BTPFlux: a building material flow analysis model to enhance the urban metabolism on French territories

E Sorin¹, R Tirado¹, E Gully¹, M Louérat¹, S Laurenceau¹

¹ Scientific and Technical Centre for Buildings (CSTB), University Paris-Est, 77447 Marne-la-Vallée, France

Abstract. Worldwide, the construction sector is the principal consumer of raw resources (50% of the natural resources) and the leading producer of solid waste (2.2 billion tons per year). Because of their quantity and their potential for development, construction wastes constitute a catalyst for establishing strategies and action programs aimed at making the management of resources circular at several territorial scales. Performing these strategies needs a detailed and structured knowledge of flows. In this context, the CSTB has developed a macro-component bottom-up-based model: BTPFlux, that aims to characterize the materiality of the building stock and the associated demolition, and renovation waste flows. A national database with generic information for every building on the metropolitan French territory was used. This database gathers information such as the surface, the typology, or the year of construction of the buildings and is then linked with a specific database characterizing existing construction products. This method provides a detailed characterization of the building material stock available on the French metropolitan territory. So, the environmental impacts, the treatment costs, and the valorisation potentials can be estimated by implementing different management scenarios for each category of waste assessed. The model was already successfully applied to the “Ile de France” region and can be replicated to any other French territory. The results will allow the stakeholders to better understand the materiality of their territory, giving them the possibility of making optimal decisions to implement the reuse and recycling of secondary resources. However, some improvements can still be made in the description levels of macrocomponents or in the description of infrastructures that BTPFlux does not currently model.

Keywords: building stock, material-flow analysis, construction sector, circular economy, material building stock

1. Introduction
The construction sector is the main consumer of raw resources (50% of the natural resources) as well as the leading producer of solid waste (2.2 billion tons per year) [1]. Most of the materials consumed by construction and renovation are stored in the built stock for several decades [2]. However, deconstruction and renovation create construction and demolition wastes (CDW), which represent an important part of the global waste produced by the cities [3-5]. Depending on the countries, 25% to 40% of the CDW are going to landfills [6-7], which is a real threat to the environment. The management of CDW must be improved to protect the environment, but also to prevent and reduce the country’s imports of raw materials. It represents a challenge in terms of material tracking, flows management, and quantities estimations.
In order to respond to this challenge, the G7 member states created the Resource Efficiency Alliance to protect and improve resource efficiency [13]. In France, the Anti-Waste Circular Economic law (AGEC) establishes new measures to develop the circular economy and reduce the environmental impacts of the country. In the construction sector, this law is supported by two important measures. The first one is the obligation to realize a diagnosis of the valorisation potential of every Product, Equipment, Material, and Waste (PEMW) before the deconstruction or rehabilitation of a building of more than 1000 m² floor area. This diagnosis is combined with a numerical platform that brings together all the diagnosis realized to provide information on the quantities of PEMW available on a municipality, in order to facilitate the exchange between the construction actors. Another measure that will support the AGEC law is the creation of an Extended Producer Responsibility Principle (EPR Principle) to the construction and demolition waste. This EPR system will provide the means to manage CDW flows for regional decision-makers. With these two measures, France is providing itself with robust instruments to develop its circular economy in the construction sector. However, to develop the valorisation in the industry, the future CDW quantities must be estimated and compared to the current industry capacities [14]. This is why the Scientific and Technical Centre for Buildings (CSTB) has developed a material flow analysis (MFA) model, named BTPFlux [15], which estimates the built-stock material and the CDW flows associated with deconstruction and renovation projects. This model can provide predictive scenarios of CDW production but can also be used as a monitoring tool for CDW production. The model aims to be used by regional decision-makers and eco-organizations.

2. State of the art

2.1 The material-flow analysis
The MFA is a powerful tool to assess and anticipate the production of CDW. Such analysis coupled with geometric information systems (GIS) is one of the most promising tools for developing circular economy strategies [9]. Several approaches of the MFA exist [3, 5, 10-12], which are grouped in two main categories: static and dynamic analysis, which are declined in bottom-up and top-down approaches. The choice of one or another of these approaches is also subject to the availability of data on the subject and territory under study. Moreover, due to the data availability variety for each territory, there is no standard approach for MFA.

The bottom-up approach is more flexible in the analysis of the stocks and material flows [9, 16], but needs an important knowledge of the building specificities of a territory, which requires important economic investment [16, 18]. To overcome this disadvantage, various authors developed building archetypes that described the architectural characteristics of buildings in a limited number of building types. These archetypes are associated with material intensities coefficients (MICs) which need important efforts to be collected and harmonized [19-21]. Despite all those efforts, the MICs used are not detailed enough to support circular economy strategies. Indeed, wastes are often considered in categories that are too large to identify the associated valorisation industries. Moreover, this type of approach can only be applied to sample of buildings and does not allow a city to plan a circular economy strategy at the scale of a neighbourhood development.

The building-to-building approach [22], on another hand, collects the available information on each building in order to determine for each building the material stock. This approach provides more accurate results and can be used at a lower geographic scale. Moreover, with the emergence of the Building Information Modelling (BIM), the available information for each building will be more and more detailed in the future. But this type of modelling is mainly used for new buildings and is expensive. This practice cannot, therefore, be generalized to the whole building stock yet. However, some rehabilitation projects with BIM models can be an essential source of information on the construction techniques and materials used in the past [23-24]. Therefore, it is important to move from a bottom-up approach to a building-by-building approach to provide a more detailed and scalable tool for estimating material stocks.
2.2 Review of French territories applications

In France, the first CDW flow study was conducted on the city of Orleans in 2012 under the name ASURET project. This study was carried out using a bottom-up approach based on the definition of multiple archetypes to characterize the buildings and infrastructures of the city. The city was divided into homogeneous districts with an estimation of the construction period of the buildings per area. The surface area of each type of building was then calculated using the National Geographic Institute’s (IGN) topographic database (BD Topo). The material stock estimation also considered the networks and roads infrastructures. This study was the first of its kind on the French territory and considered five categories of materials and established the basis for the study of CDW flows.

Following this, a study on the Ile de France region was carried out by Augiseau [25-26]. This study also used a bottom-up approach and considered buildings and infrastructure archetypes to estimate material-built stock quantities on a territory. The analyse of the urban metabolism gave macroscopic information on 27 categories of material. However, the territorial decision-makers need more detailed information to develop their circular economy strategies [15].

To provide to French territorial decision-makers a tool to develop their circular economy strategies, the CSTB developed its own material-flow analysis model, named BTPFlux to overstep the limits identified in the precedent research. So, the objectives of this model are:

- to estimate in nature and quantity, and with a high resolution, the building stock of a French territory;
- to detail the CDW flows for all Product, Equipment, Material and Waste categories;
- to help local authorities to estimate the potential of valorisation of their territory;
- to be updated according to the progress of data collection on construction systems and materials used in buildings.

3. Method

The BTPFLux model is a hybrid approach between the building-by-building and the bottom-up approaches. It is based on several bricks developed by the CSTB:

- The Base de Données Nationale des Bâtiments (BDNB): A French database on buildings which was created by joining multiple building-related databases (around 20). This database contains many information on the geometry, the structure, the energy consumption, the use, etc. of more than 20 millions of buildings.
- A python package TyPy: a database and a management tool for building typologies. The TyPy database contains more than 300 components of buildings which can be aggregated into macro-components (Figure 1). The TyPy management tool selects components in the database using the information of the BDNB, to estimate the materiality of the buildings. Every component of the database has material and waste properties determined by Environmental Product Declaration when possible, and by the bibliography otherwise.

![Figure 1. Example of the composition of an exterior wall as a macro-component [15].](image)

- A geometric service software: The geometric service is a software that calculates the building’s geometric properties from its geospatial data. By using the geospatial data of the BDNB, the geometric service provides the area, perimeter, and the azimuth of the buildings’ envelope.
The python package BTPFlux itself: In addition to ensure the various requests to the BDNB, TyPy and the geometric service, BTPFlux defines the deconstruction and renovation scenario and statistic method to extrapolate the results calculated on a well-defined buildings sample to the whole building population of the territory. Figure 2 shows the model structure, which is separated into five main operations.

![Diagram of BTPFlux model](image)

**Figure 2. Structure of the BTPFlux model [15]**

### 3.1 Data merging and sample generation

The BDNB database provides many information on the building stock, like the main building use, the construction period, electric consumption, geospatial coordinates, building system. However, each building has not the same level of information. To estimate the building material composition, the TyPy package needs key information; for instance, building use, building construction period. So, to provide an optimal estimation, only buildings with this key information are considered.

For residential use, only the buildings with Energy Performance Diagnosis (EPD) are considered in the sample, because EPD provides precious information on the insulation materials and other structural elements of the buildings. For the non-residential uses the EPD coverage is too low to allow the same approach. So, for this case, every building with geospatial data and year of construction information is considered. Currently, for non-residential use, only the educational, office, and industrial use can be treated by the model.

### 3.2 Data enrichment

A building is modelled by the association of components and assemblies (Figure 3). With the information available in the sample, the TyPy package uses algorithms of association, based on bibliographic studies and known professional rules, to select the appropriate macro-components. The built stock is segmented by use, construction period (Table 1), and material of some building elements, as exterior wall and roof. Each macro-component in the database is dimensionless and has its own properties, like density or thermal conductivity. The database has more than 100 macro-components and 300 components in February 2022.
After determining the macro-components present in the building, the quantities must be estimated. To do so, the geometry service is used. This software developed by the CSTB uses the geospatial information available on the BDNB to determine the surface of the building envelope. The floor area is then determined by considering the height of the building and, when available, the number of floors. So, the mass of each component of the buildings is known. And, as for each component of TyPy, a mass repartition in the different waste categories is specified, the total waste quantities of each building can be estimated. So, the waste mass estimation can be performed at the macro-component, building or territorial scale.

### Flows assessment

As the quantities of waste for each building of the territory can be modelled, the CDW flows can be estimated by determining which building is demolished and renovated. In France, residential buildings built during the period 1945-1970 present multiple pathologies due to their conception, mostly concerning the thermal performance. While the building built before 1945 are more adaptable and preserved for their architectural quality. So, it was assumed that pre-1945 residential buildings are mostly renovated when the buildings built between 1945 and 1970 can be both, renovated and demolished. Buildings built between 1970 and 1995 can also be renovated in order to respond to new thermal regulations. For the non-residential buildings, renovation and demolition can be realised for any period because the lifespan of those buildings is mostly linked to investment strategies.

For residential buildings, the demolition rates were calculated by comparing the number of dwellings demolished yearly to the total number of buildings on the considered construction period [27-31]. The demolition rates for non-residential buildings were calculated by comparing areas demolished per year to the total area of building in the territory [27-31]. The demolition rates were estimated with a high and a low value and are presented in Table 2.
Table 2. Demolition rates according to the main building use

| Main building use       | Low value | High value |
|-------------------------|-----------|------------|
| Individual housing      | 0.00825   | 0.02258    |
| Collective housing      | 0.00474   | 0.01297    |
| Industrial              | 0.00730   | 0.00730    |
| Office and education    | 0.00212   | 0.00940    |

3.5 Extrapolation

Once the CDW flows of the buildings sample are estimated, the territory scale must be considered. As long as the sample has a sufficient variety of buildings compared to the population, it is possible to extrapolate the results. The extrapolation is realized by considering a statistical weight for each building in the sample. This statistical weight is calculated as follows. To provide usable results, the number of buildings in the sample should be at least 1,500 [15].

Firstly, the total area surface of buildings with the same use, construction period, and main material of the exterior wall is calculated for the sample and the population ($S_{cat\_sample}$, $S_{cat\_pop}$). The total area surface of buildings with the same use and construction period is calculated ($S_{cp\_sample}$, $S_{cp\_pop}$). Then, the proportion of each category by construction period is calculated by dividing $S_{cat\_i}$ by $S_{cp\_i}$ for the population and the sample ($P_{cat\_pop}$, $P_{cat\_sample}$). The repartition of each building category of the sample (repartcat) is then adjusted by dividing $P_{cat\_sample}$ by $P_{cat\_pop}$.

Secondly, the weight of the sample (samplew) in the population for each construction period is estimated according to the total surface area, equation 1.

$$samplew(use, per) = \frac{\sum_{sample} S_{building}(use, per)}{\sum_{population} S_{building}(use, per)}$$  \hspace{1cm} (1)

Finally, the statistic weight of each building of the sample can be estimated according to equation 2.

$$building_{statw}(use, per, mat) = \frac{repartcat(use, per, mat)}{samplew(use, per)}$$  \hspace{1cm} (2)

4. Application to 4 French territories

The model can be applied to all the territories of metropolitan France by considering national assumptions for deconstruction and renovation scenarios and for the disposal repartition to the various outlets. As an example, the model was applied to the 4 biggest French cities which present various population density (Table 3).
Table 4 presents the sample size for each metropolis.

| Metropolis name                              | Main city name | Population (in thousands of inhab) | Density (inhab/km²) |
|----------------------------------------------|----------------|------------------------------------|---------------------|
| Métropole du Grand Paris                     | Paris          | 7 075                              | 8 689               |
| Métropole d’Aix-Marseille-Provence           | Marseille      | 1 890                              | 600                 |
| Métropole de Lyon                            | Lyon           | 1 400                              | 2 621               |
| Métropole européenne de Lille                | Lille          | 1 174                              | 1 747               |

Table 3. Main information on the 4 biggest French cities (INSEE)
Table 4. Sample size for each metropolis

| Main city name | Sample size (in buildings number) |
|----------------|----------------------------------|
| Paris          | 57 296                           |
| Marseille      | 24 657                           |
| Lyon           | 14 514                           |
| Lille          | 19 106                           |

This difference in density implies differences in building typologies that can be partially observed through the distribution of the building use present in the samples of each metropolis. However, the repartition observed at the metropolitan level must be qualified. Indeed, the metropolis of Aix-Marseille-en-Provence has a population density of 600 inhabitants/km². But half of the population of the metropolis is concentrated in Marseille, which has a population density of 3,608 inhabitants/km², which explains the importance of collective housing compared to individual housing. On the other hand, the population of the Lille metropolis is much more spread out over all its municipalities and presents a predominance of individual housing (Figure 4).

These observations must be considered carefully because the distribution of buildings in the sample is not necessarily the same as the one of the global population, especially with regard to the distribution between housing and non-residential buildings because the selection rules of the sample are different for these two types of use.

![Figure 4](image_url)

Figure 4. Repartition of the main building uses of the sample for each metropolis understudy

The waste quantities linked to deconstruction scenarios can be determined for each metropolis, Table 5 presented the result for inert waste (iw) and non-hazardous waste (nhw) for both, minimum and maximum rates. Figure 5 and Figure 6 show the repartition for both waste types in more detailed categories.
Table 5. Total waste quantities of inert and non-hazardous wastes for each metropolis

|                     | Paris   | Lille   | Lyon    | Marseille |
|---------------------|---------|---------|---------|-----------|
| Inert wastes (Mtons) | min     | 1.04    | 0.23    | 0.30      | 0.37      |
|                     | max     | 2.365   | 0.50    | 0.70      | 0.83      |
| Non-hazardous wastes (ktons) | min | 49      | 17      | 16        | 21        |
|                     | max     | 122     | 38      | 35        | 51        |

As expected, the concrete and stone represent most of the waste produced by deconstruction. For non-hazardous wastes, which are the one with the greatest valorisation potential, wood and gypsum represent more than 80%. The repartition between those two categories seems to be linked to the collective/individual housing repartition. This makes sense considering that the wood deposit is probably mainly produced by the carpentry demolition of the individual housing.
Those results provide a first estimation of the waste quantities produced in a year for the 4 metropolises studied. The model can also be applied to thermal renovation operation.

By working with the local actors, the estimations can be improved by considering, for example, specific deconstruction and renovation scenarios and local waste management networks.

5. Conclusion
The BTPFlux model developed by the CSTB can be applied to any territory of metropolitan France to propose a first estimate of the quantities of waste related to deconstruction and thermal renovation produced each year, as long as this territory represents a sufficient size. The method requires a sample of at least 1500 buildings to be representative, which represents a territory with around 15 thousand buildings. This approach lies between the bottom-up and the building-by-building approaches by estimating the materiality of each building of a well characterized sample. This allows to consider the urban specificities of the studied territories and to propose a detailed and configurable approach. By working with local actors, it is possible to further detail the approach by using territorialized deconstruction and renovation scenario or by considering specific local waste management networks. This model can help policy makers to establish circular economy strategies by comparing the PEMW quantities produced by their territory to the recovery sector capacity. By giving information on their capacity to be self-sufficient in resources when the material consumption is known. One of the future features of the model is to consider the material consumption. And, if wanted by the policy makers, the model can be applied to neighbouring territories in order to investigate the trading opportunities with them.

The result presented here were compared to waste estimation made by measurement in the waste collection centre. And the results provided by the model are coherent with those estimations. However, some categories, like bricks or metals, are not well estimated by the model. For the bricks it was a programming issue which was solved in the newest version of the model. But the estimation for metals is uncomplete because the networks and equipment of buildings are not yet considered by the model. Many limitations still need to be overcome to become a tool that can help local authorities to implement their CE strategies. First, only 3 tertiary uses are considered by the model and the algorithms to estimate the materiality of these buildings still need to be improved in addition to considering the other types of tertiary buildings. Some elements of the buildings are not yet considered, such as networks, equipment, or most of the finishing work for example. These elements are key to the development of the circular economy, and developments are underway to allow their integration soon. Only about ten categories of waste are considered by the model, the objective is to increase the number of categories to match the categories of Product, Equipment, Material and Waste of the diagnosis of the valorisation capacity which is around 40 categories. The quality of the building component stock is not considered. The valorisation potential of the PEMW is only considered by the repartition of every category in the different disposals. One future way of improvement of the model is to consider more categories and the service life of the components to better estimate the reuse and recycling potential of the building stock. But first, the focus is made on correctly describe the materiality of the building stock, by considering every use and most of the different building systems. Finally, the reliability of the statistical approach needs to be improved to apply the approach on a neighbourhood scale.

To ensure an efficient monitoring of the evolution of the building stock, the building database, still under development, is regularly updated, approximately every 4 to 5 months, with a consistent update once a year.

This approach could be applied to territories outside metropolitan France if the following conditions are met:
- Access to a building database with at least, for most buildings, information on the main use, the period of construction, the main structural material and geospatial coordinates.
- Information on the deconstruction and renovation rates of buildings of the territory for different uses, as well as the disposal rates in the different outlets.
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