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Improving the life cycle greenhouse gas emissions of transport infrastructure assets – a case study in Brussels, Belgium

Soroosh Ataee[1] * **and A Stephan**[1]

[1] Faculty of Architecture, Architectural Engineering and Urban Planning, Université catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium

* Corresponding author: soroosh.ataee@uclouvain.be

Abstract. Infrastructure transportation assets represent a significant share of environmental effects associated with built stocks. Although there is a growing body of knowledge on the life cycle assessment of buildings and material flow analysis of building stocks, infrastructure assets have received less attention. Existing life cycle assessment studies tend to rely on process analysis which is known to underestimate embodied environmental flows. The aim of this paper is to introduce a bottom-up parametric model for infrastructure transport assets, which can support a detailed characterization of the stock in a consistent and transparent manner. It relies on comprehensive hybrid exchange data for the quantification. This paper establishes the approach and equations used in the proposed model. The model consists of four main steps, namely: developing parametric representations of transport infrastructure assets, quantifying their material stock and replacement-related flows, quantifying life cycle embodied environmental flows and visualizing the results. One pilot case study of a road (including pedestrian sidewalks and bike lanes) and light railway, is used to demonstrate the model. Results assessing this pilot case study over 60 years are presented, including the material stock and replacement flows, as well as life cycle embodied greenhouse gas emissions (LCEGHG). Together these results provide important insights into material/infrastructure asset hotspots assets (e.g. steel lighting posts). Emissions-intensive material products and assets have a notable impact on results of LCEGHG, and they dominate both Initial greenhouse gas emissions (IEGHG) and recurrent greenhouse gas emissions (REGHG). However, they contribute marginally to the total mass. Another important observation is the significance of REGHG representing ~30% of LCEGHG. Interestingly, steel, asphalt and concrete are the main contributors to both REGHG and IEGHG. Future research consists of automating the proposed model and packaging it as a python-based Rhinoceros Grasshopper plugin before conducting testing and verification.

1. Introduction

Climate change is one of the most significant and urgent challenges of humanity. Infrastructure assets represent intense land-use activities with wide-ranging ecological, social, economic and environmental impacts. Urban and other types of infrastructure assets have expanded by a factor of two since 1960 [1]. Roads, trains, tramways, bike lanes, and other transportation infrastructure assets account for a significant portion of the environmental impacts associated with built stocks [2]. Governmental entities or local municipal councils typically own these assets. As such, enhancing their environmental performance through better material selection and construction is simplified, as opposed to building stocks, which have a large number of owners with varying interests [3]. Although there is an extensive knowledge on building life cycle assessment and material flow analysis, transport infrastructure assets

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have received less attention. Among the several studies that have quantified the life cycle environmental performance of transport infrastructure assets, the majority of them have assessed the life cycle environmental flows of the road and pavement constructions [4], [5], [6], [7], [4], [5], [8]. Fewer studies considered the life cycle and material flows assessment of railway and bicycle path construction and maintenance [9], [10]. Moreover, studies on the life cycle environmental performance of urban transportation infrastructure assets currently lack transparency [4]. Process analysis, which is known to underestimate embodied environmental flows, is commonly used in existing life cycle assessment studies [11]. So far, none of them has developed a comprehensive parametric model for an integrated life cycle and material flow analysis of transport infrastructure assets that can tackle the above-mentioned limitations.

The aim of this paper is to develop a bottom-up, dynamic, and multi-scale parametric model for the integrated life cycle assessment and material flow analysis of infrastructure transportation assets. The model will integrate LCA (life cycle assessment) and MFA (material flow analysis) across spatial scales, from materials to infrastructure assets and their stock.

The scope of this study includes the initial and recurrent embodied and operational environmental and material flows of different types of transport infrastructure assets in Belgium. These are equivalent to stages A1-A3 and B2 and B4 in European standard 15978. The period of analysis is 60 years.

This research is significant as it offers an innovative, comprehensive and parametric model to the planners, policy makers and industry. Section 2 describes method and case study. Section 3 presents the results and Section 4 discusses the findings and concludes the paper.

2. Method

2.1. Overall modelling approach

Figure 1 represents the research method. A section of the Boulevard du Souverain (Brussels, Belgium) is first considered and its material stock and associated life cycle greenhouse gas emissions (as if built today and maintained) are quantified over 60 years to establish a pilot case study. The case study data are based on construction details, assumptions and fieldwork. The repair and replacement are defined based on different scenarios and assumptions. Embodied greenhouse gas emissions are calculated based on the EPIC database. The functional unit considered is 1km of road and it is defined based on the literature review. The functional unit is selected based on the 1km length of the section of the road for 60 years. By selection of 1km length of section, it can be possible to include different types of infrastructure transportation assets (like rail and pedestrian ways). Results are used to provide design guidelines and suggestions.

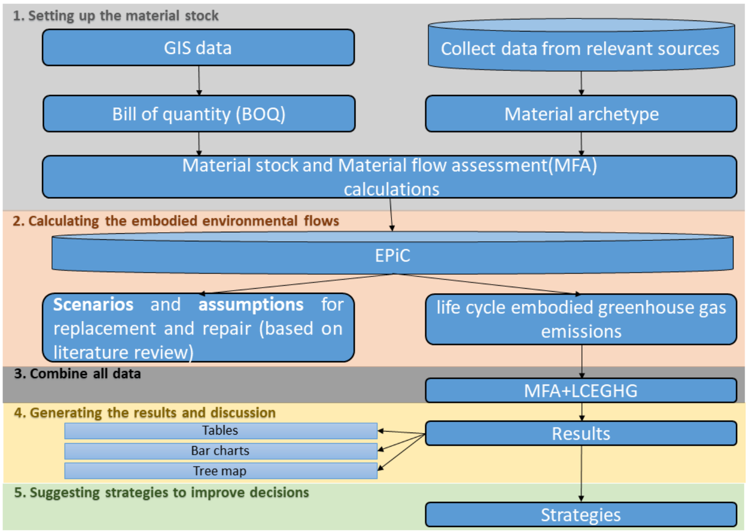

Figure 1. Process diagram of the overall research.

2.2. Quantifying material stocks of transport infrastructure assets

The mass of a infrastructure transportation asset (it) of a section, in kilograms, is calculated as per Equation (1), by:

- Extracting data from construction details and fieldwork;
- Multiplying width and thickness of material based on its intensity and density, specifically for each layer of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km.
- Multiplying the quantity of each material by its relevant material intensity coefficient specifically for building stations and elements (like sign posts) of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km.

$$MA_{it} = \sum_{n}^{N}\sum_{s=1}^{M}\sum_{s=1}^{S}\sum_{l=1}^{L}(W_{l,s} \times T_{l,s} \times I_{l,s} \times D_{m,\,l,s}) + \sum_{n}^{N}\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,it} \times MI_{m,e,a}\right) + \sum_{n}^{N}\sum_{b=1}^{B}\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,b} \times MI_{m,e,a}\right) \quad (1)$$

Where: MA_{it} = mass of a transportation assets asset (it) in kg/km ; $Q_{m,e,a,it}$ = quantity of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in kg; W l,s = Road width of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in m; $T_{l,s}$ = Road thickness of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in m; $I_{l,s}$= Intensity of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in no unit; $D_{m,\,l,s}$ = Density of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in kg/m^3; $Q_{m,e,a,b}$= quantity of material m in the element e in the assembly a in the transportation asset (it) per 1 km, in kg; N = number of Items in the transportation assets asset (it) per 1 km, in number of items; $MI_{m,e,a}$ = Material intensity of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, without unit; B = Total number of buildings b; L = total number of layers l and; S = total number of sections s; M = total number of materials m; E = total number of elements e and A = total number of assemblies a.

2.3. Quantifying embodied greenhouse gas emissions of transport infrastructure assets

Embodied greenhouse gas emissions are quantified using the path-exchange hybrid analysis technique developed by Treloar [12], validated by Crawford [13], formulated by Lenzen and Crawford [14] and automated by Stephan, Crawford and Bontinck [15]. This method combines monetary input-output statistics at a sectorial level, extracted through structural path analysis [16]. Particular data points are then replaced with more dependable process-based records for the specific material. The hybrid data gives a systemically complete account of greenhouse gas emissions, through input-output records, wherein the maximum amount of more reliable data is integrated. Hybrid data is therefore as reliable as the underlying process data while being systemically complete [17].

Life cycle embodied greenhouse gas emissions of the infrastructure transportation asset it in kgCO2e is calculated as per Equation (2), by:

- Deriving the quantity of materials from equation (1);
- Multiplying the quantity of each material by its relevant hybrid embodied greenhouse gas emissions coefficient, taken from EPiC database [12], [13]. The main reasons for using EPiC database is that, it is the only available database based on the hybrid approach (which is the combination of the process and input-output analysis), moreover it is a pilot case study.
- Replacing materials over 60 years, based on average material service lives from literature review and replacing fractions of materials over 60 years based on maintenance requirements

$$LCEGHG_{it} = \underbrace{\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,it} \times GHGC_m\right)}_{\mathrm{IEGHG}_{it}} + \underbrace{\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,it} \times GHGC_m\right) \times RP_{m,e,a,it}}_{\mathrm{REGHG}_{it}}$$

Where: $LCEGHG_{it}$ = life cycle embodied greenhouse gas emissions of the infrastructure transportation assets in kgCO2e/km; $IEGHG_{it}$ = initial embodied greenhouse gas emissions of the infrastructure transportation assets in kgCO2e/km, $REGHG_{it}$ = recurrent embodied greenhouse gas emissions of the infrastructure transportation assets in kgCO2e/km, $GHGC_m$ = hybrid greenhouse gas emissions coefficient of material m in kgCO2e/FU of material ; $Q_{m,e,a,it}$ = quantity of material m in the element e in the assembly a in the transportation assets asset (it) per 1 km, in kg; $RP_{m,e,a,it}$ = Replacement index of material m. Other items are defined in Equation 1.

2.4. Quantifying embodied greenhouse gas emissions of transport infrastructure assets

2.4.1. Material replacement and details

Transport infrastructure assets need to be maintained and replaced to minimize risks to users and ensure that the services they deliver are of the required quality (e.g. lighting at night). Road maintenance is critical to transport efficiency, road user experience and safety. In particular, road pavements can have significant environmental impacts at both construction and use stage [14]. Concerning the environmental effect assessment, the effect of replacement and maintenance of materials is calculated based on information from the literature [15]. Table 1 presents the parameters associated with material maintenance and replacements.

Table 1. Maintenance requirements, average service lives and resulting replacement indices

Number	Name	Maintenance requirements	average service life	Replacement index of material/element
Surface layer				
1	Asphalt	5% repair of asphalt top layer-5 years*	30*	1.6
2	Concrete	0,1% repair-10 years*	40*	0.5005
3	Cobblestones	Relay-20 years*	20*	2
4	Concrete tiles or blocks	Relay and 10% new tiles-20 years*	40*	0.7
5	Concrete paving stones	Relay and 10% stone-20 years*	40*	0.7
Road marking				
1	Solvent paint		1*	59
2	Cold plastic coating		3*	19
Electrical services				
1	Lighting column		40*	0.5
2	Data cable		20*	2
Building station				
	uPVC pipe		40*	0.5

Note: * from Trigaux, Wijnants, De Troyer and Allacker [15]

3. Case study description

The boulevard du Souverain, located in Brussels, Belgium, is an important road with two sidewalks of about 4 meters, a wide traffic strip of 8 meters, a path reserved for horse riders that is 4.5 meters wide, a strip of some 7 meters reserved for walkers, a cycle track, two exclusive tramway lanes and a second roadway for cars. In total, it has a width of 40.4 meters. In addition, it was planted with four rows of trees and it became the first public road in Auderghem lit by electricity. Today, the boulevard is part of the main boulevards of Brussels. This boulevard was selected as a case study because it includes different types of infrastructure transportation assets, available data and different types of material categories.

A section of the boulevard du Souverain (Brussels, Belgium) selected as a pilot case study and its embodied greenhouse gas emissions are calculated as if it were to be built today. Data for the different elements and assemblies are based on construction details, field work (measurement on site) and assumptions. Figure 2 and table 4 present the characteristics of the selected section of the boulevard du Souverain.

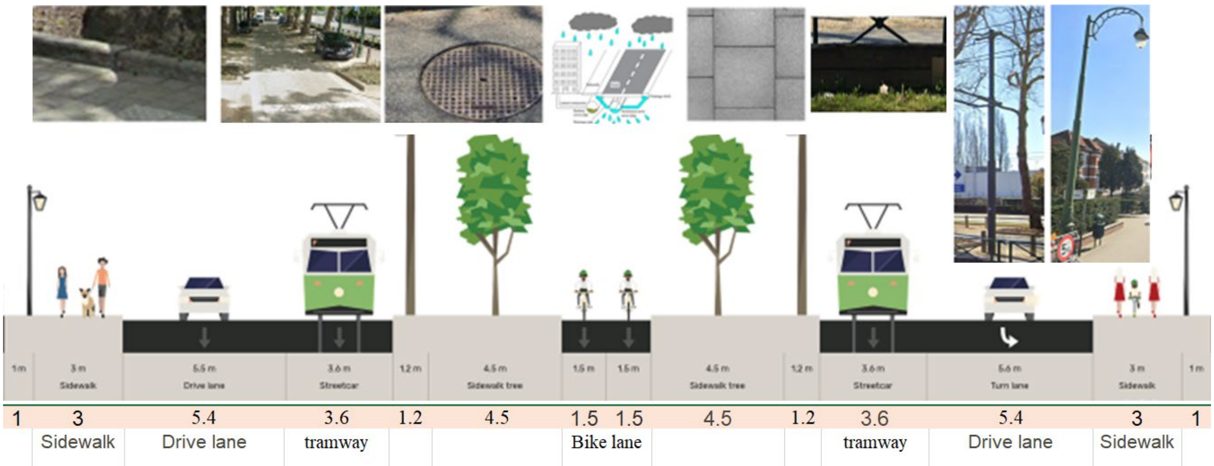

Figure 2. Section of the Boulevard du Souverain, Brussels, Belgium. Note : all dimensions are in metres

Table 2. Characteristics of pilot case study.

Case study characteristic	Base case/layers	Width(meter)
Main street road	Asphalt, Asphalt base course(aggregate), Aggregate base course (gravel), Granular sub-base(sand)	5.4
Pedestrian way	Concrete tiles ('Concrete 25 MPa), Binder (cement mortar), base course(gravel), Granular sub-base(sand)	4
Bicycle way	Concrete tiles ('Concrete 25 MPa), Binder(cement mortar), base course(gravel), Granular sub-base(sand)	1.5
Tram way	Painting (water based), 'Stainless steel products, 'Concrete 25 MPa (foundation), steel bars	3.6
Light post	Painting (water based), 'Hot rolled galvanised structural steel, bulb(polycarbonate), 'Concrete 25 MPa (foundation), steel bars, 'Concrete 25 MPa (foundation)	
Railing	Painting (water based), Stainless steel products, Base for railing'(Laminated veneer lumber (LVL))	
Planter box	Concrete blocks	
Underground pipes	uPVC pipe - 225.3 mm outer dia., 11.1 mm thick, 'uPVC pipe - 114.3 mm outer dia., 4.85 mm thick	
Street pits	Concrete 25 MPa (foundation), steel bars, 'Stainless steel products	

4. Results

This section presents the calculated mass of materials and embodied greenhouse gas emissions per 1 km of the case study. The results are summarised in Figure 3 and Figure 4.

Figure 3 compares the mass of materials and life cycle greenhouse gas emissions (LCEGHG) of different types of materials for the case study. Steel, asphalt, concrete are the top contributors to LCEGHG. Results show that steel contributes to about 48% of LCEGHG of the case study but less than 2% of total mass of material. This is because of having an emissions-intensive nature in comparison with other material types. Asphalt is the second most important contributor. It represents about 28% of LCEGHG and 13% of the total mass. This is mostly because of high replacement and maintenance index that asphalt has (Replacement index=1.6). Concrete represents less than 7% of both LCEGHG and total mass.

Figure 4 depicts the breakdown of the material stock and LCEGHG by infrastructure transport asset for the case study. The most significant observation to emerge from the results was that the main street road dominates the mass quantity(50%+) and light post represent 1% of the total mass, but both contribute to around 35% of the total LCEGHG. This is due to the use of emissions-intensive steel in the light posts and it highlights the requirement for reducing the use of emissions-intensive material such as steel in the design of transport infrastructure assets.

Figure 5 depicts the initial (IEGHG) and recurrent greenhouse gas emissions (REGHG) by different material categories of the case study. It shows the importance of REGHG in the total LCEGHG. The main observation is that among the main emissions-intensive material categories (steel, asphalt and concrete), replacement and maintenance plays and important role. The REGHG of steel, asphalt and concrete represent about 33%, 38% and 40% of total LCEGHG, respectively. Because of the significantly short service life of paint used in this pilot study (1 year), the REGHG dominates the total LCEGHG.

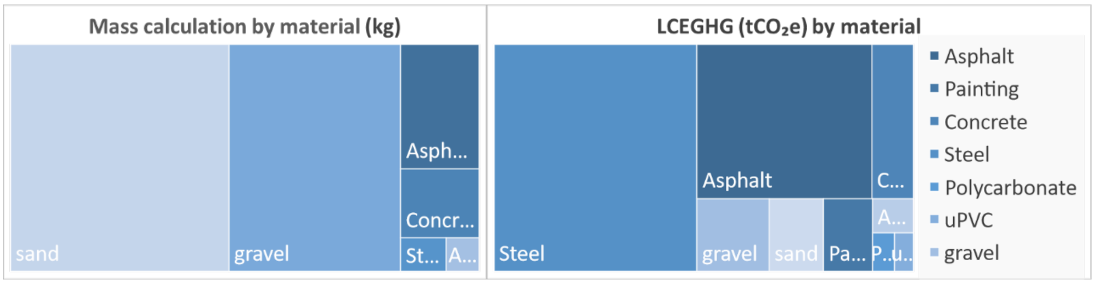

Figure 3. Mass and embodied greenhouse gas emissions of 1 km of the boulevard du souverain, by material.

Table 4. Percentage of mass and LCEGHG by material type.

Material type	Percentage of mass by material (%)	Percentage of LCEGHG (tCO_2e) by material (%)
Asphalt	14	28
Painting	0	4
Concrete	7	7
Steel	2	48
Polycarbonate	0	1
uPVC	0	20
gravel	38	6
Aggregate	1	1
sand	39	4

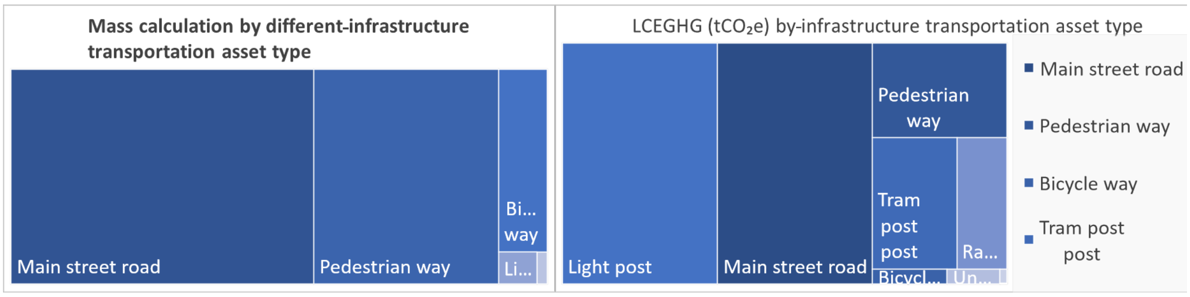

Figure 4. Mass and embodied greenhouse gas emissions of the Boulevard du Souverain, by infrastructure transportation asset.

Table 3. Percentage of mass and LCEGHG by different transportation asset type.

Material type	Percentage of mass (%)	Percentage of LCEGHG (tCO_2e) (%)
Main street road	56	35
Pedestrian way	34	12
Bicycle way	8	1
Tram post	0	10
Light post	1	35
Railing	0	6
Planter box	0	0
Underground pipes	0	1
Street pits	0	0

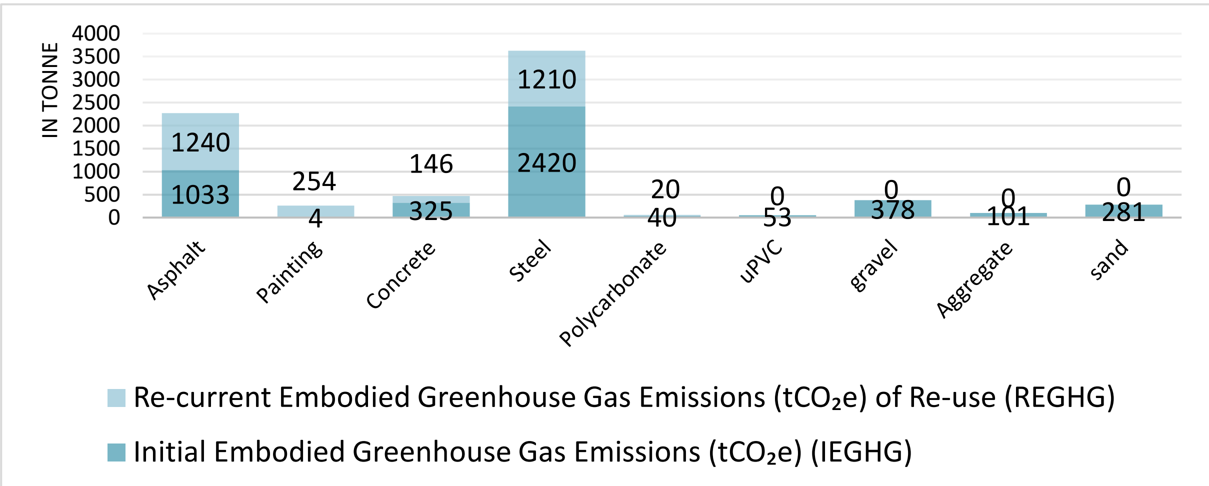

Figure 5. Initial and re-current greenhouse gas emissions, by material category.

5. Discussion and conclusion

This paper has evaluated the material stock and life cycle embodied greenhouse gas performance of a boulevard. The nested structure of the method for LCEGHG and material stock assessment is applied, enabling an analysis at various scale, i.e. from materials, elements, assemblies, into transport infrastructure assets n, . In reviewing the literature, very little data was found on the association between material flow assessment and environmental impacts [4, 16, 17].

The methodology is illustrated by assessing a section of the Boulevard du Souverain in Brussels, Belgium. The main finding of this research is about the significance of emissions-intensive material and assets in the sustainable design of infrastructure transport assets. They represent about half of LCEGHG, while they have a very small contribution towards the total mass. This finding was also reported by [15]. Very little was found in the literature on the question of impact of infrastructure elements (e.g. light-posts) in the LCEGHG of infrastructure transport assets. The environmental impact assessment shows the importance of recurrent greenhouse gas emissions (REGHG), which contributes about 30 % of the LCEGHG. This was included in previous research papers and represented 20% (this paper only considered pavements and roads) of LCEGHG in [18], 20% (they used life cycle environmental cost indicator) in [15] and 19% (this study is only for the roads layers and it did not take into the accounts other types of infrastructure transportation asset like tram posts) in [19]. In the road sections, the surface layer plays a critical role, with a contribution of about 36% towards the LCEGHG. Therefore, the selection of more environmentally friendly surfacing materials and the improvement of their maintenance and replacement scenarios are important parameters to reduce the environmental impact of road infrastructure. The high impact of surface layer in the infrastructure transport assets was also highlighted in [8], [15] [20] [21].

This study focuses on a single case study and as such its results are valid for the case study only. Also, we used Australian-based hybrid embodied greenhouse gas emissions coefficients which tends to overestimate embodied greenhouse gas emissions as compared to Belgian conditions, due to a more greenhouse gas emissions intensive economy.

To develop a full picture of material flow and environmental impact assessment for infrastructure transportation assets, additional studies are needed. Future studies should include more international case studies to verify the results, automating the proposed model and packaging it as a python-based Rhinoceros Grasshopper plugin. The scope also needs to be expanded to include operational environmental impacts and the environmental impacts associated with the transport modes themselves. Moreover, it can be useful to consider the compliance of the current approach to the standards like (ISO and EN standard series) as one of the objectives of the future studies.

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