Urban Metabolism of Paris and Its Region

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Summary

The article presents the results of a research project aimed at (1) examining the feasibility of material flow analysis (MFA) on a regional and urban scale in France, (2) selecting the most appropriate method, (3) identifying the available data, and (4) calculating the material balance for a specific case. Using the Eurostat method, the study was conducted for the year 2003 and for three regional levels: Paris, Paris and its suburbs, and the entire region. Applying the method on a local scale required two local indicators to be defined in order to take into account the impact of exported wastes on MFA: LEPO, local and exported flows to nature, and DMC_{corr}, a modified domestic material consumption (DMC) that excludes exported wastes (and imported ones if necessary).

As the region extracts, produces, and transforms less material than the country as a whole, its direct material input (DMI) is lower than the national DMI. In all the areas, LEPO exceeds 50% of DMI; in contrast, recycling is very low. The multiscale approach reveals that urban metabolism is strongly impacted by density and the distribution of activities: the dense city center (Paris) exports all of its wastes to the other parts of the region and concentrates food consumption, whereas the agricultural and urban sprawl area consumes high levels of construction materials and fuel. This supports the use of MFA on an urban and regional scale as a basis for material flow management and dematerialization strategies and clearly reveals the important interactions between urban and regional planning and development, and material flows.

Introduction

Material flow analysis (MFA) is a powerful tool that helps elucidate national, regional, and urban metabolism. It provides indicators of (un)sustainability and can contribute to the definition of a public environmental policy (Bringezu et al. 1998). MFA is now widely used at the national scale (see for instance Weisz et al. 2006), although it is not extensively used in developing countries.

Although MFA has proven to be useful on a national scale, analyses focused on smaller areas are necessary to gain a better understanding of what material consumption is and how it can be controlled and reduced. Most of the world population is concentrated in urban areas (77% in France, just above 50% in the world), such that the total consumption of these areas is inclined to be higher than elsewhere. Furthermore, most of the products consumed in urban areas are imported. Cities can thus be considered as types of attractors for materials. Because these imported materials come from various parts of the world, the environmental imprint of cities is a worldwide mosaic. Thus, the analysis of urban material flows can help to elucidate not only urban functioning but also issues on a larger scale.

Pioneering studies in the field highlight the importance of urban metabolism and provide some data on the urban material balance (Wolman 1965; Odum 1975; Duvigneaud 1980; Boyden et al. 1981). These studies, however, remain quite focused and do not go beyond the condemnation of cities as parasites, importing "fresh" materials and exporting wastes. More recently, new methodological developments and case studies provide encouraging results and pave the way for further studies. MFA has now been shown to be relevant not only in describing socionatural interactions but also in supporting public policies and action (see for instance for Vienna: Daxbeck et al. 1997; for Stockholm: Burström et al. 1998; for Geneva: Faist Emmenegger and Frischknecht, 2003; for Hamburg, Vienna, and Liepzig: Hammer et al. 2006).

Paris is, by far, the largest urban area in France and one of the most important in Europe, together with London and the Ruhr conurbation; its population ranks 20th in the world. Paris was not, however, included in Decker's study of energy and material flow through the world's 25 largest cities (Decker et al. 2000), and its metabolism has never been analyzed fully beyond an early attempt (Dambrin 1982). In France, only Lille has been the subject of MFA, but the study focused only on a subset of locally relevant material flows (Duret 2009).

This article summarizes the results of a research project aimed at examining the feasibility of MFA on a regional and urban scale in France. The scope of the study includes selecting the most appropriate methodology for the analysis, identifying the available data, and presenting the results of MFA for Paris and its region (Île-de-France).[1] In the first section, the methodology for the study is presented and the case study is introduced. In the second section, the data used and the results of the MFA conducted in 2003 for three areas—Paris (2.2 million inhabitants), Paris and its suburbs (6.3 million inhabitants), and the greater region of Paris (11.3 million inhabitants)—are presented. The results are discussed and the three areas compared, and a detailed analysis of domestic material consumption (DMC), with particular emphasis on construction materials, is presented. Finally, the results obtained from this study are compared to other urban MFA.

Method and Case Study

Method

Established methodologies exist to conduct MFA. For the purposes of this project, the method developed by the Statistical Office of the European Communities (Eurostat 2001) was chosen. This method was not originally designed for local or regional case studies, only for studies on a national scale, and a discussion of its application at the regional level can be found in work by Hammer and colleagues (2003). The Eurostat method has been used extensively and allows comparisons between studies on different territorial scales—national *versus* regional or urban—and between cities and regions. It is based on data available at the national level, and we have assumed that at least some of these data exist at the regional level. The analysis is based on the determination of the main inputs and outputs

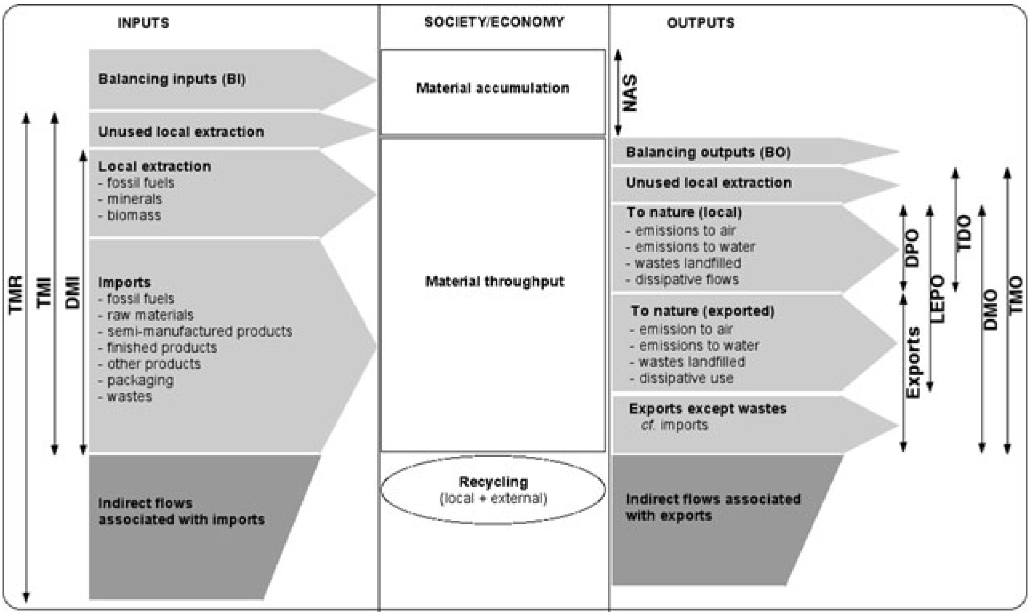

Figure 1 Main flows and indicators in material balance according to the method adapted from Eurostat (2001). Note the following: (1) The system (Society/Economy) is limited by its political or administrative borders; it comprises the society as a whole (population and artifacts) and excludes nature from which it extracts primary material. (2) Water balance is not included (except in the case of balancing outputs). For an explanation of indicators, see table 1.

for the system under consideration and does not require a description of the material circulation within the system; it is thus a fairly easy analysis to perform. This ease of use is important to develop a method that is both useful for research and applied purposes and to provide the rationale as to why this method was chosen rather than Brunner and Rechberger's (Brunner and Rechberger 2004). Their method may appear more scientific and systematic, but it is less easily applied to the available data because it is based on the analysis of processes inside the system under study, where the outputs are calculated on the basis of the inputs and transfer coefficients that characterize those processes. Furthermore, their method requires that the main processes and activities be predefined—"to nourish, to clean, to reside and work, to transport and communicate" (Brunner and Rechberger 2004, 44–48)—such that the social metabolism is interpreted a priori and cannot be as easily transferred to other cases.[2] Finally, the Eurostat method can provide some global indicators in the context of sustainability policies, while the Brunner and Rechberger method cannot.

To capture the material impact of regional and urban activities, we followed the territorial principle rather than the residential principle: Flows accounted are local ones and defined by the physical boundaries of the system under study (resulting from administrative boundaries, see *Case Study* section below). For the purposes of this study, we used an adaptation of a methodological guide published by Eurostat in 2001 (Eurostat 2001). The principles of the adapted method, the main flows to be determined, and the main resulting indicators are shown in figure 1. (See table 1 for an explanation of all indicators and abbreviations.) Our first adaptation of the method does not depend on the local character of the case study.

To balance the MFA—that is, based on the conservation of mass principle—it is necessary to take into account the so-called "memorandum

Table 1 Explanation of indicators and abbreviations

Indicator/ abbreviation	*Explanation*
BI	balancing inputs
BO	balancing outputs
DMC	domestic material consumption = DMI − exports
DMC_{corr}	corrected domestic material consumption = DMI − imported wastes − exports except wastes
DMI	direct material input DMI + BI = NAS + DMO + BO
DMO	direct material output
DPO	domestic processed output
LEPO	local and exported processed output = DPO + exported flows to nature
NAS	net addition to stock
TDO	total domestic output
TMI	total material input TMI + BI = NAS + TMO + BO
TMO	total material output
TMR	total material requirement

items." For instance, according to the simplified equation

$$(\text{fuel} + \text{oxygen}) \rightarrow (\text{carbon dioxide} + \text{water}),$$

combustion involves oxygen (as an input) and water (as an output); these two flows must be weighed for combustion processes to balance. It would also be possible to include only carbon, instead of CO_2, and hydrogen, instead of H_2O, in the MFA, but that would be required for every compound emitted during combustion processes (and other processes). Balanced items are not included in indicators such as direct material input (DMI), direct material output (DMO), and so on. As a result, there is no relation between DMI and DMO or more generally between inputs and outputs. To maintain physical links between the indicators—and the conservation of matter, the very principle of MFA—balancing inputs (BI) and outputs (BO) are included, as shown in figure 1. This balance is also necessary to estimate the net addition to stock (NAS), as NAS = DMI + BI − DMO − BO.

Adaptation of the method to the regional and local scales had only one consequence on the method itself. When it is applied at the national level, the method considers four main outputs: flows to nature, unused domestic extraction (actually not included in current accounts), exports, and indirect flows associated with exports. It then indirectly assumes that flows to nature are domestic ones (at least at the time of their emission). On the regional or local scale, such an assumption is no longer valid: Cities rarely dispose or locally treat their liquid or solid wastes. Wastewater treatment plants, sanitary landfills, and waste incinerators are often located several kilometers away from cities and outside their administrative borders. Wastes can consequently be considered as exports, and at least in part, so can flows to nature. Using the Eurostat method, without taking this into account, would create a bias by minimizing flows to nature, as they would be limited to the locally emitted part of those flows; it would also minimize recycling, as it often occurs outside the city; it could also minimize total exports (wastes + other exports) as some of the exported wastes are not accounted for in trade statistics that are often used to assess exports (for instance wastewater transported outside the city by sewage pipes).

Thus, for our analysis, certain flows had to be categorized (and care was taken to avoid double counting):

- exports were categorized into wastes exported and other exports,
- flows to nature were categorized into local and remote flows to nature, and
- recycling was categorized into local and remote recycling.

We also added the LEPO indicator (local and exported processed outputs) to the adapted Eurostat method. LEPO was calculated in the following way: For one particular study area, solid and liquid wastes were divided into two categories, those that are locally treated (or discharged to nature) and those that are exported. For each category, and according to the different treatments applied, the flow was further divided into flows to nature (emissions to air and water, landfilling, and dissipative use) and recycling.

(For instance, incineration results in emissions to air and in clinker, and a part of this clinker is recycled and the other part is landfilled.) Flows to nature resulting from local treatment of solid and liquid wastes were added to other local flows to nature to assess domestic processed output to nature (DPO). In the case study, emissions to air resulting from the local treatment of solid and liquid wastes were not included in the sum to avoid double counting of the data contributing to global air emissions from every source (see below, *Data Collection* section). Flows to nature resulting from remote treatment were added, and the resulting sum represented the exported processed outputs to nature. LEPO was obtained by adding this flow to DPO.

Remote treatment of wastes also has an impact on DMC. In the established Eurostat method:

$$\text{DMC} = \text{DMI} - \text{Exports}$$

However, when applied on a local scale, DMC does not accurately reflect domestic material consumption in its socioeconomic sense and is minimized because of the increase in exports due to exported wastes. To overcome this problem, the exported wastes can be subtracted from the total exports to calculate DMC. It could be argued that it consequently becomes necessary to subtract imported wastes from DMI: In our case study, however, there are no imported wastes, but a generalized application of this method adapted for the local scale would have to take this into account. To avoid any confusion between DMC as it appears in the Eurostat method and DMC in the method adapted for the local scale, we define the latter as DMC_{corr} (corrected DMC):

$$\text{DMC}_{\text{corr}} = \text{DMI} - \text{Imported wastes} - \text{Exports except wastes}$$

Or:

$$\text{DMC}_{\text{corr}} = \text{DMI} - \text{Imported wastes} - \text{Total exports} + \text{Wastes exported}$$

In our case study, no wastes are imported; therefore:

$$\text{DMC}_{\text{corr}} = \text{DMI} - \text{Exports except wastes}.$$

Case Study

France is divided into administrative regions that are themselves divided into *départements* made up of many municipalities.[3] Due to its specific role, Paris is both a municipality and a *département*. The urban area of Paris is within the administrative region of Île-de-France, which is itself currently divided into three zones (figure 2 and table 2): (1) Paris (P); (2) its dense suburb called *Petite couronne* (PC), which includes three administrative *départements* (Hauts-de-Seine, Seine-Saint-Denis, Val-de-Marne); and (3) the rest of the region called *Grande couronne* (GC). GC is characterized by urban sprawl, industrial activities, and intensive agriculture and is made up of four *départements* (Seine-et-Marne, Yvelines, Essonne, Val-d'Oise). Île-de-France is the most highly populated region of France and has the highest population density and gross domestic product (both in volume and per capita) in the country.

Initially, the study focused only on the Paris area, but it soon became apparent that such a choice was very restrictive for proper analysis. The administrative boundaries of Paris do not contain the urban area as a whole; they just encompass the very dense city center within the large urban zone. Material flows, however, can be impacted both by urban shape (density versus sprawl) and a variety of activities (residential, tertiary, industrial, and agricultural). As such, for the purpose of this study, we defined three concentric areas around Paris and conducted an MFA for each of these: (1) Paris (P); (2) Paris and its dense urban *Petite couronne* suburbs (PPC); and (3) the entire Île-de-France region (IdF). Consequently, area 3 (IdF) includes area 2 (PPC), and area 2 (PPC) includes area 1 (P). Internal flows have, of course, been subtracted out when calculating MFA for areas 2 and 3 (PPC and IdF). When possible, specific results for PC or GC are discussed in the article.

Results and Discussion

Data Collection

One of the objectives of this research was to assess the feasibility of MFA on a regional scale in

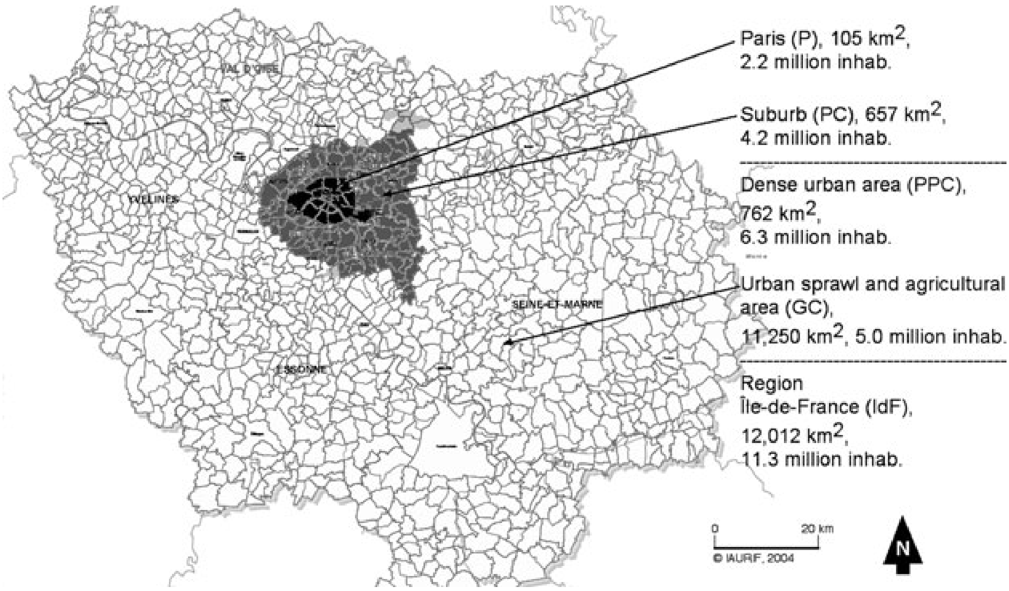

Figure 2 Study areas of the Île-de-France (IdF) region. inhab. = inhabitants; one square kilometer (km^2, SI) ≈ 0.386 square miles. *Source* (map): IAURIF (2008); copyright IAU Île-de-France. All rights reserved. Used with permission.

France. To this aim, we examined the availability of data for this type of analysis. Data required for MFA are mainly available at the regional and, albeit to a lesser extent, at the *département* levels. In this case, we benefited from the particular administrative status of Paris as both a municipality and a *département* and found that nearly all the required data were available (this is not likely to be the case for other cities in France).

The origin of the data and its quality are summarized in table 3. The most precise, continuous, and homogenous of the data were data on local extraction of biomass (thanks to agricultural statistics), data on imports and exports, except for fossil fuels (thanks to freight statistics), and data on household wastes. Data on the local extraction of minerals, on imports, on the local extraction of fossil fuels, on other solid wastes and

Table 2 Land use, Île-de-France, 2003, as a percentage (%) of the territory

%	*P*	*PC*	*PPC*	GC	*IdF*
Water	3	2	2	1	1
Forest	7	8	8	24	22
Agriculture	0	3	3	55	48
Parks and squares	12	10	10	4	4
Housing	39	40	39	7	12
Economic activities (secondary and tertiary)	5	10	9	1	2
Public facilities	18	12	13	2	3
Transport	15	11	11	2	3
Other	1	5	4	3	3
Total	**100**	**100**	**100**	**100**	**100**

Source: IAURIF 2008.
Note: P = Paris; PC = dense suburb of Paris; PPC = dense urban area (PPC = P + PC); GC = urban sprawl and agricultural area; IdF = Île-de-France region = P + PC + GC.

Table 3 Data: origin and quality

Flow	*Data origin and remarks*
Local extraction	
Fossil fuels	Discontinuous data. DGEMP (Direction générale de l'énergie et des matières premières/Energy and Raw Materials Branch, Ministry of Industry) and INSEE (Institut national de la statitistique et des études économiques/National Institute for Statistics and Economic Studies). Minor flow.
Minerals	Discontinuous data. DRIRE (Direction régionale de l'industrie, de la recherche et de l'environnement/Regional Branch of Industry, Research and the Environment) and UNICEM (Union nationale des industries de carrières et matériaux de construction/National Union of Quarries and Building Materials Industries).
Biomass	Detailed annual data for crops at *département* level. Older update for wood. Discontinuous data for hunting (not very important in the region). AGRESTE (Agricultural statistics, Ministry of Agriculture).
Oxygen	Deduced from emissions.
Imports	
Fossil fuels	Incomplete data, sometimes old, required compilation from various studies. Primarily from DGEMP.
Others	Detailed annual data at département level, including detailed nomenclature of products. SITRAM (Freight database, Ministry of Transport).
To nature	
To air: emissions	Data at *département* level (2000). CITEPA (Centre interprofessionnel technique d'études de la pollution atmosphérique/Interprofessional Technical Center for Studies on Atmospheric Pollution).
To air: water	Deduced from emissions.
Landfill	Biennial data for municipal wastes (should become annual), rare for other wastes. Studying waste treatment requires the compilation of various reports. ORDIF (Observatoire regional des déchets d'Île-de-France/Ile-de-France Region Waste Management Observatory), ADEME (Agence de l'environnement et de la maîtrise de l'énergie/Energy and Environment Management Agency), DREIF for construction and demolition wastes (Direction régionale de l'équipement en Île-de-France/Regional Directorate for Public Works in Île-de-France, dependent on the Ministry of Public Works).
To water	Unequal data. SIAAP (Syndicat interdépartemental pour l'assainissement de l'agglomération parisienne/Interdepartmental Syndicate for Sanitation in the Paris Region), AESN (Agence de l'eau Seine-Normandie/Seine-Normandie Water Basin Agency).
Dissipative flows	Incomplete and scattered data. Only fertilizers (direct data), road salt (rough estimate), agricultural use of sewage sludge and other wastes (direct data), road and tire wear have been taken into account. Road wear is assumed to be 1 millimeter/year and is calculated on the basis of road surface. Tire wear is assumed to be 6 kilograms/300,000 kilograms for trucks and 1 kilogram/50,000 for private vehicles, that is 0.16 grams/vehicle/kilometer for trucks (8 wheels) and 0.8 grams/vehicle/kilometer for cars (4 wheels).
Exports	Detailed annual data at *département* level, including detailed nomenclature of products. SITRAM.
Recycling	See "Landfill" entry, above.

liquid wastes, and on emissions to air, are of lesser quality or are not entirely compatible with MFA. Despite these limitations, we successfully used the available data to calculate direct flows; we could not, however, calculate hidden flows (unused domestic extraction and indirect flows) from these data. The year 2003 was chosen as the reference year based on the quality and quantity of

Table 4 Main results of the material flow analysis 2003

	Paris (2,166,000 inhab.)		*PPC (6,321,000 inhab.)*		*IdF (11,259,000 inhab.)*	
	kt	*t/cap*	*kt*	*t/cap*	*kt*	*t/cap*
INPUT						
Local extraction						
Fossil fuels	0	0.0	0	0.0	540	0.0
Minerals	0	0.0	0	0.0	16,990	1.5
Biomass	0	0.0	30	0.0	6,010	0.5
Total local extraction	0	0.0	30	0.0	23,540	2.1
Imports						
Fossil fuels	3,910	1.8	13,050	2.1	26,100	2.3
Others	15,240	7.0	56,450	8.9	88,350	7.8
Total Imports	19,160	8.8	69,500	11.0	114,450	10.2
DMI	19,160	8.8	69,530	11.0	137,990	12.3
OUTPUT						
To nature						
Emissions to air	6,710	3.1	24,470	3.9	53,840	4.8
Waste landfilled	0	0.0	2,500	0.4	20,010	1.8
Emissions to water	0	0.0	10	0.0	40	0.0
Dissipative flows	150	0.1	440	0.1	2,400	0.2
DPO	6,860	3.2	27,410	4.3	76,290	6.8
Exportations						
Exported flows to nature	4,100	1.9	9,610	1.5	69	0.0
Exports excluding wastes	8,380	3.9	40,410	6.4	58,500	5.2
Total exports	12,480	5.8	50.020	7.9	58,570	5.2
DMO	19,340	8.9	77,430	12.2	134,860	12.0
LEPO	10,960	5.1	37,020	5.9	76,360	6.8
RECYCLING						
Local	0	0.0	4,210	0.7	7,320	0.7
External	1,850	0.9	440	0.1	0	0.0
Total recycling	1,850	0.9	4,660	0.7	7,320	0.7
Wastes exported	5,950	2.7	10,050	1.6	70	0.0
DMC	4,830	2.2	19,070	3.0	79,420	7.1
DMC_{corr}	10,780	5.0	29,120	4.6	79,490	7.1
BI oxygen (combustion)	6,560	3.0	24,010	3.8	52,650	4.7
BO water (combustion)	3,280	1.5	12,010	1.9	26,330	2.3
NAS	3,100	1.4	4,110	0.7	29,460	2.6

Note: P = Paris; PPC = dense urban area (Paris and its dense suburb, taken together); IdF = Île-de-France region. One kiloton (kt) = 10^3 tonnes (t) = 10^3 megagrams (Mg, SI) ≈ 1.102 × 10^3 short tons. t/cap = tonnes per capita. DMI = direct material input; DPO = domestic processed output; DMO = direct material output; LEPO = local and exported processed output; DMC = domestic material consumption; DMC_{corr} = corrected domestic material consumption; BI = balancing inputs; BO = balancing outputs; NAS = net addition to stock.

available data. For MFA to develop, however—and it should conceivably be conducted every year or at the very least every five years for effective environmental policies to be implemented—it will be necessary for government to improve data production, collection, and availability.

General Results

The main results of our MFA are summarized in table 4 and figure 3. As shown in table 4, fossil fuel extraction, mineral and biomass extraction, imports (fossil fuels and others), emissions to air,

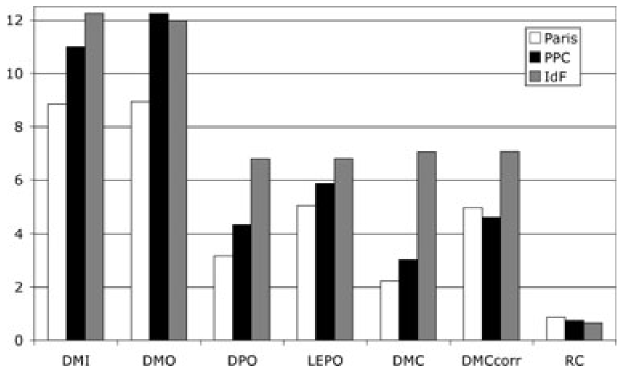

Figure 3 Main indicators of MFA for Paris, PPC, and IdF, 2003 (tonnes per capita). P = Paris; PPC = dense urban area; IdF = Île-de-France region. For an explanation of indicators, see table 1. RC = recycling.

and exports, excluding wastes, are calculated from direct (or semidirect in the case of fuel) data. Landfilled waste, emissions to water, and dissipative flows resulting from waste and wastewater treatment have been calculated according to the method outlined above, in the *Method* section. Dissipative flows are known directly (fertilizers for instance) or indirectly (see table 3). NAS is the result of subtracting balanced outputs from balanced inputs.

We first looked at the impact of applying MFA at a local level on DMC (as it is defined by the Eurostat method). We found that the value for DMC ranges from 2.2 tonnes per capita (t/cap) in Paris, to 3.0 t/cap in PPC and 7.1 t/cap in IdF.[4] These DMC values are very low, particularly for the areas of Paris and PPC, and clearly are the result of the exportation of waste (as discussed above, in the *Method* section), highlighting the importance of using DMC_{corr} to accurately analyze local socioeconomic metabolism. The DMC_{corr} for the Paris and PPC areas are 5.0 t/cap and 4.6 t/cap, respectively. DMC_{corr} is the same as DMC for IdF as the region exports nearly no wastes. Results for DMI and DMC can be compared with national figures provided by Eurostat (2008); other comparisons are not possible as flows to nature are not accounted for at the national level. For 2003, DMI on the local scale is 8.8 t/cap for Paris and 12.3 t/cap for IdF, compared with a DMI of 16.5 t/cap at the national level. DMC_{corr} for the areas of Paris and IdF is lower than the national DMC (5.0 t/cap and 7.1 t/cap versus 13.2 t/cap, respectively). The primary reason that local DMC and DMI are lower than national values is that, beyond its industrial and agricultural activities, the region extracts, produces, and transforms less material than the rest of the country. These processes upstream of social metabolism, lead to increased emissions and wastes and, as a consequence, to higher DMI and DMC values. In fact, the opposite occurs in this region; it imports many goods that are produced outside of its boundaries. The elaboration of these goods requires much more consumption of materials than their final material content. As cities generally consume significantly more than they produce, further research is required on indirect flows for regional and, especially, urban MFA. DMC and DMI at the local level may also be lower because an increase in stock is less important in the Île-de-France region than in other regions in France. For instance, only 10% of new buildings (in terms of floor area) in France are constructed in Île-de-France (MEEDDM 2008) although nearly 20% of the French population lives there. The distance between DMI and DMC is also important: The percent of DMI to DMC_{corr} is 178% in Paris, 239% in PPC, and 174% in IdF, while it is 125% at the national level.

We also examined the total flows to nature as represented by LEPO. LEPO values were 5.1 t/cap for Paris, 5.9 t/cap for PPC, and 6.8 t/cap for IdF. These data reveal that more than half the region's DMI is returned to nature (57%, 53%, and 55% of DMI for Paris, PPC and IdF, respectively). Furthermore, the data show that flows to nature exceed commercial exports and that limiting MFA to monetary flows is particularly irrelevant. The high emissions to air in LEPO (61% of LEPO in Paris, 66% in PPC, 71% in IdF) clearly illustrate the importance of

Table 5 Wastes landfilled, by geographic origin of wastes, 2003 (kg/cap)

Origin of wastes	*Paris*	*PC*	*GC*	*IdF*
Household and related wastes	98	83	150	116
Ordinary industrial wastes	115	67	64	75
Demolition wastes	1,654	1,746	1,301	1,533
Agricultural wastes	0	0	32	14
Dangerous industrial wastes	0	18	63	34
Wastewater treatment wastes	4	4	7	6
Total	**1,872**	**1,919**	**1,617**	**1,778**

Note: One kilogram (kg, SI) ≈ 2.204 pounds (lb).

dematerialization and decarbonization. These values can also be compared with the very low recycling rates, even when both local and external recycling are considered: less than 1 t/cap, about 10% of DMI in Paris, 7% in PPC, 5% in IdF. If demolition wastes are excluded from the analysis, the amount of wastes landfilled remains low due to the wide use of incineration. The different categories and the geographical origins of landfilled wastes, 86% of which are demolition wastes, are presented in table 5. Landfilling mainly occurs in GC (86% of total landfilled wastes, table 4). These data clearly reveal that the French waste policy, which places emphasis on household wastes, insufficiently addresses other types of wastes.

Our results for NAS are very low, and we propose two reasons to explain these values. First, Île-de-France—and especially its dense part—may already be saturated with materials (see also below in the section *Comparison to Other Regions*), or characterized by a high rate of stock turnover—a less probable hypothesis as, for instance, the renewal of buildings is very slow. Second, NAS is not calculated directly but is the result of subtracting DMO+BO from DMI+BI; thus, the calculation of NAS is susceptible to various sources of errors (especially for BO and BI) that may limit its accuracy.

We also compared the three study areas with each other. Our data show that every flow, except DMC_{corr} and recycling, increases with the size of the area. These increases are likely due to activities, in particular for the primary and secondary sectors, which are all the more developed and diversified since the study area around the city center is large. Furthermore, these activities require and create very large material flows. The increased flows may also be due to the type of area defined within each zone: IdF includes areas of urban sprawl, whereas Paris and PPC are made up of densely populated zones (see the next section, *Detailed Analysis of DMC*).

The city center (Paris) depends almost entirely on other areas for inputs and flows to nature that are, with the exception of emissions to air and dissipative flows, exported to other parts of the region. This dependence decreases slightly in the dense urban zone (PPC), mainly because some solid waste incinerators and wastewater treatment plants are located in the *Petite couronne* (figure 2). IdF is self-sufficient in regards to flows to nature (or, more precisely, does not directly export them) but is evidently not self-sufficient in regards to inputs: Local extraction represents only 17% of DMI for this region compared with 70% for France as a whole. In view of achieving sustainability, therefore, it would be important to replace imports (and their indirect flows) with local recycling.

Detailed Analysis of DMC

The detailed results help to partially explain the observed differences between the areas under study and may help in creating effective policies. Using the available data, DMC was estimated not only for P, PPC, and IdF but also for PC and GC (figure 4). As figures concern specific products, the distinction between DMC and DMC_{corr} is no more necessary. A slight underestimation exists of the imports and exports because some of the detailed rail data on the *département* scale could not be made available to the general public. An

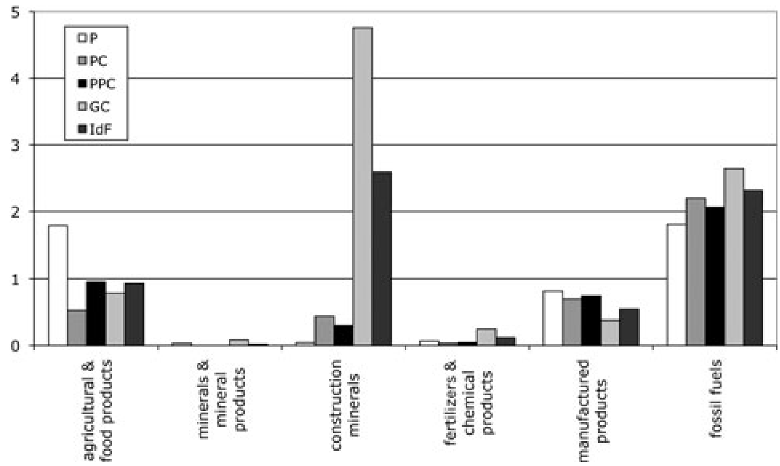

Figure 4 Domestic material consumption (DMC), 2003 (tonnes per capita). P = Paris; PC = dense suburb of Paris; PPC = dense urban area (PPC = P + PC); GC = urban sprawl and agricultural area; IdF = Île-de-France region.

overview of rail transport on the regional scale and of the quality of DMC calculated without taking rail transport into account are presented in table 6. It is assumed that the results for agricultural and food products, fertilizers and chemical products, manufactured products, and fossil fuels are reliably accurate but are less so for minerals and construction materials.

Food consumption per capita is higher in Paris than anywhere else in France. Because Paris is both an employment and tourist destination, there are more mouths to feed than inhabitants: MFA reliably reflects the functioning of this urban area. In consequence, organic wastes are also likely to be of great importance. In Paris, daily food DMC reaches 10,600 t, which is 4.9 kg/cap if the official population of the capital is used (as shown in figure 4). Even if the population is increased by 50% to account for every potential consumer of food in the city (which is probably an overestimate of the eating population and, as a consequence, an underestimate of its per capita food consumption), DMC still amounts to 3.3 kg/cap, which is much more than an average person can eat in one day. As we have previously shown for nitrogen (Barles 2005), a great proportion of the food products entering Paris thus likely ends up as solid waste. This urban waste

Table 6 Rail transport of goods of the Île-de-France (IDF) region, 2003

	Imports		*Exports (Ex)*		*Internal traffic (IT)*	
	Rail (kt)	*% of DMI*	*Rail (kt)*	*% of Ex*	*Rail (kt)*	*% of IT*
Agricultural & food products	1,009	4.1	387	2.7	5	0.0
Minerals & mineral products	554	13.5	557	14.2	120	0.7
Construction materials	3,915	10.9	181	2.7	124	0.2
Fertilizers & chemical products	156	3.1	315	8.4	5	0.1
Manufactured products	1,336	4.3	1,739	7.0	26	0.1
Fossil fuels	100	0.4	73	1.1	214	4.0
Total	**7,070**	**5.5**	**3,253**	**5.4**	**494**	**0.3**

Note: DMI = direct material input; kt = kilotons.

could be effectively used for the production of fertilizers or biogas, but this option is rarely considered in city centers because agricultural and organic issues are not deemed relevant in these areas. The origin of food and agricultural products and the distance between DMI and DMC are also points of concern. At the regional scale, DMI is 2.2 t/cap, of which local extraction represents 0.5 t/cap, while DMC is 0.9 t/cap and exports are 1.3 t/cap; as such, despite its very high production levels, regional agriculture in this area is no longer solely restricted to the local food supply (see also Billen et al. 2009).

The consumption of manufactured products is higher in Paris than in PC and as such higher in PC than in GC. This is likely the result of unequal living standards in these areas and a reflection of the importance of the service sector in Paris.

As a result of both the repartition of various activities and urban sprawl, fossil fuel consumption is higher in GC than in PC and higher again in PC than in Paris (and in France than in IdF: 2.0 and 1.7 t/cap, respectively): Per capita consumption is 50% higher in GC than in Paris.[5] These results are not surprising and support more detailed studies on energy-urban form relationships (see for instance Newman and Kenworthy 1999, VandeWeghe and Kennedy 2007).

Construction materials in GC make up a significant proportion of the DMC; however, the value is biased due to a lack of detailed rail data (see above for discussion of this bias). To assess the impact of this bias on the consumption of construction materials, we assumed all 2003 rail traffic for this particular material was within PPC (table 7). Although this assumption leads to a threefold increase in DMC in PPC, it remains significantly different than the DMC in GC.

This difference may be due to the fact that the construction sector is more dynamic in GC than in PPC. In France, a permit is required to build (for housing or other buildings), and a builder must inform the administration when construction begins. As such, a database exists on a municipality scale of every construction job, its start date, and expected floor area (this information is required to obtain a permit) (MEEDDM 2008). Results from 2001 to 2003 (it is assumed that

Table 7 DMC for construction materials (1) without rail and (2) assuming that all rail traffic is within PPC

	(1)		*(2)*	
	kt	*t/cap*	*kt*	*t/cap*
PPC	1,897	0.3	5,754	0.9
GC	23,492	4.8	23,492	4.8
IdF	25,389	2.3	29,122	2.6

Note: DMC = domestic material consumption; PPC = dense urban area (Paris and its dense suburb, taken together). GC = urban sprawl and agricultural area; IdF = Île-de-France region; kt = kilotons; t/cap = tonnes per capita.

some of the construction was started in 2001 but not completed until 2003) are shown in figure 5. In each year, around 60% of the construction (in terms of floor area to be built) is located in GC. These data do not, however, explain the difference in the consumption of construction materials between this area and the other parts of IdF. Another explanation may be that the type of buildings constructed in these areas differs: Approximately 49% of dwellings (in terms of number of dwellings and not of floor area) built between 2001 and 2003 in GC are single family, whereas this percentage is 13% for PPC, 0% in Paris, and 16% in PC. Does the construction of a single-family house consume more construction materials than an apartment dwelling? The answer to this question is disputed in France. Even if the answer is that it does not, as we have assumed here, construction of a single-family house indisputably requires more infrastructure and public works than the construction of an apartment building. The low-density housing that is often characteristic of urban developments in GC therefore has a significant impact not only on energy but also on construction materials.

Conversely, the region is far from self-sufficient with regard to construction materials: Local extraction is only 1.5 t/cap, whereas regional consumption is 2.6 t/cap and landfilled demolition wastes are 1.5 t/cap (table 5). These data help to define two targets for dematerialization: first, controlling urban extension (which is generally only linked to the energy issue) to reduce the demand for construction materials and

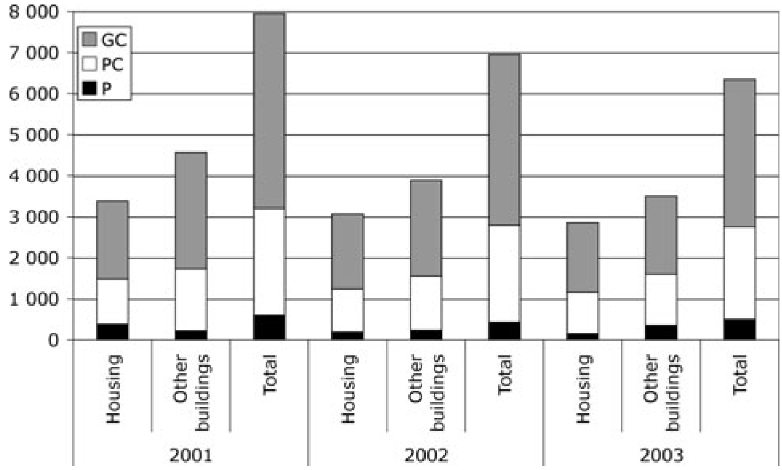

Figure 5 Expected floor area of construction begun in 2001, 2002, and 2003 in thousand square meters (1,000 m^2). *Source of data*: MEEDDAT, 2008. P = Paris; PC = dense suburb of Paris; GC = urban sprawl and agricultural area.

second, recycling demolition wastes to reduce their extraction.

Comparison to Other Regions

Few MFA exist on regional and especially urban scales. Where they do exist, comparisons are often not possible because different methods have been used. Recently, Hammer and colleagues (2006) published results for Hamburg, Vienna, and Liepzig based on the Eurostat method (table 8). These three cities differ significantly from Paris and its urban area as they are less populated and larger and, therefore, less dense. Their economic and political roles are also quite different: Hamburg is a major harbor, Vienna a capital, and Liepzig a regional center. As such, the only indicator we were able to compare directly is DMC. DMC for both Hamburg and Liepzig are higher than that for Paris and IdF; DMC for the Vienna center is equal to the DMC for Paris. Of the three cities studied by Hammer and colleagues, Vienna also has the highest density (see table 8).

Table 8 Main characteristics of Hamburg, Vienna, Liepzig, and Paris

	Hamburg (2001)		*Vienna (2001)*		*Liepzig (2001)*		*Paris & IdF (2003)*		
	Center	*Urban Area*	*Center*	*Urban Area*	*Center*	*Urban Area*	*P*	*PPC*	*IdF*
Area (km^2)	755	8616	415	4596	298	4386	105	762	12012
Population (*1,000)	1726	3264	1550	2120	493	1091	2166	6321	11259
Density (inhab./km^2)	2286	379	3736	461	1658	249	20629	8295	937
DMC (t/cap)	8.2	11.4	5.0	8.8	—	25.3	5.0	4.6	7.1

Source: Hammer and colleagues (2006) for Hamburg, Vienna, and Liepzig; present study for Paris. P = Paris; PPC = dense urban area (Paris and its dense suburb, taken together); DMC = domestic material consumption; IdF = Île-de-France region; inhab./km^2 = inhabitants per square kilometer; t/cap = tonnes per capita.

Although a more detailed analysis is required to take into account the various origins and uncertainties of the data, we nevertheless propose that Paris experiences a kind of material saturation that explains its low DMC (see also discussion above). Vienna's low DMC may also be explained by a similar material saturation.

Conclusion

The first goal of our study was to examine the feasibility of MFA on the regional and urban scale in France. We conclude that such an analysis is possible and that the Eurostat method can be applied successfully to this type of analysis. Some adaptations of the Eurostat method were necessary, however, to take into account the importance of exported wastes and flows to nature and their impact on DMC. Two local indicators were thus defined: LEPO, a measure of the local and exported flows to nature, and DMC_{corr}, a modified DMC that is calculated by excluding exported wastes from exports (and, where necessary, imported wastes from imports). Improvements to the production and/or collection of public data are necessary to allow for more precise and replicable analyses, over the short and long term.

MFA allows urban functioning to be weighed. DMI, DMC, and DMC_{corr} are lower on the local scale compared with the national scale, reflecting the fact that urban areas import most of what they consume and "create" large hidden flows. LEPO are also considerable: They exceed 50% of DMI, whereas recycling is nearly nonexistent. These results question the validity of the current public policies concerning waste recycling and emission reduction.

The study was conducted at three levels, and the results clearly highlight the value of using such a multiscaled approach. Our data show that Paris depends on a wide area for its material provision and on the suburbs and the region as a whole for its waste treatment. These results demonstrate the material consequences of both the concentration of activities in the city center—consumption of food—and urban sprawl in the region—high consumption of construction materials and fuel. The link established between construction materials flows and planning issues is also worth noting. It reveals the need for new public policies, especially concerning waste management—to reduce construction materials imports—and urban planning—to reduce their consumption. In addition, more research and the development of action plans to link urban and agricultural policies to improve the use of urban fertilizers and to favor local food supply are required. Such policies would necessitate an in-depth interdisciplinary analysis of the governance of material flows.

Further studies on urban metabolism to characterize the urban environmental imprint would not only require capturing the hidden flows (Barles 2008), but also comparing data in space and time (Decker et al. 2000; Kennedy et al. 2007). Furthermore, to obtain significant results, it would be important to link MFA to the particular socioecological conditions that influence material flows and their evolution. This type of analysis would thus lead to a better understanding of such systems.

Acknowledgements

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Notes

1. More details are available in the research report (Barles 2007).
2. They mention that additional activities can complete this list "to analyse and solve a particular resource-oriented problem" (Brunner and Rechberger 2004, p. 44). Such a definition of main activities is perhaps relevant today in developed countries but probably not in other parts of the world or during other times (cleaning was not so important two or three hundred years ago and working simply does not exist in some societies).
3. More precisely, *départements* are divided into *cantons* consisting of municipalities. This distinction is not necessary here.
4. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.
5. It has to be kept in mind that this fuel consumption does not represent all of the energy consumption within the area as it does not take into account imported electricity.

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