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Towards achieving circularity in residential building materials: Potential stock, locks and opportunities

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A B S T R A C T

The 21st century globalization and growth are being accompanied by a tremendous use of residential building materials and has increased the demand for aggregates in concrete-based materials. In the context of France, natural aggregate quarries are dispatched throughout the various regions and generally seem to satisfy the need for aggregates in residential construction. Such however is not the case in those fast growing cities/regions with few natural aggregate quarries. As a follow-up to the waste framework directive 2008/98/EC urging better resource use, this paper explores the ability to achieve circularity practices in residential building materials in French regions. To do so, the framework proposed in this paper aims to close the loop of residential building materials in France and reduce its natural aggregates' consumption. Stock and flows of materials consumed, construction and demolition wastes generated and recycled materials from this sector were assessed through a regional-level material flow analysis. Based on our results, an average reduction in regional natural aggregate extraction of 20% is obtained when using stock and flows of recycled aggregates stemming from the residential component of construction and demolition wastes and re-injected in new dwellings. The residential wastes employed to reduce natural resource extraction include: concrete, block concrete, stone, solid and hollow bricks from baked clay, tiles, mortar, mineral plaster, glass, sand, and asphalt. The findings of this study also present an overview of the locks and opportunities to achieving the sustainable use of residential building materials.

1. Introduction

The need for raw materials is continuously increasing for residential construction and civil work engineering structures. Natural aggregates are at the heart of this worldwide demand. The decrease of this crucial resource for concrete production and the decrease of landfill disposal available areas lead to seek for new opportunities to meet these challenges. They are also in line with the 11th, 12th and 13th sustainable development goals for a better production and consumption of resources in cities as well as for climate change reduction (Assembly, 2015). According to the latest French statistics (UNPG, 2019), 435 million tons of aggregates were used in France, with 27% of this quantity allocated to concrete. Moreover, 71.5% were extracted locally from various regions, while the remainder was imported from Belgium, Norway, Germany or Switzerland. Another interesting aspect about the use of French aggregates is the emergence of recycled aggregates as an alternative locally-produced source. In 2017, French regions recycled 27.7 million tons of recycled aggregates, in relying on construction and demolition wastes -C&DW (mainly from the construction sector), slag or shale. The nation's primary production source is indeed natural quarries (UNPG, 2019).

Recycled aggregates from C&DW have proven to be effective if used in new concrete for new constructions. They tend to be chosen for their durability, but also to help promote a circular economy process in the construction sector. The durability property of recycled aggregates from C&DW has been validated in accordance with the current state-of-the-art. For instance, several authors have studied the effect of recycled aggregates as a heterogeneous material on concrete mechanical properties (Adessina et al., 2019; Idir et al., 2010). Others have focused on studying the water absorption properties of concrete made with recycled aggregates in comparison with natural aggregates. The granularity of recycled aggregates has also been studied, and the authors of these works have shown

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its effect on various concrete types. A recent state-of-the-art report on the durability and mechanical properties of recycled aggregate concrete was provided in our most recent paper (Ben Fraj and Idir, 2017) wherein 68 works on this topic were reviewed. It was also highlighted in this paper an ecological profitability distance in Paris' region that makes it more advantageous to supply recycled aggregates than natural ones, which also optimize the transport costs of aggregates. Furthermore, the use of recycled aggregates in concrete has been studied in national and European projects in order to standardize and broaden the use of recycled aggregates. For instance, France's RECYBETON project (de Larrard and Colina, 2019) aims to provide a general state-of-art on how recycled aggregates are produced and implemented in concrete. That project's purpose is to offer recommendations and a formulation of recycled concrete using these kinds of aggregates. The durability and mechanical properties of French recycled aggregates have been studied, in conjunction with a life cycle assessment of recycled concrete. SeRaMCo (Secondary Raw Materials for Concrete Precast Products) is a European project that seeks to replace natural (primary) materials with high-quality recycled materials from C&DW (SeRaMCo, 2017). Other projects are developing different methodologies and guides to enhance the use of wastes and C&DW in recycled concrete (e.g. HISER (Hiser, 2018), BAMB (BAMB, 2018), C2CA (C2CA, 2011), Aufbaukörnung (BMBF, 2013)).

When assessing this state-of-the-art, the limited interest in using recycled aggregates within the French economic sectors is quite noticeable, with one of the main reasons being that France contains several natural aggregate quarries dispatched throughout the country. Moreover, the current standard (NF EN 206/CN) (AFNOR, 2014) only addresses low substitution rates of recycled gravel but no recycled sand use. Thus, the research gap identified consists of enhancing the use of recycled aggregates in France, given that the durability and environmental impacts of these materials have already proven to be acceptable (Ben Fraj and Idir, 2017; Lotfi et al., 2017; Pedro et al., 2018; de Larrard and Colina, 2019; Tazi et al., 2020). In this light, the aim of the present paper is to fill this research gap by developing a replicable methodology towards achieving circular economy practices in residential building materials. The proposed approach is intended to close the loop currently existing in the French residential building materials, to re-inject recycled aggregates originating from the residential portion of C&DW in new dwellings, and to provide afterwards a set of practices towards implementing a circular economy in this sector; closure of this particular material consumption loop was decided due to the fact that French practitioners (DEMOCLES Project) stated that C&DW from buildings can indeed be optimized to comply with the "2008/98/EC" Directive at no additional cost to project owners (Récylum, 2016). The remaining challenge within this objective will thus be to quantify the potential stock of C&DW from French dwellings, which will then serve as a potential deposit for reducing the extraction/depletion of natural aggregates extracted from French regions.

Next, a framework for achieving such objective is provided. The locks and remaining opportunities for this sector's resilient material consumption towards more circularity will also be discussed. This paper has been structured as follows. Section 2 describes the analysis method employed to achieve circularity in residential building materials and thus reduce natural resource extractions from a region. This methodology is based on a Material Flow Analysis (MFA). Section 3 discusses the results and the main findings of this paper towards instituting a circular economy across France's regions. This section concludes with the set of locks and opportunities presented for a better use of recycled aggregates in this sector. Lastly, the paper closes with a general conclusion.

2. Methods and data

2.1. Research methodology to assess the circularity of residential building materials

The main objective of this paper is to provide a replicable methodology towards achieving circularity of buildings materials. The proposed methodology is applied to the French residential sector. Then, an assessment of locks and opportunities based inter-alia on experts' feedback towards a sustainable use of residential building materials are provided. A further section is provided afterwards aiming to assess the robustness of the proposed model when applied to other locations, regions or countries.

In order to assess the circularity of building materials in the residential sector at a regional level, we set the following methodology presented in Fig. 1.

As presented in this figure, the steps of the proposed model are:

1. Locate the residential sector (city, region, country …)
2. Extract territorial residential buildings information: extract number of dwellings, types of dwellings (type 1 and type 2), construction period, dwelling surface (total floor area).
3. Extract territorial natural quarries information: "mean annual natural aggregates extraction" from the same location (mean tons/year).
4. Construct material cadaster: the objective is to link dwellings with material taxonomy based on material intensity factors (available in the supplementary materials), it contains quantities of all materials used in the construction of a dwelling per period.
5. Assess market variation: collect data about buildings at the end of life that will be demolished and turned into C&DW. Dwellings' population in a territory could either have a lifetime distribution or a replacement rate (as presented in this model and according to the availability of data).
6. Assess EoL management: Three EoL scenarios were considered in this paper for C&DW: landfill, recycle and incinerate. These scenarios are the same for inert and non-inert materials extracted from the dwelling cadaster (from step 4).
7. Quantify Inert material flows from C&DW that can be recycled into aggregates (RA) through an MFA (mean tons/year): this flow's aim is to be re-injected in new dwellings to close material loop.
8. Assess the circularity of residential building materials per location: through a circularity criteria that calculates the potential natural resource extraction reduction. It is based on the difference of mean annual flows of NA and RA. These recycled flows are re-injected in the residential material flows (new buildings) towards closing its loop as well as reducing its natural resource consumption.

This model contains the following variables presented in Fig. 2. These variables are the ones to be assessed for the robustness of the proposed model (available in section 3.3) and towards using it for another territory, city, country.

The proposed model is applied next to the French territory (metropolitan France). Data and variables are assessed accordingly:

2.1.1. Locate the territory (city, region, country …)

We focused in this paper on the residential sector in mainland France (including the nearest island "*LaCorse*" (FR-COR)). We assigned locations in 13 regional areas, as shown in Table 1.

2.1.2. Extract territorial residential buildings information

We used a simple classifier in order to segment data from each

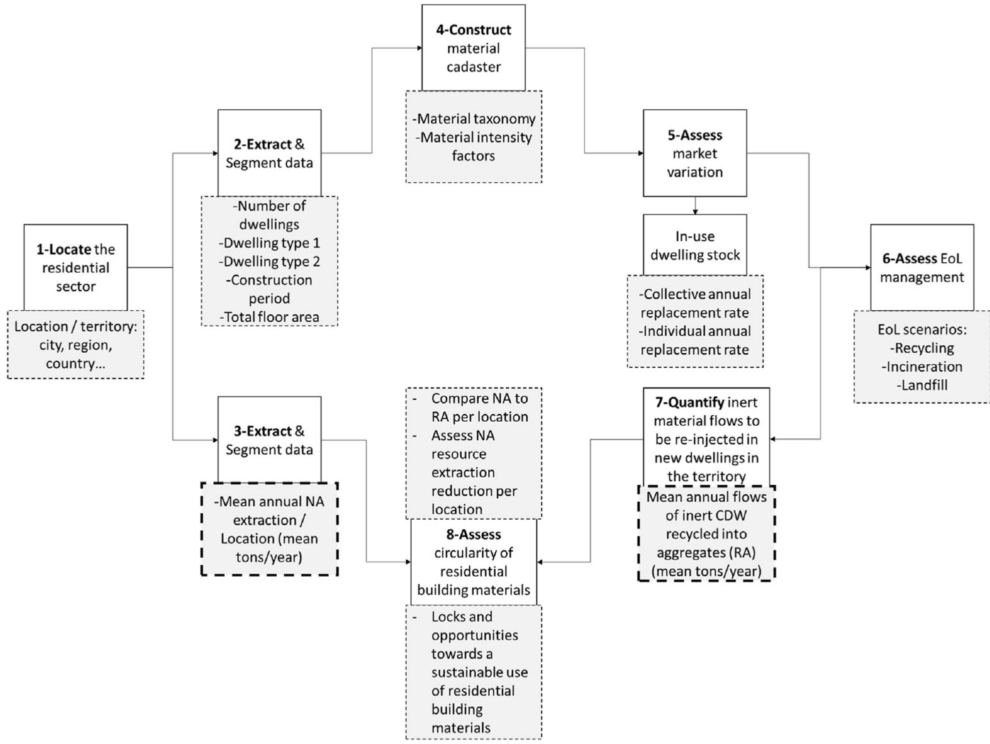

Fig. 1. Model framework to assess circularity of the residential building materials. Bold hatched rectangles are the flows (tons/year) to be assessed as a part of the circularity criteria.

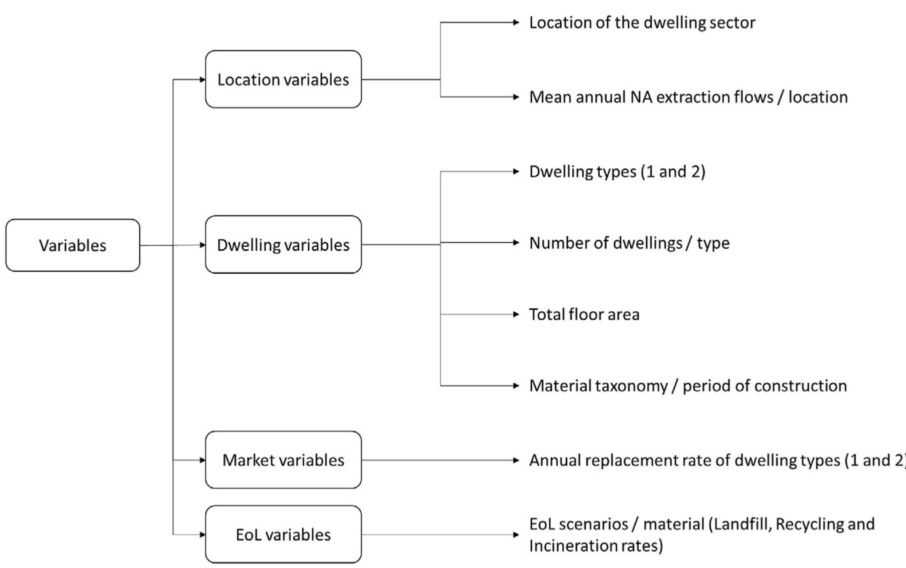

Fig. 2. Model variables.

location (region) in order to sort them within the main classes of variables as presented in Fig. 2. They are as following:

- Dwelling type 1: after assigning a location to the dwellings, we next classify them into "*individual*" or "*collective*" building stock. The individual category can be subdivided between single-family and terraced dwellings, while the collective category is subdivided between multi-family construction and large apartment blocks. This classification system was adopted in order to align output data with the Tabula outputs (TABULA/EPISCOPE, 2012) to assess subsequent waste management within the residential sector. The Tabula project models various typological approaches for building energy assessment.
- Dwelling type 2: this second classification corresponds to the use status of dwellings. In France, such buildings (whether individual or collective) can serve as either: primary residences (main use), occasional residences (infrequent use), second homes (infrequent or holiday use), or vacant property (empty building) (Haran and Kaldi, 2017). To assess the stock currently in use (for market uncertainties assessment). This paper considers mainly primary residences, which do happen to represent 81% of the total residential stock throughout Metropolitan

Table 1
Regional classification of the French dwelling (residential) sector. Regions sorted taking into account INSEE order, with the prioritization of FR-GES region for testing queries.

Region Code	Name
FR-GES	Grand-Est
FR-OCC	Occitanie
FR-NAQ	Nouvelle-Aquitaine
FR-ARA	Auvergne-Rhone-Alpes
FR-BFC	Bourgogne-Franche-Comté
FR-BRE	Bretagne
FR-CVL	Center-Val de Loire
FR-IDF	Ile-de-France
FR-HDF	Hauts-de-France
FR-NOR	Normandie
FR-PDL	Pays de la Loire
FR-PACA	Provence-Alpes-côte d'Azur
FR-COR	Corse

Table 3
Rate of primary dwellings from total French dwellings. Classification per French administrative regions (INSEE, 2019).

Region	Primary dwelling rate (in %)
FR-GES	87
FR-OCC	76
FR-NAQ	79
FR-ARA	80
FR-BFC	83
FR-BRE	79
FR-CVL	84
FR-IDF	90
FR-HDF	89
FR-NOR	82
FR-PDL	83
FR-PACA	75
FR-COR	60

France and 60% in Corsica (La Corse Island - FR-COR). Moreover, according to the latest census, the average floor area of individual and collective dwellings is'$112.2m^2$' and'$63m^2$', respectively (INSEE, 2017). Additional characteristics of the French residential sector are found in section 2.1.2.1.

- Construction period: dwellings were sorted into six main construction periods, as characterized by the use of specific construction materials. This classification helps construct a material cadaster of the residential sector per period of construction. For instance, dwellings constructed before 1945 used mainly bricks or stones, whereas the use of concrete in the French residential sector was democratized after this period. This may also help the decision maker when dealing with potential output flows from wastes from the residential sector. Indeed, it gives him an insight about the waste stream's characteristics. These periods are presented in Table 2.

With these inputs, it becomes possible to generate the territorial number of dwellings, their total floor area and their corresponding material taxonomy.

2.1.2.1. The French residential sector data. The residential sector is a diverse and open ecosystem (Hu et al., 2010a). Its material stocks are continuously moulting. French dwellings were unravelled within the main administrative regions of France (see Table 1). Special emphasis has been placed on primary residential buildings since they represent the most relevant stock of materials. This stock is highly susceptible to being affected by the residential replacement rate (market variation). Table 3 presents the average primary residential rates from the total base of residential buildings by region.

As seen in this table, primary residential construction in Metropolitan France is up to 81% on average, with a lower bound of 75% for the "Provence-Alpes-Cote d'Azur" (FR-PACA) region and an upper bound of 90 % for the "Ile-de-France" region (FR-IDF). As for "La Corse" region (FR-COR), considered as a touristic region, the primary residential rate is 60 %. Also, these primary residences are sorted by individual vs. collective buildings.

With this in mind, it then becomes possible to derive data about the number of residential buildings (individual and collective) as well as their material taxonomy.

2.1.2.2. Number of primary residences and their material taxonomy. Several sources were reviewed in order to analyze the current stock of primary residences in France. First and foremost, this paper relies on Augiseau's thesis, which provides a general taxonomy of the FR-IDF residential buildings (Augiseau, 2017; Augiseau and Barles, 2017). This taxonomy was based, among other things, on experts' feedback and residential inventories in this region from 1914 to 2006. Material intensity factors are related to residential buildings (dwellings), their underground surfaces (parking, basement …) as well as other surfaces (balcony/loggia, common corridors …) were also included in the material taxonomy (Augiseau, 2017)). Additional sources consisted of the Tabula project (TABULA/EPISCOPE, 2012) and national housing and statistics databases (Haran and Kaldi, 2017; INSEE, 2017, 2019; SDES, 2019). The material breakdown and regional residential statistics used in this paper are available in supplementary data section, Tables A1 to A4. The most relevant materials considered in this paper have been categorized into inert vs. non-inert. Their end-of-life (EoL) management issues will be discussed in section 2.1.6.

2.1.3. Extract mean annual natural aggregates flows from the same territory

National aggregate industry statistics (UNPG, 2019) were used in order to extract the mean annual flows of natural aggregates from each territory in France. These quantities are the ones that will be compared to the mean annual flows of recycled inert materials. These ones are from C&DW from the regional residential sector in order to be re-injected in new dwellings (as shown in Fig. 1).

2.1.4. Link dwelling with material taxonomy: material cadaster

When treating different residential building materials across different time periods, a specific classification serves to map the stock and flows for French regions. Fig. 3 presents an overview of the cadaster model employed to map both the collective and individual dwellings. The main discrepancies are revealed when collecting and sorting construction type data by period, which may differ between collective and individual dwellings and their respective materials. Each period is characterized by a specific architecture with its own embedded materials (Augiseau, 2017). For instance, note the presence of concrete in individual dwellings since 1971, whereas the widespread use of this material in collective dwellings only began in 1991.

Table 2
Periodic classification of dwellings considered.

Before 1919	From 1919 to 1945	From 1946 to 1970	From 1971 to 1990	From 1991 to 2005	From 2006 to 2013

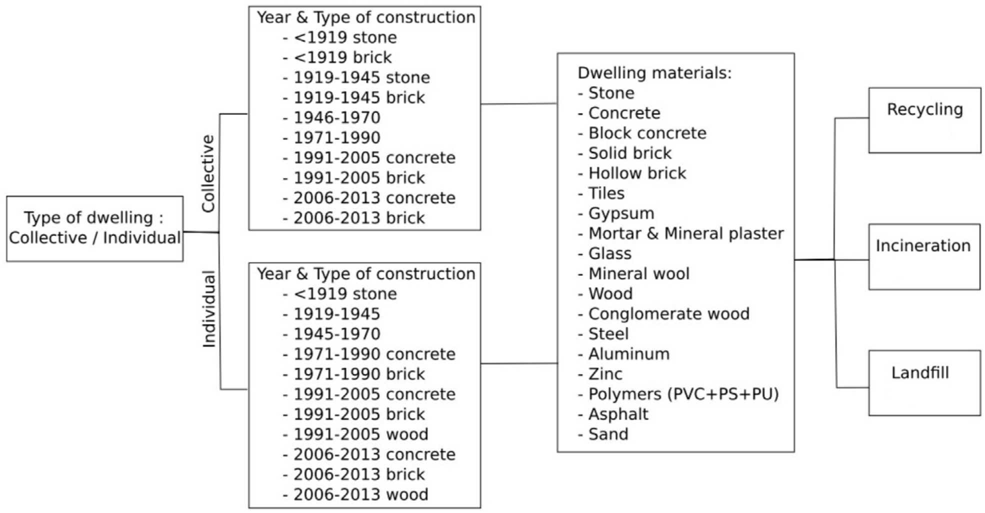

Fig. 3. Map of flows used for MFA of collective dwellings.

Material flows taxonomy data were extracted from (Augiseau, 2017; Augiseau and Barles, 2017), they are specific to the "Île-de-France" region (Paris region), yet their extrapolation can be assumed to other French regions since the 1920s. The robustness of this assumption is further discussed in section 3.3. Next, the stock in use and its variables are generated, as mainly characterized by the number of individual and collective dwellings in each region and their corresponding floor areas. This stock in use is complemented by an annual replacement rate of both individual and collective dwellings (discussed in section 2.1.5). An uncertainty propagation analysis was conducted to take into account both market and data uncertainties ((discussed in section 2.1.5.1)).

2.1.5. In-use dwelling stock and market uncertainties

Market uncertainties deal with buildings at their EoL. These dwellings are either subject to a lifetime distribution or a replacement rate. The French dwelling sector is based on a replacement rate.

The following section aims to justify the use of replacement rate variables instead of a lifetime distribution for the French residential sector. At first, a brief state of art on the life cycle of buildings is provided and this variable is assessed and discussed accordingly. Then, a description of the French residential sector is presented and how a replacement rate fits more its construction/demolition phases. When producing a state-of-art on residential building life cycles, two main types of papers were distinguished regarding the life cycle assessment: a fixed life cycle, and a statistical distribution. For example, Bohne et al. (2006) estimated statistically that the life cycle distribution of Norwegian buildings is a Sigmoid curve that generates an expected life cycle of 126±43% years for residential buildings, which for the experts at Cerema (Center for Studies and Expertise on Risks, Environment, Mobility and Urban and Regional Planning) was considered excessive if applied to French residences. Furthermore, the life cycle distribution of residential buildings was also approximated by various functions (normal, log-normal Weibull, etc.). Other papers relied on experts' feedback to yield a fixed residential building life cycle. The following Fig. 4 from Table 4 offers an outlook of the average lifetime of residential buildings extracted from the literature. Let's point out here the building life cycle underestimation in the literature; moreover, confusion is often found between the building's structural lifetime and its service lifetime, with the latter being used to assess flows and stock since it is followed by the demolition phase.

Theoretically speaking, the residential structural lifetime can be up to 50 years, but the service life cycle could be unlimited and extend indefinitely thanks to maintenance and renovation flows it receives (Meikle and Connaughton, 1994). For this reason, we state herein that dwellings are not being demolished mainly due to their age (Aksözen et al., 2017b), but in reality their life cycle is primarily influenced by the economic constraints of households rather than structural issues, i.e., in general, reuse, renovation and demolition activities are economically driven in France. This might not be the case in other locations such as China, Hong Kong or Singapore where the life cycle of dwellings is also influenced by regulatory, planning or social reasons (Arora et al., 2019; Langston et al., 2008).

It is also assumed that when replacing and constructing new residences, the quality and design of the building need not follow the most recent architectural type with its design materials. The dwelling's owner can in fact choose one of the two types of dwellings (individual or collective) from any of the six architectural

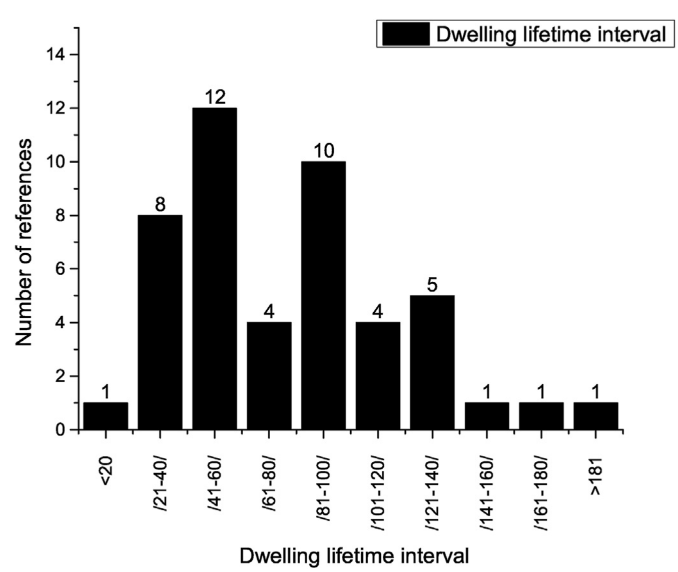

Fig. 4. Average lifetime of residential buildings (data extracted from Table 4). Vertical axis is the number of references and horizontal axis is the lifetime interval (in years) considered by the state of art. to be changed.

Table 4
The average lifetime for residential buildings extracted from the literature (partial state of art). Redundant references correspond to several values of buildings lifetime stated by the authors.

Reference	Geographical location of the reference	Building's lifetime interval (years)	Lifetime characteristics (Authors' judgement, Experts' judgement, Probabilistic distribution)
Hu et al. (2010b)	Beijing	<20	Expert judgement
Lau et al. (2017)	Hong Kong	/21–40/	Authors' judgement
Komatsu et al. (1994)	Japan	/21–40/	Authors' judgement
Sandberg et al. (2016)	EU	/21–40/	Authors' judgement
Shi et al. (2012)	China	/21–40/	Authors' judgement
Hu et al. (2010b)	Beijing	/21–40/	Expert judgement
Hu et al. (2010b)	Beijing	/21–40/	Probabilistic distribution
Zhou et al. (2019)	China	/21–40/	Probabilistic distribution
Cao et al. (2019)	China	/21–40/	Probabilistic distribution
Bergsdal et al. (2007a)	Norway	/41–60/	Authors' judgement
Müller (2006)	The Netherlands	/41–60/	Authors' judgement
Kotaji et al. (2003)	EU + Canada	/41–60/	Authors' judgement
Richter et al. (2008)	USA	/41–60/	Authors' judgement
Komatsu et al. (1994)	Japan	/41–60/	Authors' judgement
Shrestha et al. (2014)	USA	/41–60/	Authors' judgement
Guggemos and Horvath (2005)	USA	/41–60/	Authors' judgement
Sandberg et al. (2016)	EU	/41–60/	Authors' judgement
Rezaei et al. (2019)	Québec, Canada	/41–60/	Authors' judgement
Stephan and Athanassiadis (2017)	Melbourne, Australia	/41–60/	Authors' judgement
Gleeson (1985)	Indianapolis, USA	/41–60/	Probabilistic distribution
Hu et al. (2010b)	Beijing	/41–60/	Probabilistic distribution
Sartori et al. (2008)	Norway	/61–80/	Authors' judgement
Sandberg et al. (2016)	EU	/61–80/	Authors' judgement
Gleeson (1985)	Indianapolis, USA	/61–80/	Probabilistic distribution
Aktas and Bilec (2012)	USA	/61–80/	Probabilistic distribution
Myers (1990)	USA	/81–100/	Authors' judgement
Smith et al. (2008)	USA	/81–100/	Authors' judgement
Bergsdal et al. (2007a)	Norway	/81–100/	Authors' judgement
Kotaji et al. (2003)	EU + Canada	/81–100/	Authors' judgement
Johnstone (1994)	New Zealand	/81–100/	Authors' judgement
Sartori et al. (2008)	Norway	/81–100/	Authors' judgement
Richter et al. (2008)	USA	/81–100/	Authors' judgement
Fay et al. (2000)	Australia	/81–100/	Authors' judgement
Sandberg et al. (2016)	EU	/81–100/	Authors' judgement
Condeixa et al. (2017)	Rio de Janeiro	/81–100/	Authors' judgement
Müller (2006)	The Netherlands	/101–120/	Authors' judgement
Kotaji et al. (2003)	EU + Canada	/101–120/	Authors' judgement
Sandberg et al. (2016)	EU	/101–120/	Authors' judgement
Johnstone (2001)	New Zealand	/101–120/	Probabilistic distribution
Johnstone (1994)	New Zealand	/121–140/	Authors' judgement
Sartori et al. (2008)	Norway	/121–140/	Authors' judgement
Sandberg et al. (2014)	Norway	/121–140/	Authors' judgement
Sandberg et al. (2016)	EU	/121–140/	Authors' judgement
Bohne et al. (2006)	Norway	/121–140/	Probabilistic distribution
Needleman (1965)	USA	/141–160/	Authors' judgement
Sandberg et al. (2016)	EU	/161–180/	Authors' judgement
Erik Bradley and Kohler (2007)	Ettlingen, Germany	>180	Probabilistic distribution

periods from the ones listed in Table 2, and without any policy or legal bounds. Next, renovation (with the aim to achieve energy or ecological performance of buildings) may increase the lifespan of buildings too. Furthermore, indicating that residential buildings have a fixed or distributed lifetime assumes that this stock will reach its EoL at the same time from a given starting year, which seems to be unrealistic; hence, this paper considers a building replacement rate (assessed in section 2.1.5.1) based on French construction statistics, with an uncertainty level extracted from (INSEE, 2019; SDES, 2019). The long-term stock accumulation was not calculated in this paper since the building life cycle decreases over time due to various constraints (design, economics, a landlord preferring to revamp the building's design, etc.), and most life cycle distributions hardly fit this trend. This assertion has also been confirmed by Aksözen et al. and Miatto et al. in (Aksözen et al., 2017b, a; Miatto et al., 2017). Another boundary considered in this paper is that no losses are generated from the C&DW reverse logistic and sorting processes. This issue has been confirmed in recent French case studies (Rouvreau et al., 2012; Récylum, 2016). However, this might not be the case for other countries or locations where a loss factor variable (recovery efficiency, transfer, losses associated with age …) should be considered for a better assessment of C&DW (Arora et al., 2020).

2.1.5.1. About the uncertainty analysis of replacement stocks. In a recent study (Artola et al., 2016), European and French data pointed to an average annual replacement rate of 2% in the French residential sector. This rate is complemented by uncertainty flows based on French residential statistics (INSEE, 2019; SDES, 2019). These uncertainties are calculated each month from 2000 to 2019 and correspond to:

- 15.4 % when accounting for the replacement of collective dwellings,
- 10.7 % when accounting for the replacement of individual dwellings.

Then, using the STAN software (v.2.6.801) for mapping flows (Cencic, 2016; Cencic and Rechberger, 2008), these uncertainty rates can then be spread over the material flows. STAN (short for substance flow analysis) is a free software that visualize material flow analysis. Its graphical model can be linked to databases and users can consider data uncertainties, statistical tools and error propagation (Cencic and Rechberger, 2008).

2.1.6. End of life management of C&DW

EoL management methodology that fit this model's data has been validated by the relevance tree for methodology selection, as developed by (Wu et al., 2014). These authors provided in their paper 6 main methods for flows' quantification from C&DW, including flows from the residential sector. Depending on type of French data available, one could choose the best methodology to quantify flows and stock from this sector using an MFA. According to the decision tree provided in that paper and under the general constraints inherent in French data, an area-based calculation was selected as the methodology for quantifying dwelling stock.

When reaching their end-of-life (EoL), residential buildings are demolished and their materials shipped to different facilities for recycling, sorting and landfill. In 2014, 53 % of French C&DW from dwellings were sent to such facilities, 23 %used on site (backfill materials) and the remainder distributed to unknown collectors (Chauvet-Peyrard and Montérmal, 2014). The following materials, as presented in Table 5, and their EoL management are being considered in this paper. Various references have been used to assess the recycling rates of these materials. When no bibliographic references were found for some materials, an intern expert feedback consensus was considered.

Hazardous wastes, such as asbestos, light bulbs and lacquers, were not considered in this material breakdown. The most recent French statistics recorded an average of 2.8 million tons of hazardous wastes from a total waste flow of 227.5 million tons of C&DW (SOES, 2014). This flow rate is less than 2 % and was therefore not considered herein.

Data generated from the area-based methodology were incorporated into a material flow analysis (MFA) to derive residential stock and flows, but also the potential annual EoL accumulation of construction and demolition wastes from France's residential sector. The MFA method will be presented next.

2.1.7. Quantify Inert material flows from C&DW that can be recycled into aggregates through an MFA

There are in general four main techniques to model and assess material flows (Müller, 2006): intensity of use technique (Tilton and Tilton, 1990), demand function (Choudhry, 1996), production function and input-output analysis. These methods have different fields of application, shortcomings and strengths (Müller, 2006). The last method includes mainly Material Flow Analysis (MFA) method and captures the mass balances in the economy. MFA also aims to quantify sustainability with a systemic methodology (Rademaker et al., 2013). MFA is a well-known concept used for stock and flows accounting; it is based on the principle of a physical balance of inputs and outputs (Brunner and Rechberger, 2016). The material stock is estimated using the following equation (1):

$$MS_{i,a}(t) = \sum_{\tau} (I_{i,a}(t) \times P_a(t)) \quad (1)$$

Where'$MS_{i,a}(t)$' is the stock of a material 'i' from building type 'a' in year 't'.'$I_{i,a}(t)$' is the intensity of material 'i' from building type 'a' in year 't'.'$P_a(t)$' regroups the physical data of building type 'a' (period of construction, location, total floor area). The initial stock is supposed to be null. Material intensities (inert and non-inert in tons/m^2) used in this paper and derived from (Augiseau, 2017; Augiseau and Barles, 2017) are available in the supplementary data file (Tables A1 and A.2).

The bottom-up approach used in this paper was considered rather than another MFA methodology to better suit the French data construction derived mainly from (Augiseau, 2017; INSEE, 2019; SDES, 2019). For instance, Augiseau in (Augiseau, 2017) used a bottom-up approach to assess material intensity in French dwellings, this method was suitable to extract buildings' information from French databases (INSEE, BD Topo, IGN). Same methodology was used by Rouvreau et al. in (Rouvreau et al., 2012) to quantify material intensity of Orleans' dwellings. This bottom-up approach has also been used to assess the stock and flows for various systems and processes; e.g. material stock (Song et al., 2019; Lee et al., 2019; Zhang et al., 2017; Tazi et al., 2019) and e-wastes (Islam and Huda, 2019; Sabbaghi et al., 2019). More specifically, MFA has been applied in various ways to evaluate the construction and building sector. Condexia et al. assessed the residential stock in the city of Rio de Janeiro (Condeixa et al., 2017). Woodward and Duffy quantified cement and concrete in Ireland (Woodward and Duffy, 2011). Bergsdal et al. in (Bergsdal et al., 2007b) modeled the Norwegian residential stock by means of a dynamic material flow analysis. This same method was employed in order to quantify C&DW in China (Huang et al., 2013; Hu et al., 2010b), Japan (Hashimoto et al., 2007), the United States (Cochran and Townsend, 2010) and the United Kingdom (Shanks et al., 2019). MFA is thus used in this paper to quantify stock and flows of the residential sector and more specifically inert material flows from C&DW that can be turned into aggregates and are then reinjected in the residential sector (as new constructions) in order to achieve circularity of materials and reach a closed loop practice.

Table 5
EoL scenarios for construction and demolition wastes from the French dwelling sector.

Materials	Treatment	Materials	Treatment
Stone (Asakura, 2013)	88% recycled + 12% landfilled	Concrete and block concrete (Asakura, 2013)	88% recycled + 12% landfilled
Solid and hollow bricks from baked clay (Asakura, 2013)	88% recycled + 12% landfilled	Tiles from baked clay	100% recycled
Gypsum (GtoG, 2016)	100% recycled	Mortar and mineral plaster	100% recycled
Glass (Tam and Tam, 2006)	85% recycled + 15% landfilled	Mineral wool (BRE/Eurobond, 2008)	100% recycled
Wood and conglomerated wood	61% recycled + 28% incinerated + 11% landfilled	Metals (steel, aluminum and zinc)	98% recycled + 2% landfilled
Polymers (PVC + PS + PU) (Tam and Tam, 2006)	70% recycled + 30% incinerated	Asphalt + Sand (Tam and Tam, 2006)	100% recycled

2.1.8. Assess the circularity criteria of the residential sector

The circularity criteria R of a region "i" (R_i from equation (2)) of the residential sector proposed in this model assesses natural resource extraction's reduction. It compares the mean annual regional natural resource extraction (NA_i) and the mean annual flows recycled into aggregates (RA_i) from inert C&DW from the same region "i". These flows are re-injected in the residential sector and are considered as a potential natural resource extraction reduction. This practice aims to close the residential building materials' loop and reduce its resources depletion. Besides, a set of locks and opportunities are provided within the results with the aim to achieve a better circularity practices in this sector.

$$R_i = NA_i - RA_i \quad (2)$$

2.2. Model application and summary of results

The model was applied to the national primary French residential stock, with respect to the steps indicated above. Main assumptions considered for the French case study are presented in Table 6 The study focused on regional flows and their potential symbiosis with regional natural aggregate quarries for waste reduction. The opportunities and locks in achieving circular economy practices in residential materials have also been assessed. These locks and opportunities are based inter-alia on the results of the MFA analysis performed in this paper, internal expert feedback as well as international feedback on the application of circular economy policies and practices in the construction sector resumed from various references and case studies.

Afterwards, a critical analysis of the proposed model, its variables and its ability to fit other locations are discussed.

3. Results

3.1. National material stock and flows

First of all, the total deposit of C&DW from French residential construction has been recorded. Fig. 5 presents this stock for each French region. According to this figure, individual dwellings account for a larger stock than collective dwellings; they also feature an average floor area higher than that of collective residences (112.2 m^2 vs 63 m^2). Moreover, an 70 % – 30 % average rate distribution exists between individual and collective dwellings. However, this rate switches to 34 % – 66 % in the FR-IDF, where collective buildings are more widespread than individual ones. This rate is explained by the small surface area of the FR-IDF Region ($12,000 km^2$) compared to other French regions and by its higher population ($12.10^6 inhabitant$).

By considering all French stock, a potential deposit of more than 4.310^9 tons of materials is contained in the French residential sector (through late 2013). This stock is broken down into 1.510^9 and 2.810^9 tons from collective and individual stock, respectively. It is possible to map residential material stock and flows using STAN, which yields the tree graphs shown in Fig. 3, as based on the model framework presented in Fig. 1. Thus, flows are mapped as presented in Fig. 6.

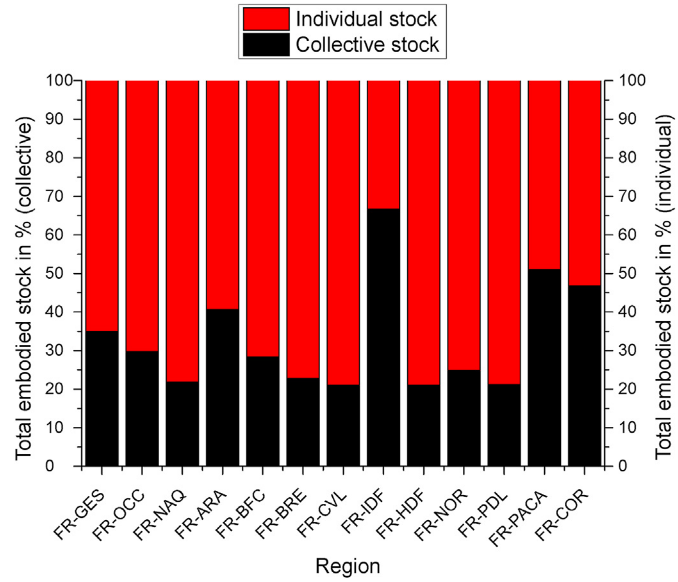

Fig. 5. Total collective and individual stocks embodied for each French region (from 1919 to 2013).

When only considering inert materials, the potential material deposit available for recycling as recycled aggregates can be calculated. For purposes of this paper, the inert materials comprise: {stone, concrete, block concrete, solid brick, hollow brick, tiles from basked clay, mortar and mineral plaster, asphalt, sand, glass}. Total inert stock, presented in Fig. 7, represents 96 % and 92 % of the total combined stock in collective and individual residences, respectively. From these inert combined flows, the two groups of mortar & mineral plaster, asphalt & sand contribute respectively to around 1.2% and below 0.5% from total embodied inert stock (See Table A6 from Supplementary data file). Asphalt is generally taken from the street curbs near demolished dwellings.

When accounting for all inert materials contained in French residential buildings using MFA and STAN, the chronology of a specific material over the various construction periods can also be replicated. Fig. 8 provides an overview of concrete input through the six main periods in collective and individual residences. This figure shows both the concrete peak loads over time and the contribution of each region to the cumulative demand for French concrete in residential building. This peak load is related to the reconstruction of the country after the Second World War. The concrete wastes resulting from residential construction have proven to be effective (i.e. concrete mix strength and environmental performance) for use as recycled aggregates in concrete

Table 6
Input assumptions concerning the application of the proposed model to the French residential sector.

Input variables of the model	Assumptions made for the French case
Number of dwellings/type	Considers only primary dwellings.
Total floor area	Average value from INSEE (2017).
Material taxonomy	Extrapolated from IdF region (Augiseau (2017)) to other French regions.
Annual replacement rate	Average value from French data SDES (2019).
Recycled flows from inert C&DW	Potentially able to replace NA that will be re-injected in new dwellings.
Reverse logistic of dwelling materials	No losses for French residential sector.
Initial stock for MFA calculus	Supposed to be null.

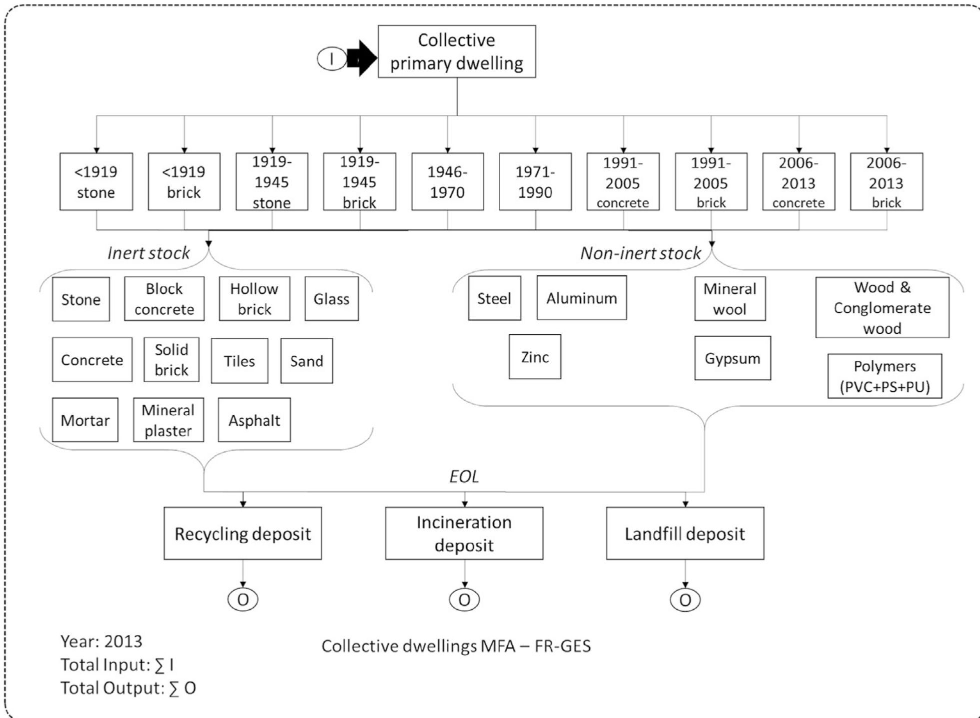

Fig. 6. Flows generated from Grand-Est (FR-GES) region using STAN software.

(Batayneh et al., 2007; Ben Fraj and Idir, 2017).

Similarly, Fig. 9 presents total glass contained in French dwellings over various time intervals: the total glass stock in individual dwellings is twice that of collective buildings. Moreover, the glass stock from FR-IDF collective residences constitute on average 30 % of all glass stock in France's collective buildings. The glass collected from residential demolition has proven to be effective for use in recycled concrete and as a sand substitute (Batayneh et al., 2007; Idir et al., 2010).

The chronological flows of all other inert materials (i.e. stone, block concrete, solid brick, hollow brick, tiles, mortar and mineral plaster, asphalt, sand) are available in the "supplementary data file, Fig. A1 and Fig. A2". Based on these flows, it is noted that only concrete, block concrete and glass flows seem to follow a Weibull distribution over the studied time periods. At this point, it is impossible to derive any further results regarding the distributions of inert materials in French dwellings. Indeed, approaching material consumption pressure of dwellings by probabilistic distributions (such as Weibull or normal distributions) will allow in future works to analyze past, present and future consumption of materials based on these distributions. Another output will also be to link over time materials' consumption to their greenhouse gas emissions (GHG) to assess their environmental footprints.

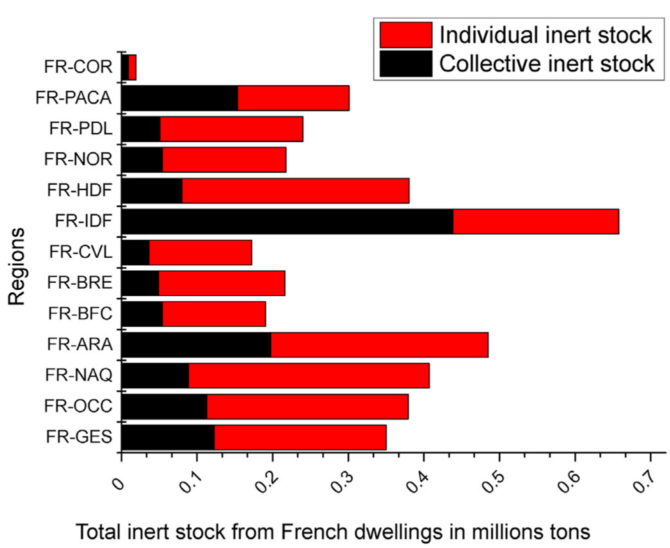

Fig. 7. Total inert stocks from French dwellings until 2013.

After addressing the general deposit of inert stock in French residential buildings, these data and the mean annual replacement rates extracted from French statistics can be used to generate the mean annual flows of materials. For next Figs. 10-15, the term "mean annual flows" means that flows subject to annual replacement rates were averaged for multiple years. Based on the foregoing information, Fig. 10 presents the mean annual replacement flows derived for each region; they correspond to both the inert and non-inert materials injected annually per region to replace former dwellings. In considering the balance principle of MFA, it is assumed that these same flows will be generated as C&DW and thus as inert and non-inert wastes. Table A5 (available in supplementary data file) displays the total mean annual flows available for recycling, incineration and landfill in each region. Fig. 11 presents the mean annual recycling flows of C&DW from French dwellings; this figure includes flows from inert and non-inert materials available for recycling, as defined in Table 5. These flows tend to follow the same total flow trends depicted in Fig. 10.

Moreover, keeping in mind the recycling flows of both collective and individual residences from each French region, it becomes possible initially to calculate the potential recycling rate of each region and then compare it with both the European waste framework targets for C&DW by 2020 (2008/98/EC) and the French Energy Transition and Green Growth Act (LTECV) (EU, 2008;

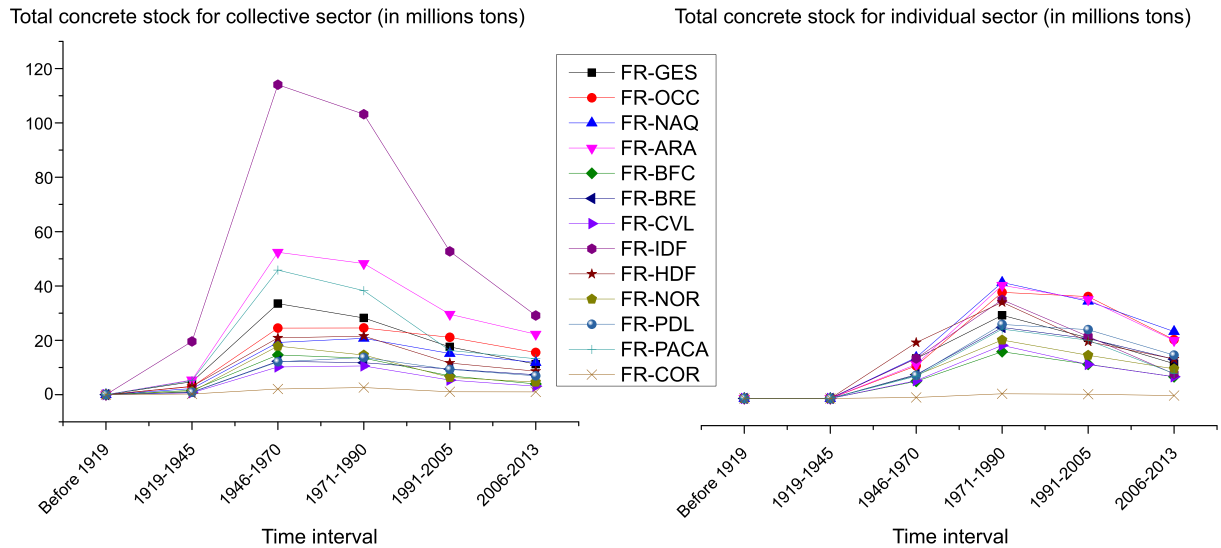

Fig. 8. Chronological concrete flows generated in French regions from collective (left figure) and individual (right figure) dwellings.

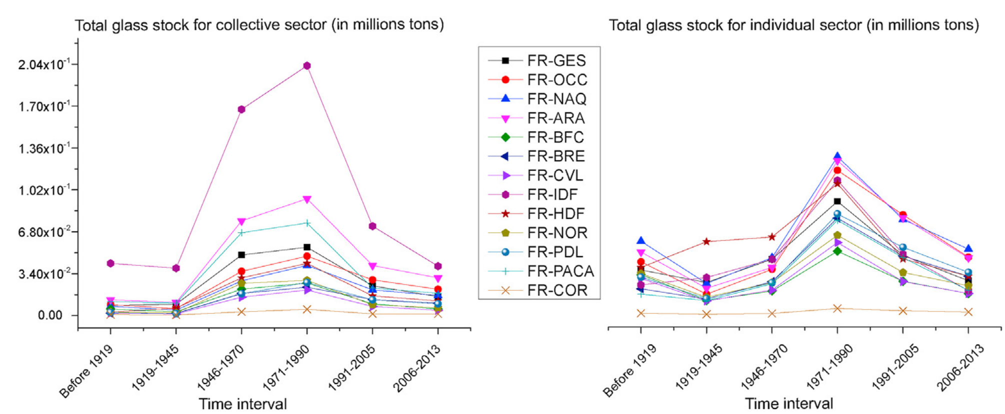

Fig. 9. Chronological glass flows generated in French regions from collective (left figure) and individual (right figure) dwellings.

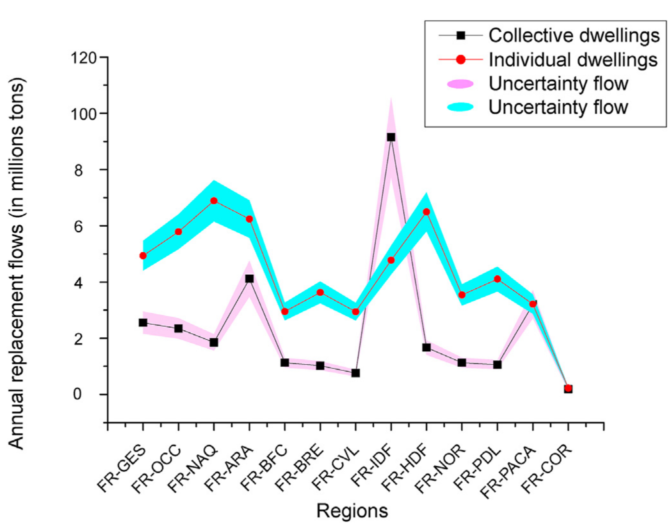

Fig. 10. Mean annual replacement flows for collective and individual dwellings in each region until late 2013. The pink and turquoise colours correspond to the uncertainty rate flows of collective and individual replacement rates, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

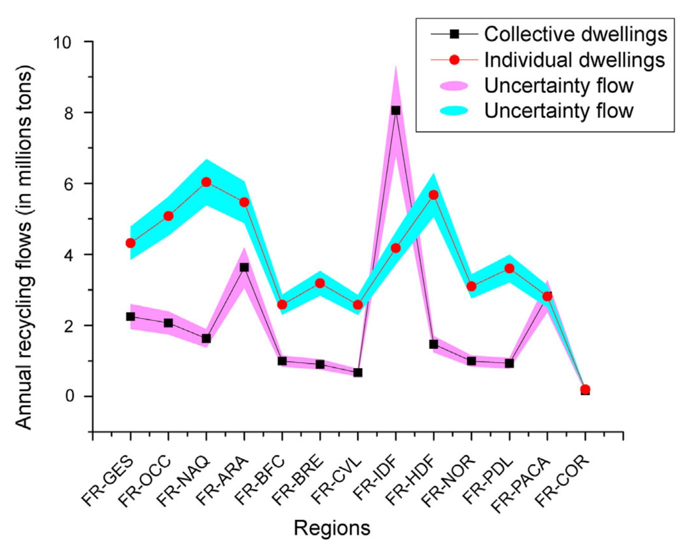

Fig. 11. Mean annual recycling flows for collective and individual dwellings in each region. The pink and turquoise colours correspond to the uncertainty rate flows of collective and individual replacement rates, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

LegiFrance, 2015), the latter targets 70% of waste recycling by 2020. A focus on inert materials and their potential recyclability as aggregates leads to assessing the ability of these flows to reduce the extraction of natural aggregates in French regions. Next, the total mean annual landfill flows remaining from inert residential materials can also be calculated. These three steps will be developed and discussed in the next section.

3.2. Achieving a circular economy in French regions

Given France's total stock of residential buildings and noting the mean annual recyclability potential of inert and non-inert materials, both the annual flows of materials and their EoL use can be determined. Fig. 12 and Fig. 13 present the mean annual flows available for recycling, incineration and landfill from collective and individual dwellings, respectively.

Thus, the recyclability rate of a region can be defined as the ratio of mean annual flows available for recycling to the mean annual C&DW flows generated in each region; according to these figures, the mean annual recyclability rate of French regions lies around 88 % for C&DW from residential buildings, which is higher than the targeted rate of 70 % to be reached by 2020, as per the LTECV Act.

Afterwards, the mean annual recyclable flows from French regions lead to separating out the inert flows that can be reused as recycled aggregates. These flows include: stone, concrete, block concrete, solid brick, hollow brick, tiles, mortar, mineral plaster, glass, asphalt, and sand. Fig. 14 shows the mean annual inert material flows available for recycling across French regions. According to the regional stock available for replacement, output recycling flows may vary from one region to the next. The FR-IDF region features the greatest mean annual inert flows from collective dwellings, whereas the "Nouvelle-Aquitaine" (FR-NAQ) region accounts for the greatest mean annual inert flows from individual dwellings.

From these annual inert flows potentially converted into recycled aggregates, a comparison can be drawn with the mean annual flows of natural aggregates extracted from the same regions (see equation (2)). In the aim of achieving a circular economy in French regions, the extent to which these inert C&DW from French dwellings could reduce natural resource extraction and thus resource depletion can be calculated. National aggregate industry statistics (UNPG, 2019), which account for total mean annual regional natural aggregate extraction, can then be introduced. Fig. 15 provides the mean annual rate of decreased natural resources' extraction in each French region based on equation (2). According to this figure, French regions can indeed reduce natural resource extraction, with rates varying from 15 % for small regions like "Bretagne" (FR-BRE) or FR-COR to 19 % from medium-sized regions, e.g. "Occitanie" (FR-OCC) or FR-GES. The "Haut-de-France" (FR-HDF) region in the north could even reach a rate of 38.91%±5.06 less natural aggregates extraction. Lastly, the highest drop in resource optimization is calculated for the FR-IDF region (i.e. over 100%), which does account for a sizable share of France's residential population compared to other regions. Also, the FR-IDF region is the most densely populated with very few natural aggregate quarries still available. It will therefore be more suitable

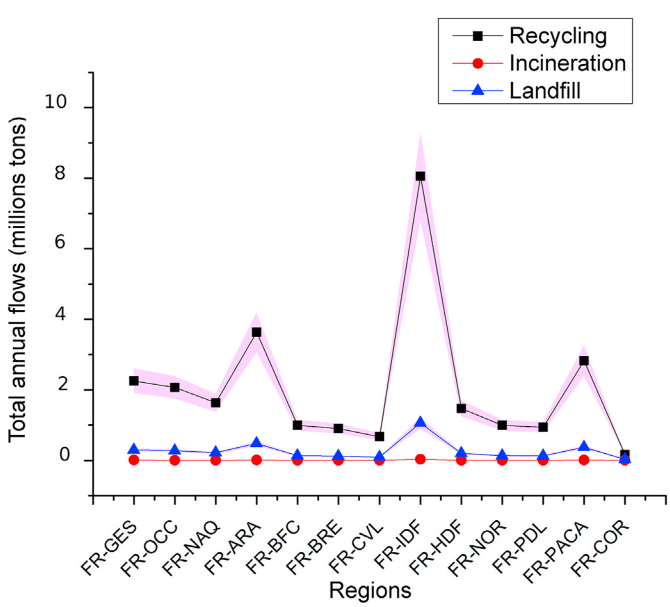

Fig. 12. Mean annual flows available for recycling, incineration and landfill from collective dwellings. Pink intervals correspond to the uncertainties of flows. Data are available in the supplementary file. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

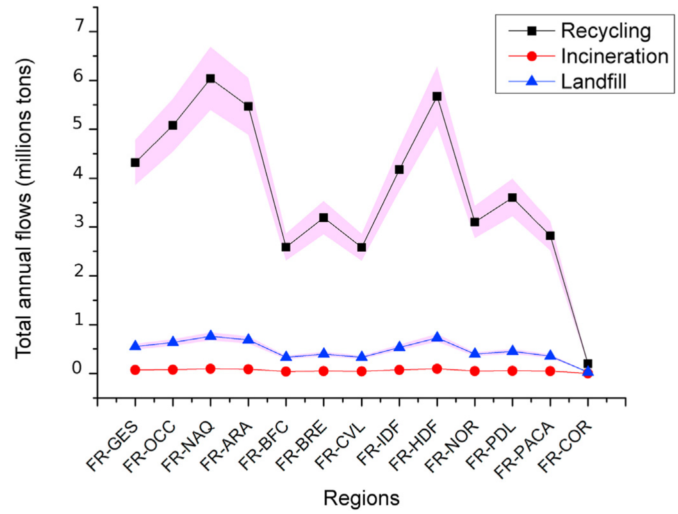

Fig. 13. Mean annual flows available for recycling, incineration and landfill from individual dwellings. Pink intervals correspond to the uncertainties of flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

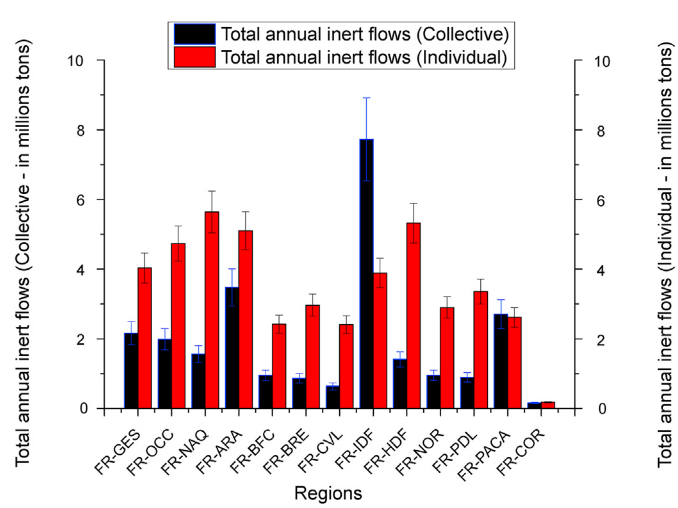

Fig. 14. Mean annual flows available from inert materials.

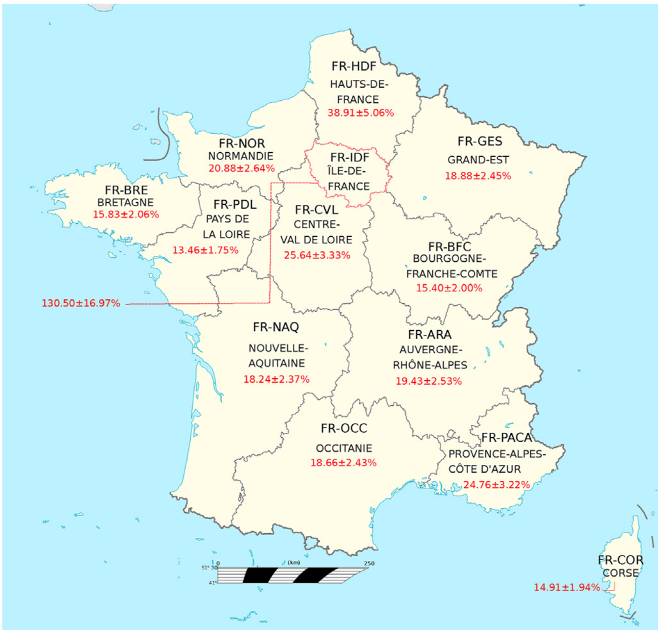

Fig. 15. Map of French regions with natural resource's extraction reduction due to the consideration of mean annual inert C&DW flows. For instance, FR-GES may reduce by 18.88%±2.45 its natural resource extraction if we consider inert flows from the residential sector.

for such regions to reduce their environmental footprint by recycling C&DW and lowering their share of resource depletion. Another opportunity for this region is its ability to export extra-recycled aggregates to close regions.

The French residential sector gives rise to a major stock capable of generating large annual construction and demolition waste flows that can be recovered as recycled aggregates. These recycled aggregates have proven to be effective when used in all classes of concretes and can thus be reused in the residential sector (in new dwellings) (Ben Fraj and Idir, 2017; de Larrard and Colina, 2019; Pacheco et al., 2019).

However, the proposed framework within this paper is based on assumptions and variables that fit the French residential sector. When applied to other locations (cities, countries …) or fast prosperous cities, the robustness and limits of this model need to be assessed, which is the aim of the next section.

3.3. Discussion: about the robustness of the proposed model

A part of this paper has intended to quantify the potential stock and flows available in French residential construction. The main purpose behind this step has been to analyze the ability of the nation's residential sector to close its construction materials' loop by using recycled aggregates derived from inert C&DW as substitutes for natural aggregates. The performance of recycled aggregates (including recycled sand) from C&DW has been proven to be efficient (Ben Fraj and Idir, 2017; Batayneh et al., 2007; Idir et al., 2010) and leads to assuming that these materials can replace natural ones. Besides, technologies used in cement based industry are getting greener (Liu et al., 2017). Other hypotheses forwarded in this paper may alter the quantities held in each French region or raise the uncertainties of final flows and deposits if the model is applied to other locations. The following section summarizes and discusses these various hypotheses.

- The first assumption forwarded herein pertains to residential construction material taxonomy that led to the construction of the material's cadaster; this notion has been extrapolated from (Augiseau, 2017), since Augiseau's thesis focuses on the FR-IDF region. This paper considers that the FR-IDF taxonomy can be extrapolated to other regions, which historically seems to be plausible for collective dwellings since the first urban planning laws to harmonize cities' architecture date back to 1919. The individual building; however; may slightly differ from one region to another. Besides, the robustness of material intensity factors extracted from this reference should be assessed and compared to other countries' dwelling factors. The proposed material taxonomy provided in this paper is based on databases that consider all complementary surfaces for total floor area calculus (parking, basement, balcony …). These surfaces' contributions to material intensity factors require further assessment if the current model is replicated for other locations.
- The second assumption pertains to the average floor area of collective and individual dwellings extracted from (INSEE, 2017). Due to the lack of data on exact floor areas of regional primary residences, an average floor area has been assumed. Should this assumption be confirmed or refuted in the future, uncertainties about material stock and flows within residential buildings may be reduced.
- Regarding the life cycle of residential structures, lifetime trends of French dwellings could not be extracted from data. Instead, a 2% dwelling replacement rate has been considered, with specific uncertainties related to collective and individual buildings. This replacement rate implies that 2 out of every 100 dwellings are being replaced by new ones each year in France, along with the corresponding level of uncertainty. We feel that this replacement rate may overcome the limitation due to a lack of building life cycle data; it may also yield insight into the future flows and deposits available as recycled aggregates for regional construction. This replacement rate has remained constant at around 2% (with corresponding uncertainties for individual vs. collective data points) every month since 2000 (SDES, 2019). Besides, if building life cycle data were available, future stock and flows of the residential sector may be calculated.
- Mastery of the overall supply chain of C&DW is assumed in this paper. We are indeed relying on French data (Rouvreau et al., 2012; Récylum, 2016) to assume that very limited to no losses are considered when quantifying the sorting, transport and recycling of residential wastes. This assumption may vary should the methodology presented in this paper be applied to other systems. The transportation and logistical parameters associated with residential materials over their life cycle must be carefully considered as well. 90% of French aggregates are in fact being transported over road networks to construction sites, which serves to exacerbate their environmental impacts. Our previous local case study (Ben Fraj and Idir, 2017) demonstrated the effect of transportation distances on the global warming potential impact of aggregates (both natural and recycled). Since no general framework exists regarding the lower and upper bounds of distances to respect between construction sites and aggregates quarries, this issue needs to be studied on a project-by-project basis. This should lead to conduct an economic analysis to help decide whether to use natural or recycled aggregates and whether to reuse aggregates on-site or allocate them to the other closest sites. This challenge proves that using recycled instead of natural aggregates in residential constructions needs extra proofs mainly from the economic point of view. Indeed, using low substitution rates of recycled aggregates may not have significant improvements in economic metrics (Martínez-Lage et al., 2020; Moro et al., 2020). Afterwards,

closed loop recycling of aggregates and C&DW should decrease greatly both its costs and environmental impacts. Besides, some high density regions (such as Paris region) with low natural aggregates quarries should be the regions with high effectiveness of circular economy practices (cost and environmental) when using recycled aggregates.

- The uncertainty of flows is an important issue to consider when conducting a material flow analysis of residential building materials (Augiseau and Barles, 2017). For this paper, replacement rate uncertainties were injected into the proposed methodology so as to assess their influence on material stock. Fig. 10; Fig.11; Fig.12; Figs. 13 and 14 show how these uncertainties affect regional recycling, incineration and landfill flows. We believe that these flows could be more reliable if based on traceability models such as building information modeling (BIM), material databases and cadasters (national or EU level), which tend to reduce uncertainties of stock and flows. Lastly, new trends in introducing blockchain to monitor C&DW seems to be an ideal perspective towards mastering the full value chain of construction materials (Perera et al., 2020) and reducing its uncertainties. This perspective could find its right place in the new French circular economy act (Act. 2020–105) (LegiFrance, 2020).
- As for the ability to fit the currently proposed model to other cities or countries, the modular and parametric nature of this model allows for its application to any other system (city, region, country) provided the required data are available. The model framework used in this paper is presented in Fig. 1. However, if data differ from a country to another, the robustness of the model could require more assessment.
- No direct correlation was found between population growth and the distribution of residential stock when analyzing French residential building data. Despite growth in the French population, only six new dwellings are being built annually for every 1,000 inhabitants. The impact of this parameter on residential construction arouses an important debate inside the scientific community (to name but two references (Mankiw and Weil, 1989; Lindh and Malmberg, 2008)) and seems to be essential for flows and stock forecasts. The human factor extends beyond growth and may also influence how circularity will be applied in the sector. This consideration was pointed out in the most recent paper of Pomponi and Moncaster (2017), along with the role of individuals and new economic models developed to implement the circular economy. Afterwards, the proposed model is a path towards applying circular economy in the country residential sector. When dealing with highly effective economic regions that may have some irregularities (such as commuters or population growth), some uncertainty variations should be considered to fit the current situation of these regions.

Afterwards, numerous locks and unexploited opportunities remain in the effort to close the loop of materials used in residential construction. The next section will summarize the main locks and opportunities towards achieving a circular economy and closing the material's loop in residential buildings.

3.4. Toward a circular economy of the residential sector in French regions: locks and opportunities

The sustainability of the residential sector and the EoL of its C&DW are two issues that need to be addressed in setting up a sector-wide circular economy. This circularity also entails improving the reverse logistics of these wastes and shifting to close the sector's concrete-based material loop. The following section presents locks and opportunities towards reaching circular economy practices in the French residential sector. These locks and opportunities are based on inter-alia on the results of the MFA analysis performed in this paper, internal expert feedback as well as international feedback on the application of circular economy policies and practices in the construction sector resumed from various references and case studies.

3.4.1. Locks

The main locks are listed and described below; they not only call into review the general state-of-the-art, but also highlight local locks inherent in the French residential sector. These locks are classified into technological, normative, econological (from ecological economics) and social:

3.4.1.1. Technological lock

- Priority to on-site sorting for a better recycling of C&DW: Once these wastes get out from the construction and demolition sites, it gets harder to sort them. In France, it was proven that the considered sorting rate of construction and demolition sites should be improved, since this rate is calculated at the sorting facility that receives C&DW and not at the specific assessed site (Récylum, 2016). Another challenge within this topic is the implementation of selective on-site sorting to separate structural (gross) wastes from secondary (finishing) wastes such as wood or carpets.

3.4.1.2. Normative locks

- Overdesign in the residential sector: The current unnecessary additional use of concrete mix or residential materials or the repeated use of components in the aim of reducing labor costs tends to increase material stock and flows in the residential sector. The most recent interviews conducted by Shanks et al. (2019) show that cement stock in structural elements can be decreased by 20% through improving the way material specifications are managed, especially in residential buildings, where concrete frame elements are most readily abundant. Eliminating overdesign in the residential sector is key to reducing not only material stock and flows, but also energy consumption.

- Recycling standards: The use of recycled aggregates from C&DW is regulated in Europe and France (the NF EN 206/CN standard (AFNOR, 2014)). The French standard describes, for example, the maximum substitution rate to respect for recycled concrete aggregate use in concrete. Up to now, no recycled concrete sand substitution is allowed in the French standard. Thus, the challenge would be to introduce recycled concrete sand substitution in this standard and increase the substitution rate of recycled concrete aggregates. This challenge was highlighted in our recent papers for recycled aggregates from C&DW and recycled sand from fines and recycled glass (Idir et al., 2010, 2020; Ben Fraj and Idir, 2017). This challenge was also highlighted by the most recent report from the RECYBETON project (de Larrard and Colina, 2019), where they outline that the limitation of recycled aggregate substitution needs to be revised upward in the NF EN 206/CN. One should also point out the various rate-use of these recycled materials from one country's standard to another. Examples of these rates are presented in Table 7, where the substitution rates of recycled concrete aggregates and recycled concrete sand vary from 0% to 100%. In major cases, these substitution rates are defined on the basis of the recycled materials' origin. Their inclusion in national standards should allow

Table 7
Maximum substitution rate of recycled concrete aggregates/sand (all types combined) in recycled concrete. Data of this table are resumed from (Bodet et al., 2015).

Country	Maximum substitution rate of recycled concrete aggregates/sand (all types combined) in concrete	Use in prestressed concrete
France	30%	No
Australia	100%	No
Austria	Substitution authorized with additional durability tests	N/A
Belgium	20%	No
Brazil	20%	No
Canada	0%	N/A
China	50%	No
Denmark	100%	No
Germany	45%	No
Italy	100%	No
Japan	100%	No
Korea	30%	No
Luxembourg	N/A	N/A
Netherlands	100%	No
Norway	30%	Yes
Russia	100%	No
Spain	20%	No
Sweden	30%	Yes
Switzerland	25%	Yes
United Kingdom	20%	No
USA	0%	N/A

underwriters to insure constructions and projects with higher recycled concrete use.

3.4.1.3. Econological lock

- For a better value-added recycling scenario of residential construction wastes: Nowadays, most of French C&DW are recycled as backfill in the construction and demolition site or as a foundation layer in roadwork. The objective will be to upgrade the recycling scenario of C&DW to be recycled in concrete for instance and use low quality C&DW or other wastes as backfill or in roadwork. However, these recycling updates should be based on standards so that aggregates from C&DW could be used with higher rates in recycled concrete. Le Moigne in (LeMoigne, 2014) considered six main scenarios for circular economy in the construction sector. One of them is about industrial ecology principles in the construction sector and how it can be implemented. We used this model as a basis to outline the potential links between the residential and civil works sectors (see Fig. 16).

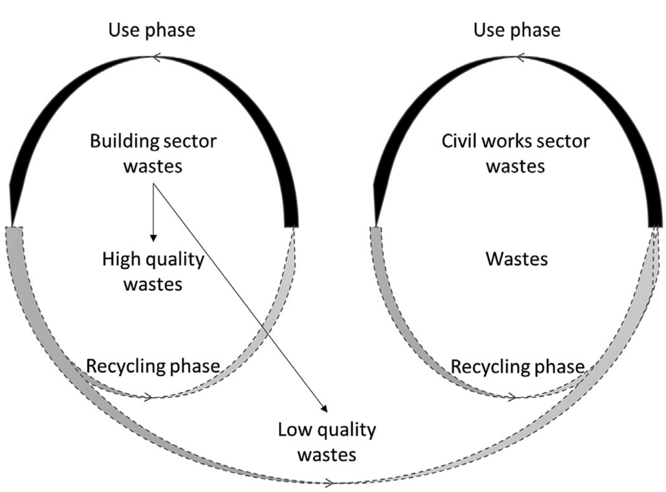

Fig. 16. Example of industrial ecology practice between the building and the civil works sectors.

3.4.1.4. Social lock

- Broaden the use of recycled aggregates: This lies in standardizing the use of recycled aggregates stemming from construction and demolition wastes and requiring this use in concrete as an alternative to natural aggregates, whenever available. This challenge could even go further the previous mentioned standard and include in public contracts the use of recycled aggregates from inert residential wastes if the global warming potential from transporting natural aggregates proves to be higher than that of the aggregate recycling process. This step could increase the use of recycled aggregates in French regions with high material imports (e.g. FR-IDF). As stated by Arora et al. in (Arora et al., 2019) however, even though standard and circular indicators have been developed to promote the use of recycled aggregates over natural ones in concrete, little interest has been shown towards this goal.

3.4.2. Opportunities

On the other hand, opportunities can be unleashed when considering the total stock and flows contained in the residential sector. Menegaki and Damigos (2018) published a recent review on major opportunities and efficient management relative to C&DW. In their work, they outlined the major parameters that positively and negatively influence C&DW generation and management. Other lessons on improved management of these wastes can be found in (Jin et al., 2017; Mahpour, 2018; Gálvez-Martos et al., 2018; Chen and Lu, 2017). We intend in this section to enrich the existing state-of-art from French experience in C&DW management.

In general, the recent European directive 2008/98/*EC* aims to implement better waste management practices and improve the value of C&DW stream. It is becoming a priority for many policies at global level (Ruiz et al., 2019). The actual French standard allow up to 30% of recycled aggregates as a substitution to natural ones for structural concrete. Recycled sand is not allowed as a substitution in recycled concrete (AFNOR, 2014). Recent research projects in France projected the use of 45% of recycled concrete aggregates and 15% of recycled concrete sand. However, this update could be improved and accompanied with the following measures:

Toward a better EHS accreditation for the construction sector: one could improve this Environmental High Quality standard (EHS) accreditation by introducing new labels for reusing secondary raw materials in a certified building or circular economy projects. An example of such label was already tested and proven to be efficient in Switzerland by introducing the so-called “Minergie-Eco” label, where recycled concrete aggregates are used if recycling plants are located in less than 25 km from the construction site (Kleijer et al., 2017; MINERGIE-P, 2013) (recycled concrete can fill up to 50% of the surface area). In the French context, the EHS lab el “NF Habitat HQE/NF batiment HQE” for technical performances (life quality, environment, economic) grants 5–10 years of tax exemption if acquired, which was an important incentive to reach a high-level environment, economic and energy performance of new buildings (residential and non-residential). French last experience about introducing energy performance labels in new building constructions also showed a high social acceptance and an inclusion of all actors toward improving the energy performance of buildings. Other Scandinavian (Danish and Swedish) case studies showed similar acceptance to the use of resource efficiency criteria in the building sector (Nuβholz et al., 2019). Besides of the economic incentives, these labels (EHS French label, circular economy project label) could be also communication strategy labels, where labelled construction sites display labels and communicate about their environmental management and engagement, circular economy practices and the use of eco-profile products (recycled aggregates, recycled concrete …) that reduce environmental impacts in the construction sector. These practices were recently encouraged by the “2018 – 937” French legislative policy for modern innovative and environmentally friendly buildings (LegiFrance, 2018). Such communication strategy also tends to increase the corporate identity and transparency in the environmental sector (Guziana and Dobers, 2013).

Industrial ecology practices: C&DW stream should enhance industrial ecology practices between the residential sector and the civil works The low quality recycled aggregates from the former C&DW sector would be used as backfill or foundation layer for roadworks in the latter one. Whereas the high quality wastes would generate high quality recycled aggregates to be used in the same sector to close its materials loop as shown in Fig. 16; such waste-based symbiosis has proven to be efficient in other case studies (A Jalil et al., 2016; Costa et al., 2010).

Audit and pre-sorting: in the French context, an initial audit would be mandatory to assess the C&DW stream before demolishing a building. This preliminary audit’s aim is to determine the most closest path to recycle these wastes. It also allows a traceability of the end of life of these wastes. This opportunity should also enhance on-site sorting of C&DW and resolve the challenge of mixing up gross (structure) wastes and finishing wastes. This sorting should allow a better management of C&DW in recycling facilities in order not to mix up these wastes, which tends to decrease the quality of generated recycled aggregates. The other consequence of this sorting would also be the development of two main recycled aggregates and one waste flow; high-quality recycled aggregates from sorted inert C&DW for recycled concrete use in the residential sector, and low-quality recycled aggregates from mixed-up C&DW for foundation layer in roadworks. The latter would contains mixed-up C&DW with dangerous and non-dangerous non sorted wastes during the deconstruction such as carpet, neon tube, plastics … These finishing wastes could form indeed an important second-hand market. The Cerema center is studying this opportunity of creation of secondary-hand market of the residential sector.

Bonus-malus-principle as a price adjustment of C&DW landfill in waste facilities: an extra tax could decrease the willingness of construction and demolition facilities to landfill C&DW stream and increase the recyclability of these wastes. However, this price adjustment may not influence the current recycling scenario for high quality wastes as backfill or foundation layer for roadworks, it may also lead to the increase of the comeback of uncontrolled landfill or the use of other EoL scenarios as warned by (Fullerton et al., 2008). Another perspective would be to implement an extra tax for natural aggregates to enhance the use of recycled ones. Thus, a price adjustment based on the bonus-malus-principle on whether these wastes will be recycled as recycled aggregates or backfill materials could enhance circular economy practices in the dwelling sector specifically and in the construction sector in general. However, this environmental tax should be applied as an incentive measure rather than a punitive one, but seems in general to be effective when used in other European countries such as Switzerland, Sweden and The Netherlands (Lindhjem et al., 2009).

Eco-distance-basis model for primary and secondary raw material use: this opportunity is a project-by-project based method that uses ecological distance to assess whether use primary raw materials or secondary (recycled) materials when dispatching construction materials into sites. Our previous local study (Ben Fraj and Idir, 2017) showed that the ecological profitability distance in Paris region is fixed at 50 km. Above this distance, it is better to use secondary materials (recycled aggregates) rather than primary raw materials (natural aggregates). This eco-distance-basis model could also be reinforced by an eco-distance-tax for natural resource extraction and use and should be applied on distance or regional bases. This last tax has proven to be efficient in the United Kingdom (Aggregates levy) and lead to a high use of recycled aggregates.

Tax exemption and loan facility for recycling facilities: could also be another incentive set up by states for a better recycling network for C&DW. Loan facilities could be such as zero interest rate eco-loans. It would help decrease distances between construction and demolition sites and recycling facilities. Besides, it should lead to the decrease of the ecological profitability distance toward a better use of secondary materials. This will also decrease the production costs of secondary materials generated from C&DW. However, this incentive should be followed by the inclusion of the use of recycled aggregates in public construction tenders. Hence, one could reach a resilient recycling facilities’ network with an ideal perimeter of 20 km radius from construction and demolition sites in order to perform circular economy practices, improve waste management and sustain natural resources. Thus, we believe that these incentives should lead to the emergence of mobile recycling facilities in order to process C&DW on-site. However, this could lead to two major issues. Close neighbors may not welcome the idea of making these facilities close to construction sites. Thus, this step should be supported by public awareness to circular economy in the construction sector. A previous study showed that the “opposed attitude” to such facilities decreases when a communication campaign (advertising, public visit, open house day …) is provided (Rahardyan et al., 2004). Such actions will also lead to the social acceptance of use of recycled materials in the construction sector. The second issue would be about the standard quality of recycled aggregates produced from a mobile facility compared to a fixed one. Indeed, while mobile platform offers important advantages in both environmental impacts and costs compared to fixed platform, it cannot offers as much diversified by-products and higher quality recycled aggregates as fixed facilities (Estanqueiro et al., 2018).

Reshape public contracts toward circular economy in the public sector: politics have already use contract incentives in order to add environmental clause for a better life cycle of the project. For instance, new French wind farm tenders aim to include an environmental clause with a 100% recycling rate of wind turbines at their end-of-life by 2023. Another example of the use of these environmental clauses is already included nowadays in the French public tenders for roadworks, where the use of recycled materials for foundations layer is required. Since the energy performance of

French buildings was introduced by public tenders, same principle could be implemented for construction materials and require the use of recycled materials with a specific rate. However, this rate could not be valid if it is higher than the one advised by national standards. Another environmental clause in public tenders could be the attribution of extra points in the scoring system if the bidder will use recycled materials from C&DW. Besides, the use of such environmental clauses in the public contracts and public tenders should not create any legal or technical imbroglios. The obligation to use recycled aggregates or secondary materials for the construction have also proven to be environmentally effective, even without considering the uptake of CO_2.

Toward integrating product-service system (PSS) in the construction sector: this can be another opportunity to consider re-using and leasing high performance concrete based products in the construction sector. Previous examples of PSS in other sectors showed the effectiveness of this methodology in reaching a higher use value of products (Mont et al., 2006; van Loon et al., 2018; Tasaki et al., 2006). This opportunity would however be applied only for new projects. Indeed, the actual construction and deconstruction activities do not allow to recover and reuse concrete-based products.

Reverse logistic and design for disassembly: constitute meaningful strategies toward achieving circular economy in the construction sector. By adopting such strategies, the construction sector could target a more circular value chains and go a step ahead towards closing the loop of its materials (Morseletto, 2020).

4. Conclusion

The model proposed in this paper fills the knowledge gap experienced across France according to the most recent report on French regional waste prevention and management plans (PRPGD) (ADEME, 2016), which note that materials contained in French residential buildings have not been quantified, nor have their EoL issues been addressed, and nor have their potential re-injection in this sector towards achieving circular economy practices been assessed. To the best of our knowledge, no models quantify the material and their EoL inherent in the French residential sector. This model, based on a material flow analysis (MFA) and a STAN software run for uncertainty assessment, can thus be used by decision-makers in cities in order to yield an outlook of material stock and flows contained in French residential buildings over a time period extending from 1919 until late 2013. It may also be used, provided all requisite data are available, to quantify residential materials in other European countries with similar architectural bases. Yet if data differ from a country to another, the robustness of the model could require more assessment, which is considered as a perspective.

The use of inert materials from the EoL of residential buildings as recycled aggregates has proven to be effective, while the application of a controlled rate of recycled aggregates in new concrete does not alter concrete durability. This paper has also pointed out that the main constraint involved in closing the concrete material loop in residential construction is not technological or environmental but rather appears to be economic. As long as natural aggregate extraction costs remain equivalent to recycled aggregate production costs, achieving circularity in the residential sector will be hampered by economic considerations, which would outline the role of circular business model in this sector, especially for regional application. However, the reverse logistics of residential materials has been well optimized, and few losses are identified in construction and demolition wastes. French waste management plans are indeed well organized, and waste traceability is now required (LegiFrance, 2020). Also, French Standard NF EN 206/CN has acknowledged the use of recycled aggregates in concrete since 2014, which is a first step towards regulating the use of aggregates in concrete. A further step suggested will entail regulating the use of natural aggregates in French residential construction whenever recycled aggregates are available. It seems however that the environmental impacts of certain recycling processes need to be further mitigated, which will require additional investigations in the future. Another lock that will require further investigation to be successfully resolved is the possibility of fitting a probability distribution to the residential material stock. Although this paper has noted that some materials, such as concrete or glass, may follow a Weibull distribution or even a double distribution based on a Weibull function, other materials do not seem to fit any probability distribution.

CRediT authorship contribution statement

Nacef Tazi: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration. **Rachida Idir:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration. **Amor Ben Fraj:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

A Jalil, E.E., Grant, D.B., Nicholson, J.D., Deutz, P., 2016. Reverse logistics in household recycling and waste systems: a symbiosis perspective. Supply Chain Manag.: Int. J. 21, 245–258.
Ademe, 2016. Translated from French: French regional waste prevention and management plan (plan rÉgional de prÉvention et de gestion des dÉchets (prpgd)). URL. https://www.ademe.fr/sites/default/files/assets/documents/fiche-plan-regional-prevention-gestion-dechets.pdf.
Adessina, A., Ben Fraj, A., Barthélémy, J.F., Chateau, C., Garnier, D., 2019. Experimental and micromechanical investigation on the mechanical and durability properties of recycled aggregates concrete. Cement Concr. Res. 126, 105900.
AFNOR, 2014. Translated from French (béton - spécification, performance, production et conformité - complément national à la norme nf en 206). URL. https://tinyurl.com/y5nrgy85.
Aksözen, M., Hassler, U., Kohler, N., 2017a. Reconstitution of the dynamics of an urban building stock. Build. Res. Inf. 45, 239–258.
Aksözen, M., Hassler, U., Rivallain, M., Kohler, N., 2017b. Mortality analysis of an urban building stock. Build. Res. Inf. 45, 259–277.
Aktas, C.B., Bilec, M.M., 2012. Impact of lifetime on us residential building lca results. Int. J. Life Cycle Assess. 17, 337–349.
Arora, M., Raspall, F., Cheah, L., Silva, A., 2019. Residential building material stocks and component-level circularity: the case of Singapore. J. Clean. Prod. 216, 239–248.
Arora, M., Raspall, F., Cheah, L., Silva, A., 2020. Buildings and the circular economy:

estimating urban mining, recovery and reuse potential of building components. Resour. Conserv. Recycl. 154, 104581.
Artola, I., Rademaekers, K., Williams, R., Yearwood, J., 2016. Boosting building renovation : what potential and value for europe ? URL. http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU(2016)587326_EN.pdf.
Asakura, H., 2013. Removing gypsum from construction and demolition waste (c&dw). In: Handbook of Recycled Concrete and Demolition Waste. Elsevier, pp. 479–499.
Assembly, G., 2015. Sustainable Development Goals. SDGs), Transforming Our World: the 2030.
Augiseau, V., 2017. La dimension matérielle de l'urbanisation. Flux et stocks de matériaux de construction en Île-de-France. Ph.D. thesis.
Augiseau, V., Barles, S., 2017. Studying construction materials flows and stock: a review. Resour. Conserv. Recycl. 123, 153–164.
BAMB, 2018. Bamb project : "buildings as materials banks". URL. https://www.bamb2020.eu/.
Batayneh, M., Marie, I., Asi, I., 2007. Use of selected waste materials in concrete mixes. Waste Manag. 27, 1870–1876.
Ben Fraj, A., Idir, R., 2017. Concrete based on recycled aggregates–recycling and environmental analysis: a case study of paris' region. Construct. Build. Mater. 157, 952–964.
Bergsdal, H., Bohne, R.A., Brattebø, H., 2007a. Projection of construction and demolition waste in Norway. J. Ind. Ecol. 11, 27–39.
Bergsdal, H., Brattebø, H., Bohne, R.A., Müller, D.B., 2007b. Dynamic material flow analysis for Norway's dwelling stock. Build. Res. Inf. 35, 557–570.
BMBF, 2013. Aufbaukörnung : "building aggregates. increasing resource efficiency in the construction sector by developing innovative technologies to produce high-quality building aggregates from secondary raw materials based on heterogeneous construction and demolition waste". URL. https://www.r-plus-impuls.de/r2-en/.
Bodet, R., Fonteny, S., Pillard, W., 2015. Translated from French: (annexe 2 : Modèle de fiche de synthèse pour les documents internationaux, p. 60. URL. http://www.irex.asso.fr/wp-content/uploads/2019/04/R15RECY025-Theme-4-Synthese-des-documents-internationaux-sur-lutilisation-des-granulats-re-cycles-dans-les-betons-UNPG-EGF-BTP-LC15RECY70.pdf.
Bohne, R.A., Brattebø, H., Bergsdal, H., Jostein Hovde, P., 2006. Estimation of the Service Life of Residential Buildings, and Building Components in norway.
BRE/Eurobond, 2008. Recycling of mineral wool composite panels into new raw materials. URL. http://www.wrap.org.uk/sites/files/wrap/xxEurobond_WRAP.pdf.
Brunner, P.H., Rechberger, H., 2016. Practical Handbook of Material Flow Analysis: for Environmental, Resource, and Waste Engineers. CRC press.
C2CA, 2011. C2ca project : "cement and clean aggregates from construction and demolition waste". URL. http://www.c2ca.eu/.
Cao, Z., Liu, G., Duan, H., Xi, F., Liu, G., Yang, W., 2019. Unravelling the mystery of Chinese building lifetime: a calibration and verification based on dynamic material flow analysis. Appl. Energy 238, 442–452.
Cencic, O., 2016. Nonlinear data reconciliation in material flow analysis with software stan. Sustainable Environment Research 26, 291–298.
Cencic, O., Rechberger, H., 2008. Material flow analysis with software stan. In: EnviroInfo, pp. 440–447.
Chauvet-Peyrard, A., Montérémal, M., 2014. Translated from French (le recyclage des déchets produits par l'activité de btp en 2014). URL. https://neci.normandie.fr/sites/default/files/documentation/datalab-44-recyclage-dechets-btp-2014-octobre2018.pdf.
Chen, X., Lu, W., 2017. Identifying factors influencing demolition waste generation in Hong Kong. J. Clean. Prod. 141, 799–811.
Choudhry, T., 1996. Real stock prices and the long-run money demand function: evidence from Canada and the USA. J. Int. Money Finance 15, 1–17.
Cochran, K., Townsend, T.G., 2010. Estimating construction and demolition debris generation using a materials flow analysis approach. Waste Manag. 30, 2247–2254.
Condeixa, K., Haddad, A., Boer, D., 2017. Material flow analysis of the residential building stock at the city of rio de janeiro. J. Clean. Prod. 149, 1249–1267.
Costa, I., Massard, G., Agarwal, A., 2010. Waste management policies for industrial symbiosis development: case studies in european countries. J. Clean. Prod. 18, 815–822.
Erik Bradley, P., Kohler, N., 2007. Methodology for the survival analysis of urban building stocks. Build. Res. Inf. 35, 529–542.
Estanqueiro, B., Dinis Silvestre, J., de Brito, J., Duarte Pinheiro, M., 2018. Environmental life cycle assessment of coarse natural and recycled aggregates for concrete. European Journal of Environmental and Civil Engineering 22, 429–449.
EU, 2008. Directive 2008/98/ec of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. URL. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN.
Fay, R., Treloar, G., Iyer-Raniga, U., 2000. Life-cycle energy analysis of buildings: a case study. Build. Res. Inf. 28, 31–41.
Fullerton, D., Leicester, A., Smith, S., 2008. Environmental Taxes. Technical Report. National bureau of economic research.
Gálvez-Martos, J.L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in europe. Resour. Conserv. Recycl. 136, 166–178.
Gleeson, M.E., 1985. Estimating housing mortality from loss records. Environ. Plann. 17, 647–659.
GtoG, 2016. Gypsum is indefinitely recyclable. URL. http://gypsumtogypsum.org/gtog/gtog-project/.
Guggemos, A.A., Horvath, A., 2005. Comparison of environmental effects of steel- and concrete-framed buildings. J. Infrastruct. Syst. 11, 93–101.
Guziana, B., Dobers, P., 2013. How sustainability leaders communicate corporate activities of sustainable development. Corp. Soc. Responsib. Environ. Manag. 20, 193–204.
Haran, L., Kaldi, M., 2017. Translated from French (le parc des logements, fiche d'analyse de l'observatoire des territoires 2017). URL. https://www.observatoire-des-territoires.gouv.fr/kiosque/2017-fiche-logement-le-parc-de-logement.
Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2007. Where will large amounts of materials accumulated within the economy go?–a material flow analysis of construction minerals for Japan. Waste Manag. 27, 1725–1738.
Hiser, 2018. Hiser project : "holistic innovative solutions for an efficient recycling and recovery of valuable raw materials from complex construction and demolition waste". URL. http://www.hiserproject.eu/.
Hu, D., You, F., Zhao, Y., Yuan, Y., Liu, T., Cao, A., Wang, Z., Zhang, J., 2010a. Input, stocks and output flows of urban residential building system in beijing city, China from 1949 to 2008. Resour. Conserv. Recycl. 54, 1177–1188.
Hu, M., Van Der Voet, E., Huppes, G., 2010b. Dynamic material flow analysis for strategic construction and demolition waste management in beijing. J. Ind. Ecol. 14, 440–456.
Huang, T., Shi, F., Tanikawa, H., Fei, J., Han, J., 2013. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour. Conserv. Recycl. 72, 91–101.
Idir, R., Cyr, M., Pavoine, A., 2020. Investigations on the durability of alkali-activated recycled glass. Construct. Build. Mater. 236, 117477.
Idir, R., Cyr, M., Tagnit-Hamou, A., 2010. Use of waste glass in cement-based materials. Déchets Sciences et Techniques 9.
INSEE, 2017. Translated from French (les conditions de logement en France- insee. URL. https://www.insee.fr/fr/statistiques/fichier/2586024/LOGFRA17k2_F6.2.pdf.
INSEE, 2019. Translated from French (dossier complet - résultats pour toutes les communes, départements, régions, intercommunalités). URL. https://www.insee.fr/fr/statistiques/2011101?geo=FRANCE-1.
Islam, M.T., Huda, N., 2019. Material flow analysis (mfa) as a strategic tool in e-waste management: applications, trends and future directions. J. Environ. Manag. 244, 344–361.
Jin, R., Li, B., Zhou, T., Wanatowski, D., Piroozfar, P., 2017. An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. Resour. Conserv. Recycl. 126, 86–98.
Johnstone, I.M., 1994. The mortality of New Zealand housing stock. Architect. Sci. Rev. 37, 181–188.
Johnstone, I.M., 2001. Energy and mass flows of housing: estimating mortality. Build. Environ. 36, 43–51.
Kleijer, A., Lasvaux, S., Citherlet, S., Viviani, M., 2017. Product-specific life cycle assessment of ready mix concrete: comparison between a recycled and an ordinary concrete. Resour. Conserv. Recycl. 122, 210–218.
Komatsu, Y., Kato, Y., Yashiro, T., et al., 1994. Survey on the Life of Buildings in japan.
Kotaji, S., Schuurmans, A., Edwards, S., 2003. Life-Cycle Assessment in Building and Construction: A State-Of-The-Art Report. Setac, 2003.
Langston, C., Wong, F.K., Hui, E.C., Shen, L.Y., 2008. Strategic assessment of building adaptive reuse opportunities in Hong Kong. Build. Environ. 43, 1709–1718.
de Larrard, F., Colina, H., 2019. Concrete Recycling: Research and Practice. CRC Press. ISBN:9781351052801. LCCN:2019009467.
Lau, W.K., Ho, K.M.K., Lam, T.Y.M., Chan, H.C.K., Ma, T., Wu, W.K.D., Tsang, C.w., 2017. Age Composition and Survival of Public Housing Stock in hong kong, p. 434. WELCOME TO DELEGATES IRC 2017.
Lee, S.J., Kim, J.W., woo Hwang, Y., Kim, J., Kim, Y., Chen, S., 2019. Butadiene substance flow analysis and management in South Korea. J. Clean. Prod. 220, 331–339.
LegiFrance, 2015. Translated from French: Act n.2015-992 of 17 august 2015 relative to energy transition for green growth (loi n.2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte). URL. https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000031044385&categorieLien=id.
LegiFrance, 2018. Translated from French (ordonnance n 2018-937 du 30 octobre 2018 visant à faciliter la réalisation de projets de construction et à favoriser l'innovation). URL. https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000037542730&categorieLien=id.
LegiFrance, 2020. Translated from French: Act n.2020-105 of 10 february 2020 relative to action against wastage and circular economy (1) (loi n.2020-105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire (1)). URL. https://www.legifrance.gouv.fr/jo_pdf.do?id=JORFTEXT000041553759.
LeMoigne, R., 2014. Translated from French (economie circulaire : les nouveaux " business models. futuribles. URL. https://www.futuribles.com/fr/article/economie-circulaire-les-nouveaux-business-models/.
Lindh, T., Malmberg, B., 2008. Demography and housing demand––what can we learn from residential construction data? J. Popul. Econ. 21, 521–539.
Lindhjem, H., Skjelvik, J.M., Eriksson, A., Fitch, T., Hansen, L.L.P., 2009. The Use of Economic Instruments in Nordic Environmental Policy 2006–2009.
Liu, X., Yuan, Z., Xu, Y., Jiang, S., 2017. Greening cement in China: a cost-effective

roadmap. Appl. Energy 189, 233–244.
van Loon, P., Delagarde, C., Van Wassenhove, L.N., 2018. The role of second-hand markets in circular business: a simple model for leasing versus selling consumer products. Int. J. Prod. Res. 56, 960–973.
Lotfi, S., Rem, P., Di Maio, F., Teklay, A., Hu, M., van Roekel, E., van der Stelt, H., 2017. Closing the Loop of Eol Concrete.
Mahpour, A., 2018. Prioritizing barriers to adopt circular economy in construction and demolition waste management. Resour. Conserv. Recycl. 134, 216–227.
Mankiw, N.G., Weil, D.N., 1989. The baby boom, the baby bust, and the housing market. Reg. Sci. Urban Econ. 19, 235–258.
Martínez-Lage, I., Vázquez-Burgo, P., Velay-Lizancos, M., 2020. Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: technical, economic and environmental analysis. Waste Manag. 104, 9–19.
Meikle, J.L., Connaughton, J.N., 1994. How long should housing last? some implications of the age and probable life of housing in england. Construct. Manag. Econ. 12, 315–321.
Menegaki, M., Damigos, D., 2018. A review on current situation and challenges of construction and demolition waste management. Current Opinion in Green and Sustainable Chemistry 13, 8–15.
Miatto, A., Schandl, H., Tanikawa, H., 2017. How important are realistic building lifespan assumptions for material stock and demolition waste accounts? Resour. Conserv. Recycl. 122, 143–154.
MINERGIE-P, 2013. Reglement zur nutzung des produktes minergie-p der qualitätsmarke minergie. URL. https://www.minergie.ch/media/reglement2013p-dt.pdf.
Mont, O., Dalhammar, C., Jacobsson, N., 2006. A new business model for baby prams based on leasing and product remanufacturing. J. Clean. Prod. 14, 1509–1518.
Moro, C., Francioso, V., Schrager, M., Velay-Lizancos, M., 2020. Tio2 nanoparticles influence on the environmental performance of natural and recycled mortars: a life cycle assessment. Environ. Impact Assess. Rev. 84, 106430.
Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553.
Müller, D.B., 2006. Stock dynamics for forecasting material flows––case study for housing in The Netherlands. Ecol. Econ. 59, 142–156.
Myers, D., 1990. Housing Demography : Linking Demographic Structure and Housing Markets. University of Wisconsin Press, Madison, Wis. Includes bibliographical references and index.
Needleman, L., 1965. The Economics of Housing. Staples Press.
Nußholz, J.L., Rasmussen, F.N., Milios, L., 2019. Circular building materials: carbon saving potential and the role of business model innovation and public policy. Resour. Conserv. Recycl. 141, 308–316.
Pacheco, J., De Brito, J., Chastre, C., Evangelista, L., 2019. Experimental investigation on the variability of the main mechanical properties of concrete produced with coarse recycled concrete aggregates. Construct. Build. Mater. 201, 110–120.
Pedro, D., De Brito, J., Evangelista, L., Bravo, M., 2018. Technical specification proposal for use of high-performance recycled concrete aggregates in high-performance concrete production. J. Mater. Civ. Eng. 30, 04018324.
Perera, S., Nanayakkara, S., Rodrigo, M., Senaratne, S., Weinand, R., 2020. Blockchain technology: is it hype or real in the construction industry? Journal of Industrial Information Integration 17, 100125.
Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: a research framework. J. Clean. Prod. 143, 710–718.
Rademaker, J.H., Kleijn, R., Yang, Y., 2013. Recycling as a strategy against rare earth element criticality: a systemic evaluation of the potential yield of ndfeb magnet recycling. Environ. Sci. Technol. 47, 10129–10136.
Rahardyan, B., Matsuto, T., Kakuta, Y., Tanaka, N., 2004. Resident's concerns and attitudes towards solid waste management facilities. Waste Manag. 24, 437–451.
Récylum, 2016. Translated from French: democles: keys for sustainable demolition (democles; les clés de la démolition durable). URL. https://www.ademe.fr/sites/default/files/assets/documents/democles-201607-synthese.pdf.
Rezaei, F., Bulle, C., Lesage, P., 2019. Integrating building information modeling and life cycle assessment in the early and detailed building design stages. Build. Environ. 153, 158–167.
Richter, B., Goldston, D., Crabtree, G., Glicksman, L., Goldstein, D., Greene, D., Kammen, D., Levine, M., Lubell, M., Savitz, M., et al., 2008. How America can look within to achieve energy security and reduce global warming. Rev. Mod. Phys. 80, S1.
Rouvreau, L., Michel, P., Serrand, M., Montfort-Climent, D., Jayr, E., Papinot, P.E., 2012. Translated from French: (The Anr Asuret Project: a Material Flow Analysis of the Construction Sector on a Construction and Territory Scale (Objective 4.2)). URL. http://infoterre.brgm.fr/rapports/RP-61849-FR.pdf.
Ruiz, L.A.L., Ramón, X.R., Domingo, S.G., 2019. The circular economy in the construction and demolition waste sector–a review and an integrative model approach. J. Clean. Prod. 119238.
Sabbaghi, M., Cade, W., Olson, W., Behdad, S., 2019. The global flow of hard disk drives: quantifying the concept of value leakage in e-waste recovery systems. J. Ind. Ecol. 23 (3), 560–573. https://doi.org/10.1111/jiec.12765.
Sandberg, N.H., Sartori, I., Brattebø, H., 2014. Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock. Energy Build. 82, 287–295.
Sandberg, N.H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimm-r, T., Filippidou, F., Stegnar, G., Zavrl, M.Š., et al., 2016. Dynamic building stock modelling: application to 11 european countries to support the energy efficiency and retrofit ambitions of the eu. Energy Build. 132, 26–38.
Sartori, I., Bergsdal, H., Müller, D.B., Brattebø, H., 2008. Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100. Build. Res. Inf. 36, 412–425.
SDES, 2019. Translated from French (taux mensuel d'annulation de logements autorisés en france entière (mayotte non compris) depuis janvier 2000. URL. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2018-11/201803-taba4-lgt-taux-annul.xls.
SeRaMCo, 2017. Secondary Raw Materials for Concrete Precast Products. URL. https://www.nweurope.eu/projects/project-search/seramco-secondary-raw-materials-for-concrete-precast-products/#tab-1.
Shanks, W., Dunant, C.F., Drewniok, M.P., Lupton, R.C., Serrenho, A., Allwood, J.M., 2019. How much cement can we do without? lessons from cement material flows in the UK. Resour. Conserv. Recycl. 141, 441–454.
Shi, F., Huang, T., Tanikawa, H., Han, J., Hashimoto, S., Moriguchi, Y., 2012. Toward a low carbon–dematerialization society: measuring the materials demand and co2 emissions of building and transport infrastructure construction in China. J. Ind. Ecol. 16, 493–505.
Shrestha, S.S., Biswas, K., Desjarlais, A.O., 2014. A protocol for lifetime energy and environmental impact assessment of building insulation materials. Environ. Impact Assess. Rev. 46, 25–31.
Smith, S.K., Rayer, S., Smith, E.A., 2008. Aging and disability: implications for the housing industry and housing policy in the United States. J. Am. Plann. Assoc. 74, 289–306.
SOES, 2014. Translated from French (enquête « déchets et déblais produits par l'activité de construction en 2014 »). URL. https://www.statistiques.developpement-durable.gouv.fr/enquete-sur-les-dechets-et-deblais-produits-par-lactivite-btp-en-2014-edd-2014.
Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., Zhang, Y., Sun, Z., 2019. Material flow analysis on critical raw materials of lithium-ion batteries in China. J. Clean. Prod. 215, 570–581.
Stephan, A., Athanassiadis, A., 2017. Quantifying and mapping embodied environmental requirements of urban building stocks. Build. Environ. 114, 187–202.
TABULA/EPISCOPE, 2012. Typology approach for building stock energy assessment – final project report. URL. https://ec.europa.eu/energy/intelligent/projects/en/projects/tabula.
Tam, V.W., Tam, C.M., 2006. A review on the viable technology for construction waste recycling. Resour. Conserv. Recycl. 47, 209–221.
Tasaki, T., Hashimoto, S., Moriguchi, Y., 2006. A quantitative method to evaluate the level of material use in lease/reuse systems of electrical and electronic equipment. J. Clean. Prod. 14, 1519–1528.
Tazi, N., Idir, R., Fraj, A.B., 2020. Sustainable reverse logistic of construction and demolition wastes in French regions: towards sustainable practices. Procedia CIRP 90, 712–717.
Tazi, N., Kim, J., Bouzidi, Y., Chatelet, E., Liu, G., 2019. Waste and material flow analysis in the end-of-life wind energy system. Resour. Conserv. Recycl. 145, 199–207.
Tilton, J.E., Tilton, J., 1990. World metal demand: trends and prospects. Resources for the Future. RFF Press.
UNPG, 2019. Translated from French (l'industrie française des granulats. edition 2019 - French aggregates industry. 2019 edition). URL. http://www.unpg.fr/wp-content/uploads/stat-unpg-chiffres-2017-web.pdf.
Woodward, R., Duffy, N., 2011. Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. Resour. Conserv. Recycl. 55, 448–455.
Wu, Z., Ann, T., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: an analytical review. Waste Manag. 34, 1683–1692.
Zhang, L., Chen, T., Yang, J., Cai, Z., Sheng, H., Yuan, Z., Wu, H., 2017. Characterizing copper flows in international trade of China, 1975–2015. Sci. Total Environ. 601, 1238–1246.
Zhou, W., Moncaster, A., Reiner, D.M., Guthrie, P., 2019. Estimating lifetimes and stock turnover dynamics of urban residential buildings in China. Sustainability 11, 3720.