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Inflows and Outflows from Material Stocks of Buildings and Networks and their Space-Differentiated Drivers: The Case Study of the Paris Region

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Abstract: Urbanization causes massive flows of construction materials and waste, which generates environmental impacts and land-use conflicts. Circular economy strategies at a local scale and in coordination with urban planning could respond to those issues. Implementing these strategies raises challenges as it requires a better knowledge of flows and their space-differentiated drivers. This article focuses on the case of the Paris region (*Ile-de-France*) in 2013. Construction materials inflows and outflows to and from anthropogenic stocks of buildings and networks are estimated and located though a bottom-up approach based on the collection and processing of geolocalized data. Flow analysis focuses on the relationship between urbanization and flows with a view to establishing context-specific circular economy strategies. Results show that regional inflows of construction materials to stocks in 2013 reach between 1.8 and 2.1 t/capita while outflows are between 1.0 and 1.5 t/capita. Both inflows and outflows are mainly driven by building construction and demolition as well as by road renewal. The region is composed of three sub-urban areas and flows per capita in the dense central city of Paris are significantly lower than in the low-density outskirt area of Grande Couronne (GC). Road renewal accounts for a larger share of flows in GC. Future research will address methodological limits.

Keywords: construction materials; material flow analysis (MFA); urbanization; circular economy; metabolism

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1. Introduction

1.1. Issues Related to Urbanization and Construction Material Flows

Urbanization is one of the main drivers of global resource demand. Cities account for more than three-quarters of the world's material and energy consumption [1,2]. Construction materials form the most important inflows into cities and emissions to the natural environment [3]. Their consumption increased tenfold from 1950 to 2005 [3] and could double again until 2060 compared to 2011 [4].

Ninety percent of the world's material consumption comes from natural resources. Indeed, the materials derived from recycling account for only one-tenth of the consumption [5]. Therefore, urbanization generates a significant extraction of largely non-renewable and sometimes scarce natural resources. It also produces massive flows of construction and demolition (C&D) waste sent to landfill. Waste management, as well as material production, transforms landscapes and generates land-use conflicts and environmental impacts [6].

1.2. A Lack of Coordination Between Circular Economy Strategies and Urban Planning

Developing circular economy strategies aims to respond to the issues raised by construction material flows. In the European Union (EU), the construction sector is the target area of the circular economy roadmap [7,8]. Construction is one of the five priority sectors defined by the European Commission [9] for the European Action Plan for a Circular Economy. It is also one of the main sectors targeted in 2020 in France by the act of law against waste and for a circular economy as well as by French regions in their circular economy roadmaps.

According to the analysis of the conceptualization of the circular economy by Reike and colleagues [10] (pp. 249–250) "the distinction of various preservation stages of resource value using hierarchical R-ladders or imperatives, is an essential operationalization principle" for circular strategies. A review of sixteen definitions of circular economy in the construction sector shows that approaches based on R-imperatives are the most common [11]. Circle Economy and colleagues [12] provide a good example of hierarchical imperatives: (1) to reduce the demand for resources and associated impacts to a minimum; (2) to identify local synergies that can satisfy these demands; (3) to use clean, renewable, recycled, or low-impact sources for the remaining needs.

Developing such strategies raises many technical, organizational, financial, and legal challenges [11,13,14]. Three limits of approaches of circular economy in construction are pointed in [11]: a lack of coordination with urban planning, a limited integration of spatial scales, and a low consideration of the local context. Indeed, a lack of coordination between strategies led by cities or regions and urban planning is observed in Europe [15,16]. According to the International Resource Panel [6], material flows should be reduced by influencing urbanization. Reducing materials flows "requires rethinking the shape of urban agglomerations to minimize infrastructure stocks" and "reducing resource consumption induced by the structure and spread of the urban fabric" [17] (p. 182). Therefore, the scale of the construction site must be exceeded in order to transform the entire existing built area [18,19]. Circular economy can only be achieved if strategies integrate different scales in a coherent way [20].

Linking circular economy and urban planning also calls for a better knowledge of construction material and waste flows and the urban drivers that shape them. Indeed, this information is critical for local authorities and construction project owners and it is needed on a scale related to stakeholders [21,22]. For example, in France, urban planning is set up at the level of local governments (intermunicipal authorities), which coordinate local stakeholders to promote local environmental policy and circular economy. In addition, understanding space-differentiated drivers is essential for urban policymaking, material-efficient spatial and infrastructure planning, and for implementing circular economy strategies at the urban and regional levels [17,21–23].

Moreover, to evaluate material potentials for reuse and to ensure circular loops in the construction sector, it is necessary to understand how, where, and when the materials are extracted from stocks [24]. Indeed, the availability of anthropogenic (secondary) resources varies greatly according to the territories. This variability impacts the potential for substitution of primary resources by secondary ones. Brunner [25] considers that three phases of urban development must be distinguished to better prioritize circular economy actions, from the reduction of flows to recycling and reuse. However, statistics on resources, and particularly anthropogenic ones, are very often limited [26]. For instance, in France, C&D waste statistics are usually available at a regional scale only and do not allow for fine distinction of materials [27]. Moreover, statistics, in France as in the rest of the EU, do not enable to link the C&D waste flows to types of projects such as public works, buildings, and civil structures [28].

1.3. Research on the Space-Differentiated Drivers of Construction Material Flows and Its Gap

Research on construction material flows strongly developed during the last 30 years [26,29]. Early studies evaluate those materials as part of their analysis of all material flows and focused on the exchange of flows between major economic activities and compared resource consumption to local production [30,31]. In recent literature, studies dealing with the construction sector alone have become abundant [29]. Research led to the development of robust methods for estimating and locating flows and it provided rich knowledge on the areas that were the subject of case studies [29]. However, it has two main gaps with regard to the challenge of better coordinating circular economy strategies and urban planning.

First, a better knowledge of flows on urban and regional levels is needed. Indeed, as shown by Lanau and colleagues [26] who review 249 publications dealing with material stocks and also often with flows, the national scale is dominant in studies of construction material flows. Only 23% of the reviewed publications tackle the urban level and 7% the regional level. A growing number of studies analyze the urban and regional scales. However, they often have a limited scope: e.g. one building type (dwellings) or one material (concrete) [29]. This scope limits the analysis of the impact on flows of urban and spatial factors, such as the distribution of flows between buildings and networks [29]. Other studies include different types of buildings and networks as well as different materials, but they are often limited to a small spatial scale like the city of Orléans (France) [32]. Therefore, tracking and locating construction material flows on a vast urban area remains a challenge [21–23].

Secondly, a better understanding of the urban and spatial drivers of construction material stocks and flows is needed. Some key studies provided a better knowledge of these drivers. Schiller [33] compared seven urban structure types in cities of Saxony (Germany) and showed that material stocks in networks are higher in low building density areas. Huang and colleagues [34] showed that the period of urban sprawl in Chinese cities matches with those of the growth in per capita material intensity. Wang and colleagues [35] highlighted the intimate relationship between local elections and road extension, thus the growth of related material stocks. Schandl and colleagues [21] showed the impact of urban planning, land use changes, and economic development on construction material stocks by period of construction. The development of case studies would provide a better understanding of the factors. Moreover, since comparison between case studies is difficult due to methodological differences [26,29], flow analysis in a vast urban area in which several sub-spaces can be distinguished would be useful.

In order to address those gaps, massive data on buildings, networks, and associated flows at urban and regional scales need to be collected and processed. This can be based on existing methods for material flow analysis (MFA) and particularly on the bottom-up approach, which is adapted to quantify and locate flows on an urban or regional level [36]. However, it is data intensive. Data quality and unavailability are considered as major barriers for bottom-up flow analysis [26,29].

Four main categories of methodological approaches can be identified: static top-down, static bottom-up, dynamic retrospective or prospective using a flow-driven model, and dynamic retrospective or prospective using a stock-driven model [29]. Those approaches are complementary and they are often combined [29]. In general, the dynamic approach is adopted to predict the flows, as in [37,38], while the static approach is used to study the current state of the construction materials flows during a reference year. Figure 1 summarizes the principles, advantages, and drawbacks of static top-down and bottom-up approaches.

The bottom-up approach is more adapted to flow analysis on an urban level than the top-down one [29]. Indeed, although the latter allows flows to be partially related to urban factors, as in [39], the processes that generate flows within the studied system cannot be precisely identified with such approach. Moreover, due to missing data, it is difficult to apply this approach on a fine spatial scale like a city [29]. Besides, the bottom-up approach can use geo-localized data on material stocks to estimate and locate flows. Indeed, many recent studies focus on localizing building stocks using spatial data and Geographic Information System (GIS) modeling approach. The latter for the study of the Japanese building stocks [40], has been largely applied in urban and regional case studies [21,35,41,42]. Therefore, although research on construction material flows at an urban level requires massive data, it can be based on existing methodological frameworks.

1.4. Objectives and Plan

This study aims at better understanding the relationship between urbanization and construction material flows with a view to establishing circular economy strategies which are coordinated with urban planning. Which urban and space-differentiated drivers shape construction material flows? To answer this question, the case-study of the Paris region (*Ile-de-France*) in France in 2013 is chosen. It is a vast urbanized area where different sub-urban areas can be distinguished. Flows and urbanization patterns in those areas are compared. Inflows and outflows of construction materials to and from anthropogenic stocks of buildings and networks in the entire region are estimated and located though a bottom-up approach. In order to study the impact of urban forms on flows, the scope of the study includes a large number of networks: road, rail, electricity, gas, heating and cooling, drinking water, non-potable water, and sewerage.

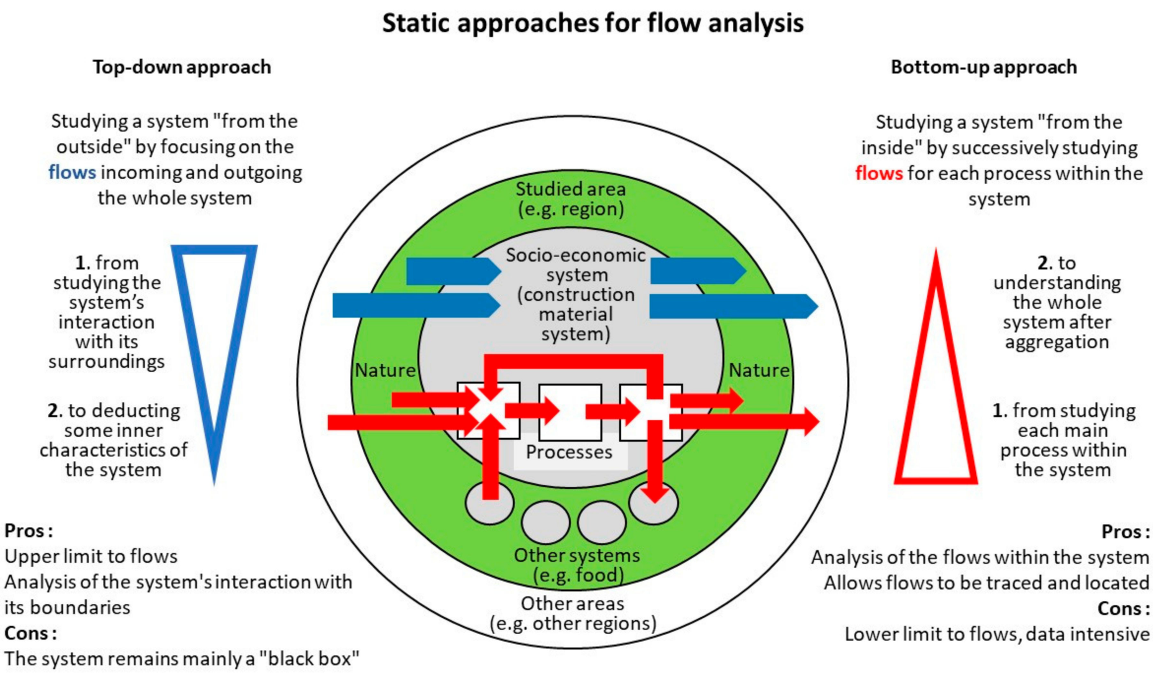

Figure 1. Comparison of static top-down and bottom-up approaches for flow analysis. Source: authors.

This article is organized as follows. Section 2 introduces the Paris region case study (2.1) and describes the methods and data used to estimate and locate regional construction material flows (2.2 to 2.5) as well as the urban indicators used to compare areas and analyze flows (2.6). Section 3 presents the results. It provides insights on construction material flows: (1) for all the region by process (3.1) and material (3.2); (2) for each sub-urban area completed with a comparison of the urban indicators (3.3 and 3.4). Section 4 discusses the quality of the data sources and the technical validation of the results. Section 5 discusses the impact of urban factors on material flows (5.1). Then, it suggests an outline for the implementation of a circular economy strategy in the region based on material flow analysis (5.2). Finally, it examines the limits of the study and identifies perspectives for future research (5.3).

2. Materials and Methods

2.1. Study Area

The Paris region covers more than 12,000 square kilometers and has about 12 million residents. The region is divided into eight administrative subdivisions called *départements* which form three intra-regional areas. As presented in Figure 2, those inner sub-urban areas are characterized by very different urban forms: Paris municipality, the dense city center, *Petite Couronne* (PC), the Paris near suburb, and *Grande Couronne* (GC), outskirt area with a low population and building density (characteristics are detailed in [43]).

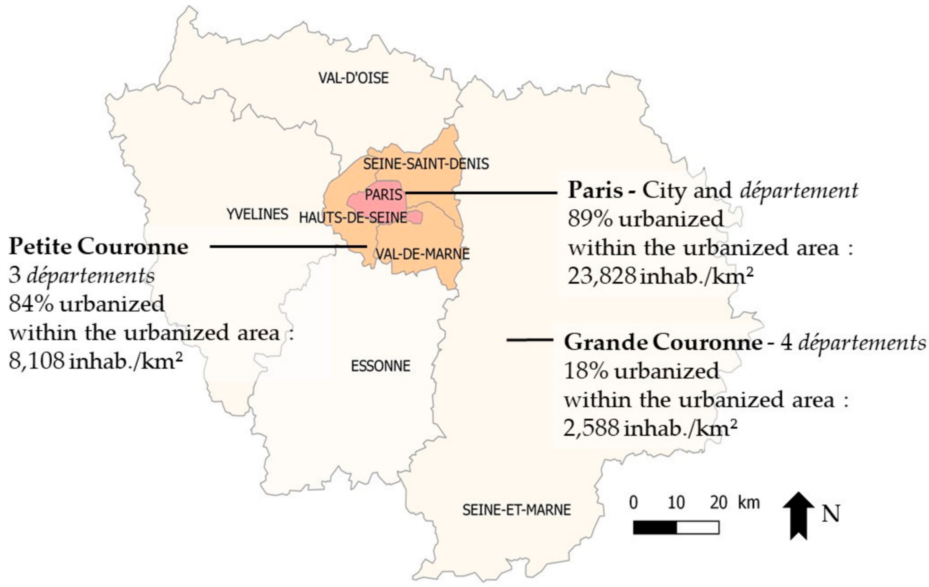

Figure 2. Urban characteristics of Paris, Petite Couronne, and Grande Couronne, 2013. Source: data from INSEE and MOS 2012, background from IGN.

The region is the subject of land planning and resources management policies. The Regional Council is in charge of the Regional Master Plan (SDRIF) which sets objectives from 2013 to 2030 for housing construction and transport network development. The Council is also in charge of the C&D waste management plan (PRPGD) and the circular economy roadmap. Another authority, the Regional and Interdepartmental Directorate for the Environment and Energy (DRIEE), is in charge of the regional planning scheme for quarries. The management of timber resources is also planned at the regional level.

2.2. Scope

This study covers material flows in the Paris region in 2013. It focuses on the direct inflows of construction materials and outflows of C&D waste to and from the anthropogenic material stocks located in buildings and networks. It excludes flows related to raw materials extraction and their transformation by industries, as well as flows associated with C&D waste management. With reference to the life-cycle stages of a building or network according to the CEN TC350 standards, this study excludes the product stage and the waste processing (C3) and disposal (C4) processes [44].

Inflows include two main categories of processes: construction, also called development for networks (A5 in CEN TC350), and refurbishment, also referred to as renewal (B5 in CEN TC350). Outflows include two main categories of processes: refurbishment-renewal, as well as demolition (C1 in CEN TC350). Other inflows and outflows during the use stage are excluded: use, maintenance, repair, replacement. Therefore, dissipative flows to nature due to the wear and tear of buildings and networks are not taken into account. Moreover, unused materials during construction-development or refurbishment-renewal, which become waste and do not enter or leave anthropogenic stocks, are excluded. However, it can be noticed that some inflows to stocks may result from the recycling or reuse of waste. Flows of excavated materials, pit-run material (which may include aggregates), and soil are also excluded in this study.

Table 1 presents the scope of this study. Due to missing data, flows associated with the construction and renovation of tunnels, as well as the development and renovation of aerodrome runways, are excluded. Twenty-six materials are taken into account, including 14 non-metallic minerals (see details in Table S1).

Table 1. Scope.

ee	Groups of Buildings or Networks	Partially or totally Included	If Partially Included, Buildings or Networks Excluded Due to Incomplete Data
Buildings	Buildings	Partially included	Sport buildings; buildings dedicated to art, entertainment, and recreation; agricultural buildings; greenhouses; silos; tolls; sport field stands; historical and religious buildings; underground car parks; light constructions, huts, meadows, awnings; sport grounds
Transport networks	Road network	Partially included	Gravel roads and paths, sidewalks, tunnels, bridges (excluding the binder courses and the surface courses overlying bridges); noise barriers; stairs
	Railway network	Partially included	Tunnels, bridges, and viaducts (excluding rails, sleepers, and ballast located on bridges and viaducts); marshalling yards
	Aerodrome runways	Not included	/
	River network	Not included	/
Energy and water networks	Electricity networks	Partially included	Pylons; transformers; wind turbines
	Gas networks	Fully included	/
	Heating and cooling networks	Fully included	/
	Drinking water networks	Partially included	Aqueducts (excluding pipelines); water towers and other water reservoirs
	Non-potable water network	Partially included	Aqueducts (excluding pipelines)
	Sewerage networks	Partially included	Sewerage treatment plants
	Pipeline transportation of dangerous goods networks	Not included	/
Telecommunication networks	Telephone cable and optical fiber	Not included	/

Source: authors.

2.3. Overall Method

Inflows and outflows to and from the anthropogenic stocks are estimated through a static bottom-up approach. Inflows and outflows associated with each selected process are estimated and then summed. Processes are: (1) the construction of buildings and the development of each group of networks (inflows only); (2) the refurbishment of buildings and the renewal of each type of networks (inflows and outflows); (3) the demolition of buildings (outflows only). Demolition of networks in the region in 2013 is unsignificant (see Section 2.4) and processes are not included. Therefore, the total inflows are equal to the sum of inflows associated with the construction-development and refurbishment-renewal of each type of building or network. Total outflows are equal to the sum of outflows associated with the refurbishment-renewal and demolition of each type of building or network.

Each flow (in kg) is calculated by multiplying dimensions (surfaces in m^2 for buildings and roads and lengths in m for other networks) by material intensities (in kg/m^2 or kg/m). Buildings and networks are grouped by archetypes and it considered that within an archetype, they have the same material intensity. This assumption is used in bottom-up studies of construction materials [26,29]. Figure 3 summarizes the bottom-up approach to estimated flows generated by buildings, road, and railway networks. The method for estimating dimensions is detailed in Section 2.4 and material intensities are presented in Section 2.5. Complete details about the method can be found in a report [27].

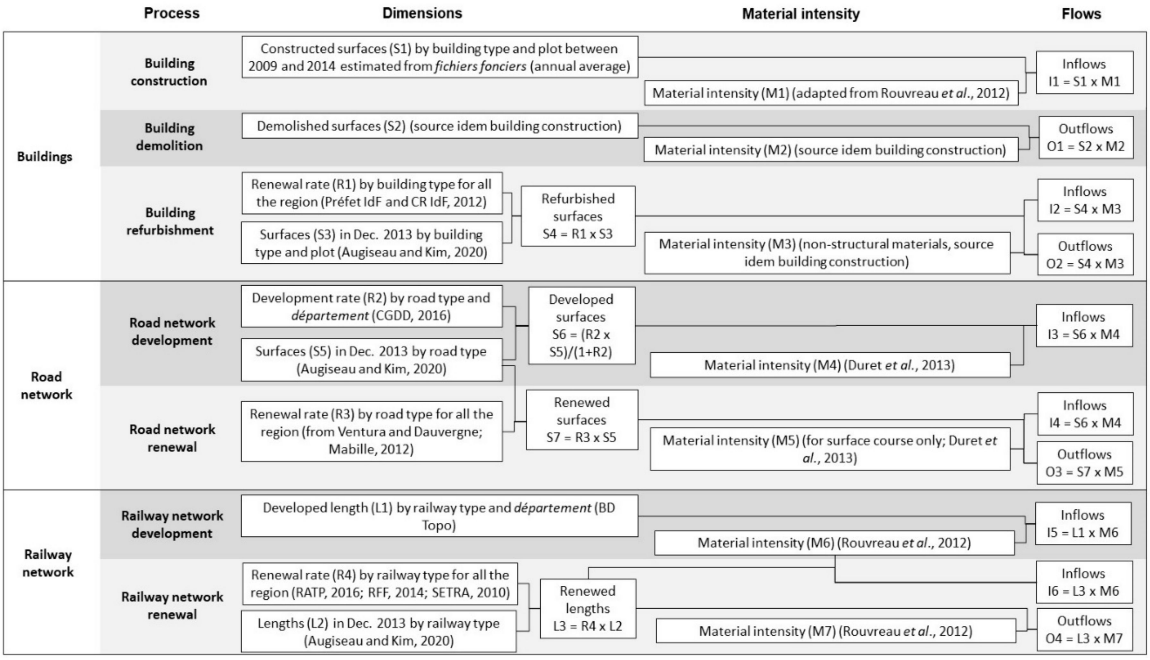

Figure 3. Methodological framework to estimate flows generated by buildings, road, and railway networks. Source: authors (data sources mentioned in this figure are presented in references [32,43,45–51].

2.4. Method for Estimating Dimensions

Two main approaches are used to estimate dimensions: (1) dimensions can be estimated directly with available data sources (case of constructed and demolished surfaces of buildings and developed lengths of railways), (2) dimensions (m^2 or m) need to be calculated by multiplying a rate (%) with the corresponding stock dimensions in 2013 (m^2 or m).

To estimate and locate anthropogenic stocks, we refer to our article on building and network stocks with a bottom-up approach in the Paris region [43]. The stocks are located up to the building plot level at their finest spatial scale. Stocks include materials located in most of the buildings (24 building archetypes), roads, railways, and energy and water networks. Data sources and the method used to estimate the dimensions of the stocks are presented in [43]. Stocks calculated in [43] are materials located in the region on 31 December 2013. Therefore, developed surfaces or lengths during the year 2013 are calculated according to the following formula:

$$\text{Developed surface or length in 2013} = (\text{Development rate} \times \text{Stock surface or length in 2013})/(1 + \text{Development rate})$$

To estimate constructed and demolished building gross floor areas during 2013, the French national land property database (*fichiers fonciers*) is used. This database registers building uses, construction dates, and building surfaces (net floor area called *surface réelle*) at the level of the building plot. We observe construction works registered in two available versions of the *fichiers fonciers*: one dated on 1 January 2009 and the other on 1 January 2014. The total data on 3,535,851 land plots are extracted to observe the changes made in buildings between those two time points. For each building plot, aboveground net floor areas in 2009 and 2014 are compared: a larger area in 2014 than in 2009 indicates a construction, and a lower area a demolition. Criteria on minimum construction year and minimum surface are also used to avoid an over-estimation of built or demolished surface areas (see Table S2). Changes during five years are observed with the two available versions of the *fichiers fonciers* used. Therefore, annual averages of constructed and demolished areas are calculated. It is assumed that those average values are representative of the year 2013. Aboveground net floor areas (*surfaces réelles*) according to *fichiers fonciers* are converted in aboveground and underground gross floor surface areas with coefficients calculated by cross-referencing BD Topo and *fichiers fonciers* (see Tables S3 and S4).

To estimate refurbished surface areas of buildings, we refer to renewal rates defined by building archetype for all the region by the Paris Regional Council and Prefect [45]. This data source indicates the refurbishment rates observed in 2012 and objectives for 2020. Those two sets of values are used respectively to calculate low and high ranges of refurbished surfaces in 2013 (see Table S5).

For network extension and renewal, available data sources are diverse and, in some cases, only available at a regional or national level. For roads, rates are applied to the surfaces of roads observed in 2013 in [43] to calculate developed and renewed surfaces.

Development rates by road type are calculated at the French *département* level from a survey on the road network by the French ministry of transportation [46]. Renewal rates are defined by road type and for all the region (see Table S6). Developed lengths of railways are known accorded to the national topological database (BD Topo) at the *département* level. Renewed length of railways in 2013 are calculated with rates multiplied with observed lengths of this network in 2013 in [43]. These renewal rates are defined at the regional level according to data from local rail transport service companies (see Figure 2).

For water and energy networks, data obtained from local energy and water suppliers [52–58] are used. These are often annual reports published by public managers which indicate for each network its total length, developed length of network in 2013, and renewed length. They are calculated at the most consistent spatial level according to those data sources and applied to the lengths of networks in 2013 according to [43]. Calculated rates and sources are summarized in Table S7.

2.5. Material Intensities

Table 2 presents the material intensities used to calculate the flows associated with the construction and demolition of buildings. Aboveground and underground surfaces are differentiated. When the construction period or the use (i.e., activity) of a building is not indicated by the *fichiers fonciers*, minimum and maximum intensities are used. Detailed intensities by material are presented in [43].

In the case of building refurbishment, data on the type of renewal works done in the region and the material intensity of derived materials are missing. Moreover, material intensity for refurbishment works varies greatly. With the absence of data, we assume that all non-structural materials are removed from the stock during refurbishment works: insulation, plasterboard, floor and ceiling, tile roof, exterior windows and doors, roof waterproofing. Material intensities are adapted from [32] (see details in [43]). Table 3 shows the material intensity of non-structural materials by building archetype. When data are missing, minimum and maximum intensities are used.

Material intensities for networks defined in [43] are used. For road renewal, only materials located in the surface course are included. For railway renewal, it is considered that concrete ties substitute wood ties [51].

2.6. Urban Indicators

Urban indicators are defined to compare the three intra-regional areas in the region and analyze flows. First average rates (in %) are calculated for each of the three area. For road extension for instance, the average rate is equal to total developed surfaces of roads in 2013 (in m^2, calculated from the formula in Section 2.4) divided by total surfaces of roads observed on 31 December 2013 in [43].

Table 2. Material intensities for constructed and demolished aboveground and underground surfaces of buildings, kg/m^2 gross floor area.

Type (Load-Bearing Structure)	Aboveground		Underground	
	Minimum	Maximum	Minimum	Maximum
Collective housing before 1914 (stone)	1979		1312	
Collective housing 1914–1947 (stone)	1958		1312	
Collective housing 1948–1974 (concrete)	1738		1590	
Collective housing 1975–2000 (concrete)	1413		1590	
Collective housing since 2001 (concrete)	1693		1590	
Collective housing with unknown construction year (stone or concrete)	1413	1979	1312	1590
Individual housing before 1914 (stone)	1859		1457	
Individual housing 1914–1947 (stone)	1859		1457	
Individual housing 1948–1974 (stone and concrete)	1094		567	
Individual housing 1975–2000 (concrete)	1045		567	
Individual housing since 2001 (mixed: concrete, brick, and timber)	1403		567	
Individual housing with unknown construction year (stone, concrete, or mixed)	1045	1859	567	1457
Shopping malls and buildings dedicated to transport and storage (steel framed)	484		1590	
Other commercial and administrative buildings before 1914 (stone)	1958		1312	
Other commercial and administrative buildings 1914–1947 (stone)	1565		1312	
Other commercial and administrative buildings 1948–1974 (concrete)	1738		1590	
Other commercial and administrative buildings 1975–2000 (concrete)	1413		1590	
Other commercial and administrative buildings since 2001 (concrete)	1506		1590	
Other commercial and administrative buildings with unknown construction year (stone or concrete)	1413	1958	1312	1590
Industrial building before 1948 (brick)	852		1590	
Industrial building since 1948 (steel framed)	522		1590	
Industrial building with unknown construction year (brick or steel)	522	852	1590	1590
Non-residential building with unknown activity (use) built before 1914 (steel, brick, or stone)	484	1958	1312	1312
Non-residential building with unknown activity 1914–1947 (steel, brick, or stone)	484	1565	1312	1312
Non-residential building with unknown activity 1948–1974 (steel or concrete)	484	1738	1590	1590
Non-residential building with unknown activity 1975–2000 (steel or concrete)	484	1413	1590	1590
Non-residential building with unknown activity since 2001(steel or concrete)	484	1506	1590	1590
Non-residential building with unknown activity and unknown construction year (steel, brick, stone, or concrete)	484	1958	1312	1590

Source: adapted from [32].

Table 3. Material intensities for refurbished aboveground and underground surfaces of buildings, kg/m^2 gross floor area.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Before 1914</th><th rowspan="2">1914–1947</th><th rowspan="2">1948–1974</th><th rowspan="2">1975–2000</th><th rowspan="2">Since 2001</th><th colspan="2">Unknown Year</th></tr>
<tr><th>Minimum</th><th>Maximum</th></tr>
<tr><td>Multi-family houses</td><td>56</td><td>56</td><td>112</td><td>62</td><td>73</td><td>56</td><td>112</td></tr>
<tr><td>Single-family houses</td><td>88</td><td>88</td><td>88</td><td>113</td><td>122</td><td>88</td><td>153</td></tr>
<tr><td>Shopping malls and buildings dedicated to transport and storage</td><td colspan="5">44</td><td>44</td><td>44</td></tr>
<tr><td>Other commercial and institutional buildings</td><td>56</td><td>54</td><td>112</td><td>62</td><td>24</td><td>24</td><td>112</td></tr>
<tr><td>Industrial buildings</td><td colspan="2">14</td><td colspan="3">89</td><td>14</td><td>89</td></tr>
</table>

Source: adapted from [32].

- Annual average road extension rate, %of total road surfaces observed on 31 December 2013
- Annual average construction rate, % of total building floor areas observed on 31 December 2013
- Annual average renewal rate, % of total building floor areas observed in stocks on 31 December 2013 (intermediate value)
- Annual average demolition rate, % of total building floor areas observed in stocks on 31 December 2013
- Urban density: the number of inhabitants on urbanized area, inhab./km^2
- Building floor area to urbanized area ratio: ratio of the total gross building floor areas over urbanized area, ratio
- Share of single-family house, % of total building floor area

Urban density and building floor area to urbanized area ratio are the most relevant indicators to study urban forms [59,60]. Urbanized area is calculated with the regional land use database (MOS 2012) and includes the built land plots, as well as urban open spaces, such as parks, gardens, and sport fields. Annual construction, demolition, and renewal rates are defined as the percentage of the total regional building gross floor areas observed in stocks on 31 December 2013 according to [43]. Besides, it can be noticed that although the refurbishment rates used to calculate refurbished surfaces are the same for all the region, those rates are applied to stocks in Paris, Petite Couronne, and Grande Couronne, whose distribution among archetypes varies. Therefore, annual average refurbishment rates vary between urban areas.

3. Results

3.1. Flows by Process at the Regional Level

Figure 4 shows per capita construction material inflows and outflows in the Paris region in 2013. For graphical simplification, only low range results are presented in the figure (details are in Table S8).

Inflows of materials to stocks reach between 1.8 (low range) and 2.1 (high range) tons per capita. Around 75% of the materials are used for the construction and refurbishment of buildings and around 25% for road renewal and development. Construction dominates for buildings with inflows between 1.2 and 1.4 t/capita when building refurbishment generates only inflows equal to 0.1 to 0.2 t/capita. For roads, renewal works produce the main inflows: 0.3 t/capita compared to 0.1 t/capita for road development. Therefore, material inflows to stocks of the region are driven mainly by building construction and road renewal. Other networks represent a small portion of the inflows: between 2% and 1.5% of the total inflows. As for roads, inflows for those networks are mainly due to renewal rather than to development.

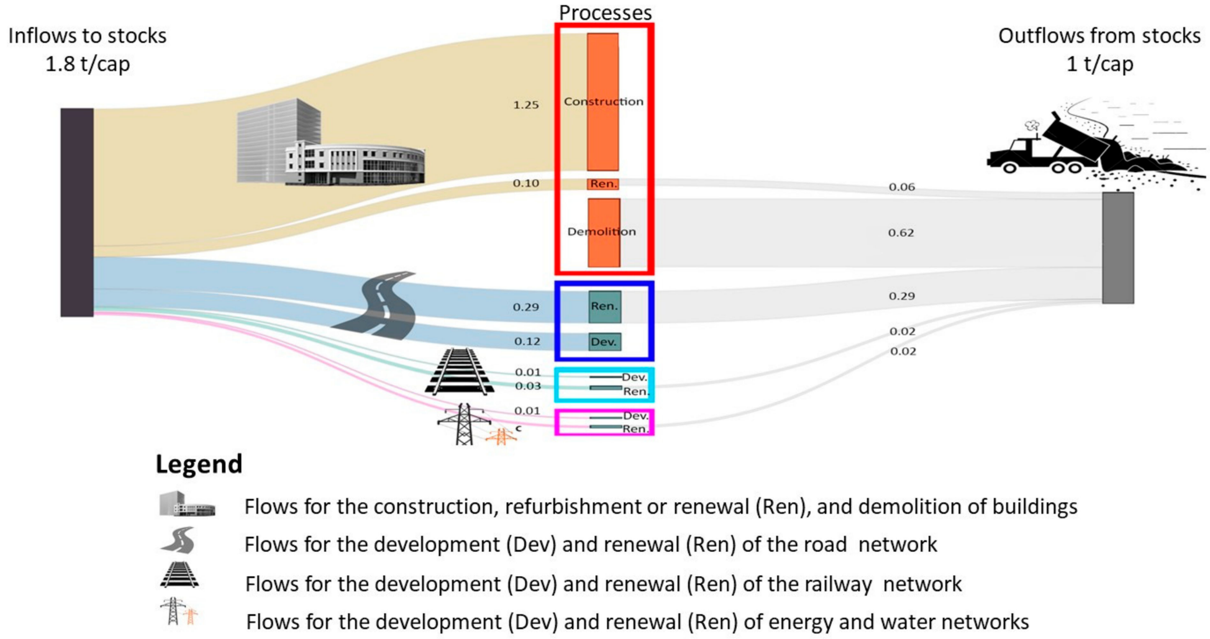

Figure 4. Inflows and outflows by process: low range results, Paris region, 2013, t/cap. Source: authors.

Outflows from stocks are of the same order of magnitude as inflows. They reach between 1.0 and 1.5 t/capita. Material outflows of the region are driven mainly by building demolition and road renewal. Indeed, building demolition dominates with flows between 0.6 and 1.0 t/capita. Road renewal generates the second flows (0.3 t/capita) and it is followed by building refurbishment (0.1 to 0.2 t/capita). Outflows resulting from other networks are very low.

3.2. Flows by Material at the Regional Level

Figure 5 presents the shares of inflows and outflows by material for the Paris region in 2013 according to the low range results (see details in Table S9). It shows that non-metallic minerals dominate: between 95 and 96% of total inflows and between 93% and 94% of total outflows. Concrete is the most important material, both in inflows and outflows, and its flows are mostly generated by building construction and demolition. Aggregates, which are used in asphalt concrete for roads and as ballast for railways, make the second largest inflows and outflows. As aggregates are also included in concrete, in total, aggregates account for about three quarters of the inflows and half of the outflows. Stone is rarely used for construction today, but it is present in a large share of demolished buildings which were constructed before 1948. Therefore, it makes 12 to 13% of outflows. Brick construction is not common in construction in the Paris region today and inflows are small. As brick and clay form a small part of stocks [37], outflows are limited. Other flows account for less than 6%.

3.3. Characterizing the Three Sub-Urban Areas With Urban Indicators

Table 4 summarizes the key urban indicators of the three sub-urban areas and compares them with the regional average values. Urban characteristics of the three urban areas are very different. Paris is nine times more densely populated and ten times more densely built than GC. In Paris, the ratio of total floor area to urbanized area reaches two, which is four times higher than PC and ten times that GC. GC has a relatively low ratio of building floor area to urbanized area, which can be explained by a high ratio of transportation network and that of single-family houses. Among the three sub-urban areas, the area with the highest road extension rate is GC, almost twice as high as PC, when road development in Paris is null in 2013.

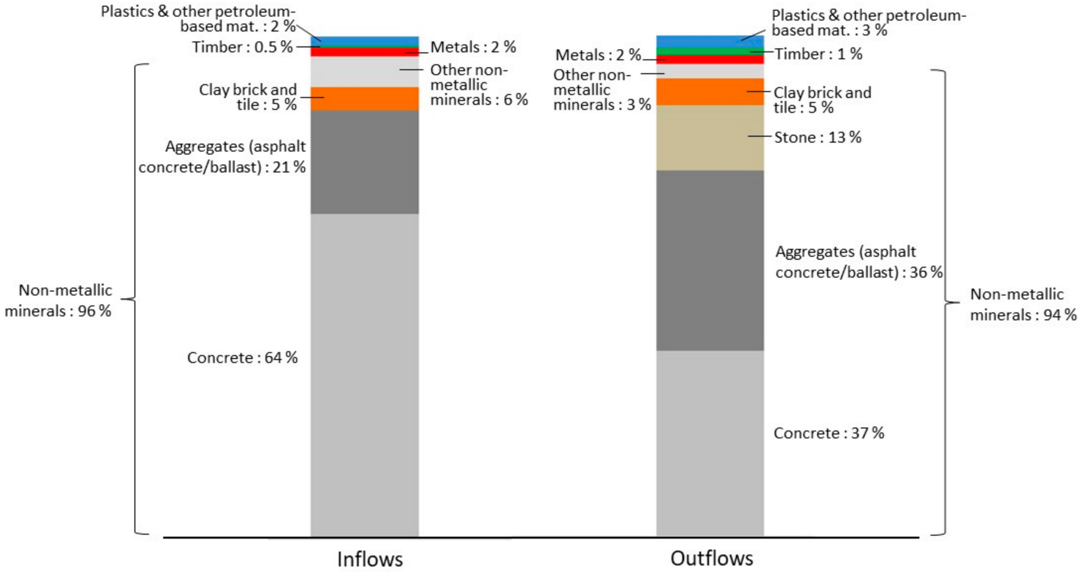

Figure 5. Inflows and outflows by material: low range results, Paris region, 2013, %. Source: authors.

Table 4. Comparison of urban indicators in Paris, Petite Couronne (PC), and Grande Couronne (GC).

Indicators	The Paris Region	Paris	Petite Couronne	Grande Couronne
Population density on urbanized area, inhab./km^2	4479	23,828	8108	2588
Building floor area to urbanized area, ratio	0.4	2.0	0.5	0.2
Share of single-family house, % of urbanized area	27	2	17	36
Annual average road extension rate, %	0.5	0	0.3	0.5
Annual average construction rate, % of building floor area	0.6	0.3	0.7	0.7
Annual average refurbishment rate, % of building floor area (intermediate value)	2.1	1.9	2.0	2.2
Annual average demolition rate, % of building floor area	0.7	0.5	0.8	0.6

Source: authors, population census by INSEE, [40].

Constructed, refurbished, and demolished areas of buildings in 2013 represent a small proportion of the total building area observed on 31 December 2013. Indeed, at the regional level, they represent only 3.4% of the total area of buildings. Urban renewal prevails among them: 1% of buildings are refurbished in 2013, while only 0.6% are constructed and 0.7% demolished. Paris is the area which has the lowest rates. The city is already totally urbanized, and the construction rate is twice as low as in other areas. Its stocks include a lower share of single-family houses, buildings which have a higher refurbishment rate than multi-family houses according to data used [45]. PC is an area where intense urban renewal takes place [61] and it has the highest demolition rate (0.8%) and a construction rate as high as in GC. Urban renewal is less intense in GC [61] where the demolition rate is lower than the construction rate. Due to the high share of single-family houses in its stocks, GC has the highest refurbishment rate.

3.4. Construction Material Flows at Sub-Urban Level: Paris, Petite Couronne, and Grande Couronne

Figure 6 compares the total per capita inflows and outflows and their material contents for the three sub-urban regions: Paris, Petite Couronne (PC), and Grande Couronne (GC) (see details in Table S8).

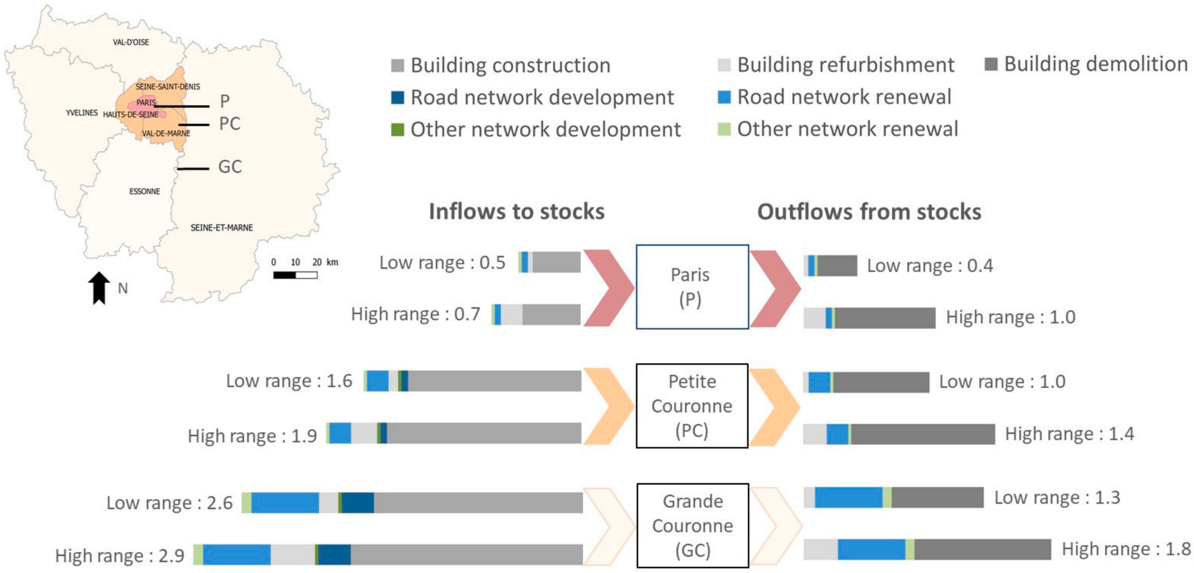

Figure 6. Inflows and outflows to and from stocks, Paris, Petite Couronne and Couronne, 2013, t/capita. Source: authors.

Per capita inflows of Paris amount for between 0.5 and 0.7 t/capita of construction materials, which is significantly low compared to the other regional areas. Buildings account for the bulk of urban consumption. Transport networks account only for 10 to 15% of the total inflows, and 7 to 9% are for road renewal. However, outflows reach between 0.4 and 1.0 t/capita, especially from building demolition.

Petite Couronne consumes 1.6 to 1.9 t/capita of construction materials, which is close to Paris consumption, mainly for building construction. The share of material inflows for transport networks is close to Paris with 11 to 12% of the total consumption. Outflows are high in this area, at 1.0 to 1.5 t/capita, and three quarters are generated by building demolition.

Grande Couronne is significantly higher in per capita inflows of materials, at 2.6 to 3.0 t/capita. Its consumption characterizes differently compared to other sub-urban areas. In GC, one-third of the materials are used for transport networks renewal and development, especially for road construction and renewal. Half of the mass consumed for road renewal is intended for local roads serving local access inside the communes. The freeways represent only one fifth of this mass and the regional and main roads the tenth. Road development accounts for 10 to 12% in total consumption, while renewal accounts for 17 to 19%. Outflows reach between 1.3 and 1.8 t/capita. In GC, the share of buildings in total inflows is lower than in Paris or PC. Renewal of the transport networks produces more than a quarter of outflows.

4. Technical Validation of the Results

4.1. Data Quality

To analyze the quality of the *fichiers fonciers* data source, we compare the calculated constructed building floor areas in our study to statistical data from Sit@del2 database, excluding covered garages of single-family houses which are not accounted in Sit@del2. Results, presented in Table S10, show a low difference and indicate that these data and the treatment we have made of them is consistent. Indeed, the differences observed are 7% for all buildings at the regional level. Non-residential building floor area in our study are underestimated for Paris according to the same database. This results from the fact that public facilities are not recorded in *fichiers fonciers*.

4.2. Validation of the Results

The comparison of the detailed consumption of aggregates in the Paris region according to the bottom-up approach and to other data sources shows that the results are consistent. The estimated inflows of aggregates in cement concrete are lower than [62], very close to [63]. Estimated inflows for asphalt concrete and road and railway network development and renewal are similar to statistics. The scope of the bottom-up approach excludes civil engineering, which generate 1.0 t/capita according to [62].

Secondly, the comparison of some outflows with corresponding C&D waste statistics (Table S12) shows consistent figures. Low range bottom-up results for refurbishment are much lower than statistics, but high range estimates are very similar. Estimated concrete waste outflows generated by all processes are close to the statistics (which are based on expert opinion). Asphalt concrete outflows from road renewal are larger than low range statistics but similar to the high range ones. Moreover, a study on C&D waste flows in 2015 carried on for the regional council with this bottom-up method [64] led to very similar results to estimates based on surveys by the council and CERC IdF.

5. Discussion

5.1. Urban Drivers Shaping Construction Material Flows

Results presented in Sections 3.3 and 3.4 show that flows vary greatly between the three sub-urban areas of the Paris region. Inflows per capita are larger in the low-density outskirts where a greater share of total flows are generated by road development and renewal. Although the Paris region is characterized by an old and dense urbanization [65], urban renewal has only become very recently the dominant pattern. Indeed, according to data on land use changes during the last forty years presented in [61], 60% of the constructed area between 2008 and 2012 took place on already urbanized land. That ratio reached only 22% in 1987, 28% in 1994, and 38% in 2003 [61]. Urban sprawl, measured in terms of new urbanized area compared to already urbanized area, went from 0.7% in 1985, 1% in 1994, and 0.5% in 2003 to 0.2% in 2012 [61].

Therefore, past urbanization led to the formation of network stocks [43], which today generate massive flows for their renewal. Network stocks drive significant construction material flows. Particularly, road dominates in renewal flows. This flow dominates in GC, which is characterized by urban sprawl and low population and low building density (see Table 4). Wiedenhofer and colleagues [37] show that maintenance plays a key role in construction material flows at the EU level. Our study shows consistent results in the case of network related material flows.

Besides, results show that building demolition leads to major outflows from stocks. Regional statistics on C&D waste in 2010 and 2015 [66,67] also indicates that flows generated by building demolition are the most important after excavated materials. Demolition can partly be related to urban factors. Indeed, demolished buildings between 2009 and 2014 in the region or mostly located in cities where the real-estate market is the most active. Moreover, demolition takes place in a context of urban densification. Indeed, when reconstruction can be observed after demolition with *fichiers fonciers*, a growth in building surface (and mass) is always with few exceptions seen (see details in [27]). Huuhka and Lahdensivu [68] also show that, in Finland, the more active the real estate market is, the bigger the demolished building surface area is.

Building demolition in the Paris region can also be related to socio-economic factors. Most of the outflows related to the demolition of buildings (53% to 69%) occur in non-residential buildings and particularly in tertiary buildings. Therefore, economic and industrial transformation is a main driver of building demolition [69,70]. Indeed, the highly competitive real estate market for tertiary buildings is the main reason why these types of buildings are rapidly obsolescent and demolished [71,72]. An office building is demolished when it presents a good outlook for the real estate portfolio of its owner [71,72]. Moreover, the region has continued to deindustrialize, and industrial buildings undergo massive demolition works. Residential buildings are often demolished to increase their added value by increasing their floor area ratio (FAR) [73].

The comparison of the Parisian area with other areas in France makes it possible to better highlight the region's specificities. Statistics on aggregates consumption, published by the producers of these materials (UNICEM) and available for all France, are used to complement our results. These statistics cover all uses of aggregates, including civil engineering works, and they have a larger scope than our study. They indicate the share of aggregates used for concrete production. As concrete is mostly used for building construction ([62] and our results), the lower this indicator, the higher the share of concrete is used for network development and renewal. Table 5 compares the Paris region with France in terms of aggregate consumption and key urban indicators. It shows that the Paris region has very different characteristics than other French regions in terms of per capita material consumption and urban indicators. First, the per capita consumption of aggregates is much lesser in the Paris region than in France. Second, a higher share of aggregates is used for concrete production. This is consistent when observing the urban area extension rate, which is more than twice higher in France than in the Paris region. The road extension rate is also twice higher in France than in the Paris region. Urban sprawl and road extension are often associated with low-density development and thus a higher share of single-family houses in residential construction [60]. This share is three or four times higher in France than in the Paris region.

Table 5. Aggregates consumption compared to urban indicators in Paris region and mainland France.

	Paris Region (Source)	Mainland France Excluding the Paris Region	Mainland France Including the Paris Region
Aggregates consumption per capita (t/cap)	1.1 (authors)	6.5	5.8
	2.5 [62]		
Share of aggregates used for concrete production (%)	68 (authors)	31	33
	50 [62]		
Urban area extension rate from 2006 to 2012 (%)	1.3	3.0	2.9
Road extension rate in 2013 (%)	0.3	0.6	0.6
Share of single-family houses in residential construction in 2013 (%) (number of dwellings, started construction projects)	14	53	47

Source: [46,62,63], population census by INSEE, Corine Land Cover 2006 and 2012, Sit@del2.

Comparison with other urban areas would allow this analysis to be completed. However, studies very often have different scopes, and differences are difficult to interpret. Compared to the two areas that are also mentioned in [43], it can be noticed that inflows in the Paris region are lower than in Orléans in France (3.2 t/capita) [32] and the canton of Geneva in Switzerland (3.9 t/capita) [30]. However, outflows are similar (respectively 1.5 and 1.0 t/capita). This comparison requires additional information on urbanization patterns in order to be pursued.

5.2. Insights for Defining Circular Economy Strategies in the Paris Region Based on Material Flow Analysis

We propose to use the framework defined by Circle Economy and colleagues [12] in Section 1.2 to outline insights for the definition of a circular economy strategy in the Paris region based on results from our material flow analysis.

Bottom-up flow analysis in the Paris region in 2013 shows that inflows per capita are lower than in other regions, but that outflows from stocks are large, as they account for around two thirds of the inflows. Moreover, top-down flow analysis shows that C&D waste flows excluding excavated materials are equal to 75% of the domestic extraction of natural resources in the Paris region [27,74]. Reducing outflows, and particularly those resulting from building demolition, could be a target for circular economy strategies in the Paris region coordinated with urban planning policies. Indeed, limiting demolition and prioritizing refurbishment and extension of existing buildings would reduce both inflows and outflows. It would enable the densification of the region through a "soft urban renewal," as recommended by the national General Directorate for Housing Development (*PUCA*) [75]. This action could follow the first steps of the circular economy strategy defined by Geldermans [76]: (1) to question the need for a new construction; (2) to explore current and future vacant buildings with regard to availability and usability.

Secondly, flow analysis shows that the Paris region has a strong potential for urban mining, which means the systematic reuse of anthropogenic materials [25]. Indeed, recycling and reuse cover only one-fifth of the construction material needs of the region in 2013 [27,74] bottom-up results show that two materials could be targeted by considering their importance in total outflow mass: concrete resulting from building demolition and asphalt concrete and aggregates resulting from road renewal. Statistics on C&D waste [62,66,67] show that asphalt concrete and aggregates from road renewal are already highly up-cycled for road renewal works. However, although concrete debris are often recycled as aggregates, those materials are largely down-cycled in civil engineering works and their use for concrete production remains marginal [62]. Flow analysis shows that concrete is the most used materials in the region in 2013. Moreover, if urban renewal remains the main pattern of urbanization as it is in 2013, then road development and associated material consumption will remain low. Therefore, developing concrete up-cycling in concrete appears like a consistent way to improve recycling. Sandanayake and colleagues [77] as well as the French national research project [78] showed that it is feasible, under certain conditions, in terms of techniques, costs, and regulation. However, reuse and recycling of C&D waste in the Paris region face strong constraints [13].

Thirdly, results from a top-down flow analysis presented in [27,74], show that local and renewable resources for construction could be better used. Indeed, used domestic extraction of natural resources only amount for around half of the regional material consumption in 2013 [27,74]. Therefore, the Paris region relies heavily on imports from other French regions or countries. The hinterland of the region is very large as nearby *départements* and regions within *Bassin Parisien* (Centre-Val de Loire and Normandie; some *départements* in Hauts-de-France, Grand Est; Yonne and Sarthe) provide only 60% of the imports of construction materials [27,74]. However, the region is as rich as other areas of France in terms of resources for construction. For instance, forests cover 25% of the region, a rate that is similar to the rest of France [79]. However, only 20% of the forest primary production are harvested every year when that share reaches 50% for all France [80].

This general framework for a circular economy strategy in the Paris region could be adapted to each sub-urban areas and cities. Urban planning is set up at the level of local governments (intermunicipal authorities), which coordinate local stakeholders to promote local environmental policy and circular economy. Flow analysis shows that flows of construction materials have very different characteristics depending on the sub-urban areas, which means that strategies for circular economy should be differentiated according to the urban context. In Paris and Petite Couronne, flow analysis point that strategies could focus on reducing outflows resulting from building demolition and better using secondary resources in building construction. In Grande Couronne, inflows could be better reduced through further limiting urban sprawl. When inflows for road development and renewal are reduced, use of secondary resources could target building construction.

5.3. Limits of the Study and Perspectives for Future Research

Our research has three major limitations. First, the bottom-up study examines a smaller portion of the built environment than the top-down analysis because of its data-intensive nature [26,29]. The scope of our research also excludes excavated materials that are particularly important in urban areas with high built density, such as Paris [81].

Secondly, the bottom-up approach has inherent uncertainties regarding material inventory and building prototyping when applied on a broader scale [26,29]. For the material inventory data used in this study, building material intensity data are more detailed for residential and tertiary buildings. As commercial and industrial buildings dominate in demolished buildings, the lower detail level of the data on material intensity used for those buildings creates uncertainty. Material inventory of buildings constructed before 1914 is also limited. Moreover, the *fichiers fonciers* data source used to allocate building prototypes includes missing data (construction year or use) which were completed by using minimum and maximum values of material intensity. This processing also impacts the accuracy of the results. Besides, the simple assumption that building refurbishment works generate flows for the renewal of all non-structural materials involves great uncertainty. Although our results and regional C&D waste statistics show that building refurbishment take up a small portion of the overall material flows as shown, inflows and outflows of non-structural materials are an important issue in developed cities where urban renewal is more active [22]. Therefore, better knowing those flows would be useful to implement circular economy strategies.

Thirdly, the estimation of constructed, renewed, and demolished surfaces or lengths of buildings and networks is based on data sources whose quality needs to be further investigated and which could be complemented with other sources. *Fichiers fonciers*, for example, had never been used to estimate constructed and demolished surfaces of buildings and the quality of this source and the method used to process data need further investigation. Data on some energy and water networks is limited and should be complemented.

To address those limits, future research could follow three directions. First, to better validate results and improve data collection and processing so as to reduce uncertainty. This calls for further data collection and field survey to improve the quality of the data. Data on material intensity could be consolidated by comparing them with data from construction companies as in [41]. Data could be collected from cities to better know the demolition and refurbishment of buildings and the renewal of networks. Results based on the method presented in this article could be compared with those data so as to improve methods. Such a study has been started at the building and neighborhood scales through projects lead by CitéSource in Est Ensemble (north-east of Paris) [81] and is to be pursued. This work could lead to a better assessment of uncertainty.

Secondly, research should aim at extending the scope of flows studied, in terms of materials, buildings, and networks and processes. Data and method to estimate and locate flows of excavated materials could lead to a better knowledge of these flows. The latter faces a lack of data on onsite excavated material usage ratio. However, promising methods have recently been applied on the case of the city of Paris [82]. Moreover, some networks (as for example telecommunication networks, bridges, and tunnels) as well as some processes (such as use, maintenance, repair, replacement) could be included in the scope by collecting data and defining methods to process them.

Finally, working on other case studies in France and other countries and comparing results would bring a better understanding of urban and space-differentiated drivers that shape flows. Collaborative research would allow a better comparison of existing case studies such as the Paris region, Orléans, and the canton of Geneva.

6. Conclusions

To analyze construction material flows in the Paris region in 2013, we used a static bottom-up approach. Based on our previous study on construction material stocks, we estimated regional material flows for building and network construction, renewal, and demolition. Our research focused on the spatial characterization of construction material flows according to three different urban areas within the region.

Inflows of construction materials to stocks in 2013 reach between 1.8 and 2.1 t/capita, while outflows from stocks are between 1.0 and 1.5 t/capita. Both inflows and outflows are mainly driven by building construction and demolition as well as road renewal. Our results showed that the characteristics of the three sub-urban areas are very different in terms of material flows from the dense central city of Paris to the low-density outskirt area. In the Paris municipality, the ratio of urbanized area to total floor area reaches two, which is four times higher than in PC and ten times higher than in GC. Inflows in Paris vary between 0.5 and 0.7 t/capita, which is respectively approximately three times and five times less than in PC and GC. Comparing Paris with the French mainland, our study showed that total per capita consumption of the Paris region, with low road expansion rates, is much lower than in the rest of France.

We discussed urban renewal, which is currently causing major material flows in the region. We noted two main factors: first, the demolition and reconstruction of buildings by ongoing urban regeneration, and second, the renewal of road networks extended in the previous decades dominated by urban sprawl in the outskirts of the region. Economic and industrial changes in the region and the highly competitive real estate market for tertiary buildings are notable factors for building demolition. As the construction sector plays an important role in urban metabolism, it is important to reduce the flows of construction materials and to increase recycling and reuse with the implementation of urban scale circular economy strategies.

Our research has some limitations to deal with in future work. The comparison between the Paris region and other urban areas will give a better understanding of the relationship between construction material flows and urbanization patterns. Analysis of the flows at smaller spatial scales (buildings, neighborhoods, or cities) within the Paris region and further comparison of results with other data sources will improve methods and analyses.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/3/1376/s1: Table S1. Scope of materials. Table S2. Criteria to estimate demolished and constructed surfaces. Table S3. Coefficients used to convert aboveground *surfaces réelles* from *fichiers fonciers* in aboveground gross floor area, absolute values. Table S4. Coefficients used to convert aboveground *surfaces réelles* from *fichiers fonciers* in underground gross floor area, absolute values. Table S5. Refurbishment rates by building type, %. Table S6. Extension, renewal, and demolition rates for the road network, 2013, %. Table S7. Extension, renewal, and demolition rates for railway, energy, and water networks, 2013, %. Table S8. Inflows and outflows to and from stocks per capita and by process, the Paris region, Paris, Petite Couronne, Grande Couronne, 2013, t/capita. Table S9. Inflows and outflows by material, Paris region, 2013, %. Table S10. Comparison between constructed buildings surfaces according to bottom-up results (2009 to 2014) and according to Sit@del2 database (2007 to 2011), urban areas within Paris region, %. Table S11. Comparison between estimated flows in this study and regional statistics on the consumption of aggregates, t/capita. Table S12. Comparison between estimated flows in this study and regional waste statistics by CR IdF (2015), t/capita.

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