615	2,678,441
2006	103,205	35,220	7139		131,520	32,880	449,415	99,969	449,415	22,158,610	5,981,005	23,734,937	11,556,615	3,372,731
2007	103,488	35,317	7159		131,520	32,880	360,826	69,001	360,826	22,186,642	5,978,568	23,727,778	11,556,615	3,928,162
2008	110,397	37,675	7637		131,520	32,880	269,753	62,885	269,753	22,207,765	5,973,774	23,720,142	11,556,615	4,729,872
2009	99,938	34,105	6913		131,520	32,880	539,853	106,348	539,853	22,239,347	5,972,548	23,713,228	11,556,615	5,467,682
2010	96,006	32,763	6641	-	131,520	32,880	338,462	81,270	338,462	22,274,862	5,972,665	23,706,587	11,556,615	6,030,896
2011	84,771	27,419	11,333	1142	131,520	32,880	155,160	66,216	155,160	22,321,610	5,978,126	23,695,254	11,555,473	6,654,036
2012	73,537	22,074	16,025	2283	131,520	32,880	506,162	88,787	506,162	22,379,593	5,988,932	23,679,229	11,553,190	7,140,186
2013	62,302	16,729	20,717	3425	131,520	32,880	203,239	41,241	203,239	22,448,811	6,005,083	23,658,512	11,549,765	7,813,586
2014	51,068	11,384	25,409	4567	131,520	32,880	163,828	28,854	163,828	22,529,263	6,026,578	23,633,104	11,545,198	8,446,456
2015	51,068	11,384	25,409	4567	131,520	32,880	100,782	18,661	100,782	22,609,715	6,048,074	23,607,695	11,540,632	9,204,556

Table A2. Construction and demolition waste (CDW) generation in Vienna (in kt/y) for the period 1990–2015 (values in italic are linearly interpolated).

Name	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Debris	560,000						510,677				728,139				734,135	914,938	1,033,872	1,174,444	1,090,976	987,620					806,611	
Gravel	276,000						376,016				208,255				171,186	65,560	144,539	181,596	121,182	132,668					226,852	
Concrete	200,000						113,095				179,746				215,962	201,859	241,778	199,760	432,296	421,395					555,020	
Ballast											73					16,760			8376	20,682					30,599	
Asphalt											87,783				86,740	68,231	74,550	78,032	83,543	76,991					206,978	
CDW buildings																										
Debris	560,001	552,152	544,303	536,454	528,605	520,756	512,907	567,197	621,488	675,778	730,069	681,519	635,314	693,070	736,871	917,189	1,022,549	1,165,929	1,094,652	995,370	958,295	921,221	884,147	847,072	809,998	809,998
Concrete	136,000	120,626	105,252	89,878	74,504	59,130	43,756	64,106	84,456	104,806	125,155	136,381	127,135	138,693	168,400	177,187	201,377	151,883	394,544	382,732	395,070	407,408	419,746	432,083	444,421	444,421
Sub-total	746,001	721,491	696,982	672,473	647,964	623,454	598,945	678,501	758,058	837,614	917,170	874,053	814,795	888,868	964,191	1,153,203	1,293,099	1,409,709	1,570,491	1,463,621	1,432,679	1,401,737	1,370,795	1,339,853	1,308,911	1,308,911
Disaggregation 1991–2010																										
Debris		0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.05	0.05	0.05	0.04	0.05	0.05	0.06	0.07	0.08	0.07	0.07	0.07					
Concrete		0.04	0.03	0.03	0.02	0.02	0.01	0.02	0.03	0.03	0.04	0.04	0.04	0.04	0.05	0.06	0.06	0.05	0.13	0.12	0.13					
Relative CDW generation using the year 2014 as reference																										
Debris		0.68	0.67	0.66	0.65	0.64	0.63	0.70	0.77	0.83	0.90	0.84	0.78	0.86	0.91	1.13	1.26	1.44	1.35	1.23	1.18	1.14	1.09	1.05	1.00	1.00
Concrete		0.27	0.24	0.20	0.17	0.13	0.10	0.14	0.19	0.24	0.28	0.31	0.29	0.31	0.38	0.40	0.45	0.34	0.89	0.86	0.89	0.92	0.94	0.97	1.00	1.00
CDW infrastructure																										
Gravel+Asphalt	276,000	292,669	309,339	326,008	342,677	359,347	376,016	356,021	336,027	316,032	296,038	257,363	239,915	261,725	257,926	133,790	219,088	259,629	204,725	209,660	254,494	299,328	344,162	388,996	433,830	433,830
Concrete	64,000	64,890	65,780	66,669	67,559	68,449	69,339	65,652	61,965	58,278	54,591	47,459	44,241	48,263	47,563	24,671	40,401	47,877	37,752	38,662	46,930	55,197	63,465	71,732	80,000	80,000
Ballast track												-	-	-		16,760	13,966	11,171	8376	20,682	22,665	24,649	26,632	28,616	30,599	30,599
Sub-total	340,000	357,559	375,118	392,677	410,237	427,796	445,355	421,673	397,992	374,310	350,629	304,822	284,156	309,989	305,488	175,222	273,455	318,676	250,854	269,003	324,089	379,174	434,259	489,344	544,429	544,429

Table A3. Material intensities MI in kg/m^3 GV and kg/m^2 UFA for residential (R), commercial (C), industrial (I), and other (O) buildings.

	Building Period	**MI_{stock} [kg/m^3 GV]**				**$MI_{input,t}$ [kg/m^3 GV]**				**$MI_{output,t}$ [kg/m^3 GV]**				**Conversion Factor [-]**	**MI_{stock} [kg/m^2 UFA]**	**MI_{input} [kg/m^2 UFA]**	**MI_{output} [kg/m^2 UFA]**
	Building Use	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**R**	**R**	**R**
Concrete	1800–1918	22	23	48	23	0	0	0	0	22	23	48	23	9.5	276	0	209.4
	1800–1918 renov.	22	23	48	23	0	0	0	0	0	0	0	0	9.5	276	0	0
	1800–1918 rooftop	321	0	0	0	321	0	0	0	0.9	0	0	0	2.9	929.9	929.9	2.6
	1919–1945	100	120	110	104	0	0	0	0	100	120	110	104	7.8	1020.1	0	784.7
	1919–1945 renov.	100	120	110	104	0	0	0	0	0	0	0	0	7.8	1020.1	0	0
	1919–1945 rooftop	119	0	0	0	119	0	0	0	0.3	0	0	0	7.8	929.9	929.9	2.6
	1946–1980	240	270	250	246	0	0	0	0	240	270	250	246	6.3	1501.4	0	1501.4
	1946–1980 renov.	240	270	250	246	0	0	0	0	0	0	0	0	6.3	1501.4	0	0
	1981–2000	300	350	150	296	300	350	150	296	300	350	150	295	7.3	1973.2	2192.4	2192.4
	2001–2015	360	310	270	336	360	310	270	336	360	310	270	336	7.3	2557.9	2630.9	2630.9
Bricks	1800–1918	220	270	170	229	0	0	0	0	220	270	170	229	9.5	2189.2	0	2094
	1800–1918 renov.	220	270	170	229	0	0	0	0	0	0	0	0	9.5	2189.2	0	0
	1800–1918 rooftop	53	0	0	0	53	0	0	0	49	0	0	0	2.9	154.9	154.9	141.7
	1919–1945	180	180	180	180	0	0	0	0	180	180	180	180	7.8	1537.9	0	1412.4
	1919–1945 renov.	180	180	180	180	0	0	0	0	0	0	0	0	7.8	1537.9	0	0
	1919–1945 rooftop	20	0	0	0	20	0	0	0	18.1	0	0	0	7.8	154.9	154.9	141.7
	1946–1980	150	150	150	150	0	0	0	0	150	150	150	150	6.3	829.5	0	938.4
	1946–1980 renov.	150	150	150	150	0	0	0	0	0	0	0	0	6.3	829.5	0	0
	1981–2000	100	100	100	100	100	100	100	100	100	100	100	100	7.3	877	730.8	730.8
	2001–2015	58	58	58	58	58	58	58	58	58	58	58	58	7.3	394.6	423.9	423.9
Mortar/plaster	1800–1918	92	81	52	88	0	0	0	0	92	81	52	88	9.5	856.6	0	875.7
	1800–1918 renov.	87	80	51	88	3.8	7.5	0	0	9.2	8.1	0	0	9.5	866.2	36.2	87.6
	1800–1918 rooftop	21	0	0	0	21	0	0	0	12.2	0	0	0	2.9	60.9	60.9	35.4
	1919–1945	93	73	29	84	0	0	0	0	93	73	29	84	7.8	667	0	729.7
	1919–1945 renov.	88	73	29	84	3.8	7.5	0	0	9.3	7.3	0	0	7.8	678.7	29.8	73
	1919–1945 rooftop	7.8	0	0	0	7.8	0	0	0	4.5	0	0	0	7.8	60.9	60.9	35.4
	1946–1980	72	44	51	65	0	0	0	0	72	44	51	65	6.3	431.6	0	450.4
	1946–1980 renov.	69	47	54	59	3.8	7.5	0	0	7.2	4.4	5.1	6.5	6.3	451	23.8	45
	1981–2000	50	16	3.6	32	50	16	3.6	32	50	16	3.6	32	7.3	453.1	365.4	365.4
	2001–2015	3.8	7.5	5	5.2	3.8	7.5	5	5.2	3.8	7.5	5	5.2	7.3	73.1	27.8	27.8

Table A3. *Cont.*

	Building Period	**MI_{stock} [kg/m^3 GV]**				**$MI_{input,t}$ [kg/m^3 GV]**				**$MI_{output,t}$ [kg/m^3 GV]**				**Conversion Factor [-]**	**MI_{stock} [kg/m^2 UFA]**	**MI_{input} [kg/m^2 UFA]**	**MI_{output} [kg/m^2 UFA]**
	Building Use	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**R**	**R**	**R**
Wood	1800–1918	18	3.3	5.8	14	0	0	0	0	18	3.3	5.8	14	9.5	161.8	0	171.3
	1800–1918 renov.	18	3	5.5	14	0.2	0	0	0	0.4	0.4	0	0	9.5	160.2	1.9	3.5
	1800–1918 rooftop	6.4	0	0	0	6.4	0	0	0	9.3	0	0	0	2.9	18.5	18.5	27
	1919–1945	13	6.6	28	14	0	0	0	0	13	6.6	28	14	7.8	94.2	0	102
	1919–1945 renov.	13	6.3	28	14	0.2	0	0	0	0.3	0.3	0	0	7.8	93	1.6	2.7
	1919–1945 rooftop	2.4	0	0	0	2.4	0	0	0	3.4	0	0	0	7.8	18.5	18.5	27
	1946–1980	5.9	3.6	3.6	5.3	0	0	0	0	5.9	3.6	3.6	5.3	6.3	50	0	36.9
	1946–1980 renov.	6.1	3.6	3.6	5.3	0.2	0	0	0	0	0	0	0	6.3	51.3	1.2	0
	1981–2000	5.4	1.2	1.2	3.3	5.4	1.2	1.2	3.3	5.4	1.2	1.2	3.3	7.3	70.2	39.5	39.5
	2001–2015	4.3	0.8	2.1	2.9	4.3	0.8	2.1	2.9	4.3	0.8	2.1	2.9	7.3	60.7	31.4	31.4
Iron/Steel	1800–1918	2.7	4.1	8.7	3.2	0	0	0	0	2.7	4.1	8.7	3.2	9.5	33.3	0	25.7
	1800–1918 renov.	2.7	4.1	8.7	3.2	0	0	0	0	0	0	0	0	9.5	33.3	0	0
	1800–1918 rooftop	6.5	0	0	0	6.5	0	0	0	0	0	0	0	2.9	18.9	18.9	0
	1919–1945	4.6	6	5.8	4.9	0	0	0	0	4.6	6	5.8	4.9	7.8	39.2	0	36.1
	1919–1945 renov.	4.6	6	5.8	4.9	0	0	0	0	0	0	0	0	7.8	39.2	0	0
	1919–1945 rooftop	2.4	0	0	0	2.4	0	0	0	0	0	0	0	7.8	18.9	18.9	0
	1946–1980	6.9	5.7	12	7.2	0	0	0	0	6.9	5.7	12	7.2	6.3	51.9	0	43.2
	1946–1980 renov.	6.9	5.7	12	7.2	0	0	0	0	0	0	0	0	6.3	51.9	0	0
	1981–2000	6.7	13	14	9.9	6.7	13	14	9.9	6.7	13	14	9.9	7.3	80.4	49	49
	2001–2015	15	9.5	13	12.8	15	9.5	13	12.8	15	9.5	13	13	7.3	109.6	109.6	109.6
Glass	1800–1918	0.3	0.3	0.7	0.3	0	0	0	0	0.3	0.3	0.7	0.3	9.5	2.9	0	2.5
	1800–1918 renov.	0.9	0.6	1	0.3	0.9	0.6	0	0	0.3	0.3	0	0	9.5	12.4	8.6	2.5
	1800–1918 rooftop	2.3	0	0	0	2.3	0	0	0	0	0	0	0	2.9	6.6	6.6	0.1
	1919–1945	0.5	0.5	0.3	0.5	0	0	0	0	0.5	0.5	0.3	0.5	7.8	4.1	0	3.8
	1919–1945 renov.	0.9	0.6	0.4	0.5	0.9	0.6	0	0	0.5	0.5	0	0	7.8	10.2	7.1	3.8
	1919–1945 rooftop	0.8	0	0	0	0.8	0	0	0	0	0	0	0	7.8	6.6	6.6	0.1
	1946–1980	0.5	0.6	0	0.5	0	0	0	0	0.5	0.6	0	0.5	6.3	4.1	0	3.4
	1946–1980 renov.	0.9	0.6	0	0.5	0.9	0.6	0	0	0.5	0.6	0	0	6.3	8.1	5.6	3.4
	1981–2000	0.6	0.9	0	0.6	0.6	0.9	0	0.6	0.6	0.9	0	0.6	7.3	4.2	4	4
	2001–2015	0.9	0.6	0.5	0.8	0.9	0.6	0.5	0.8	0.9	0.6	0.5	0.8	7.3	9.5	6.6	6.6

Table A3. *Cont.*

	Building Period	**MI_{stock} [kg/m^3 GV]**				**$MI_{input,t}$ [kg/m^3 GV]**				**$MI_{output,t}$ [kg/m^3 GV]**				**Conversion Factor [-]**	**MI_{stock} [kg/m^2 UFA]**	**MI_{input} [kg/m^2 UFA]**	**MI_{output} [kg/m^2 UFA]**
	Building Use	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**C**	**I**	**O**	**R**	**R**	**R**	**R**
Mineral wool	1800–1918	0	0.3	0.1	0.1	0	0	0	0	0	0.3	0.1	0.1	9.5	3.2	0	0.2
	1800–1918 renov.	1.3	1.2	1	0.1	1.3	1.2	0	0	0	0.3	0	0	9.5	18.1	12.4	0.2
	1800–1918 rooftop	1.5	0	0	0	1.5	0	0	0	0.1	0	0	0	2.9	4.3	4.3	0.3
	1919–1945	0	0.1	0	0	0	0	0	0	0	0.1	0	0	7.8	1.8	0	0.1
	1919–1945 renov.	1.3	1.2	1.1	0	1.3	1.2	0	0	0	0.1	0	0	7.8	14.9	10.2	0.1
	1919–1945 rooftop	0.6	0	0	0	0.6	0	0	0	0	0	0	0	7.8	4.3	4.3	0.3
	1946–1980	0.7	0.9	0	0.7	0	0	0	0	0.7	0.9	0	0.7	6.3	11.2	0	4.4
	1946–1980 renov.	1.3	1.2	0.3	0.7	1.3	1.2	0	0	0.7	0.9	0	0	6.3	11.9	8.1	4.4
	1981–2000	1.3	0.3	0	0.8	1.3	0.3	0	0.8	1.3	0.3	0	0.8	7.3	0	9.5	9.5
	2001–2015	1.3	1.2	0.8	1.2	1.3	1.2	0.8	1.2	1.3	1.2	0.8	1.2	7.3	13.9	9.5	9.5
Polystyrene	1800–1918	0	0	0	0	0	0	0	0	0	0	0	0	9.5	0	0	0
	1800–1918 renov.	1.6	0.4	0.4	0	1.6	0.4	0	0	0	0	0	0	9.5	14.3	15.2	0
	1800–1918 rooftop	0.7	0	0	0	0.7	0	0	0	0.3	0	0	0	2.9	2.1	2.1	1
	1919–1945	0	0	0	0	0	0	0	0	0	0	0	0	7.8	0	0	0
	1919–1945 renov.	1.6	0.4	0.4	0	1.6	0.4	0	0	0	0	0	0	7.8	11.8	12.6	0
	1919–1945 rooftop	0.3	0	0	0	0.3	0	0	0	0.1	0	0	0	7.8	2.1	2.1	1
	1946–1980	0.2	0.2	0.2	0.2	0	0	0	0	0.2	0.2	0.2	0.2	6.3	1.4	0	1.4
	1946–1980 renov.	1.6	0.4	0.4	0.2	1.6	0.4	0	0	0.2	0.2	0	0	6.3	9.4	10	1.4
	1981–2000	0.2	0	0	0.1	0.2	0	0	0.1	0.2	0	0	0.1	7.3	1.3	1.3	1.3
	2001–2015	1.6	0.4	0.7	1.1	1.6	0.4	0.7	1.1	1.6	0.4	0.7	1.1	7.3	11	11.7	11.7

Table A4. Results Part A—All buildings (material flows given in kt/y, material stocks in kt).

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Population	**1,502,772**	**1,522,449**	**1,537,523**	**1,549,436**	**1,542,667**	**1,539,002**	**1,542,191**	**1,540,875**	**1,542,252**	**1,548,537**	**1,571,123**	**1,553,956**	**1,592,846**	**1,610,410**	**1,632,569**	**1,652,449**	**1,661,246**	**1,671,221**	**1,680,135**	**1,689,995**	**1,702,855**	**1,717,084**	**1,741,246**	**1,766,746**	**1,797,337**	**1,840,226**
0. All buildings																										
MAT_FLOW_INPUT		3610.25	4021.00	4762.08	5090.88	5180.72	5309.75	3700.09	3430.83	3909.79	3311.99	2996.34	2747.64	3189.69	3180.65	3363.21	3618.09	3151.85	3951.11	3761.23	3184.12	3374.52	2934.29	3523.70	3386.10	3789.07
Concrete		2424.48	2689.97	3168.99	3381.51	3439.58	3522.98	2482.54	2308.51	2618.09	2231.69	2365.78	2163.98	2514.22	2514.22	2669.67	2862.84	2497.52	3145.46	2977.35	2517.99	2675.66	2315.24	2807.89	2701.25	3030.73
Bricks		795.07	883.57	1043.24	1114.08	1133.44	1161.24	814.43	756.42	859.61	730.81	405.93	373.42	429.85	429.85	454.90	486.02	427.16	531.55	504.46	430.46	455.86	397.79	477.16	459.98	513.06
Mortar and plaster		249.43	293.68	373.52	408.94	418.62	432.52	259.11	230.10	281.70	217.30	69.89	68.08	76.27	71.87	68.85	78.76	67.72	73.83	80.77	71.33	70.83	69.55	65.29	61.32	62.76
Wood		26.32	31.10	39.72	43.55	44.59	46.09	27.36	24.23	29.80	22.85	23.48	21.09	25.51	25.28	26.89	29.61	24.87	32.57	31.02	25.29	27.06	22.89	28.28	26.86	30.69
Iron/steel		84.32	90.25	100.94	105.69	106.99	108.85	85.61	81.73	88.64	80.01	88.16	79.75	94.34	94.34	100.82	108.87	93.65	120.65	113.64	94.50	101.07	86.05	106.58	102.14	115.87
Glass		9.98	10.47	11.35	11.74	11.84	11.99	10.09	9.77	10.34	9.63	11.13	10.70	12.64	11.60	10.88	13.23	10.61	12.06	13.70	11.47	11.35	11.05	10.04	9.10	9.44
Mineral wool		12.60	13.75	15.83	16.75	17.00	17.36	12.85	12.10	13.44	11.77	16.28	15.66	18.46	16.96	15.93	19.32	15.54	17.63	20.00	16.77	16.60	16.16	14.71	13.35	13.84
Polystyrene		8.05	8.21	8.50	8.62	8.66	8.71	8.09	7.98	8.17	7.94	15.70	14.94	18.38	16.53	15.26	19.43	14.78	17.36	20.28	16.30	16.09	15.55	13.76	12.09	12.69
MAT_FLOW_OUTPUT		622.65	594.16	565.66	537.16	508.67	480.17	543.39	606.60	669.82	733.03	739.06	718.39	762.18	801.20	935.38	1061.90	1031.37	1313.12	1243.33	1217.67	1179.91	1150.48	1094.62	1054.07	1049.21
Concrete		170.08	157.65	145.21	132.78	120.35	107.91	130.13	152.35	174.57	196.79	200.28	189.94	203.73	228.68	262.43	295.21	274.97	438.89	415.29	417.97	425.93	433.89	441.85	449.81	449.81
Bricks		275.12	264.00	252.88	241.76	230.64	219.52	247.73	275.95	304.17	332.38	330.81	323.08	336.68	354.06	430.74	481.40	486.80	571.83	526.38	514.65	487.46	460.28	433.09	405.90	405.90
Mortar and plaster		146.28	142.50	138.72	134.94	131.16	127.38	137.40	147.42	157.43	167.45	170.68	168.15	181.97	178.67	195.62	231.87	217.97	241.39	241.98	228.23	213.48	203.43	172.50	154.32	150.15
Wood		18.35	17.76	17.18	16.59	16.01	15.42	17.04	18.65	20.26	21.87	21.78	21.33	22.13	22.82	27.15	30.70	30.71	33.95	31.29	30.37	28.22	25.29	22.71	20.16	20.11
Iron/steel		8.66	8.13	7.60	7.07	6.54	6.01	7.06	8.12	9.17	10.22	10.28	9.81	10.46	11.51	13.48	15.13	14.60	20.93	19.65	19.62	19.52	19.42	19.33	19.23	19.23
Glass		2.48	2.45	2.42	2.39	2.35	2.32	2.39	2.45	2.52	2.58	2.91	3.13	3.67	3.03	2.98	3.89	3.17	3.27	4.33	3.61	3.09	3.89	2.60	2.30	2.03
Mineral wool		1.38	1.36	1.35	1.33	1.32	1.30	1.33	1.36	1.39	1.42	1.85	2.33	2.77	1.94	2.35	2.91	2.48	2.28	3.45	2.56	1.80	3.35	2.04	1.89	1.61
Polystyrene		0.31	0.31	0.31	0.30	0.30	0.30	0.30	0.31	0.31	0.32	0.46	0.63	0.76	0.49	0.63	0.80	0.67	0.58	0.96	0.67	0.42	0.93	0.51	0.46	0.37
MAT_STOCK	273,662.28	276,649.88	280,076.72	284,273.14	288,826.86	293,498.92	298,328.49	301,485.20	304,309.43	307,549.40	310,128.35	312,385.63	314,414.88	316,842.39	319,221.84	321,649.66	324,205.86	326,326.34	328,964.33	331,482.23	333,448.68	335,643.29	337,427.10	339,856.18	342,188.21	344,928.07
Concrete	94,483.40	96,737.79	99,270.12	102,293.90	105,542.63	108,861.87	112,276.93	114,629.35	116,785.50	119,229.02	121,263.93	123,429.42	125,403.47	127,713.96	129,999.51	132,406.75	134,974.38	137,196.93	139,903.50	142,465.56	144,565.59	146,815.32	148,696.67	151,062.71	153,314.16	155,895.08
Bricks	120,381.47	120,901.42	121,521.00	122,311.36	123,183.69	124,086.49	125,028.22	125,594.91	126,075.37	126,630.82	127,029.24	127,104.37	127,154.72	127,247.88	127,323.67	127,347.83	127,352.44	127,292.80	127,252.52	127,230.60	127,146.41	127,114.81	127,052.33	127,096.40	127,150.48	127,257.64
Mortar and plaster	47,969.37	48,072.52	48,223.70	48,458.50	48,732.49	49,019.94	49,325.08	49,446.79	49,529.48	49,653.74	49,703.59	49,602.80	49,502.74	49,397.04	49,290.24	49,163.47	49,010.37	48,860.12	48,692.56	48,531.36	48,374.46	48,231.81	48,097.92	47,990.71	47,897.72	47,810.32
Wood	6481.21	6489.18	6502.51	6525.06	6552.01	6580.59	6611.26	6621.59	6627.18	6636.72	6637.70	6639.40	6639.16	6642.54	6645.00	6644.74	6643.65	6637.82	6636.44	6636.17	6631.10	6629.95	6627.55	6633.12	6639.81	6650.39
Iron/steel	3780.08	3855.73	3937.85	4031.20	4129.82	4230.26	4333.10	4411.66	4485.27	4564.74	4634.53	4712.41	4782.34	4866.22	4949.05	5036.40	5130.14	5209.18	5308.90	5402.88	5477.77	5559.32	5625.95	5713.20	5796.11	5892.75
Glass	274.89	282.40	290.42	299.35	308.70	318.19	327.86	335.56	342.87	350.69	357.73	365.95	373.52	382.49	391.06	398.95	408.29	415.74	424.53	433.91	441.77	450.03	457.19	464.62	471.43	478.84
Mineral wool	236.28	247.50	259.89	274.37	289.78	305.47	321.52	333.05	343.78	355.84	366.18	380.61	393.94	409.64	424.66	438.24	454.65	467.71	483.06	499.61	513.82	528.62	541.43	554.09	565.55	577.78
Polystyrene	55.59	63.33	71.23	79.42	87.74	96.10	104.52	112.30	119.98	127.83	135.44	150.68	164.99	182.61	198.65	213.29	231.93	246.04	262.82	282.14	297.77	313.44	328.06	341.32	352.95	365.27

Table A5. Results Part B—Residential buildings.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Population	**1,502,772**	**1,522,449**	**1,537,523**	**1,549,436**	**1,542,667**	**1,539,002**	**1,542,191**	**1,540,875**	**1,542,252**	**1,548,537**	**1,571,123**	**1,553,956**	**1,592,846**	**1,610,410**	**1,632,569**	**1,652,449**	**1,661,246**	**1,671,221**	**1,680,135**	**1,689,995**	**1,702,855**	**1,717,084**	**1,741,246**	**1,766,746**	**1,797,337**	**1,840,226**
1. Residential buildings																										
MAT_FLOW_INPUT		1574.74	1985.49	2726.57	3055.37	3145.21	3274.24	1664.58	1395.32	1874.28	1276.48	1876.77	1628.07	2070.12	2061.08	2243.64	2498.52	2032.28	2831.54	2641.66	2064.55	2254.95	1814.72	2404.13	2266.53	2669.50
Concrete		1019.78	1285.28	1764.29	1976.82	2034.88	2118.28	1077.85	903.81	1213.39	826.99	1482.43	1280.64	1630.88	1630.88	1786.33	1979.50	1614.18	2262.12	2094.00	1634.65	1792.31	1431.90	1924.55	1817.91	2147.39
Bricks		316.99	405.48	565.16	636.00	655.35	683.15	336.34	278.33	381.52	252.72	239.68	207.16	263.59	263.59	288.64	319.76	260.90	365.29	338.21	264.20	289.60	231.53	310.90	293.72	346.81
Mortar and plaster		172.08	216.33	296.16	331.58	341.26	355.16	181.75	152.75	204.35	139.95	42.07	40.27	48.46	44.06	41.04	50.95	39.90	46.02	52.96	43.51	43.01	41.73	37.48	33.51	34.94
Wood		19.46	24.23	32.86	36.68	37.73	39.23	20.50	17.37	22.94	15.99	19.87	17.47	21.89	21.66	23.27	25.99	21.25	28.95	27.40	21.68	23.44	19.27	24.66	23.24	27.07
Iron/steel		22.50	28.43	39.13	43.88	45.17	47.04	23.80	19.91	26.83	18.20	58.51	50.10	64.70	64.70	71.17	79.22	64.00	91.00	83.99	64.85	71.42	56.41	76.93	72.49	86.22
Glass		6.39	6.87	7.75	8.14	8.25	8.40	6.49	6.18	6.74	6.03	8.67	8.25	10.19	9.14	8.43	10.78	8.16	9.61	11.25	9.02	8.90	8.59	7.59	6.65	6.99
Mineral wool		9.95	11.10	13.18	14.10	14.35	14.71	10.20	9.45	10.79	9.11	11.68	11.07	13.87	12.36	11.33	14.72	10.94	13.03	15.41	12.17	12.00	11.57	10.11	8.75	9.24
Polystyrene		7.60	7.76	8.05	8.17	8.21	8.26	7.63	7.53	7.72	7.48	13.85	13.10	16.54	14.69	13.42	17.59	12.94	15.52	18.44	14.46	14.25	13.71	11.92	10.25	10.85
MAT_FLOW_OUTPUT		318.84	309.83	300.82	291.82	282.81	273.80	298.48	323.15	347.83	372.50	380.05	383.15	397.23	390.28	462.28	531.13	514.39	545.17	517.41	488.71	447.89	415.42	356.51	312.91	308.04
Concrete		34.89	33.76	32.63	31.50	30.37	29.24	32.34	35.43	38.53	41.62	42.01	42.39	42.78	43.16	53.79	59.97	60.13	64.14	58.07	55.78	58.78	61.78	64.79	67.79	67.79
Bricks		158.58	153.44	148.31	143.17	138.04	132.90	146.97	161.04	175.11	189.17	190.93	192.68	194.43	196.19	244.50	272.56	273.30	291.55	263.93	253.54	227.71	201.87	176.03	150.20	150.20
Mortar and plaster		106.57	104.32	102.07	99.82	97.58	95.33	101.49	107.64	113.80	119.96	124.33	124.45	134.95	127.50	136.25	166.20	150.20	157.57	163.23	150.06	135.89	126.42	96.07	78.47	74.30
Wood		13.74	13.34	12.93	12.53	12.12	11.71	12.83	13.94	15.05	16.16	16.27	16.17	16.53	16.69	19.87	22.57	22.15	23.73	21.76	20.96	18.92	16.11	13.65	11.22	11.17
Iron/steel		2.46	2.38	2.30	2.22	2.14	2.06	2.28	2.50	2.72	2.94	2.96	2.99	3.02	3.05	3.80	4.23	4.24	4.53	4.10	3.94	3.71	3.49	3.27	3.04	3.04
Glass		1.70	1.69	1.69	1.68	1.67	1.66	1.68	1.70	1.73	1.75	2.08	2.32	2.82	2.14	2.02	2.86	2.16	1.97	3.08	2.35	1.82	2.62	1.33	1.02	0.75
Mineral wool		0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.70	0.70	1.13	1.63	2.05	1.18	1.56	2.08	1.67	1.28	2.47	1.58	0.82	2.36	1.05	0.90	0.62
Polystyrene		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.35	0.51	0.65	0.36	0.49	0.66	0.53	0.40	0.79	0.50	0.24	0.75	0.33	0.28	0.19
MAT_STOCK	180,064.39	181,320.29	182,995.95	185,421.70	188,185.25	191,047.65	194,048.08	195,414.17	196,486.35	198,012.79	198,916.77	200,413.49	201,658.41	203,331.29	205,002.10	206,783.46	208,750.85	210,268.74	212,555.12	214,679.36	216,255.20	218,062.26	219,461.56	221,509.19	223,462.81	225,824.26
Concrete	57,284.21	58,269.10	59,520.62	61,252.27	63,197.59	65,202.10	67,291.15	68,336.66	69,205.04	70,379.90	71,165.27	72,605.70	73,843.95	75,432.06	77,019.78	78,752.32	80,671.85	82,225.90	84,423.88	86,459.81	88,038.68	89,772.22	91,142.33	93,002.09	94,752.22	96,831.82
Bricks	79,293.71	79,452.12	79,704.16	80,121.01	80,613.84	81,131.15	81,681.41	81,870.78	81,988.07	82,194.49	82,258.04	82,306.79	82,321.27	82,390.43	82,457.84	82,501.97	82,549.17	82,536.77	82,610.52	82,684.79	82,695.45	82,757.35	82,787.01	82,921.89	83,065.42	83,262.03
Mortar and plaster	35,695.36	35,760.87	35,872.88	36,066.97	36,298.73	36,542.41	36,802.24	36,882.51	36,927.62	37,018.16	37,038.15	36,955.89	36,871.71	36,785.21	36,701.77	36,606.56	36,491.32	36,381.02	36,269.47	36,159.21	36,052.67	35,959.79	35,875.11	35,816.52	35,771.56	35,732.21
Wood	5343.30	5349.02	5359.91	5379.84	5403.99	5429.60	5457.12	5464.79	5468.22	5476.11	5475.94	5479.54	5480.84	5486.20	5491.17	5494.58	5498.00	5497.10	5502.32	5507.96	5508.67	5513.19	5516.35	5527.36	5539.38	5555.28
Iron/steel	2064.39	2084.43	2110.48	2147.31	2188.97	2232.00	2276.97	2298.49	2315.90	2340.01	2355.28	2410.82	2457.93	2519.61	2581.26	2648.64	2723.63	2783.39	2869.86	2949.76	3010.67	3078.38	3131.30	3204.97	3274.41	3357.59
Glass	178.46	183.14	188.32	194.39	200.86	207.44	214.18	218.99	223.46	228.48	232.76	239.36	245.29	252.65	259.66	266.07	273.98	279.98	287.62	295.79	302.46	309.54	315.51	321.76	327.39	333.62
Mineral wool	163.21	172.46	182.87	195.36	208.76	222.42	236.44	245.95	254.70	264.80	273.21	283.76	293.20	305.02	316.19	325.97	338.60	347.87	359.63	372.56	383.15	394.34	403.54	412.60	420.46	429.09
Polystyrene	41.75	49.15	56.70	64.55	72.52	80.52	88.58	96.01	103.33	110.84	118.12	131.63	144.21	160.11	174.43	187.36	204.30	216.71	231.83	249.48	263.44	277.45	290.41	302.00	311.97	322.63

Table A6. Results Part C—Commercial buildings.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Population	**1,502,772**	**1,522,449**	**1,537,523**	**1,549,436**	**1,542,667**	**1,539,002**	**1,542,191**	**1,540,875**	**1,542,252**	**1,548,537**	**1,571,123**	**1,553,956**	**1,592,846**	**1,610,410**	**1,632,569**	**1,652,449**	**1,661,246**	**1,671,221**	**1,680,135**	**1,689,995**	**1,702,855**	**1,717,084**	**1,741,246**	**1,766,746**	**1,797,337**	**1,840,226**
2. Commercial buildings																										
MAT_FLOW_INPUT		1488.78	1488.78	1488.78	1488.78	1488.78	1488.78	1488.78	1488.78	1488.78	1488.78	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05	849.05
Concrete		1074.91	1074.91	1074.91	1074.91	1074.91	1074.91	1074.91	1074.91	1074.91	1074.91	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99	669.99
Bricks		307.12	307.12	307.12	307.12	307.12	307.12	307.12	307.12	307.12	307.12	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35
Mortar and plaster		57.13	57.13	57.13	57.13	57.13	57.13	57.13	57.13	57.13	57.13	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20	24.20
Wood		3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.73	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86
Iron/steel		39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53	20.53
Glass		3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Mineral wool		2.26	2.26	2.26	2.26	2.26	2.26	2.26	2.26	2.26	2.26	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87	3.87
Polystyrene		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23
MAT_FLOW_OUTPUT		174.71	162.06	149.41	136.76	124.11	111.46	134.20	156.93	179.67	202.41	204.24	190.96	207.55	235.91	267.14	299.74	282.04	455.06	432.61	436.85	441.08	445.31	449.54	453.77	453.77
Concrete		86.07	78.00	69.92	61.84	53.76	45.68	58.41	71.13	83.85	96.58	99.96	93.19	101.66	118.59	131.34	148.36	130.15	248.63	238.11	242.59	247.06	251.54	256.02	260.49	260.49
Bricks		59.71	56.30	52.89	49.47	46.06	42.65	50.11	57.58	65.04	72.51	71.35	66.52	72.56	81.08	94.83	106.45	106.78	147.55	138.66	138.49	138.32	138.14	137.97	137.80	137.80
Mortar and plaster		23.19	22.39	21.60	20.80	20.00	19.21	21.13	23.05	24.98	26.90	26.41	25.11	26.74	28.84	32.78	35.87	36.65	45.36	42.90	42.68	42.47	42.25	42.03	41.81	41.81
Wood		1.24	1.18	1.12	1.06	1.00	0.94	1.07	1.19	1.32	1.44	1.43	1.35	1.45	1.59	1.81	2.00	1.99	2.71	2.56	2.56	2.56	2.57	2.57	2.57	2.57
Iron/steel		3.07	2.80	2.53	2.26	1.99	1.72	2.16	2.61	3.05	3.49	3.58	3.34	3.64	4.22	4.71	5.32	4.78	8.65	8.27	8.40	8.53	8.66	8.79	8.93	8.93
Glass		0.68	0.66	0.64	0.62	0.60	0.58	0.61	0.65	0.68	0.71	0.72	0.70	0.72	0.77	0.80	0.85	0.81	1.09	1.06	1.07	1.08	1.09	1.10	1.11	1.11
Mineral wool		0.66	0.65	0.64	0.63	0.61	0.60	0.62	0.65	0.67	0.69	0.69	0.68	0.70	0.73	0.76	0.79	0.77	0.95	0.93	0.93	0.94	0.94	0.95	0.95	0.95
Polystyrene		0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
MAT_STOCK	58,908.63	60,222.71	61,549.43	62,888.80	64,240.82	65,605.49	66,982.82	68,337.40	69,669.25	70,978.36	72,264.73	72,909.54	73,567.63	74,209.12	74,822.26	75,404.16	75,953.47	76,520.48	76,914.46	77,330.89	77,743.09	78,151.06	78,554.80	78,954.31	79,349.58	79,744.86
Concrete	22,941.05	23,929.88	24,926.79	25,931.78	26,944.85	27,965.99	28,995.21	30,011.71	31,015.48	32,006.54	32,984.86	33,554.89	34,131.70	34,700.03	35,251.43	35,790.08	36,311.71	36,851.56	37,272.92	37,704.80	38,132.21	38,555.14	38,973.59	39,387.57	39,797.07	40,206.57
Bricks	26,778.22	27,025.62	27,276.44	27,530.67	27,788.31	28,049.37	28,313.84	28,570.84	28,820.38	29,062.45	29,297.06	29,351.06	29,409.90	29,462.69	29,506.97	29,537.48	29,556.39	29,574.96	29,552.77	29,539.46	29,526.32	29,513.36	29,500.57	29,487.95	29,475.51	29,463.06
Mortar and plaster	7717.26	7751.21	7785.94	7821.48	7857.81	7894.94	7932.87	7968.87	8002.94	8035.10	8065.33	8063.12	8062.22	8059.68	8055.05	8046.47	8034.80	8022.35	8001.20	7982.50	7964.01	7945.75	7927.71	7909.88	7892.28	7874.67
Wood	425.55	428.05	430.61	433.22	435.90	438.63	441.42	444.09	446.63	449.05	451.34	451.78	452.30	452.72	453.00	453.05	452.92	452.79	451.95	451.25	450.55	449.85	449.15	448.45	447.74	447.04
Iron/steel	909.39	946.25	983.37	1020.77	1058.43	1096.37	1134.57	1172.34	1209.66	1246.53	1282.97	1299.92	1317.11	1334.00	1350.32	1366.14	1381.35	1397.10	1408.98	1421.25	1433.38	1445.38	1457.25	1468.99	1480.60	1492.20
Glass	71.31	73.93	76.57	79.23	81.92	84.62	87.34	90.03	92.68	95.30	97.89	99.17	100.47	101.75	102.99	104.18	105.33	106.52	107.43	108.37	109.30	110.22	111.13	112.03	112.92	113.81
Mineral wool	59.31	60.90	62.51	64.14	65.77	67.42	69.09	70.73	72.34	73.93	75.50	78.68	81.87	85.05	88.19	91.31	94.39	97.49	100.41	103.35	106.29	109.22	112.15	115.07	117.99	120.91
Polystyrene	6.54	6.86	7.18	7.51	7.83	8.16	8.49	8.81	9.13	9.45	9.77	10.91	12.05	13.19	14.32	15.45	16.58	17.71	18.82	19.93	21.04	22.15	23.26	24.37	25.48	26.59

Table A7. Results Part D—Industrial buildings.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Population	**1,502,772**	**1,522,449**	**1,537,523**	**1,549,436**	**1,542,667**	**1,539,002**	**1,542,191**	**1,540,875**	**1,542,252**	**1,548,537**	**1,571,123**	**1,553,956**	**1,592,846**	**1,610,410**	**1,632,569**	**1,652,449**	**1,661,246**	**1,671,221**	**1,680,135**	**1,689,995**	**1,702,855**	**1,717,084**	**1,741,246**	**1,766,746**	**1,797,337**	**1,840,226**
3. Industrial buildings																										
MAT_FLOW_INPUT		324.27	324.27	324.27	324.27	324.27	324.27	324.27	324.27	324.27	324.27	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35	125.35
Concrete		180.95	180.95	180.95	180.95	180.95	180.95	180.95	180.95	180.95	180.95	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67	96.67
Bricks		120.64	120.64	120.64	120.64	120.64	120.64	120.64	120.64	120.64	120.64	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77	20.77
Mortar and plaster		4.34	4.34	4.34	4.34	4.34	4.34	4.34	4.34	4.34	4.34	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79
Wood		1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Iron/steel		16.89	16.89	16.89	16.89	16.89	16.89	16.89	16.89	16.89	16.89	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65
Glass		-	-	-	-	-	-	-	-	-	0.00	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Mineral wool		-	-	-	-	-	-	-	-	-	0.00	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Polystyrene		-	-	-	-	-	-	-	-	-	0.00	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
MAT_FLOW_OUTPUT		109.55	103.47	97.40	91.32	85.24	79.16	92.74	106.33	119.91	133.49	131.08	122.19	133.30	148.65	174.30	195.59	197.30	268.61	252.18	251.59	250.99	250.40	249.81	249.21	249.21
Concrete		44.52	41.63	38.75	35.86	32.97	30.08	35.86	41.64	47.42	53.20	52.89	49.30	53.79	60.64	70.13	78.82	77.03	113.93	107.56	107.95	108.33	108.72	109.10	109.49	109.49
Bricks		46.68	44.40	42.11	39.83	37.54	35.26	40.86	46.45	52.05	57.65	56.13	52.33	57.09	63.18	74.79	83.84	86.37	110.98	103.76	103.05	102.34	101.63	100.92	100.21	100.21
Mortar and plaster		12.58	11.96	11.33	10.70	10.08	9.45	10.97	12.48	14.00	15.51	15.12	14.09	15.38	17.03	20.14	22.58	23.20	30.03	28.09	27.91	27.74	27.56	27.38	27.21	27.21
Wood		2.77	2.66	2.55	2.45	2.34	2.23	2.55	2.86	3.18	3.49	3.35	3.13	3.41	3.73	4.48	5.02	5.34	6.25	5.80	5.72	5.63	5.55	5.46	5.38	5.38
Iron/steel		2.89	2.72	2.55	2.39	2.22	2.05	2.41	2.78	3.14	3.50	3.45	3.22	3.51	3.93	4.59	5.15	5.15	7.18	6.75	6.75	6.74	6.74	6.73	6.73	6.73
Glass		0.08	0.08	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.10	0.09	0.09	0.10	0.10	0.13	0.14	0.16	0.16	0.15	0.15	0.14	0.14	0.13	0.13	0.13
Mineral wool		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Polystyrene		0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
MAT_STOCK	20,757.91	20,972.63	21,193.43	21,420.30	21,653.26	21,892.29	22,137.39	22,368.92	22,586.86	22,791.23	22,982.01	22,976.29	22,979.45	22,971.50	22,948.20	22,899.25	22,829.01	22,757.06	22,613.81	22,486.98	22,360.75	22,235.11	22,110.06	21,985.61	21,861.75	21,737.89
Concrete	9221.97	9358.40	9497.72	9639.93	9785.03	9933.01	10,083.89	10,228.99	10,368.30	10,501.84	10,629.59	10,673.38	10,720.75	10,763.64	10,799.67	10,826.21	10,844.07	10,863.71	10,846.45	10,835.56	10,824.29	10,812.63	10,800.58	10,788.15	10,775.34	10,762.52
Bricks	8363.35	8437.31	8513.55	8592.07	8672.88	8755.97	8841.35	8921.13	8995.31	9063.89	9126.88	9091.52	9059.96	9023.64	8981.23	8927.20	8864.13	8798.53	8708.31	8625.32	8543.04	8461.47	8380.60	8300.45	8221.00	8141.56
Mortar and plaster	2153.61	2145.38	2137.76	2130.78	2124.42	2118.68	2113.57	2106.95	2098.81	2089.15	2077.99	2064.66	2052.35	2038.77	2023.52	2005.17	1984.39	1962.97	1934.74	1908.44	1882.32	1856.38	1830.61	1805.01	1779.60	1754.18
Wood	390.90	389.58	388.37	387.26	386.26	385.37	384.58	383.48	382.07	380.34	378.29	375.69	373.32	370.66	367.68	363.95	359.68	355.10	349.60	344.55	339.59	334.71	329.91	325.20	320.58	315.96
Iron/steel	611.66	625.66	639.83	654.16	668.67	683.34	698.18	712.65	726.76	740.51	753.90	755.10	756.54	757.69	758.41	758.48	757.99	757.50	754.97	752.88	750.79	748.70	746.62	744.54	742.47	740.39
Glass	10.90	10.82	10.75	10.67	10.60	10.53	10.47	10.39	10.31	10.22	10.12	10.20	10.30	10.39	10.47	10.52	10.56	10.59	10.61	10.64	10.68	10.72	10.77	10.82	10.87	10.92
Mineral wool	1.18	1.17	1.16	1.15	1.15	1.14	1.13	1.12	1.11	1.10	1.09	1.38	1.67	1.95	2.24	2.52	2.80	3.08	3.36	3.64	3.92	4.21	4.49	4.77	5.05	5.33
Polystyrene	4.34	4.31	4.29	4.28	4.26	4.24	4.23	4.21	4.19	4.17	4.14	4.36	4.57	4.78	4.98	5.19	5.38	5.58	5.76	5.94	6.12	6.31	6.49	6.66	6.84	7.02

Table A8. Results Part E—Other buildings.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Population	**1,502,772**	**1,522,449**	**1,537,523**	**1,549,436**	**1,542,667**	**1,539,002**	**1,542,191**	**1,540,875**	**1,542,252**	**1,548,537**	**1,571,123**	**1,553,956**	**1,592,846**	**1,610,410**	**1,632,569**	**1,652,449**	**1,661,246**	**1,671,221**	**1,680,135**	**1,689,995**	**1,702,855**	**1,717,084**	**1,741,246**	**1,766,746**	**1,797,337**	**1,840,226**
4. Other buildings																										
MAT_FLOW_INPUT		222.46	222.46	222.46	222.46	222.46	222.46	222.46	222.46	222.46	222.46	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17	145.17
Concrete		148.84	148.84	148.84	148.84	148.84	148.84	148.84	148.84	148.84	148.84	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67	116.67
Bricks		50.33	50.33	50.33	50.33	50.33	50.33	50.33	50.33	50.33	50.33	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14	20.14
Mortar and plaster		15.88	15.88	15.88	15.88	15.88	15.88	15.88	15.88	15.88	15.88	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82
Wood		1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Iron/steel		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46	4.46
Glass		0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Mineral wool		0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Polystyrene		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
MAT_FLOW_OUTPUT		19.56	18.79	18.03	17.27	16.50	15.74	17.97	20.19	22.41	24.64	23.69	22.09	24.10	26.36	31.66	35.43	37.64	44.29	41.12	40.53	39.94	39.36	38.77	38.18	38.18
Concrete		4.59	4.26	3.92	3.58	3.25	2.91	3.53	4.15	4.77	5.39	5.42	5.05	5.51	6.27	7.17	8.07	7.66	12.18	11.55	11.65	11.75	11.84	11.94	12.04	12.04
Bricks		10.15	9.86	9.57	9.28	9.00	8.71	9.79	10.88	11.97	13.06	12.39	11.55	12.60	13.62	16.61	18.56	20.35	21.75	20.03	19.57	19.10	18.63	18.17	17.70	17.70
Mortar and plaster		3.94	3.83	3.72	3.61	3.50	3.39	3.82	4.24	4.66	5.08	4.82	4.49	4.90	5.29	6.46	7.22	7.92	8.43	7.76	7.58	7.39	7.21	7.02	6.84	6.84
Wood		0.60	0.59	0.57	0.56	0.54	0.53	0.59	0.66	0.72	0.78	0.74	0.69	0.75	0.81	0.99	1.11	1.23	1.26	1.16	1.13	1.10	1.06	1.03	1.00	1.00
Iron/steel		0.24	0.23	0.21	0.20	0.19	0.18	0.21	0.23	0.26	0.29	0.29	0.27	0.29	0.32	0.38	0.43	0.44	0.58	0.54	0.54	0.54	0.53	0.53	0.53	0.53
Glass		0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Mineral wool		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Polystyrene		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01
MAT_STOCK	13,931.35	14,134.25	14,337.92	14,542.35	14,747.54	14,953.49	15,160.21	15,364.70	15,566.97	15,767.01	15,964.83	16,086.31	16,209.40	16,330.47	16,449.28	16,562.79	16,672.53	16,780.06	16,880.94	16,984.99	17,089.63	17,194.86	17,300.68	17,407.08	17,514.07	17,621.06
Concrete	5036.17	5180.41	5325.00	5469.91	5615.17	5760.76	5906.69	6051.99	6196.68	6340.75	6484.19	6595.45	6707.07	6818.24	6928.64	7038.14	7146.75	7255.77	7360.26	7465.38	7570.41	7675.33	7780.16	7884.90	7989.54	8094.17
Bricks	5946.19	5986.38	6026.85	6067.61	6108.66	6150.00	6191.63	6232.17	6271.62	6309.98	6347.26	6355.01	6363.59	6371.12	6377.64	6381.17	6382.75	6382.54	6380.92	6381.03	6381.60	6382.64	6384.15	6386.12	6388.55	6390.99
Mortar and plaster	2403.14	2415.07	2427.12	2439.27	2451.54	2463.91	2476.40	2488.46	2500.11	2511.33	2522.13	2519.13	2516.46	2513.38	2509.91	2505.27	2499.87	2493.77	2487.16	2481.22	2475.46	2469.89	2464.50	2459.30	2,454.28	2449.26
Wood	321.45	322.53	323.62	324.73	325.85	326.99	328.14	329.23	330.26	331.22	332.12	332.39	332.70	332.95	333.15	333.16	333.06	332.83	332.57	332.42	332.29	332.20	332.14	332.10	332.11	332.11
Iron/steel	194.63	199.39	204.17	208.95	213.75	218.56	223.38	228.18	232.94	237.68	242.38	246.56	250.75	254.92	259.06	263.14	267.17	271.20	275.08	279.00	282.92	286.85	290.77	294.70	298.63	302.57
Glass	14.23	14.50	14.77	15.05	15.32	15.60	15.88	16.15	16.42	16.69	16.96	17.21	17.45	17.70	17.94	18.18	18.42	18.65	18.88	19.11	19.33	19.56	19.79	20.02	20.25	20.48
Mineral wool	12.59	12.97	13.34	13.72	14.10	14.48	14.87	15.25	15.62	16.00	16.38	16.79	17.21	17.62	18.03	18.44	18.85	19.26	19.66	20.06	20.46	20.85	21.25	21.65	22.05	22.44
Polystyrene	2.96	3.00	3.05	3.09	3.14	3.18	3.23	3.27	3.32	3.36	3.40	3.78	4.16	4.54	4.91	5.29	5.66	6.04	6.41	6.79	7.16	7.54	7.91	8.29	8.66	9.03

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