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Assessing material and embodied flows related to building services in office buildings — the case of Brussels, Belgium

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Abstract. An increasing number of cities and regions are promoting reuse as a key strategy in the transition towards a more circular economy in the construction sector. However, the reuse supply chains for building services are currently underdeveloped in most cities and regions. There is a need for a better understanding of the material flows at the city and regional levels. This study describes a bottom-up approach to quantify material flows related to building services as well as their embodied environmental and economic flows. It relies on the selection of a minimum of 1 new construction or renovation project representing material inflows and 1 demolition or renovation project representing material outflows. Actual products from bill of quantities and pre-demolition audits are mapped against a list of 234 archetypes, and archetypal inflows and outflows are extrapolated to the city or regional level. This model is applied to all office buildings in the Region of Brussels, Belgium. Results show that rectangular ductwork is responsible for almost 30% of annual inflows of building services, which amount to 32 km/year, 1,6 kt/year, require 96 thousand m³ of freshwater/year, 131 TJ of primary energy/year, emit 9,9 kt CO_2 eq/year, cost 3;4 MEUR/year to project developers, and whose installation in buildings represents 51 khours/year. In addition, results show that the outflows of black steel pipes, recessed luminaires and electrical cables exceed the inflows on an annual basis, suggesting that there is significant potential for covering needs through the reuse of those products.

1 . Introduction

Over the past century, the world population has quadrupled while the global annual consumption of building materials has increased by a factor of 42 [1]. Today, the construction industry is estimated to account for around 40% of the anthropogenic energy use and material flows, globally, while generating 13-29% of the total waste in developed economies [2]. In recent years, an increasing number of cities and regions have initiated a transition towards a circular economy, where “resources are used in a more sustainable way” [3]. In June 2019, Brussels Environment published a roadmap identifying priority actions for the implementation of circular economy principles in the construction sector in Brussels, Belgium. The roadmap focuses on circular design, building maintenance, reuse and remanufacturing in Brussels [4]. Building services (plumbing, heating, ventilation and electrical services) are considered a priority for the development of a more circular economy in the construction sector [5]. They are responsible for ~30% of the investment costs of a new office building [6] and ~27% of the initial

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embodied environmental effects of a commercial building [7]. Furthermore, they contribute 16% of the material flows associated with the construction of office buildings and their refurbishment in Brussels [5]. Currently, reuse supply chains for building services are underdeveloped in most cities and regions, including Brussels [8]. The development of reuse supply chains requires a better understanding of material flows at the city and regional levels [9] and in particular the recurrent outflows that are related to building demolition projects because they can lead to a stable commercial offer [10]. A number of studies have already assessed these flows using a mix of bottom-up, top-down, static and dynamic approaches, such as [11] and [12]. However, these studies fail to capture detailed information about building services products, and they do not consider embodied environmental and economic flows.

This paper aims to propose a bottom-up approach to quantify material and embodied environmental and economic flows of building services products in office building stocks. It uses the Region of Brussels, Belgium as a case study to demonstrate the potential and relevance of the developed approach. Section 2 describes the proposed bottom-up approach including data requirements, reference projects selection, and quantification algorithms. Section 3 then applies the developed approach to the Region of Brussels, Belgium to illustrate its potential. Section 4 discusses the modelling approach, presents its limitations, and concludes the paper. This paper covers the material flows of building services products that are related to new construction, renovation, and demolition projects. Material flows related to the replacement of products that would not be part of a renovation project are not taken into account.

2 . Methodology: Designing a bottom-up approach to quantity material and embodied flows related to building services in office buildings in cities and regions

The bottom-up approach relies on the selection of a minimum of 1 new construction or renovation project representing material inflows and 1 demolition or renovation project representing material outflows. Bill of quantities and pre-demolition audits are collected from the reference projects and actual products are mapped against a list of archetypes. In this study, an archetype refers to a very typical example of a certain group of building services products. For example, chillers with a capacity between 500 and 1 000 kW would be modelled using the same archetype. This is an efficient manner to streamline the modelling [13], and helped to reduce the 666 products described in the case study to 117 archetypes (see Section 3). Figure 1 presents the overall modelling approach used, its data requirements and the different steps involved. It will be referred to throughout Sections 2 and 3. The study consists of 4 main steps. The first step relates to defining archetypes for building services products and creating a database of embodied environmental and economic flows. The second step relates to defining a set of criteria for the selection of reference projects and finding statistics related to the development of office space in the region under study. Using the results of steps 1 and 2, the third step deals with the identification of reference projects, and the establishment of archetypal inflows and outflows from bill of quantities and pre-demolition audits. Finally, the last step aims to extrapolate the archetypal material flows at the regional level and calculate associated embodied environmental and economic flows.

As in most bottom-up approaches to model the built environment, a large amount of data is required. In this case, data requirements encompass environmental data on construction products, prices of building services, annual floor areas of new construction, renovation and demolition of office buildings, bill of quantities and pre-demolition audits. While the first 3 types of data might be obtained via open-access databases, sometimes national or regional, bill of quantities and pre-demolition audits must be collected directly from project developers. It is important to note that bill of quantities and pre-demolition audits are essential in this approach and the model cannot be used if those are lacking.

The selection of reference projects is based on the study of available statistics related to the office building stock and its development at the regional level. This study aims to determine a dominant type of work for each specific flow (for example, renovation over demolition for material outflows), as well as a dominant building type affected by this type of work (for example, buildings dating from the 70s of more than 10 000 m²). If a dominant typology cannot be determined, it may be necessary to consider several reference projects for the same flow.

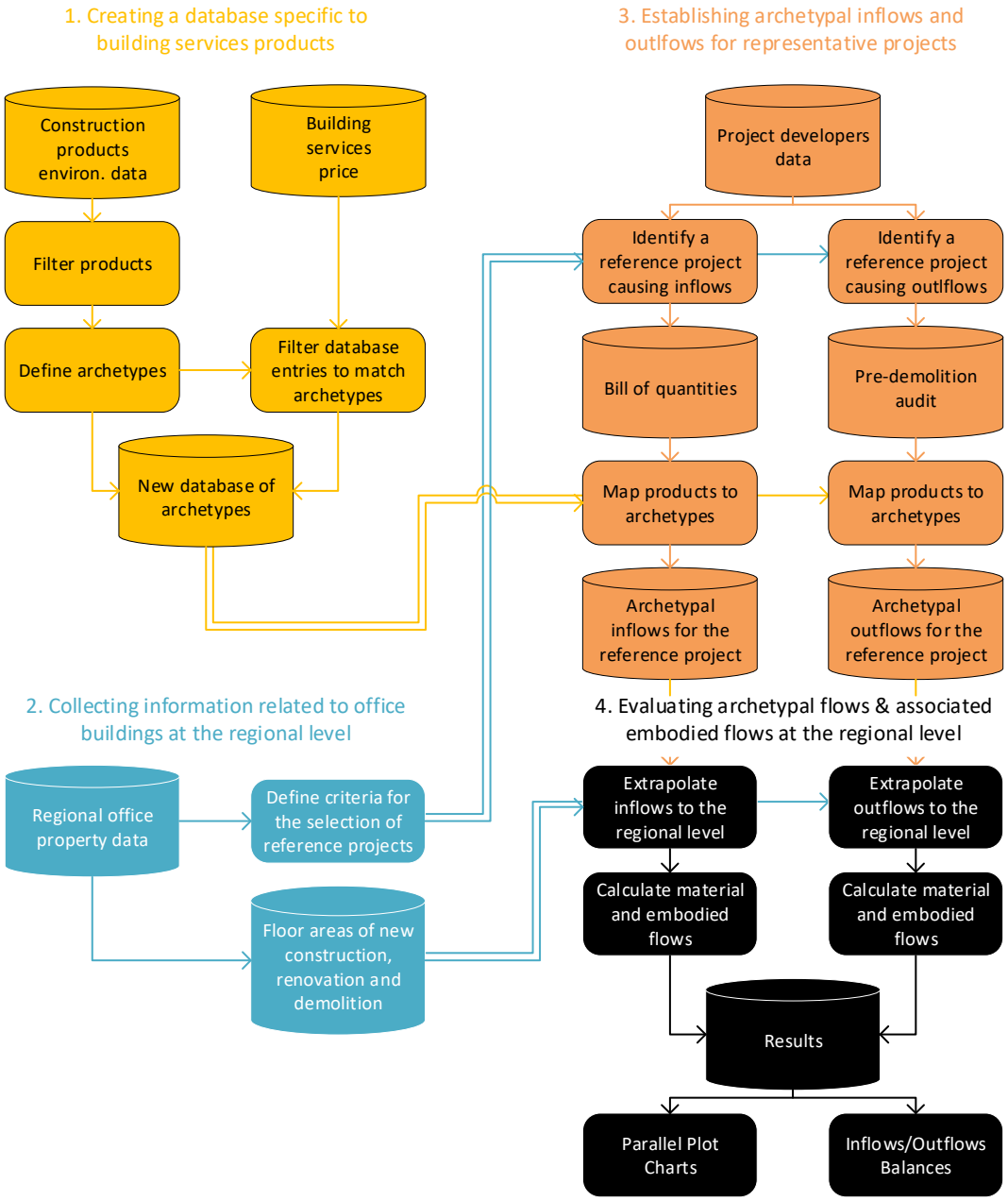


Figure 1 Overall modelling approach. Inspired by [13]

The proposed model uses actual product quantities, as recorded in the bill of quantities and pre-demolition audits of the reference projects, to quantify archetypal inflows and outflows at the regional level. Each product is mapped against a list of archetypes. These quantities are then multiplied by a factor that depends on the number of reference projects for a specific flow. In the case where there is only 1 reference project related to the inflows, for example, this factor is obtained by the ratio between the floor area of new construction and renovation in the region and the floor area of the reference project.

This study relies on existing product-level databases to quantify embodied environmental and economic flows of building services. The embodied environmental flows that are considered in this study are freshwater use, primary energy use, and greenhouse gas emissions. Primary energy use is a good proxy for other environmental effects [14]. Freshwater use is a primary flow that does not correlate

well with the primary energy use [15]. Greenhouse gas emissions are a critical environmental effect given the climate emergency [16]. The life cycle stages taken into account comprise raw material extraction, material manufacture, processing and transport as well as the installation process, corresponding to modules A1 to A5 according to [17]. The embodied economic flows that are considered in this study are the net purchase price and the installation labour hours. The net purchase price relates to the industry tender price, plus a nominal allowance for fixings, waste and applicable trade, while the installation labour hours relate to man-hours for each operation, as defined in [18]. It should be noted that, preferably, a different database should be used to quantify embodied environmental and economic flows of incoming and outgoing products. This is because it is likely that current extraction, manufacturing, transport, and installation processes are not equal to those of the past. Where the database related to inflows is used to quantify embodied flows of outgoing products, these should be interpreted as indicative.

3 . Application of the proposed model to the Region of Brussels

In the absence of a Belgian environmental database related to building services products, this study used the French database INIES [19]. This database includes a series of 1 084 datasets related to mechanical and electrical (M&E) products. Regarding products purchase price and installation labour hours, this study relied on the Fifty-Second Edition of Spon's Mechanical and Electrical Services Price Book (2021) edited by AECOM [18]. This UK publication is 879 pages long and covers the widest range and depth of engineering services. The floor areas of new construction, renovation and demolition were found in annual reports on the development of office space in Brussels [20]. Finally, this study used information from 1 bill of quantities and 1 pre-demolition audit respectively quantifying the building services products required and disposed of as part of reference projects. Those documents were collected from 2 project developers in Brussels. The bill of quantities was split into 2 PDFs totalling 640 M&E products. The pre-demolition audit was an excel spreadsheet including 26 M&E products.

As described in Section 2, the method entails 4 steps. During the first step, the INIES database was filtered, and 443 generic datasets related to building services products were found. Those products are later referred to as archetypes. Those were used to filter the Spon database, which brought the new database to 231 products. An average exchange rate of 1,1632 EUR : 1 GBP was used to convert the prices from the Spon price book [21]. It is important to note that the embodied environmental intensities in the generic datasets are increased by a safety factor of +30% to +100% depending on the existence and number of environmental declarations available for the product concerned (see [22] for more details). During the second step, the criteria for the selection of reference projects were formulated as follows: renovation projects of office buildings dating from the 70s or 90s with a floor area of over 10 000 m² in Brussels. This is because renovation concerns 62% of the new construction and renovation projects, and 77% of the demolition and renovation projects (by floor area, between 2009 and 2013), office buildings dating from the 70s and the 90s represent almost 50% of the floor area of the stock, and office buildings of more than 10 000 m² represent more than 50% of the floor area of the stock [20]. During the third step, 2 reference projects were selected for this study: the first one concerns the renovation of a 16 000 m² office building dating from 1972, and the second one concerns the renovation of a 40 000 m² office building dating from 1969. The first project represents 6% of the new construction and renovation projects, and the second represents 20% of the demolition and renovation projects (by floor area, for an average year between 2009 and 2013) [20]. Subsequently, every building services product was mapped against archetypes from the new database, except for 49 products that were not covered by the new database, representing around 7% of the total number of products. The mapping resulted in 117 archetypes for the bill of quantities and 19 archetypes for the pre-demolition audit. Those archetypes were further simplified to respectively 95 and 18 archetypes by grouping the archetypes only differentiating by a different value of a similar variation parameter (i.e. diameter 160 mm, and 200 mm for circular ductwork, etc.). The associated quantities were summed by archetype, and archetypal inflows and outflows were made available. During the fourth step, statistics related to the development of office space were used to extrapolate

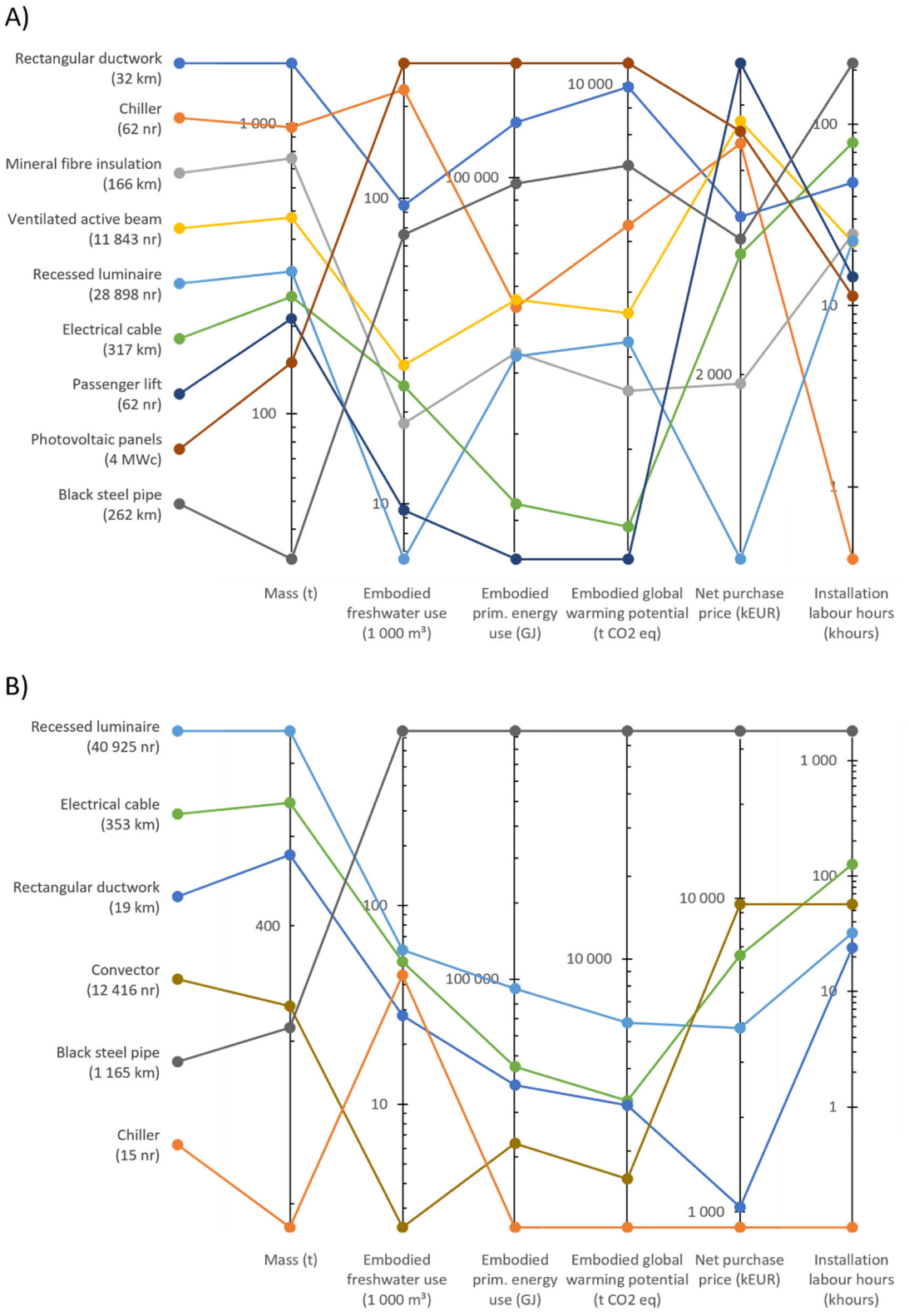


Figure 2 Mass, embodied freshwater, embodied energy, embodied greenhouse gas emissions (GHG), net purchase price, and installation labour hours for building services inflows (A) and outflows (B) of the Region of Brussels, for an average year, by archetype category and using Log10 scales. Inspired by [13]

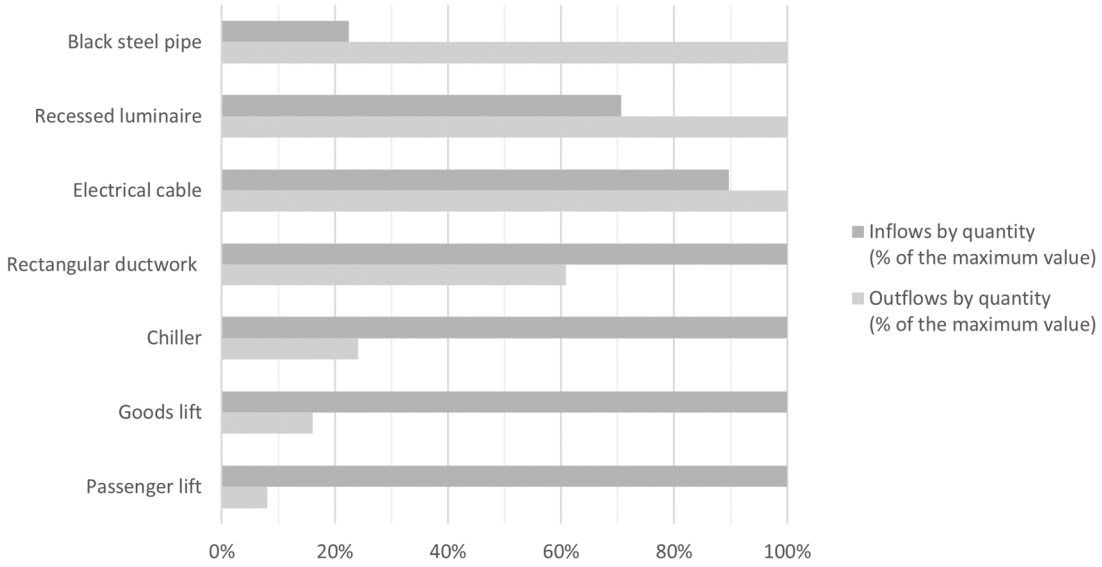


Figure 3 Building services inflows and outflows of the Region of Brussels, for an average year, by archetype category

archetypal inflows and outflows at the regional level. Average annual floor areas of new construction and renovation were summed and used to extrapolate inflows, while average annual floor areas of demolition and renovation were summed and used to extrapolate outflows. The mass, the embodied environmental and economic flows were directly calculated from the archetypal inflows and outflows quantities and the new database.

Figure 2 depicts the mass, the embodied environmental and economic flows of building services products inflows and outflows, across respectively 9 and 6 categories of the 234 archetypes used in this study. The selected categories are the top 5 products related to each indicator; therefore, the number of inflows and outflows categories is not equal. Note further that a logarithmic scale (base 10) had to be used as masses and embodied flows differed by orders of magnitude for different categories. The significance of quantities and embodied flows should be noted. For example, the annual inflow of electrical cables alone represents 317 km which is equivalent to ~6 times the perimeter of the Region of Brussels. The installation labour hours related to the annual inflow of black steel pipe is 221 khours which is equivalent to the annual working time of 138 workers (based on an annual working time of 1 600 hours per worker). Figure 2 confirms the importance of presenting multiple indicators at the same time to capture the multifaceted environmental effects of the built environment more comprehensively, as previously identified by [23] and [13]. As expected, the highest correlation is between embodied primary energy use and the embodied greenhouse gas emissions, with R^2=0.999. The lowest correlation is between the mass and the embodied freshwater use, with R^2=0.002. Results show that the products with the largest embodied environmental flows and the highest purchase prices are photovoltaic panels, rectangular ductwork, and chillers for the inflows, as well as black steel pipes, recessed luminaires, and electrical cables for the outflows. Those products should therefore be targets for reuse.

Figure 3 compares the quantities of products that appear as both inflows and outflows at the regional level. Results show that the outflows of black steel pipes, recessed luminaires and electrical cables exceed the inflows on an annual basis. This finding suggests that there is significant potential for covering needs through the reuse of those products. It is important to realise that, depending on the product, there may be a significant technology gap between outgoing and incoming products. In addition, the dependence of the quantities of certain products on the selected reference projects should be highlighted. For example, Figure 3 shows a significant difference between the inflows and outflows of black steel pipe. This discrepancy is explained by the fact that the project selected for inflows calculation is rectangular and the heat distribution network is in the centre of the plan. The project

selected for outflows calculation is H-shaped and the heat distribution network follows the perimeter. Figure 3 also shows a significant increase in the use of rectangular ducts. This difference is explained by the recent introduction of European directives setting increasingly ambitious energy targets for office buildings [24]. Until then it was common practice to equip office spaces with supply air only, whereas nowadays they are equipped with both supply and exhaust air for heat recovery.

4 . Discussion and conclusion

The proposed model follows previous attempts to model the building stock of cities [5, 23], but provides a more detailed approach to building services products quantity estimation. This level of detail enables decision-makers to trace back embodied environmental and economic flows to a particular building services product, which is rarely available in existing studies. In addition, this model allows the identification of products for which outflows exceed inflows and there is a significant reuse potential at the regional level. This is notably the case for black steel pipes, recessed luminaires, and electrical cables in the Region of Brussels. Decision-makers can thus focus their efforts on developing reuse supply chains for these products as a priority. The application of the model to the Brussels region also demonstrates that the assumption whereby the mass of outgoing materials during a renovation would be equal to the mass of incoming materials cannot be validly applied to building services products. In this case study, the mass of incoming building services products would be 2 times greater than that of outgoing building services products during a renovation (by floor area). This difference is partly explained by the recent introduction of European directives setting increasingly ambitious energy targets for office buildings, which leads to a higher demand for building services products. It would be interesting to assess the environmental effects of the implementation of these directives, considering the energy savings as well as the embodied flows, and to deduce the payback time of the environmental investment provided. In addition, the parametric nature of the model allows its application to any other city or region, if the needed data are available. Data requirements are detailed in Section 2. They can be obtained relatively easily in many cities. However, the method requires expert knowledge, and a significant amount of work related to the definition of archetypes, the selection of reference projects, and the mapping of products against archetypes.

The proposed model suffers from 2 main limitations: uncertainty and data intensity. The uncertainty stems from a few parameters, including database mismatches, data encoding errors from third party material, reference projects selection, product mapping against archetypes, and finally from embodied environmental and economic intensities of buildings services products. Since the model quantifies indicators that are dependent on a series of upstream calculations, uncertainty is propagated across the model and increases at every calculation. In addition, the data-intensive nature of the model reduces its potential widespread application.

The embodied environmental and economic flows of building services in office building stocks have rarely been evaluated while being responsible for significant environmental and economic effects. This study proposes a bottom-up modelling approach to quantify building services inflows and outflows at a city or regional level, as well as associated embodied freshwater use, primary energy use, greenhouse gas emissions, net purchase price, and installation labour hours. The application of the model to the Region of Brussels, Belgium illustrates the potential of the model through the breadth of outputs it generates, including the identification of products for which outflows exceed inflows and there is a significant reuse potential at the regional level. Decision-makers can thus focus their efforts on developing reuse supply chains for these products as a priority. This will ultimately help improve resource efficiency and reduce the environmental damage caused by the built environment.

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