Life Cycle Assessment of residential streets from the perspective of favoring the human scale and reducing motorized traffic flow. From cradle to handover approach

ABSTRACT

Currently, few studies have compared the variations in environmental impact throughout the different stages of the life cycle of urban construction elements; and of these, only a minority approach it from the perspective of favoring mobility on a human scale and reducing the space allocated to motorized traffic flow.

This study, by means of quantitative data, shows the environmental implications associated with prioritizing the non-motorized mobility of a city's inhabitants during the design process of an urban construction element, the residential street (referring to the stages of the production and the construction process: the "cradle to handover" approach). An emerging methodology in urban themes was used in order to obtain the environmental analysis: Life Cycle Assessment (LCA).

The results show that the increase in the human scale and the favoring of non-motorized mobility generate a lower environmental impact (considering the same uses of materials for the different zones of analysis). Additionally, it was possible to establish the influence that the specific use of materials employed in the construction of the streets may have, as well as the importance that an LCA acquires in the design of the urban environment.

Keywords: *Cradle to handover; Ecoindicator 99; Environmental impacts; Life cycle assessment; Non-motorized traffic flow; Pedestrian environment; Street design; Street materials; Sustainable cities; Urban planning*.

1. Introduction

The street is one of the principal elements that define the configuration of the urban environment: "Streets lie at the heart of communities, shape human health and environmental quality, and serve as the foundation of urban economies. In many cities, streets make up more than 80% of all public space, and collectively have the potential to foster business activity" (GDCI & NACTO, 2016). Several researchers (Gilderbloom et al., 2015; Haider et al., 2018; Kwan & Hashim, 2016; Lindelöw et al., 2014) show the advantages that can accrue from an environment in which the human scale is prioritized during the design process of urban planning.

In recent years, aspects related to the analysis of streets, which favor a pedestrian environment over motorized traffic flow, have been studied and developed. Nevertheless, the majority of studies carried out focus exclusively on the usage stage, neglecting to use integral environmental data from the complete life cycle (Mendoza, Oliver-Solà, Gabarrel, Rieradevall, & Josa, 2012). If used, this data would allow the environmental load produced in the various stages of the life cycle of a specific street to be known from the design process.

Some of the studies which justify the consideration of environmental criteria (Araújo et al., 2014; Loijos et al., 2013; Mendoza, Oliver-Solà, Gabarrel, Rieradevall, & Josa, 2012; Noshadravan et al., 2013; Oliver-Solà et al., 2009) focus on comparisons and the exclusive implications involved in choosing the materials for a specific section of the street (usually sidewalks or travel lanes). However, from the perspective of favoring the human scale and reducing the space allocated to motorized traffic, no evidence has been found about the figures or proportions that show the possible environmental impact of the stages incorporated in the streets.

Therefore, the aim of this work is, using quantitative data, to show the environmental ramifications when priority is given to the inhabitants of a city during the design process of a street (referring to production and construction stages: the "cradle to handover" approach). To achieve this objective, a methodology has been used with which it is expected to obtain a greater perspective of its use in the urban environment: LCA.

The analysis compares the environmental behavior of 18 options that are grouped into three types of residential street sections: the conventional, favoring motor traffic flows, and two redesigned sections that prioritize the human scale and non-motorized traffic flows. All use the typical urban infrastructure building materials.

2. Method and data

2.1. Description of Life Cycle Assessment

2.1.1. Aim and scope

The defined aim of the LCA is to compare three street sections whose width varies as a result of favoring motorized and non-motorized flows, as well as the different materials they are made from. The aim of the study is to establish the possible environmental impacts generated by the different streets, in addition to finding the most environmentally suitable combination of materials and sections.

Previous works have related the “cradle to handover” perspective (or similar: “cradle to gate” and “cradle to site” (Malmqvist et al., 2018)) with the objective of providing information which contributes to defining the repercussions of the construction itself. Some recent manuscripts, which have considered these limits of the system, are listed in **Table 1**. In this sense, this research is a “cradle to handover” study –according to Annex 57 of the International Energy Agency (Seo et al., 2016)–, which includes the production stages: extraction of the raw materials (A1), transport (A2) and production of the materials (A3). It also includes the construction process stage, which is composed of: transport from production to the site (A4) as well as the building process itself (A5) – according to the Norm UNE-EN 15804 (AENOR, 2014)–. **Fig. 1** shows the analysis of the flow in the life cycle inventory (LCI) used in this study.

Table 1

LCA studies that consider the stages directly related to the construction process.

Stage	Authors	Highlights
Cradle to gate	(Cass & Mukherjee, 2011)	Development of a method that quantifies pavement life cycle emissions.
(A1-A3)	(Moretti et al., 2018)	Analysis of environmental impacts of two types of road cross-sections.
	(Sandanayake et al., 2018)	Comparison of greenhouse gas (GHG) emissions and energy consumption in wood and concrete buildings.

Cradle to site (A1-A3+A4)	(Gardezi et al., 2016)	Development of an embodied carbon prediction tool for conventional housing.
Cradle to handover (A1-A3+A4-A5)	(Smith & Durham, 2016)	Environmental evaluation of pavements considering economic, environmental and mechanical performance criteria.
	(Mohajerani et al., 2018)	Evaluation of the impacts generated by the incorporation of biosolids in conventional materials.

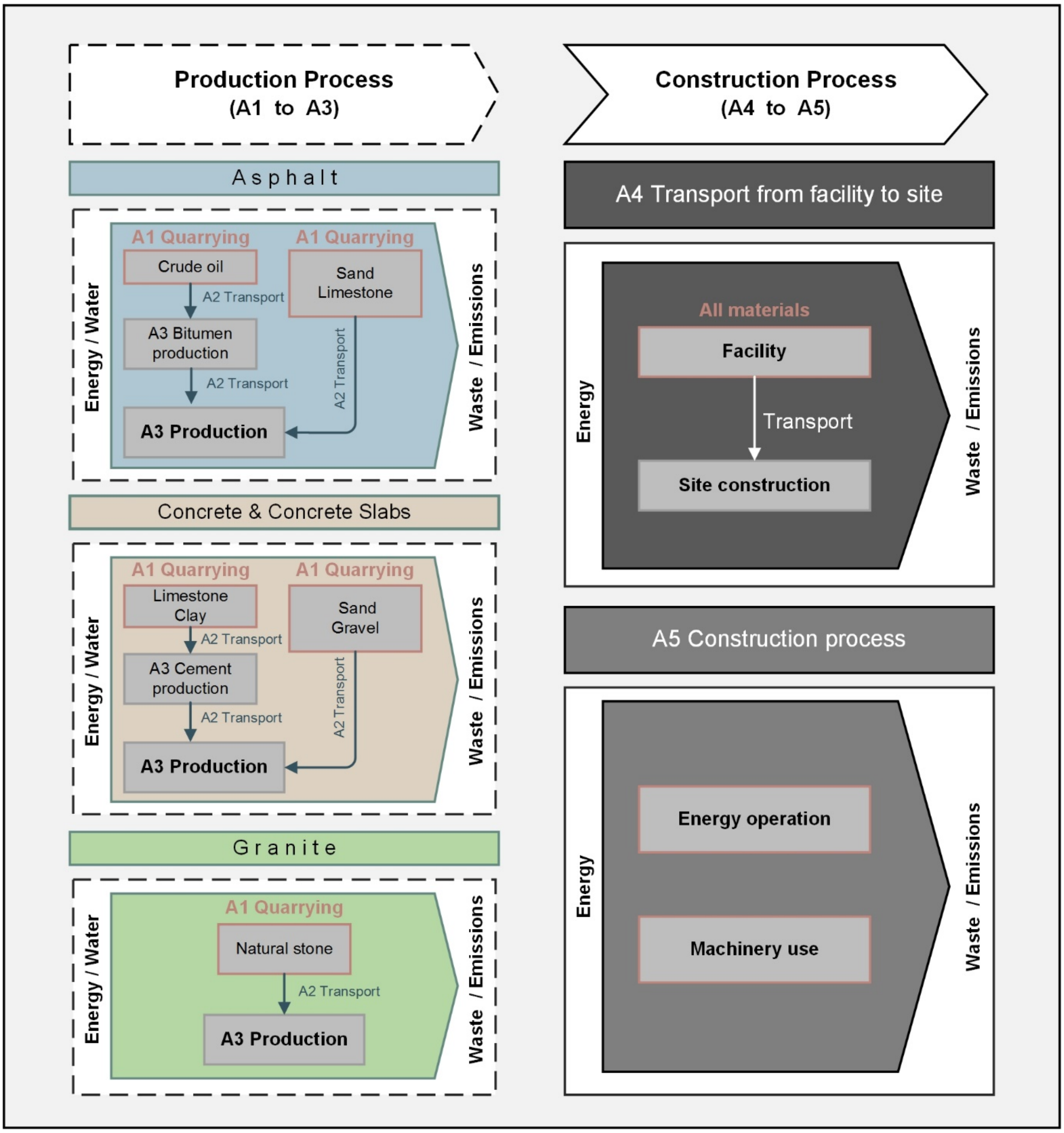

Fig. 1. Flowchart of the LCI.

Additionally, according to the configurations established from the streets under study, the linear meter (ml) was the functional unit, since it is the one that best defines the evaluation of the environmental impacts of each integrated zone. Previous research (Moretti et al., 2018; Petit-Boix et al., 2014) confirms that this functional unit is a reliable and objective parameter in this type of analysis. A constant total width of 13 meters was considered for the 18 options.

2.1.2. Data inventory

The Ecoinvent database, recognized internationally as a source of consistent and updated data (Frischknecht et al., 2007), was used to obtain the LCI. Applied to the field of research it mostly deals with information related to the European region, and it has been widely used in previous LCA studies (García-Guaita et al., 2018; Heinonen et al., 2016; Ortíz et al., 2010; Thiers & Peuportier, 2012).

The BEDEC materials database (ITEC, 2017) was used to quantify the materials and energy of the processes needed to develop stages A1-A5 of each street. The BEDEC database incorporates elements and construction materials of different types, whose technical characteristics belong in praxis to the Spanish ambit.

2.1.3. Impact assessment method and categories

The results of the environmental impact were processed using the Software LCA Manager 1.3 (Simpple, 2010), which allows the resources used and their environmental effects to be analyzed by means of the LCA methodology (AENOR, 2006). LCA Manager 1.3 has been used in previous research (Ortiz et al. 2010), with the results confirming its reliability.

The environmental impact method chosen was Ecoindicator 99, recognized as being one of the most used in performing the LCA. Ecoindicator 99 allows the environmental load of a product or process to be expressed as an individual score (Pré consultants, 2018). This method has been used in previous studies with reliable and comparable results (Biswas et al., 2017; Faludi et al., 2012; Kellenberger & Althaus, 2009; Pushkar, 2014; Sianipar & Dowaki, 2014).

The included categories of environmental impact are of global interest and are grouped in the following areas of protection (AoP):

- Ecosystem quality (EQ): acidification-eutrophication, ecotoxicity and land occupation.
- Human health (HH): carcinogenics, climate change, ionizing radiation, ozone layer depletion and respiratory effects.
- Resources (RS): fossil fuels and mineral extraction.

2.2. Life cycle inventory

2.2.1. Production stages (A1-A3)

In the analysis of stages A1-A3, a study was made of all the materials of each street configuration that generated variations in the results. They were then used to conform the travel lane (TL), the pedestrian zone (PZ), the buffer zone (BZ) and the bicycle lane (BL), as well as the materials used in the lower layers (base and sub-base). The materials omitted from this study were those used for the curbs and those related to urban installations and fixtures (common elements in all the options studied, which do not show variations in the comparative analysis). The data for quantifying the materials was obtained from BEDEC and adapted to the characteristics of this study, for stages A1-A3 as well as for stage A5.

The streets are built of the typical inert materials most commonly used in construction. Most are petrous in origin: limestone, clays, sands, gravel, granites, and artificial and natural graded aggregates, among others; the exception is mastic asphalt, which contains the petroleum derivative bitumen. All of them are available as construction materials in Ecoinvent. The necessary quantity of each of these materials was obtained in order to make a linear meter of each option (1x13m), and then a waste coefficient (ITEC, 2017) was applied to them. **Table 2** shows the data used for the analyzed stages (A1-A3, and A4-A5) and the Ecoinvent datasets.

Table 2

LCI for functional unit (one linear meter) of each street zone.

Stage	Material/process	Conventional					Redesign A					Redesign B							Ecoinvent material/process
		TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL + PL Asphalt	TL + PL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	BL Asphalt	BL Concrete	
A1-A3	Water (kg)	89.78	60.38	34.50	-	25.20	70.54	47.44	38.81	-	28.35	38.48	25.88	43.13	-	31.50	18.11	12.08	Tap water, at user
	Coarse aggregates (ton)	3.98	2.05	1.17	-	-	3.13	1.61	1.32	-	-	1.71	0.88	1.47	-	-	0.62	410.55	Gravel, crushed, at mine
	Cement (kg)	129.65	-	-	-	31.50	101.87	-	-	-	35.44	55.57	-	-	-	39.38	-	-	Portland cement, strength class Z 42.5, at plant
	Concrete base (m^3)	-	-	-	0.42	0.42	-	-	-	0.47	0.47	-	-	-	0.53	0.53	-	-	Concrete, normal, at plant
	Fine aggregates (kg)	-	-	-	24.81	205.38	-	-	-	27.91	231.05	-	-	-	31.01	256.73	-	-	Silica sand, at plant
	Asphalt (kg)	540.23	-	220.50	-	-	424.46	-	248.06	-	-	231.53	-	275.63	-	-	115.76	-	Mastic asphalt, at plant
	Concrete/concrete slabs (m^3)	-	1.32	-	0.33	-	-	1.04	-	0.37	-	-	0.57	-	0.41	-	-	0.35	Concrete, exacting, at plant
	Granite slabs (kg)	-	-	-	-	742.56	-	-	-	-	835.38	-	-	-	-	928.20	-	-	Natural stone plate, polished, at regional storage
	Sand (kg) for BZ	-	-	444.00	473.60	444.00	-	-	744.00	793.60	744.00	-	-	714.00	875.60	714.00	-	-	Silica sand, at plant
A4	Operation lorry (tkm)	253.40	181.38	101.87	77.11	87.78	199.10	142.51	129.27	102.39	113.42	108.60	77.73	136.88	113.40	119.26	39.50	41.71	Transport, lorry 16-32t, EURO5
A5	Machinery E10-6 (unit)	20.56	38.80	7.65	0.65	8.82	16.15	30.49	8.61	0.73	9.92	8.81	16.63	9.56	0.82	11.03	4.02	9.54	Building machine
	Energy (kg)	2.38	2.46	0.86	0.01	-	1.87	1.93	0.97	0.01	-	1.02	1.06	1.07	0.01	-	0.45	0.57	Diesel, at regional storage
	Energy (kWh)	-	-	-	-	0.06	-	-	-	-	0.07	-	-	-	-	0.08	-	-	Electricity, low voltage, production ES, at grid / ES

2.2.2. *Construction process stages (A4-A5)*

The transport from the factory to the site stage (A4) studies the impact connected with the operation (O_L in tkm) of the transport vehicle used, by means **Eq. (1)**.

$$O_L = WD \tag{1}$$

Where W is the weight required by the functional unit for each material used in making the street; D is the distance from the factory to the roadworks. The average distance from a minimum of two factories to the final reference point (the theoretical center of Barcelona city, Plaza Cataluña) was evaluated as D. The values of D were obtained using Google Maps as a georeferencing system and were as follows: 60 km for aggregates, 40 km for concrete and granite slabs, 20 km for cement, concrete and asphalt. The lorry chosen for the transport complied with all the specifications of weight and maximum size for short journeys, as established by the Spanish Ministry of Development (Ministerio de Fomento, 2017).

The usage share of the machinery (PU_M, **Eq. (2)**) was evaluated for the construction process stage (A5), as well as the operating energy (E_O in kg of diesel or kWh, as the case may be) of the machinery used in building each option **(Eq. (3)**).

$$PU_M = \left({}^{TU}/_{UL_M}\right) \tag{2}$$

$$E_O = TU \; x \; P_M \tag{3}$$

Where TU is the usage time of each machine; UL_M is the useful life of the machine equal to 10,000 h (Frischknecht et al., 2007); and P_M can be either the fuel or the machine's potency, depending on the situation; the machinery's consumption needs are shown in **Table 3**.

Table 3

Fuel consumption or potency of machinery.

Machine	Fuel consumption (kg/h) or potency (kW)
Tanker truck 10 m^3	8.3
Vibratory roller	10.8
Motor Grader	14.1
Dumper	2.2
Asphalt paver	8.7
Concrete paver	11.4
Vibrating tray	1.2
Concrete mixer	0.7

2.3. Case studies description

Three types of sections (**Fig. 2**) were designed, referring to types of secondary streets for a residential area (GDCI & NACTO, 2016); one conventional (CO) and two redesigned (RA and RB). Each study section can be described as follows: (i) in the reference case CO, priority is given to the TL for motorized vehicular traffic, while the pavements (PZ and BZ) comply with the minimum widths recommended by the Global Designing Cities Initiative (GDCI) and the National Association of City Transportation Officials (NACTO). (ii) In the RA case, emphasis is laid on increasing the widths of PZ and BZ, and the space dedicated to motorized traffic flow is composed of a TL and a parking lane (PL). Finally, (iii) the section of the RB cases is designed to be as respectful as possible to the alternatives to motorized transport. In this last case, unlike the others, only one TL is included; and so the areas dedicated to PZ, including the BL in both directions, are increased.

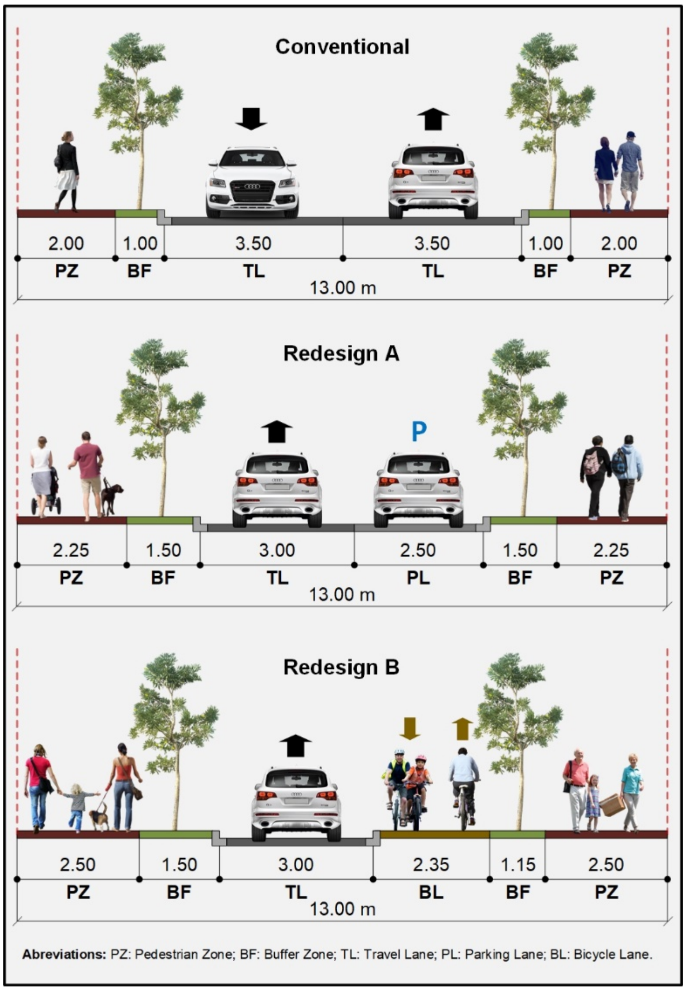

Fig. 2. Street sections (CO, RA y RB).

By means of alterations in their constituent materials, the three sections to be studied were also evaluated to determine the environmental effects they might provoke. The materials used were of the type commonly used as street components in European urban environments: two for TL (asphalt and concrete); three for PZ (asphalt, concrete slabs and granite slabs); two for (asphalt and concrete) and finally, one for BZ (silica sand). **Fig. 3** details the design composition of each material variation used, all satisfying the established requirements for their application (Alabern i Valentí & Guilemany i Casadamon, 1999; MAC, 2018).

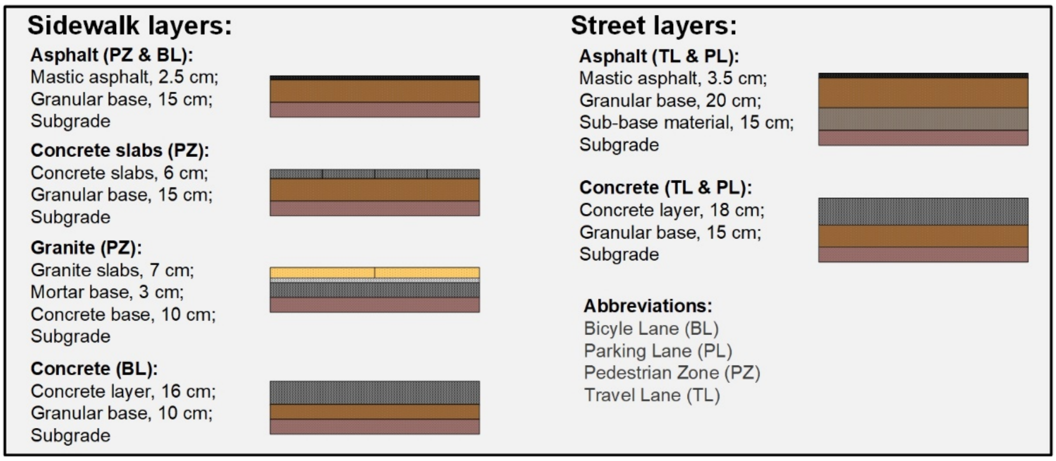

Fig. 3. Detail of surfaces for TL, PZ and BL.

The combination of the three types of section and the different materials produces 18 different case studies (**Table 4**).

Table 4

Case studies description.

Typology	Case	Zone - Total Width (m) – Material	Most common material in: MF^{A} zones – GM^{B} zones
Conventional	1	TL-7.00-Asphalt; PZ-4.00-Asphalt; BZ-2.00-Sand	Asphalt - Asphalt
	2	TL-7.00-Asphalt; PZ-4.00-Concrete; BZ-2.00-Sand	Asphalt - Concrete
	3	TL-7.00-Asphalt; PZ-4.00-Granite; BZ-2.00-Sand	Asphalt - Granite
	4	TL-7.00-Concrete; PZ-4.00-Asphalt; BZ-2.00-Sand	Concrete - Asphalt
	5	TL-7.00-Concrete; PZ-4.00-Concrete; BZ-2.00-Sand	Concrete - Concrete
	6	TL-7.00-Concrete; PZ-4.00-Granite; BZ-2.00-Sand	Concrete - Granite
Redesign A	7	TL & PL-5.50-Asphalt; PZ-4.50-Asphalt; BZ-3.00-Sand	Asphalt - Asphalt
	8	TL & PL-5.50-Asphalt; PZ-4.50-Concrete; BZ-3.00-Sand	Asphalt - Concrete
	9	TL & PL-5.50-Asphalt; PZ-4.50-Granite; BZ-3.00-Sand	Asphalt - Granite
	10	TL & PL-5.50-Concrete; PZ-4.50-Asphalt; BZ-3.00-Sand	Concrete - Asphalt
	11	TL & PL-5.50-Concrete; PZ-4.50-Concrete; BZ-3.00-Sand	Concrete - Concrete
	12	TL & PL-5.50-Concrete; PZ-4.50-Granite; BZ-3.00-Sand	Concrete - Granite
Redesign B	13	TL-3.00-Asphalt; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Asphalt
	14	TL-3.00-Asphalt; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Asphalt - Concrete
	15	TL-3.00-Asphalt; PZ-5.00-Granite; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Granite
	16	TL-3.00-Concrete; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Concrete - Asphalt
	17	TL-3.00-Concrete; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Concrete - Concrete
	18	TL-3.00-Concrete; PZ-5.00-Granite; BL-2.35-Concrete; BZ-2.65-Sand	Concrete - Granite

^{A}Motorized flow; TL & PL ^{B}Green mobility; PZ & BL.

The information in table 4 is organized into six comparative groups (**Table 5**) taking into account the similarity of the materials used for each section. This was done with the aim of comparing the environmental consequences of increasing the percentage aimed at the human scale in a specific residential street, without the differences in materials being a factor of variability.

Table 5

Comparatives showing similar ratios of materials.

Comparative	Most common material in: MF[A] zones – GM[B] zones	Case – Section typology
C-1	Asphalt – Asphalt	1-CO ; 7-RA ; 13-RB
C-2	Asphalt - Concrete	2-CO ; 8-RA ; 14-RB
C-3	Concrete - Concrete	5-CO ; 11-RA ; 17-RB
C-4	Concrete - Asphalt	4-CO ; 10-RA ; 16-RB
C-5	Asphalt - Granite	3-CO ; 9-RA ; 15-RB
C-6	Concrete - Granite	6-CO ; 12-RA ; 18-RB

[A]Motorized flow; TL & PL [B]Green mobility; PZ & BL.

3. Results and discussion

In this study it was found that prioritizing the human scale leads to a reduction in the environmental impact, as long as conventional materials such as concrete and asphalt are used in configuring residential streets. In the graphs of the comparative groups C1-C4 (**Fig. 4**), it can be seen that an 11.54% increase in the areas destined for human scale (RA cases) may generate reductions of between 6.94% (C-4) and 11.09% (C-2). Meanwhile, an increase of 30.77% (including 18% of the space destined for BL) may generate reductions of between 9.49% (C-4) and 22.27% (C-2) in the total environmental impact (RB cases).

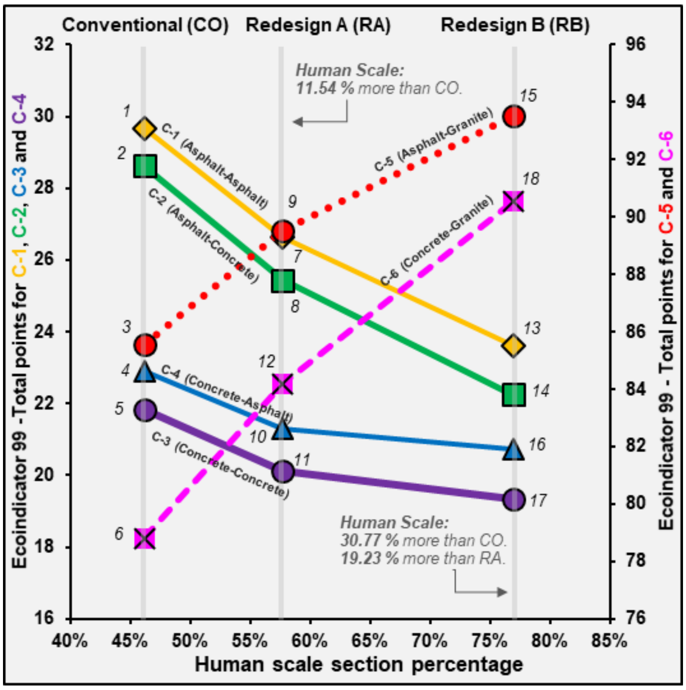

Fig. 4. Comparisons between cases showing similar ratios of materials.

Fig. 4 also shows that, unlike the results of the C1-C4 groups, the use of granite increases the environmental impact even when the human scale is favored. For instance, if the RA sections are used, the environmental impact is increased by 4.61% in C-5 and 6.85% in C-6; in the case of the RB sections the increases are 9.26% in C-5 and 14.90% in C-6, all in respect of the CO sections. This shows that the use of granite (as well as its production) generates important environmental issues and therefore, as there are alternative materials with equivalent functional and service capacities, the use of granite should be limited in configuring residential streets.

A comparison is made in **Fig. 5** between cases 11 of the RA and 17 of the RB, the cases with the best general environmental performance, and the six design cases CO (1-6). From this comparison it can be deduced that they establish a reductive environmental impact, which (i) ranges from 7.88% (case 5) to 76.50% (case 3) with regard to case 11; and (ii) from 11.44% (case 5) to 77.40% (case 3) with regard to case 17. Additionally, comparing the RA and RB, the section that incentivizes greater non-motorized traffic flows (case 17; including BL) shows the best environmental behavior, reducing impacts by 3.86%. This is congruent with Gehl's research (Gehl, 2010): "The desire for a healthy city is strengthened dramatically if walking or biking can be a natural part of the patterns of daily activities".

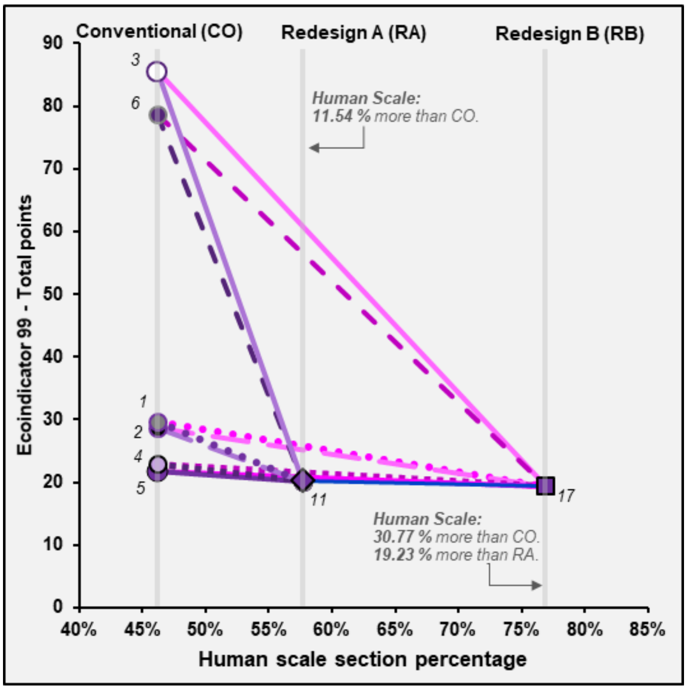

Fig. 5. Comparison of the CO cases (1-6) with those that produce less environmental impact in RA (11) and RB (17).

Similarly, the results of the case studies show the influence that the definition of the materials used in making the streets has; the use of granite in PZ (average of C5-C6) produces noticeable variations regarding the behavior of the cases in which it is not used (average of C1-C4), increasing the total impact by 270% (**Fig. 6**). Previous studies have also shown that granite generates higher environmental loads in comparison to other materials used in urban infrastructure (Mendoza, Oliver-Solà, Gabarrel, Josa & Rieradevall, 2012; Mendoza, Oliver-Solà, Gabarrel, Rieradevall & Josa, 2012).

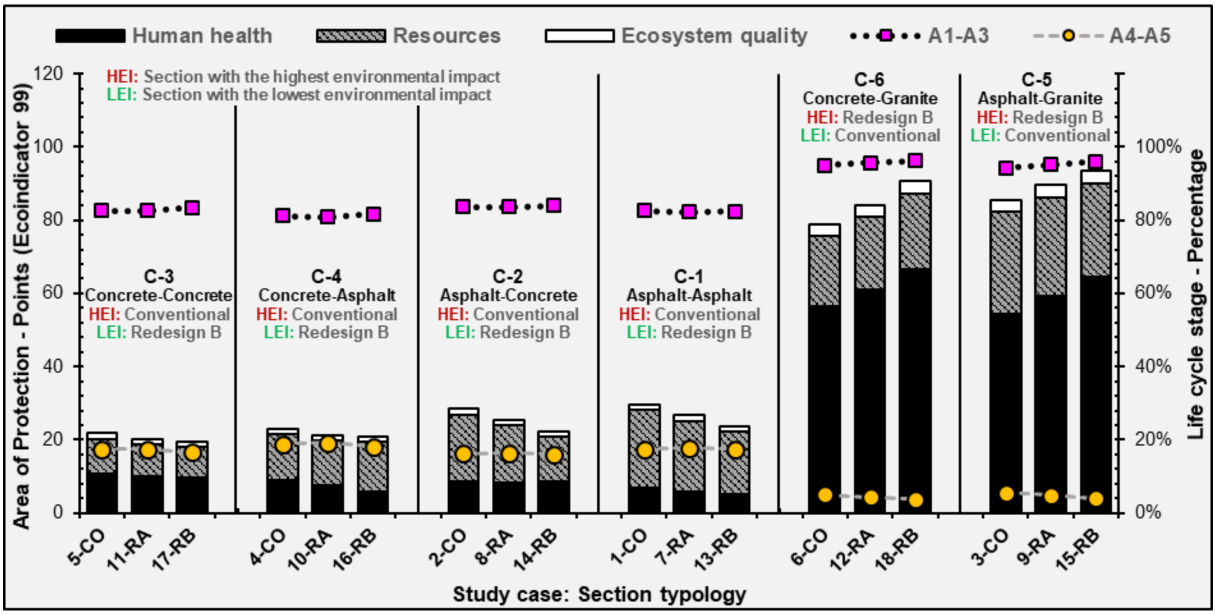

Fig. 6. Comparisons of the cases showing similar ratios of materials used.

Additionally, when comparing the cases that only used asphalt and concrete as materials in all sections of the street (**Fig. 6** and **Table 6**), it was seen that they affected each of the AoP differently except for EQ, where the variation is reduced (2%) in comparison with RS and HH. Concrete generates 73% more impact on HH, with its most important categories being the impact on climate change and its respiratory and carcinogenic side effects, which respectively produce 113%, 51% and 70% more impact than asphalt. Asphalt has a greater impact on the RS, generating 121% more fossil fuel consumption. Some authors agree with the previously established data, for example (Mendoza, Oliver-Solà, Gabarrel, Rieradevall & Josa, 2012) discovered that the primary energy demand of asphalt is higher than that of concrete, but its contribution to global warming is lower.

Table 6

Values of Ecoindicator 99 for the most important impact categories for concrete and asphalt.

Impact Category	C-1 (Concrete)	C-3 (Asphalt)
Carcinogenic	1.06	0.59
Climate change	3.60	1.69
Respiratory effects	5.43	3.60
Fossil fuels	8.68	19.16
Total	20.43	26.65

In the street sections where asphalt was used, the most affected AoP is RS (>70%), whereas for concrete and granite it is HH (≈50%, ≈70%, respectively; **Fig. 6**). These environmental implications occur in more than 80% of the A1-A3 stages (greater environmental implication); therefore, their influence will define and establish the complete environmental profile of each street, as has also been shown in previous studies (Cass & Mukherjee, 2011).

In this study (**Table 7**), A1-A3 represents ≈85% for the cases C1-C4 and ≈96% for the cases of C5-C6, followed by A4 with ≈15% for C1-C4 and ≈4% for C5-C6; finally, there is A5, with less than 3% in all the cases. Although each study is limited by its own conditions, it is important for similar research to consider the "cradle to handover" approach; despite the discrepancies that may arise due to these conditions, the extent of the A4-A5 stages' environmental impact should not be underestimated, as other studies have also concluded (Kellenberger & Althaus, 2009).

Table 7

Values of Ecoindicator 99 for the AoP of the life cycle stages.

	Asphalt (C-1)			Concrete & Asphalt (C2&C4)			Concrete (C-3)			Granite (C5&C6)		
Area of protection	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5
Ecosystem quality	1.14	0.30	0.02	1.17	0.26	0.02	1.19	0.22	0.02	3.01	0.26	0.02
Human health	4.64	1.20	0.08	6.90	1.05	0.07	9.16	0.90	0.07	59.22	1.05	0.07
Resources	1.17	2.58	0.51	11.37	2.26	0.44	6.57	1.93	0.37	20.79	2.25	0.36
Stage representativeness (%)	84%	16%	2%	85%	15%	2%	85%	15%	2%	96%	4%	1%

By emphasizing the weight of each of the categories evaluated by the Ecoindicator 99 (**Fig. 7**), it was found that the greatest impact of the materials used was on the exhaustion of fossil fuel supplies, respiratory disorders and climate change. Regarding asphalt, more than 72% of the impact is due to fossil fuel consumption (RS), 13.53% to respiratory side effects and 6.33% to climate change. As it is a petrol derivative, it is considered a non-renewable source. Previous research (Araújo et al., 2014) indicates that the most obvious impact of paving materials is their consumption of natural resources.

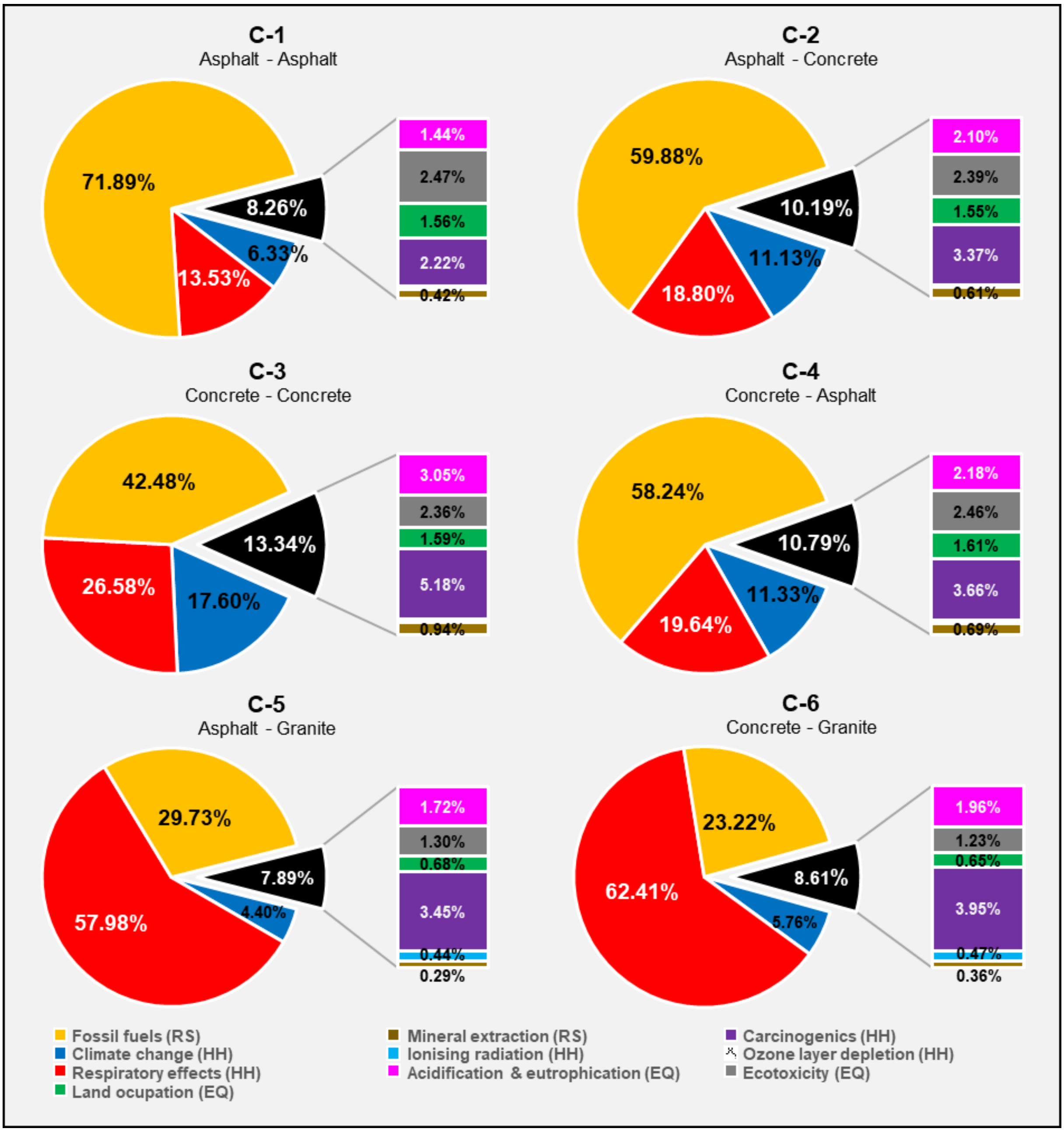

Fig. 7. Percentage corresponding to each impact category, according to the average results of each comparison.

In **Fig. 7**, it can also be seen that 42.48% of concrete's environmental impact corresponds to the exhaustion of fossil fuels, 26.58% to respiratory side effects, 17.60% to climate change and 5.18% to carcinogenic effects. The use of fossil fuels is linked to the high temperatures needed in cement production. The emission of particles and volatile elements, such as mercury, is also an inherent part of this industry (Bustillo-Revuelta, 2008) (impact on HH). Previous research has shown that concrete is an important contributor to climate change (Venkatarama

Reddy & Jagadish, 2003), due mainly to the GHGs generated by the chemical reactions in clinker production (Damtoft et al., 2008).

Finally, the impact categories most affected by the use of granite (whether combined with asphalt or concrete) are respiratory effects, with almost 60%, climate change with 5%, carcinogenic effects with 3.7% (HH) and fossil fuel consumption (RS) with 26% (**Fig. 7**). Previous studies have attributed the environmental load of human toxicity to the stainless steel used in saw blades, due to their chromium content. Similarly, it has been found that the granite related processes emit significant quantities of GHGs (even more than concrete and asphalt) (Mendoza, Oliver-Solà, Gabarrel, Josa & Rieradevall, 2012).

4. Conclusions

The main findings of this research are as follows. (i) Giving priority to the human scale and promoting non-motorized traffic flow when configuring a residential street can lead to a reduction in the environmental impact generated by the production and construction stages. (ii) It confirms that omitting a detailed analysis of the environmental consequences of material selection for a specific section of street may occasion significant environmental effects. (iii) Applying the LCA in the design phase can lead to a reduction in the environmental effects generated in the production and construction stages of a residential street.

Knowing the impact generated in the production and construction stages of a residential street designed on a human scale, compared with a street that prioritizes motorized traffic (as well as the impact generated by varying the building materials in each zone), It will reinforce the priority (widely demonstrated in the usage stage) by developing a residential street design oriented towards achieving a pedestrian environment. Likewise, the consequences of choosing specific materials are also shown. Obtaining this will be a further step towards developing more sustainable cities.

Despite the previous guidelines, the use of materials such as granite generates increases in environmental impact of up to 14.9% for a linear meter of PZ, even when an environment favoring the human scale is prioritized. However, using conventional materials such as concrete and asphalt can generate reductions from 11% (increasing to 11.5% PZ+BF) to 22.27% (increasing to 31% PZ+BZ+BL). If the three analyzed materials are compared, granite generates 270% more environmental damage than concrete and asphalt. The last two, although they have similar general consequences, occasionally show different effects in each of the impact categories studied. For instance, asphalt consumes 121% more fossil fuels than concrete, which for its part causes 73% more harm to human health (producing 113%, 51% and 79% more climate change, respiratory and carcinogenic effects than asphalt).

Finally, it is essential to carry out more analysis such as this, which will include different typologies as well as a wider study of alternative materials (among which, those reincorporated in the life cycle); this will lead to LCA becoming an integral feature of the construction industry with regard to the process of urban planning.

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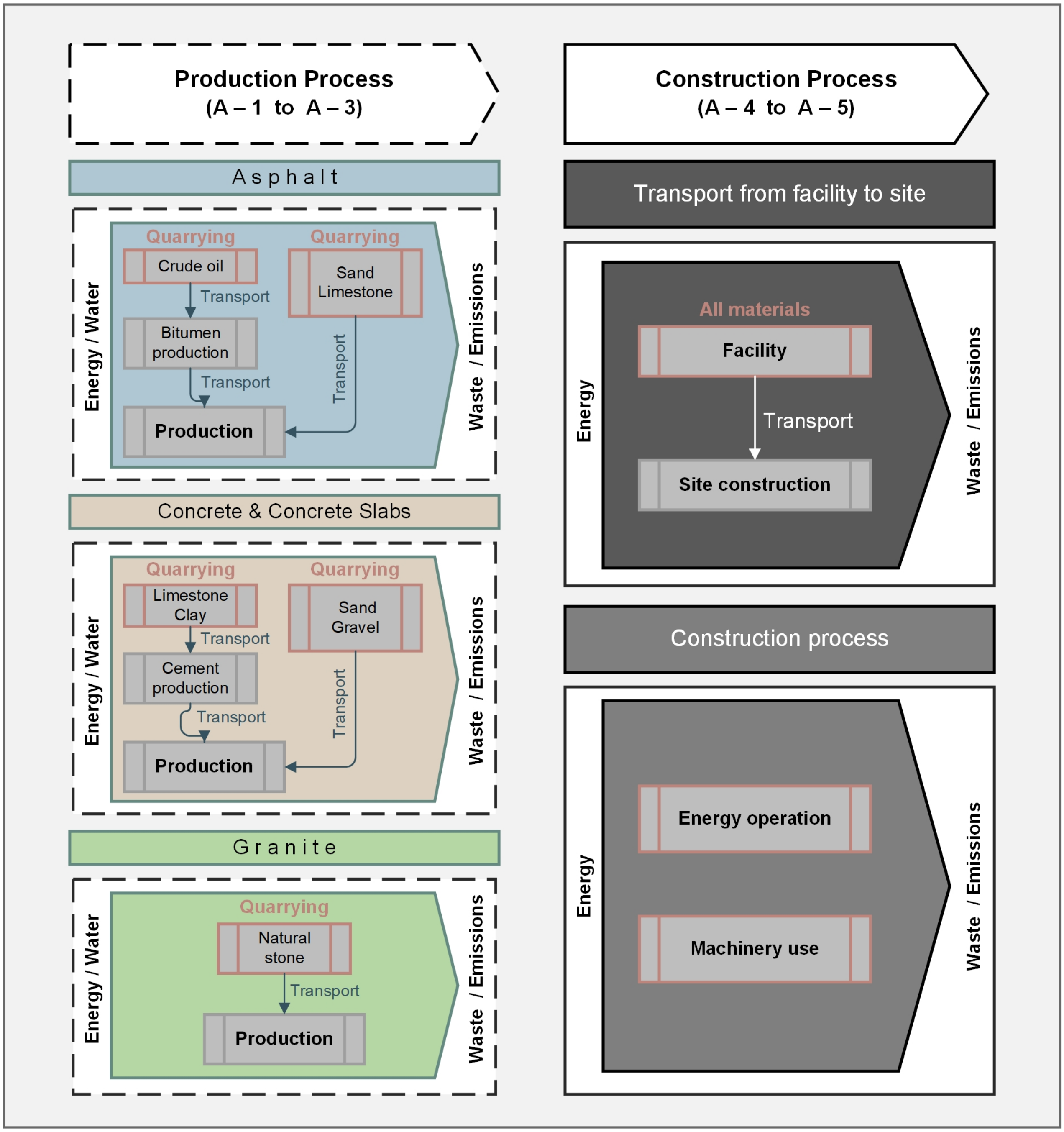

Production Process
(A – 1 to A – 3)
Construction Process
(A – 4 to A – 5)
Asphalt
Quarrying
Crude oil
Transport
Bitumen production
Transport
Production
Quarrying
Sand Limestone
Transport
Energy / Water
Waste / Emissions
Concrete & Concrete Slabs
Quarrying
Limestone Clay
Transport
Cement production
Transport
Production
Quarrying
Sand Gravel
Transport
Energy / Water
Waste / Emissions
Granite
Quarrying
Natural stone
Transport
Production
Energy / Water
Waste / Emissions
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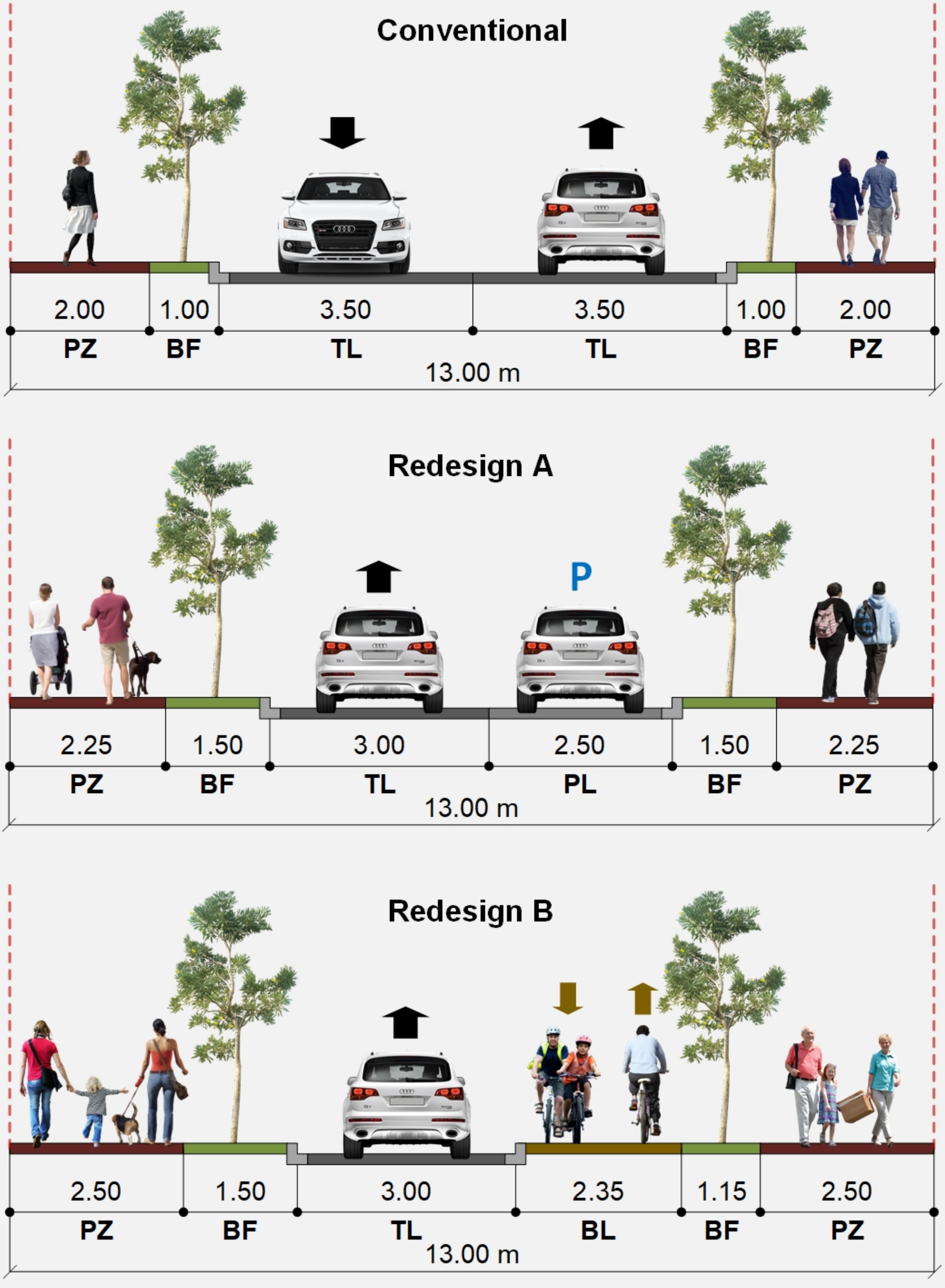
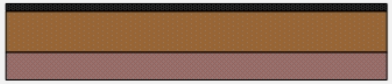
All materials
Facility
Transport
Site construction
Energy
Waste / Emissions
Construction process
Energy operation
Machinery use
Energy
Waste / Emissions



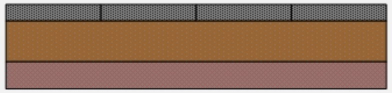
Abreviations: PZ: Pedestrian Zone; BF: Buffer Zone; TL: Travel Lane; PL: Parking Lane; BL: Bicycle Lane.

Sidewalk layers:

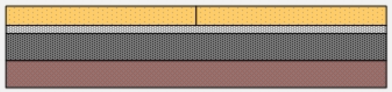
Asphalt (PZ & BL):
Mastic asphalt, 2.5 cm;
Granular base, 15 cm;
Subgrade



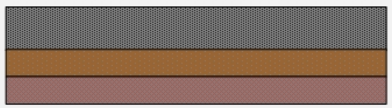
Concrete slabs (PZ):
Concrete slabs, 6 cm;
Granular base, 15 cm;
Subgrade



Granite (PZ):
Granite slabs, 7 cm;
Mortar base, 3 cm;
Concrete base, 10 cm;
Subgrade

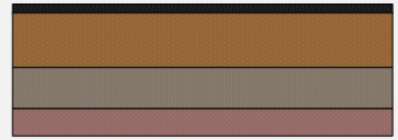


Concrete (BL):
Concrete layer, 16 cm;
Granular base, 10 cm;
Subgrade

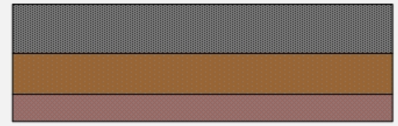


Street layers:

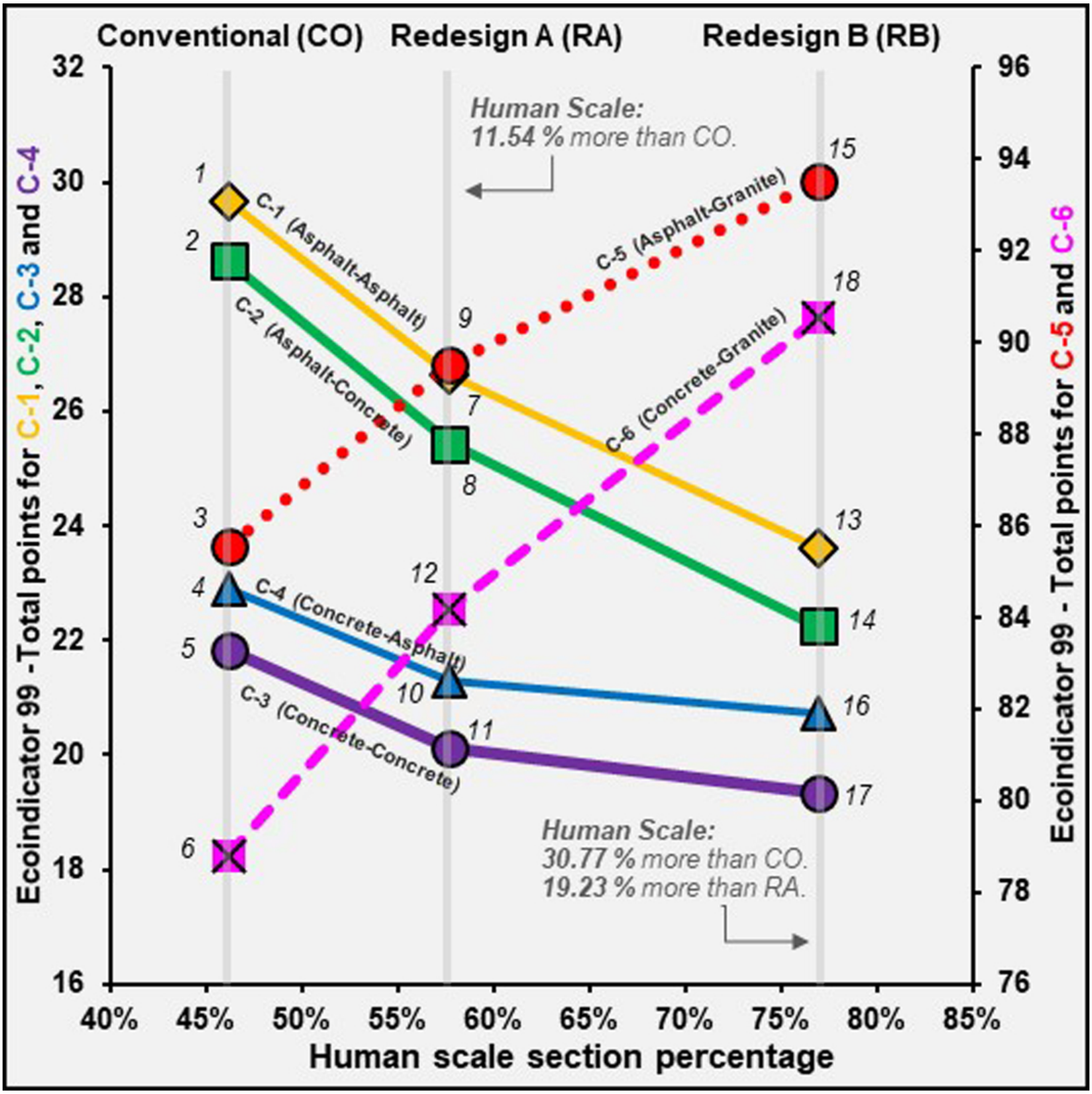
Asphalt (TL & PL):
Mastic asphalt, 3.5 cm;
Granular base, 20 cm;
Sub-base material, 15 cm;
Subgrade



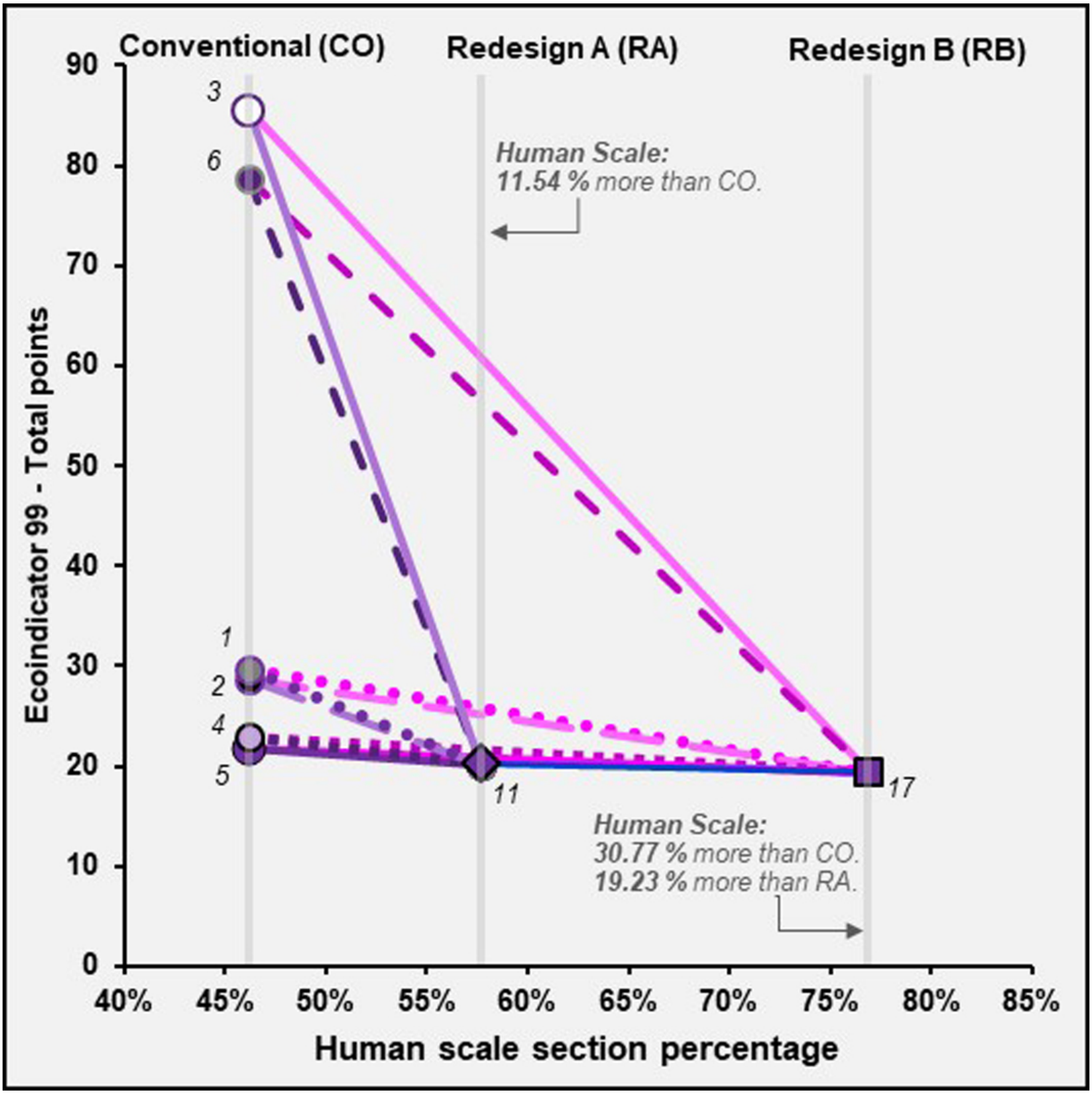
Concrete (TL & PL):
Concrete layer, 18 cm;
Granular base, 15 cm;
Subgrade



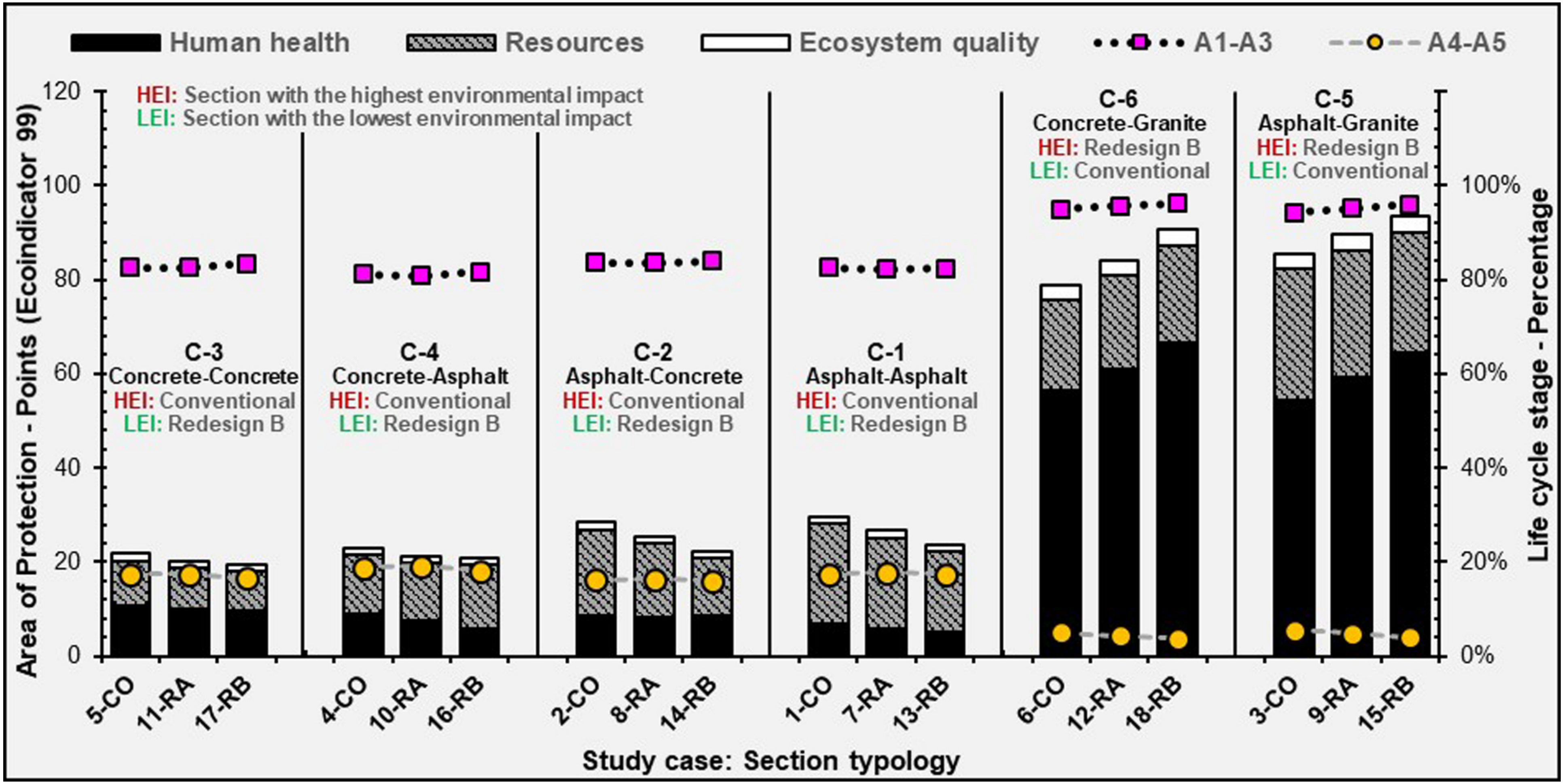
Abbreviations:
Bicyle Lane (BL)
Parking Lane (PL)
Pedestrian Zone (PZ)
Travel Lane (TL)



Conventional (CO)
Redesign A (RA)
Redesign B (RB)
Human Scale:
11.54 % more than CO.
Human Scale:
30.77 % more than CO.
19.23 % more than RA.
C-1 (Asphalt-Asphalt)
C-2 (Asphalt-Concrete)
C-3 (Concrete-Concrete)
C-4 (Concrete-Asphalt)
C-5 (Asphalt-Granite)
C-6 (Concrete-Granite)
Ecoindicator 99 -Total points for C-1, C-2, C-3 and C-4
Ecoindicator 99 - Total points for C-5 and C-6
Human scale section percentage



Conventional (CO)
Redesign A (RA)
Redesign B (RB)
Ecoindicator 99 - Total points
Human scale section percentage
Human Scale:
11.54 % more than CO.
Human Scale:
30.77 % more than CO.
19.23 % more than RA.
3
6
1
2
4
5
11
17
0
10
20
30
40
50
60
70
80
90
40%
45%
50%
55%
60%
65%
70%
75%
80%
85%



Human health
Resources
Ecosystem quality
A1-A3
A4-A5
HEI: Section with the highest environmental impact
LEI: Section with the lowest environmental impact
Area of Protection - Points (Ecoindicator 99)
Life cycle stage - Percentage
120
100
80
60
40
20
0
100%
80%
60%
40%
20%
0%
C-3
Concrete-Concrete
HEI: Conventional
LEI: Redesign B
C-4
Concrete-Asphalt
HEI: Conventional
LEI: Redesign B
C-2
Asphalt-Concrete
HEI: Conventional
LEI: Redesign B
C-1
Asphalt-Asphalt
HEI: Conventional
LEI: Redesign B
C-6
Concrete-Granite
HEI: Redesign B
LEI: Conventional
C-5
Asphalt-Granite
HEI: Redesign B
LEI: Conventional
5-CO
11-RA
17-RB
4-CO
10-RA
16-RB
2-CO
8-RA
14-RB
1-CO
7-RA
13-RB
6-CO
12-RA
18-RB
3-CO
9-RA
15-RB
Study case: Section typology

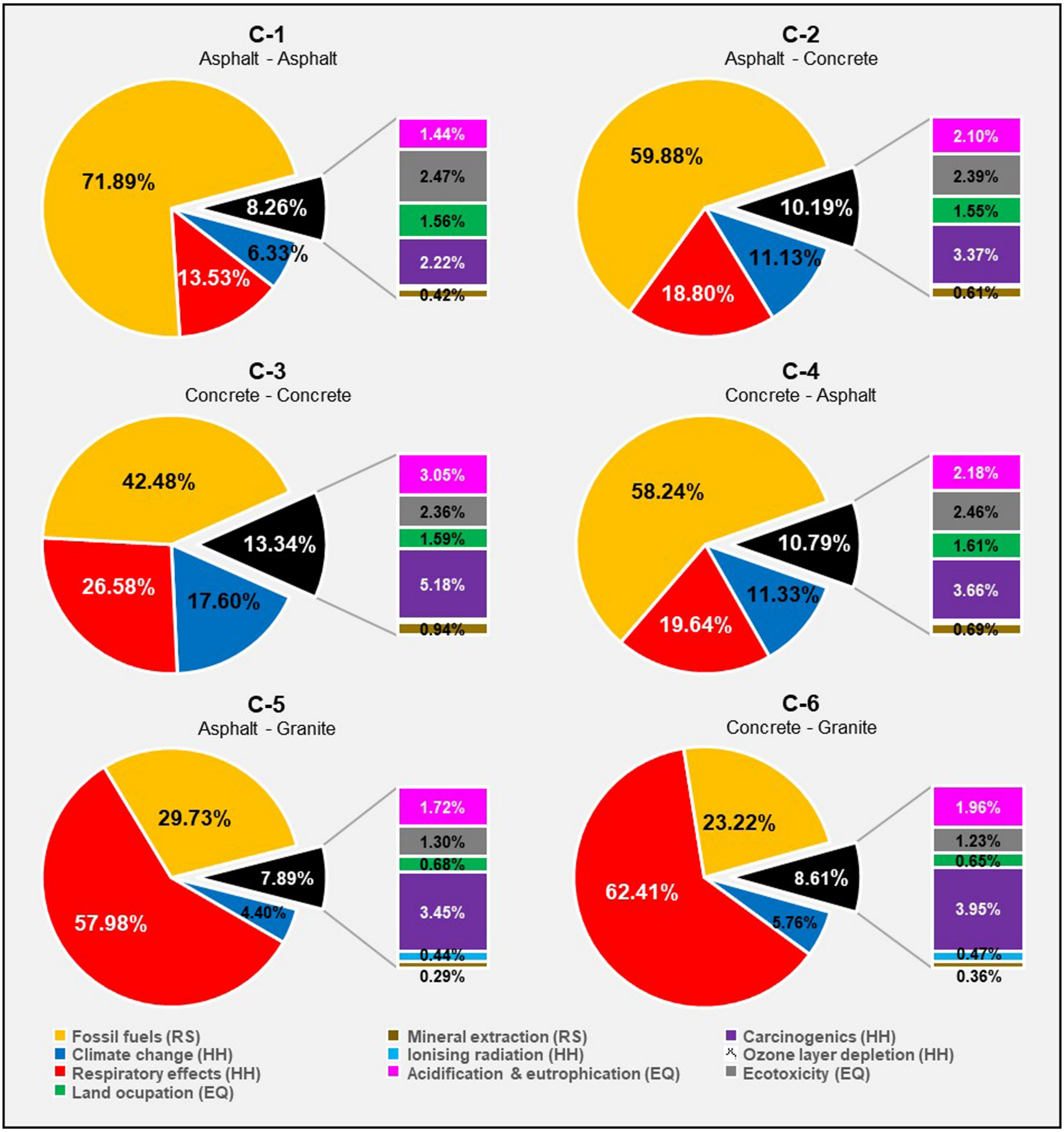

C-1
Asphalt - Asphalt
71.89%
8.26%
6.33%
13.53%
1.44%
2.47%
1.56%
2.22%
0.42%
C-2
Asphalt - Concrete
59.88%
10.19%
11.13%
18.80%
2.10%
2.39%
1.55%
3.37%
0.61%
C-3
Concrete - Concrete
42.48%
13.34%
26.58%
17.60%
3.05%
2.36%
1.59%
5.18%
0.94%
C-4
Concrete - Asphalt
58.24%
10.79%
11.33%
19.64%
2.18%
2.46%
1.61%
3.66%
0.69%
C-5
Asphalt - Granite
29.73%
7.89%
57.98%
4.40%
1.72%
1.30%
0.68%
3.45%
0.44%
0.29%
C-6
Concrete - Granite
23.22%
8.61%
62.41%
5.76%
1.96%
1.23%
0.65%
3.95%
0.47%
0.36%
Fossil fuels (RS)
Climate change (HH)
Respiratory effects (HH)
Land ocupation (EQ)
Mineral extraction (RS)
Ionising radiation (HH)
Acidification & eutrophication (EQ)
Carcinogenics (HH)
Ozone layer depletion (HH)
Ecotoxicity (EQ)

Table 1

LCA studies that consider the stages directly related to the construction process.

Stage	Authors	Highlights
Cradle to gate (A1-A3)	(Cass & Mukherjee, 2011)	Development of a method that quantifies pavement life cycle emissions.
	(Moretti et al., 2018)	Analysis of environmental impacts of two types of road cross-sections.
	(Sandanayake et al., 2018)	Comparison of greenhouse gas (GHG) emissions and energy consumption in wood and concrete buildings.
Cradle to site (A1-A3+A4)	(Gardezi et al., 2016)	Development of an embodied carbon prediction tool for conventional housing.
Cradle to handover (A1-A3+A4-A5)	(Smith & Durham, 2016)	Environmental evaluation of pavements considering economic, environmental and mechanical performance criteria.
	(Mohajerani et al., 2018)	Evaluation of the impacts generated by the incorporation of biosolids in conventional materials.

Table 2

LCI for functional unit (one linear meter) of each street zone.

Stage	Material/process	Conventional					Redesign A					Redesign B							Ecoinvent material/process
		TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL + PL Asphalt	TL + PL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	BL Asphalt	BL Concrete	
A1-A3	Water (kg)	89.78	60.38	34.50	-	25.20	70.54	47.44	38.81	-	28.35	38.48	25.88	43.13	-	31.50	18.11	12.08	Tap water, at user
	Coarse aggregates (ton)	3.98	2.05	1.17	-	-	3.13	1.61	1.32	-	-	1.71	0.88	1.47	-	-	0.62	410.55	Gravel, crushed, at mine
	Cement (kg)	129.65	-	-	-	31.50	101.87	-	-	-	35.44	55.57	-	-	-	39.38	-	-	Portland cement, strength class Z 42.5, at plant
	Concrete base (m^3)	-	-	-	0.42	0.42	-	-	-	0.47	0.47	-	-	-	0.53	0.53	-	-	Concrete, normal, at plant
	Fine aggregates (kg)	-	-	-	24.81	205.38	-	-	-	27.91	231.05	-	-	-	31.01	256.73	-	-	Silica sand, at plant
	Asphalt (kg)	540.23	-	220.50	-	-	424.46	-	248.06	-	-	231.53	-	275.63	-	-	115.76	-	Mastic asphalt, at plant
	Concrete/concrete slabs (m^3)	-	1.32	-	0.33	-	-	1.04	-	0.37	-	-	0.57	-	0.41	-	-	0.35	Concrete, exacting, at plant
	Granite slabs (kg)	-	-	-	-	742.56	-	-	-	-	835.38	-	-	-	-	928.20	-	-	Natural stone plate, polished, at regional storage
	Sand (kg) for BZ	-	-	444.00	473.60	444.00	-	-	744.00	793.60	744.00	-	-	714.00	875.60	714.00	-	-	Silica sand, at plant
A4	Operation lorry (tkm)	253.40	181.38	101.87	77.11	87.78	199.10	142.51	129.27	102.39	113.42	108.60	77.73	136.88	113.40	119.26	39.50	41.71	Transport, lorry 16-32t, EURO5
A5	Machinery E10-6 (unit)	20.56	38.80	7.65	0.65	8.82	16.15	30.49	8.61	0.73	9.92	8.81	16.63	9.56	0.82	11.03	4.02	9.54	Building machine
	Energy (kg)	2.38	2.46	0.86	0.01	-	1.87	1.93	0.97	0.01	-	1.02	1.06	1.07	0.01	-	0.45	0.57	Diesel, at regional storage
	Energy (kWh)	-	-	-	-	0.06	-	-	-	-	0.07	-	-	-	-	0.08	-	-	Electricity, low voltage, production ES, at grid / ES

Table 3

Fuel consumption or potency of machinery.

Machine	Fuel consumption (kg/h) or potency (kW)
Tanker truck 10 m^3	8.3
Vibratory roller	10.8
Motor Grader	14.1
Dumper	2.2
Asphalt paver	8.7
Concrete paver	11.4
Vibrating tray	1.2
Concrete mixer	0.7

Table 4

Case studies description.

Typology	Case	Zone - Total Width (m) – Material	Most common material in: MF^A zones – GM^B zones
Conventional	1	TL-7.00-Asphalt; PZ-4.00-Asphalt; BZ-2.00-Sand	Asphalt - Asphalt
	2	TL-7.00-Asphalt; PZ-4.00-Concrete; BZ-2.00-Sand	Asphalt - Concrete
	3	TL-7.00-Asphalt; PZ-4.00-Granite; BZ-2.00-Sand	Asphalt - Granite
	4	TL-7.00-Concrete; PZ-4.00-Asphalt; BZ-2.00-Sand	Concrete - Asphalt
	5	TL-7.00-Concrete; PZ-4.00-Concrete; BZ-2.00-Sand	Concrete - Concrete
	6	TL-7.00-Concrete; PZ-4.00-Granite; BZ-2.00-Sand	Concrete - Granite
Redesign A	7	TL & PL-5.50-Asphalt; PZ-4.50-Asphalt; BZ-3.00-Sand	Asphalt - Asphalt
	8	TL & PL-5.50-Asphalt; PZ-4.50-Concrete; BZ-3.00-Sand	Asphalt - Concrete
	9	TL & PL-5.50-Asphalt; PZ-4.50-Granite; BZ-3.00-Sand	Asphalt - Granite
	10	TL & PL-5.50-Concrete; PZ-4.50-Asphalt; BZ-3.00-Sand	Concrete - Asphalt
	11	TL & PL-5.50-Concrete; PZ-4.50-Concrete; BZ-3.00-Sand	Concrete - Concrete
	12	TL & PL-5.50-Concrete; PZ-4.50-Granite; BZ-3.00-Sand	Concrete - Granite
Redesign B	13	TL-3.00-Asphalt; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Asphalt
	14	TL-3.00-Asphalt; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Asphalt - Concrete
	15	TL-3.00-Asphalt; PZ-5.00-Granite; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Granite
	16	TL-3.00-Concrete; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Concrete - Asphalt
	17	TL-3.00-Concrete; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Concrete - Concrete
	18	TL-3.00-Concrete; PZ-5.00-Granite; BL-2.35-Concrete; BZ-2.65-Sand	Concrete - Granite

[A]Motorized flow; TL & PL [B]Green mobility; PZ & BL.

Table 5

Comparatives showing similar ratios of materials.

Comparative	Most common material in: MF[A] zones – GM[B] zones	Case – Section typology
C-1	Asphalt – Asphalt	1-CO ; 7-RA ; 13-RB
C-2	Asphalt - Concrete	2-CO ; 8-RA ; 14-RB
C-3	Concrete - Concrete	5-CO ; 11-RA ; 17-RB
C-4	Concrete - Asphalt	4-CO ; 10-RA ; 16-RB
C-5	Asphalt - Granite	3-CO ; 9-RA ; 15-RB
C-6	Concrete - Granite	6-CO ; 12-RA ; 18-RB

[A]Motorized flow; TL & PL [B]Green mobility; PZ & BL.

Table 6

Values of Ecoindicator 99 for the most important impact categories for concrete and asphalt.

Impact Category	C-1 (Concrete)	C-3 (Asphalt)
Carcinogenic	1.06	0.59
Climate change	3.60	1.69
Respiratory effects	5.43	3.60
Fossil fuels	8.68	19.16
Total	20.43	26.65

Table 7

Values of Ecoindicator 99 for the AoP of the life cycle stages.

	Asphalt (C-1)			Concrete & Asphalt (C2&C4)			Concrete (C-3)			Granite (C5&C6)		
Area of protection	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5
Ecosystem quality	1.14	0.30	0.02	1.17	0.26	0.02	1.19	0.22	0.02	3.01	0.26	0.02
Human health	4.64	1.20	0.08	6.90	1.05	0.07	9.16	0.90	0.07	59.22	1.05	0.07
Resources	1.17	2.58	0.51	11.37	2.26	0.44	6.57	1.93	0.37	20.79	2.25	0.36
Stage representativeness (%)	84%	16%	2%	85%	15%	2%	85%	15%	2%	96%	4%	1%