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What are the environmental impacts of aggregate consumption? Comprehensive Life Cycle Assessment models

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ABSTRACT

Despite the massive and ever-growing consumption of aggregates, knowledge about their environmental footprint is limited. Indeed, my literature review on aggregate Life Cycle Assessments (LCA) highlighted several shortcomings, such as weak technological, temporal, and geographical representativeness, data of low- or unknown quality, and varied system boundaries. I thus developed comprehensive models, based on field data collected in Quebec's quarries that produced almost 7 million tons of aggregates in 2020. Results show that blasting and machinery are major contributors to several categories of environmental impact, along with diesel consumption. The link between environmental impacts and the nature of the extracted rock is demonstrated for the first time: the harder it is, the more explosive it requires, which increases the impacts. Moreover, the more abrasive the rock is, the faster it wears crushers, calling for higher maintenance that increases human and ecosystem toxicities. A pronounced sensitivity of the impacts to the electricity mix is also shown based on a scenario analysis carried on Europe, China, and different Canadian and American regions. Additionally, aggregate transportation to the consumer can more than double the impact of the aggregate at quarry's gate, with strong regional variability. In a near future, I call for considering consistent system boundaries in LCA databases, including and/or refining blasting, energy consumption, machinery manufacturing and maintenance models, as well as customizing truck transportation models, for more accurate aggregate LCAs.

Keywords: aggregates; LCA; carbon footprint; environmental impacts; variability; sensitivity parameters;

1. Introduction

1.1 Context

Despite aggregates being the most consumed material worldwide, with an ever-growing demand (Bendixen et al., 2021; Miatto et al., 2017), knowledge about their environmental footprint is currently limited and uncertain, calling for comprehensive Life Cycle Assessment (LCA) models based on recent field data. Indeed, Miatto et al. estimated that each human being consumed almost 5 tons of non-metallic resources on average in 2010, accounting for a total of 34 billion metric tons (Gt) extracted over a year (2017). This massive production is responsible for serious environmental impacts addressed in several studies, but some studies lack quantitative information. These studies describe that near-site qualitative impacts mainly include landscape deterioration, noise, dust, potential sedimentation, and pollution of water bodies. They also include land use and land use change (LULUC) (Langer and Arbogast, 2002) and their potential environmental consequences such as loss of habitats and ecosystem erosion, greenhouse gas (GHG) releases, and deterioration of air quality (Foley et al., 2005). But some environmental impacts appear at larger scales and/or over the entire life cycle of the aggregate. Namely, some impacts occur from the quarry preparation (i.e. removal of the top soil layer), the end-of-life (EoL) of the aggregates, and various stages including extraction, transportation, crushing, and sieving. For instance, during these activities, the use of vehicles, building machines, and other production equipment such as the crushing unit, consume energy whose supply chains are complex, emitting GHGs (Ghanbari et al., 2018) and other pollutants in several areas worldwide.

To quantify the different kinds of environmental impacts of aggregate production and consumption at local and global scales, over their entire life cycle, and including the supply

chain of all the consumptions related to this production, the most adequate method is LCA. Some aggregate LCAs have already been conducted based on real production sites or site archetypes. Gravel and sand are the most important kinds of non-mineral resources extracted in the world, respectively representing 41 and 31% of the global production (Miatto et al., 2017). I thus propose to examine further LCAs published on virgin gravels - that I will call indifferently crushed stones or aggregates in the rest of this article – to understand the state of knowledge and its shortcomings.

1.2 Literature review on aggregate LCAs

In an LCA, the Life cycle inventory (LCI) is the list and quantities of input and output flows needed to deliver the functional unit, i.e. an elementary quantity of the product or service analyzed. Several LCIs have been developed on aggregates in the past. First, several models are included in ecoinvent, the reference LCI database (“ecoinvent Version 3,” n.d.). The “*mine, gravel/sand*” process relating to the production of round and crushed gravels in ecoinvent v2.2 is detailed in Ecoinvent’s report n°7 (Kellenberger et al., 2007). It is based on the study of four Swiss quarries considered representative of the country between 1997 and 2001. Nevertheless, the report specifies that the performance of the sites can vary widely. The operating assumptions relate to the average quarry surface (12000 square meters, i.e. 129167 square feet), operating period (50 years), annual production (400 to 500000 metric tons per site), and machinery amortization (150 tons of machinery, a lifespan of 25 years: 5 silos of 7 tons, 3 sieves of 5 tons each, 4 crushers of 25 tons each, 1000 meters of conveyor). The machinery is modeled using the generic process from ecoinvent “*industrial machine, heavy, unspecified*”, thus not accounting for the specific compounds of such machines. Moreover, the production representativeness is limited – even more when considering round rocks are less and less extracted, and these LCIs exclude the consumption of explosive to dynamite

hard rocks (process “*explosive, tovox*”) as well as the blasting emissions. Only one LCI fromecoinvent v3 includes the consumption and emissions related to blasting activities (“*blasting*”). It was developed based on three quarries in the state of Sao Paulo, and is supposed to be representative of typical stones in Brazil and up-to-date technologies in 2015. On-site transportation is considered 100% through conveyors. The three quarries produce 2.1% of the national production, and the LCI roughly accounts for capital good amortization and excludes tear and wear. Two other LCIs from ecoinvent (one production process, and its market equivalent) include explosive consumption without the blasting emissions. They are based on the operation of the Rajbandh stone quarry in India. They roughly include capital goods amortization (i.e. buildings and machinery), and exclude their tear and wear as well as transportation from the extraction site to the crushing unit. Moreover, it has limited representativeness with only one production site assessed. Finally, when comparing the consumption of tovox to dynamite in one kilogram of stone, I calculated a factor of 5 between the Indian LCI ($7.09 \cdot 10^{-5}$ kg of tovox per kilogram of stone) and the Brazilian LCI ($3.7 \cdot 10^{-4}$ kg), indicating wide variability between sites and/or practices.

Later, the Swiss models of ecoinvent were adapted to Quebec conditions during the initiative to develop the LCI database for this territory by the CIRAIG research center (Lesage and Samson, 2016). However, adaptation only includes the regionalization of the flows of water and electricity consumption, leading to extremely limited representativeness of Quebec’s aggregate production. However, one quantity changes: the electricity consumption per ton of aggregate produced, from $3.98E-3$ kWh/t in the Swiss model to more than twice higher for the Quebec process ($9.06E-3$ kWh/t). The source of this new data remains unknown.

The French national syndicate for the production of aggregates (UNPG) also carried out three studies on the main types of aggregates used in the construction sector in France: aggregates from massive rocks (UNPG, 2011a) and alluvial (or loose) rocks (UNPG, 2011b), as well as recycled aggregates (UNPG, 2011c). In the first two cases, the analysis considers all the activities carried out on the production site: clearing and exploitation of the site, processing, and marketing of the finished products, then final redevelopment of the site after shutdown. It omits certain elements considered negligible by NF P 01-010 (AFNOR, 2004), the former French standard for LCA of construction products. The system boundaries for recycled aggregates - originating from concrete and precast elements, recycled aggregates from former pavements called reclaimed asphalt pavement (RAP), ballast, natural gravel, or earthworks - include the treatment of materials from demolition, development, or earthworks activities: sorting and/or crushing and/or screening, then transport to fixed or mobile installations. It does not include the demolition itself, nor the transportation or energy consumption linked to the possible drying of the aggregates. The massive rock aggregate LCI is based on the study of eight sites in 2007, including four eruptive rock sites and four limestone sites, considered representative of the distribution of national production. Blasting is excluded from the LCI. For the LCI of loose rock aggregates, site measurements were also carried out in 2007 on eight different sites, including five sites in water, two dry sites, and a mixed site (60% in water and 40% above water). Finally, the LCIs of recycled aggregates come from seven recycling facilities including three fixed and four mobile facilities, also considered representative of the country. The LCIs of these three types of aggregates are provided in a usable format and have been reviewed by a third party according to the NF EN 15804+A1 standard for LCA of the built environment in Europe and France (AFNOR, 2014). Nevertheless, the energy consumptions in these studies seem underestimated when compared to internal data from Eurovia's production sites, Eurovia being one of the most important

producers of aggregates in France and Quebec, for pavements, railways and other infrastructure, buildings, asphalt roofing, and other civil engineering structures.

Among the other LCAs published on aggregates, Stripple's seminal road LCA proposed an aggregate LCI (Stripple, 2001). Based on Swedish data, the system boundaries of the LCA exclude blasting as well as capital goods, and the data are now outdated. Then, Korre and Durucan developed LCA models of several types of aggregates for the United Kingdom industry: crushed rock aggregates, land-won sand and gravel aggregates, marine sand and gravel aggregates, as well as recycled aggregates (2009). The system boundary of the LCA tool developed by these two researchers is unclear but seems to only include energy consumption due to on-site production and transportation. Capital goods as well as blasting seem excluded again. Mladenovic et al. (2015) compared two hardfacing techniques using natural aggregates and foundry slag aggregates, but most of the LCIs used in the study come from the GaBi database, which are black boxes generated from non-transparent industrial models, and the data collections date of the 2000s. Jullien et al. (2012) presented truncated LCIs of aggregates from three French quarries - one massive rock quarry and two alluvial rock quarries. The study finds significant differences between the environmental impacts linked to these LCIs and those ofecoinvent. However, these LCIs are incomplete as they only account for energy consumption as well as certain air emissions flows. Other inputs, such as capital goods amortization and maintenance or consumption of explosive, are excluded from the system boundaries. Some LCIs are also made available in the Federal LCA Commons, the open-source database from the United State government. Yet, these models exclude a large part of the complete production system of aggregates. For instance, the “production of aggregate” process only accounts for energy consumption (“Production of Aggregate,” n.d.). Finally, Ghanbari et al. propose a quantification of energy consumption and GHG emissions

related to the production of natural and recycled aggregates, but this study excludes blasting and capital goods once more (Ghanbari et al., 2018).

This literature review of aggregate LCAs thus highlights numerous shortcomings of the models published so far: weak technological, temporal, and geographical representativeness, obsolete and/or unrepresentative data, unknown data reliability, and varied system boundaries. The common exclusion of blasting or even tovox consumption for hard rocks seems especially surprising in the generic ecoinvent models, and so are the exclusion of capital goods, or the sole consideration of generic industrial machine amortization. The variability of explosive consumed to dynamite hard rocks also needs to be better understood, as a factor of 5 can be found in the two ecoinvent's models accounting for it. These multiple limits call for developing a comprehensive and up-to-date model, with specifically larger representativeness of the product types and nature of rocks.

To better understand the variability of inventories and environmental impacts related to the production of aggregates from massive rocks, as well as to cover a production area that has not yet been assessed, I propose to: (1) build comprehensive LCA models for different types of aggregates produced in Quebec based on recent field data; (2) study the environmental impacts and contributors of these aggregates; and (3) perform scenario analyses to discuss the expected variability of aggregate's impacts depending on the nature of rocks, the electricity mix, the nature of the installation, and the transportation distance to the consumer.

2. Method

2.1. Goal and scope

My goal is to carry out LCAs on average and specific productions of aggregates in Quebec, Canada, to understand the environmental impacts of aggregate production and consumption, their variability, and the factors of this variability. Following ISO 14040 and 14044 (International Organization for Standardization, 2006a, 2006b), I will develop average production models for the years 2020 and 2021 to assess the interannual variability of impacts, as well as develop models for specific sites to assess the inter-site variability. Among the five specific production units appraised, three fixed unit productions will be studied: the quarries of Laval (limestone rock), Saint Bruno (volcanic rock), and Saint Philippe (limestone). Two mobile production units will also be studied, each used in two different sites over the period considered: the “SDE” mobile unit installed in Val-des-Monts and Shawinigan sites, and the “SBE” unit installed in Roxton Pond and Sainte Justine. Then, scenario analyses will be conducted to give a large overview of the potential environmental impacts of aggregates: from different types of rocks, with different electricity mixes from Europe, China, or different North American regions, from fixed vs mobile installations, or with transportation to the consumer by 12-wheel truck or trailer truck on average regional distances.

The generic functional unit (FU) will be “to provide one metric ton of aggregates at the quarry gate”, and I will also assess the impact of aggregate transportation to customers, with the following FU: “to provide one metric ton of aggregates at customer”. The system boundaries considered are from cradle-to-quarry’s gate, or cradle-to-customer, and thus include all activities from blasting to crushing (+ transport to customer for the second FU):

the illustration of the first FU scope can be found in Figure 1. I detail the operations of aggregate production depending on the type of installation. After obtaining the authorization to operate, a site is prepared for operation by stripping and discovery work. Then, for a massive rock site, the next step consists of drilling and blasting. The third step consists of transporting the uncrushed stones from the pit to the crushing unit, which is either electrified or using diesel if it is fixed, and runs on diesel if it is mobile. Transport can be by trucks or electric conveyor belts. In the case of a mobile operation, the crushing unit is located near the working face: the main transport on-site takes place after the crushing, by truck. The greater the production of a site, the more the transport distance between the working face and the crushing site or the quarry's gates will increase over time. It should also be noted that a quarry is often a multifunctional site, where virgin aggregate ("stone", "pebble") and recycled aggregates will be produced, and aggregates and material from earthwork will be received to be stored (storage platform).

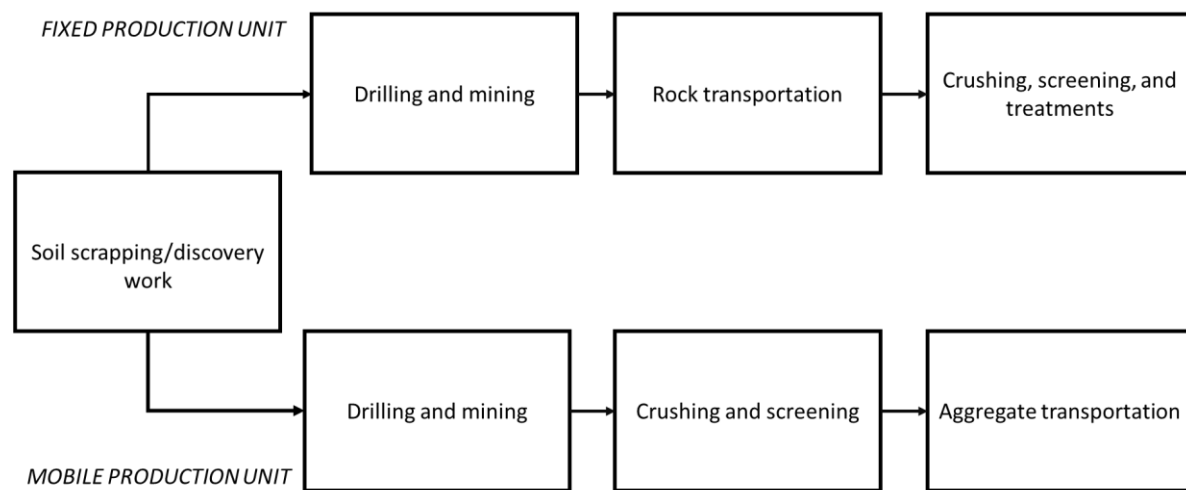


Figure 1 Life cycle stages of aggregate production - fixed versus mobile production unit

Alluvial installations, also called "sandpits" in Quebec, are different from hard rock production sites: these sites are often in the water and consist of deposits of the glacial eras from where alluvial rocks, also called round rocks or loose rocks, are extracted. In Quebec,

they are found in Gaspésie and Bromont. Outside of Quebec, deposits may be underwater. For this type of production, operations also start by stripping the site, then exploiting the deposit with a cable or bucket shovel, or with a vacuum system. On fixed installations, a conveyor belt of variable size (from 1 to 6 km) then transports the material before processing. Extraction of loose rocks for aggregate production is increasingly rare (about 2% of Eurovia's production in 2020 and 2021 according to the data processed as part of the project) and thus not modeled specifically. But the specificity of their production will be considered in Eurovia's average production models, via their specific energy consumption and the absence of explosive usage.

2.2. Inventory development method

2.2.1. Background database and data collection

As a background database, I will use Ecoinvent v3.7 to develop my models, with the cut-off approach. The data collection is performed through Eurovia's data records, analytics, and interviews with quarry managers and production directors from the Eurovia Quebec subsidiary conducted in 2021-2022. The entire production of aggregates by Eurovia in Quebec is considered and includes around 30 sites with a majority of fixed production units and some mobile installations - including five Eurovia's mobile units and complementary rented mobile units. The sites produced 6.9 million metric tons (Mt) of virgin aggregates in 2020 and 9.4 Mt in 2021 (resp. 8.7 and 12.3 Mt of all kinds of aggregates). The tonnage of aggregates of all kinds produced in Quebec annually is estimated at 107 Mt, including virgin and recycled aggregates (Association des constructeurs de routes et grands travaux du Québec, n.d.). Extrapolating the production data from Eurovia, which produces around 77% of virgin aggregates and 23% of recycled aggregates, I estimate that Quebec produces 82 Mt

of virgin aggregates and that the company then supplies between 8 and 12% of Quebec's virgin aggregate.

2.2.2. Data collection prioritization

To prioritize data collection to optimize LCI quality, I screen major contributors of theecoinvent regionalized process for Quebec aggregates - "*gravel, crushed, CA-QC, production*", calculating the impacts using the TRACI 2.0 characterization method. This hotspot analysis is performed on Simapro. The off-road diesel (ORD) consumed by the machinery is a major contributor (70% to the depletion of the ozone layer, 37% to the impact on climate change, 78% to smog, 48% to acidification, 15% to eutrophication, 42% of the respiratory effects, 63% of the depletion of fossil fuels), just like the amortization of premises with metal frames (21% on the depletion of the ozone layer, 30% of the impact on climate change, 17% from smog, 32% from acidification, 29% from eutrophication, 26 and 32% from carcinogenic and non-carcinogenic health impacts, 28% from respiratory effects, 21% from ecotoxicity, 26 % of fossil fuel depletion). Heat consumption presents notable but often non-major contributions (4% of the depletion of the ozone layer, 16% of the impact on climate change, 10% of acidification, 16% of eutrophication, 27 and 7% of the carcinogenic and non-carcinogenic health impacts), as the amortization of the machinery (4% of the depletion of the ozone layer, 6% of the impact of climate change, 3 % smog, 6% acidification, 19% eutrophication, 34% carcinogenic health impact, 12% respiratory effects, 34% ecotoxicity). The amortization of the conveyor is also reflected in a few indicators (6% eutrophication, 15 and 7% carcinogenic health impact, and 6% ecotoxicity). Mine infrastructure, which includes the impacts of initial site preparation for rock extraction, contributes significantly to eutrophication (11%) carcinogenic and non-carcinogenic health impacts (8 and 16%), and ecotoxicity (24%). Electricity consumption has a secondary impact on most indicators, except

on ecotoxicity (11%). In conclusion, my models will have to focus on the validation of the energy consumption data linked to the production of aggregates and the improvement of the amortization of the quarries' modeling, in particular that of the premises and the machinery. I will also dig into the blasting stage, which has rarely been dealt with so far in published studies, and whose consumption is variable in the two studies considering it.

2.3. Life cycle inventories

2.3.1 Energy and water flows

Foreground data: data records and calculations

Production data were collected by production zone of Eurovia Quebec subsidiary. First, Eurovia's environmental reporting for the period from 10/2019 to 9/2020 (called 2020) was obtained from the environmental department of Eurovia group. These consumptions include standard diesel, gasoline, light fuel oil (LFO), natural gas, electricity, water, and ORD. Six production zones are studied, corresponding to the group's materials production "regions": Gaspesie quarries, North Materials, Aggregates Sainte Clotilde, Eastern Townships quarries, RSMM quarries, and Outaouais quarries. By dividing total consumptions by the tonnage produced, I calculate the consumption per ton (Table 1). Details on data and calculations can be found in the supplementary material provided with this article.

Table 1 Consumption flows per functional unit and production type

<i>Region</i>	<i>Diesel (L/t)</i>	<i>Gasoline (L/t)</i>	<i>LFO (L/t)</i>	<i>Natural gas (m3/t)</i>	<i>Electricity (kWh/t)</i>	<i>ORD (L/t)</i>	<i>Water (m3/t)</i>
<i>Fixed</i>	1.87E+1	4.94E-1	6.36E-4	4.25E-3	1.95E+0	4.52E-3	1.31E-5
<i>Mobile</i>	8.43E+0	0	0	0	9.40E-1	4.61E0	1.31E-5

Globally, diesel is used for stationary heavy machinery, such as fixed crushing unit generators, while gasoline is used for staff road trips (foreman vans and others). LFO is scarcely consumed for the heating of office buildings and workshops. Electricity is used by the pumps and in crushing activities in many fixed production sites such as in the quarries of Laval, St Bruno, St Philippe, and Bromont. Finally, ORD is used for mobile machinery: trucks, loaders, and mobile crushing units.

The water consumed comes mainly from the environment: the consumption of running water is rare as sites are generally not connected to the water network. It will be considered that the water consumed comes 75% from rainwater and 25% from groundwater based on Eurovia's experts. The water is used to reduce dust emissions: it then goes into settling ponds, and only overflows can be discharged into the environment. But water discharges are very low and meet the thresholds settled by the Ministry of the Environment. Moreover, no flocculation product is used in Eurovia Quebec's quarries.

Background data: LCIs of fuels consumed

Different kinds of fuels are used for different purposes. The impacts generated by the use of these fuels are due to the gas released by the combustion itself but also to the supply chain providing these fuels. The combustion impacts do not depend on the context of the combustion, but the supply chain impacts depend on the type of petroleum extracted, the technology and practices to extract, transport, and refine it. Moreover, these impacts can vary widely (Masnadi et al., 2018; Meili et al., 2018). To account for some regional aspects of these consumptions, I use several regional data for Quebec and Canada. Only GHG emissions are regionalized, following the method and using the data detailed in the supplementary material.

2.3.2. Blasting

Explosive consumption by type of rock

Explosive activities are not accounted for in most aggregate LCAs, although a blasting process exists in the ecoinvent database. It includes the production of ammonium nitrate produced in Switzerland called tovox, its transport to the quarry, and airborne emissions based on stoichiometric calculations (EcoInvent, n.d.). According to data from Quebec sites (cf Denis Bouchard, Eurovia's expert), explosive consumption varies according to the type of rock: these consumptions per cubic meter of exploded rock are shown in Table 2.

The density of rocks varies according to their nature. The cellular rocks present densities around 2.55 t/m^3 while the rocks with metallic structures can go up to densities of 3.2 or 3.3 t/m^3 , for chalcopyrite stones for example which contain iron sulfides. The rocks used for road aggregates in Quebec have densities in the range $[2.55-2.85] \text{ t/m}^3$. I will consider an average density of 2.7 t/m^3 of rock to recalculate the consumption of explosives per ton. The results are presented in Table 2.

Table 2 Consumption of explosives to blast different kinds of rocks

<i>Type of rock</i>	<i>Explosive consumption</i>	
	kg/m^3 of rock	kg/t of rock
<i>Limestone rocks</i>	0.45	0.17
<i>Dolomitic rocks and slate</i>	0.70	0.26
<i>Hard rocks (volcanic, sandstone)</i>	1.00	0.37

Explosive consumption on average and by installation type

To create representative average explosive consumption models per type of Eurovia's Quebec production– for fixed and mobile installation, on average, in 2020 and 2021 – I calculated the product ratios and the associated rock types (Table 3).

Table 3 Types of rocks extracted on average by Eurovia Quebec and by type of production unit

Type of rock	2020	2021
Average production (t)		
<i>Limestone rocks</i>	31%	33%
<i>Dolomitic rocks</i>	21%	17%
<i>Volcanic rocks</i>	46%	48%
<i>Loose rocks</i>	2%	2%
Total	100%	100%
Mobile production (t)	2020	2021
<i>Limestone rocks</i>	13%	16%
<i>Dolomitic rocks</i>	42%	40%
<i>Volcanic rocks</i>	45%	43%
Total	100%	100%
Fixed production (t)	2020	2021
<i>Limestone rocks</i>	51%	47%
<i>Dolomitic rocks</i>	0%	0%
<i>Volcanic rocks</i>	49%	53%
Total	100%	100%

Sums can differ from 100% due to round numbers

Moreover, I calculated that exactly half of Eurovia’s production came from fixed production units in 2020, and the rest from mobile units (resp. 58 and 42% in 2021), leading to the average consumption of explosives by type of production shown in Table 4.

Table 4 Explosive consumption depending on the type of installation

<i>Type of production</i>	<i>Explosive consumption (kg/kg of rock)</i>	
	2020	2021
<i>AVERAGE QUEBEC PRODUCTION</i>	2.77E-04	2.76E-04
<i>MOBILE PRODUCTION</i>	2.97E-04	2.93E-04
<i>FIXED PRODUCTION</i>	2.67E-04	2.75E-04

Site-specific consumptions

Consumption of explosives for the specific sites of St Bruno (metamorphic rock, similar to volcanic rock), Laval (sedimentary rock, i.e. crystalline limestone), and Saint Philippe (same as Laval's rocks), as well as for the operations of SBE – operating at 50 % at Roxton Pond (very abrasive sandstone) and 50% at Sainte Justine (dolomite) - and SDE mobile units – operating at 50% at Val-des-Monts and 50% at Shawinigan (granitic rock, i.e. volcanic) - for 2020 were also calculated (Table 5). Inter-site explosive consumption variability is shown to be high compared to inter-technology variability (i.e. fixed vs. mobile crushing).

Table 5 Site-specific explosive consumptions and type of rock

<i>Site</i>	<i>Type of rock</i>	<i>Explosive consumption (kg/kg)</i>
<i>Laval</i>	Limestone	1.67E-04
<i>Saint Bruno</i>	Volcanic rock	3.70E-04
<i>Saint Philippe</i>	Limestone	1.67E-04
<i>SDE - Val des Monts/Shawinigan</i>	Volcanic rock	3.70E-04
<i>SBE - Roxton Pond/Sainte Justine</i>	50% limestone- 50% dolomite	2.13E-04

2.3.3. Dust emission

Dust emissions are not measured on-site in Quebec. Nevertheless, quarries producing more than 500,000 t/year of aggregates must report their emissions in the Canadian National Pollution Inventory (NPRI). Default emission factors are recommended by the Government of Canada depending on the type and method of production. These data come from the 5th report of the USA EPA, chapter 11, corresponding to the environmental impacts of the mineral industry (US EPA, 2004). I recalculated the emission values according to the ecoinvent classification of particulate matter (PM) flows and reported them in Table 6. In Quebec, the crushing units are generally not equipped with a bag filter (cf. Denis Bouchard). The sensitivity of the environmental results to the filter will be shown in the case of the Laval quarry, whose crusher is equipped with a filter.

Table 6 Dust emissions depending on the equipment of the crushing unit

Crushing unit type	Dust emissions (kg/t of rock)		
	PM >10µm	PM 2.5-10µm	PM <2.5µm
<i>Without filter</i>	0.0027	0.0012	0.0006
<i>With filter</i>	0.0006	0.0007	0.00005

2.3.4. Facilities and machinery

Overview

The main piece of equipment is a crushing unit, the operation of which is detailed in Figure 2 in the case of three crushing-stage units. Three crushing stages are required for aggregates used in concrete and asphalt mixture due to the generally small size of their aggregates.

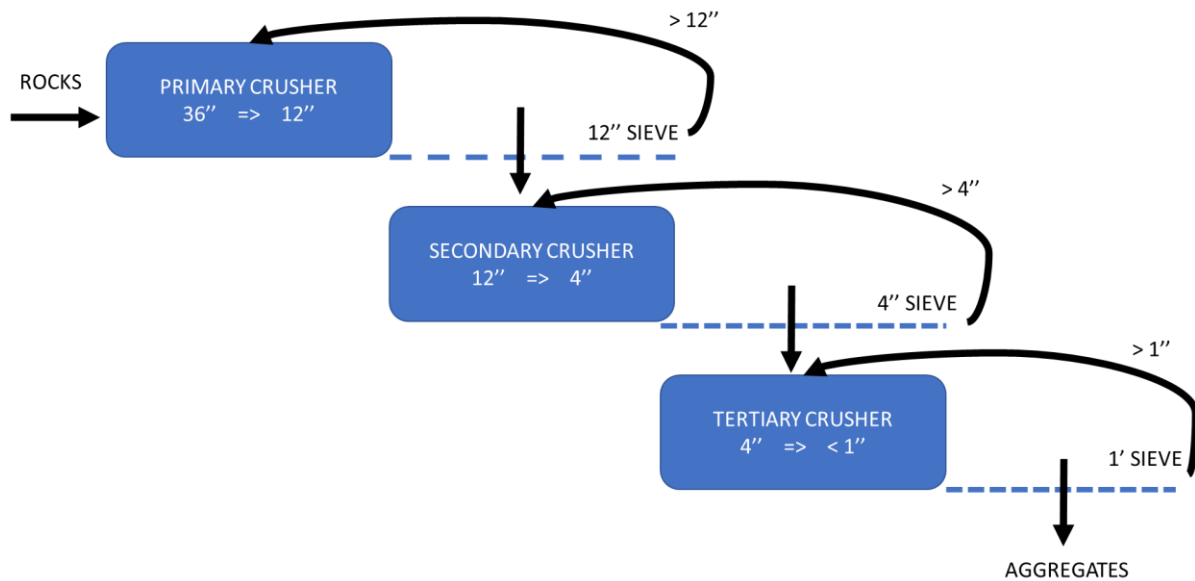


Figure 2 Crushing unit to produce aggregates used in pavements

This equipment can be inserted into a metal structure in certain fixed units and is mounted on tires in the case of mobile units. These structures are not similar to the metal constructions modeled in ecoinvent that are a main contributor to the final impact. The actual metal masses of Eurovia facilities will be declared in the production tool. There are no concrete premises on the quarries contrary to what is modeled in ecoinvent, but the fixed crushing units have concrete slabs to accommodate the elements of production equipment. At the EoL, the metals from the wear parts are 100% recycled. The models developed for Quebec’s fixed and mobile crushing units are detailed below.

Mobile units

The total weight of the different elements of a mobile crushing unit is 154.5 metric tons of steel, based on the SBE and SDE units. The description of its composition is detailed in the supplementary material. Apart from the crushers and sieves, a container is linked to the generator to operate the various crushing and sieving equipment. A second vehicle (45-foot semi-trailer) serves as a temporary office for employees, a warehouse to store replacement parts, and a repair shop for equipment. The lifespan of the various materials can be estimated

at around 25 years. The consumption of steel parts linked to the amortization of the crushing unit finally calculated is equal to 14.4 g of industrial machinery amortized in capital per ton of aggregate produced, for the production of 430000 metric tons per year. As done in ecoinvent's aggregate processes and due to lack of data from Eurovia's suppliers, I chose the ecoinvent process "*Industrial machine, heavy, unspecified {RoW}| market*" to model this amortization.

Wear parts consumed by the two mobile units – SDE and SBE - were compiled (Table 10). The data was provided by the operation site managers. The differences in maintenance between the two units are explained by the nature of the rock: the softer the rock, the lower the maintenance. Conversely, a more abrasive rock wears out the machinery more quickly. Parts are made of manganese steel, i.e. 18% of manganese and the rest of steel. Manganese hardens on impact, while steel is not strong enough for these units. Manganese steel, also called Hadfield steel or mangalloy, does not exist in ecoinvent. Therefore, I will only consider the material impact of manganese and steel manufacturing, without considering the impact of mixing the two materials. I calculated 36.6 and 49.3 mg of wear parts consumption per kilogram of crushed stone respectively for the SDE and SBE plants, i.e. an average of 42.9 mg/kg of aggregate produced. Metal recycling is not accounted for, as mobile units are mainly owned by subcontractors, meaning that Eurovia does not control the recycling. This is a conservative approach.

Table 10 Annual maintenance of two Quebec mobile units – SBE and SDE units

<i>Wear parts</i>	<i>SDE units</i>	<i>SBE units</i>	<i>Mass (kg/unit)</i>	<i>SDE maintenance (mg/kg)</i>	<i>SBE maintenance (mg/kg)</i>
<i>Primary sleeve</i>	3	2	1 500	10.47	6.98
<i>Primary hammer</i>	2	2	1 665	7.74	7.74
<i>Secondary mantle</i>	3	2	1 160	8.09	5.40

<i>Secondary dry hammer</i>	3	2	1 390	9.70	6.47
<i>Third mantle</i>	4	3	615	5.72	4.29
<i>Third hammer</i>	4	3	815	7.58	5.69

Fixed units

Because collecting information on the amortization of each Eurovia's fixed unit quarry in Quebec was too time-intensive, data collection was carried out on three representative fixed plants: Laval, Saint-Bruno, and Saint-Philippe. The characteristics of these sites were given by Denis Bouchard (see supplementary material). The basin is dug into the rock and does not include any particular structure (neither concrete nor liner). Concrete infrastructure was built to accommodate the various elements of the crushing unit. The different slabs are detailed in an Excel spreadsheet, and the total masses of 30-32 MPa concrete used have been compiled in the supplementary material. The mass of industrial machinery and metal structures was roughly assessed on the metal frame part because no traceability document allowed us to make a more precise estimate. The quarries also have roads: they are often paved for customer access near cities (small sites) but remain unpaved on larger production sites. They will therefore be neglected as most of the sites are unpaved. The data relating to the equipment outside the conveyor belt could only be collected on the Laval quarry and are presented in the supplementary material, for a lifespan of 25 years, and lead to amortizing 10.7 g of industrial machines per ton of aggregates produced. We also need to assess LULUC. The lands occupied were previously generally woods or agricultural fields, estimated under a ratio of resp. 30-70% in Quebec. The redevelopment is very variable, i.e., the working faces can be left as they are or further redeveloped. Redevelopment will be neglected, considering current practices in Quebec.

The final inventories to be considered per ton produced are calculated according to the production and lifespan of each site. The data is presented in Table 11. In Simapro, these inventories have been recalculated for each kilogram produced. Note that I modeled three sites considered representative of Quebec, although significant economies of scale make the mass of steel used per ton produced decrease rapidly on the largest facilities, and, vice versa, increase on the small ones.

Table 11 LULUC, infrastructure and equipment amortization for fixed crushing unit quarries

	Laval	St-Bruno	St-Philippe
Annual production (kt)	1200	1100	775
Site lifespan (years)	40	30	65
Land transformation (m²/t)			
Ponds	1.15E-03	8.71E-05	7.94E-04
Rest	3.51E-01	1.59E-02	1.65E-02
Land use (m².an/t)			
Ponds	4.58E-02	2.61E-03	5.16E-02
Rest	1.40E+01	4.77E-01	1.07E+00
Infrastructure amortization			
Concrete 30-32 MPa (m ³ /t)	3.18E-05	2.99E-05	1.49E-05
Equipment amortization			
Industrial machinery + metal frame (t/t)	1.07E-05	(1.07E-05)	(1.07E-05)
Conveyor belt (m/t)	4.E-05	5.E-05	2.E-05

For the maintenance of the fixed unit, the parts worn annually as well as their number, total mass, and composition are indicated in Table 12. Data collection was carried out in Laval's quarry (cf Pauline Swinnen). The maintenance inventories per kilogram of aggregate produced are calculated according to the annual production of Laval's quarry and presented in Table 12. As declared by Denis Bouchard, 10% of the conveyor needs replacement per year on average. The 10% tungsten included in the liners of the secondary crusher is neglected because no process is available in ecoinvent v3.7. On the other hand, it can be taken into account in the future with ecoinvent v3.8 using one of the two new tungsten processes.

Table 12 Fixed unit maintenance

Wear parts	Number	Mass (kg/year)	Maintenance (mg/kg)	Composition
<i>Feeders</i>	1	1600	1.33E+00	Steel
<i>Primary sleeve</i>	1	2041	1.70E+00	Steel, 18% manganese
<i>Primary hammer</i>	3	3402	2.83E+00	Steel, 18% manganese with 2% chrome
<i>General liners</i>	1	1588	1.32E+00	Steel
<i>Secondary shield</i>	12	1905	1.59E+00	20% ceramic, 80% manganese
<i>Secondary dry hammer</i>	8	6169	5.14E+00	Steel, 18% manganese with 2% chrome
<i>Liners for secondary crusher</i>	24	1043	8.69E-01	90% steel, 10% tungtene carbonate
<i>External screws' pads</i>	150	680	5.67E-01	Steel
<i>Internal screws' pads</i>	25	283	2.36E-01	Steel
Spare part	Ratio		Maintenance (m/an)	Composition
<i>Conveyor belt replacement</i>	10%		1.40E-07	Mixed (see ecoinvent process)

2.3.5. Aggregate downstream transportation

Aggregate transport includes the entire life cycle of the transportation service, i.e. manufacturing and maintenance of the truck as well as fuel production and combustion. The vehicle EoL is excluded as the impact is negligible (de Bortoli et al., 2017). Because the generic truck transportation processes in ecoinvent are not representative of the construction practices, I developed new tailored models.

Average loads and distances

Upstream transport - between the pit and the processing facility - is considered in the site energy consumption data presented above. Data on the downstream transport of aggregates were also provided by Denis Bouchard, vice-president of materials at Eurovia Quebec: average supply distances from quarries to customers, type of truck used, and average full load. The information is summarized in Table 7. In addition, no double freight can generally be set up. Thus, the new aggregates transport models will consider trucks empty returns. The

average transport distance for aggregates is 16.9 km between quarries and Eurovia’s customers in Quebec. Average full loads vary by the quarry, with a 2020 production weighted average of 32.8t, but an average of 35.5 and 22.0 tons resp. for semi-trailers and 12-wheel trucks.

Table 7 Transportation characteristics for aggregates, from the quarry to the consumer, by region

<i>Production zone</i>	<i>Vehicle type</i>	<i>Average distance from quarry to consumer (km)</i>	<i>Average full load (t)</i>
<i>GASPESIE QUARRIES</i>	Semi-trailer	45.5	35
<i>NORTH MATERIALS</i>	12-wheel trucks & semi-trailer	3.1	22
<i>AGGREGATES SAINTE-CLOTILDE</i>	Semi-trailer	32.9	36
<i>EASTERN TOWNSHIP QUARRIES</i>	Semi-trailer	6.7	34
<i>RSMM QUARRIES</i>	Semi-trailer	19.9	37
<i>OUTAOUAIS QUARRIES</i>	Semi-trailer	7.9	34
<i>QUEBEC WEIGHTED AVERAGE</i>		16.9	35.5

Fuel consumption

The fuel consumption for the trucks used by Eurovia in Quebec is shown in Table 8. These data relate to average driving cycles for the semi-trailer truck, in full-load or empty modes, while rural and urban modes have been differentiated for the 12-wheel truck, but not the load condition. Consumption is higher than the average for Quebec’s truck fleet, evaluated at 39.5L/100km by a provincial study carried out in 2000 (Government of Canada, 2009). This can be explained by the high tonnages of materials transported by the trucks used in construction. Moreover, the Quebec survey refers to a consumption difference of 5L/100km between summer and winter. I assumed that the data collected from Eurovia rather relate to summer consumption, as road construction activities mostly stop in winter in Quebec due to the cold weather.

Table 8 Fuel consumption of trucks depending on the load and driving conditions

Vehicle	Load & driving conditions	Consumption
Semi-trailer truck	Full, average	50L/100km
	Empty, average	39L/100km
12-wheel truck	Average, rural	40L/100km
	Average, urban	52L/100km

Emissions

Only emissions from small trucks (under 4.54 t) are regulated in Canada, based on US EPA regulations. The reference emission models for vehicles in North America are those of the MOVES models, and particularly of MOVES3 which updated the data dating from 2009 in the previous version of MOVES (US EPA, 2020). But I did not find a way to extract the unitary emissions of the vehicles from MOVES3. Thus, I chose to use the European vehicle emission models from HBEFA v4.1 (Matzer et al., 2019). Despite the geographical difference, HBEFA has the advantage of simulating consumption and emissions in real conditions. I considered the average Swiss truck fleet in 2020 and calculated the consumption as well as the regulated emissions (CO, CO₂, NO_x, HC, PM) of heavy trucks (see SM). However, the simulated consumption does not correspond to heavily loaded large-capacity trucks used in construction. Thus, I adjusted the emissions to the consumption data of Eurovia's fleet, considering consumption and emissions to be proportional. Final fuel consumption and emissions of trucks to transport aggregates in different operating conditions are presented in Table 9.

Table 9 Consumptions and emissions of aggregate trucks in different operating conditions

		Conso (L/100km)	Ratio HBEFA/Eurovia	CO	CO ₂	HC	NO _x	PM
Semi-trailer truck	Full, average	50	1.61	1.19E+00	1.34E+03	1.20E-01	2.83E+00	4.82E-02
	Empty, average	39	1.25	9.30E-01	1.04E+03	9.40E-02	2.21E+00	3.76E-02

	Double trip (empty return)	89	2.86	2.12E+0	2.38E+3	2.10E-1	5.04E+0	8.60E-2
12-wheel truck	Rural, average	40	1.29	9.54E-01	1.07E+03	9.64E-02	2.27E+00	3.86E-02
	Urban, average	52	1.67	1.24E+00	1.39E+03	1.25E-01	2.95E+00	5.01E-02
	Double trip (empty return)	92	2.96	2.19E+0	2.46E+3	0.22E-1	5.21E+0	8.90E-2

2.4. LCIA

As recommended in the ISO 21930 standard relating to LCAs of construction products in North America (International Organization for Standardization, 2017), I used the TRACI characterization method (v2 1.05) to calculate potential impacts to the environment. The calculations are carried out using the LCA software Simapro 9.1.0.11.

3. Results and interpretation

3.1. Hotspot analysis: environmental levers of aggregate production impacts

Fixed production

Figure 3 presents the hotspot analysis of the average 2021 fixed aggregate production from cradle-to-gate. It highlights the major contribution of blasting (in red) on the final impact of the aggregate at quarry's gates: from 18% of the total impact on ozone depletion to 86% on acidification. Blasting especially accounts for 42% of the carbon footprint of aggregate production. The regular diesel, globally burned by generators (in black) is the second biggest contributor overall – accounting for a substantial part of the impacts on the following categories: global warming (47% of the impact), ozone depletion (75%), fossil fuel depletion (70%), respiratory effects (26%), smog (17%), acidification (13%) and eutrophication (13%). On health impacts (carcinogenics and non-carcinogenics) as well as ecotoxicity, on the other hand, the conveyor belt manufacture and maintenance are the second most important contributor. The maintenance of the conveyor belt brings more impact than the original

conveyor's manufacturing. Recycling of machinery spare parts allows for reducing the environmental impacts on health (both for carcinogenic and non-carcinogenic diseases, resp. by 8 and 4%), ecotoxicity (-8%), and slightly on eutrophication (-1%). The production of manganese (in purple) for the different spare parts of the crushing unit generates one-quarter of the carcinogenic impacts, especially due to the maintenance of the hammers. Dust generated on-site only contributes to 15% of the total respiratory effects: scopes 2 and 3 emissions are far more important than scope 1 emissions, according to the GHG protocol definition of scopes (WBCSD and WRI, 2004). Interestingly, the original machinery amortization (in blue), which is the only equipment considered by theecoinvent models, only brings limited impacts (0 to 5% maximum, on ecotoxicity). Just as electricity, accounting for 0 to 6% of the impact, and ORD, mostly consumed by trucks on site.

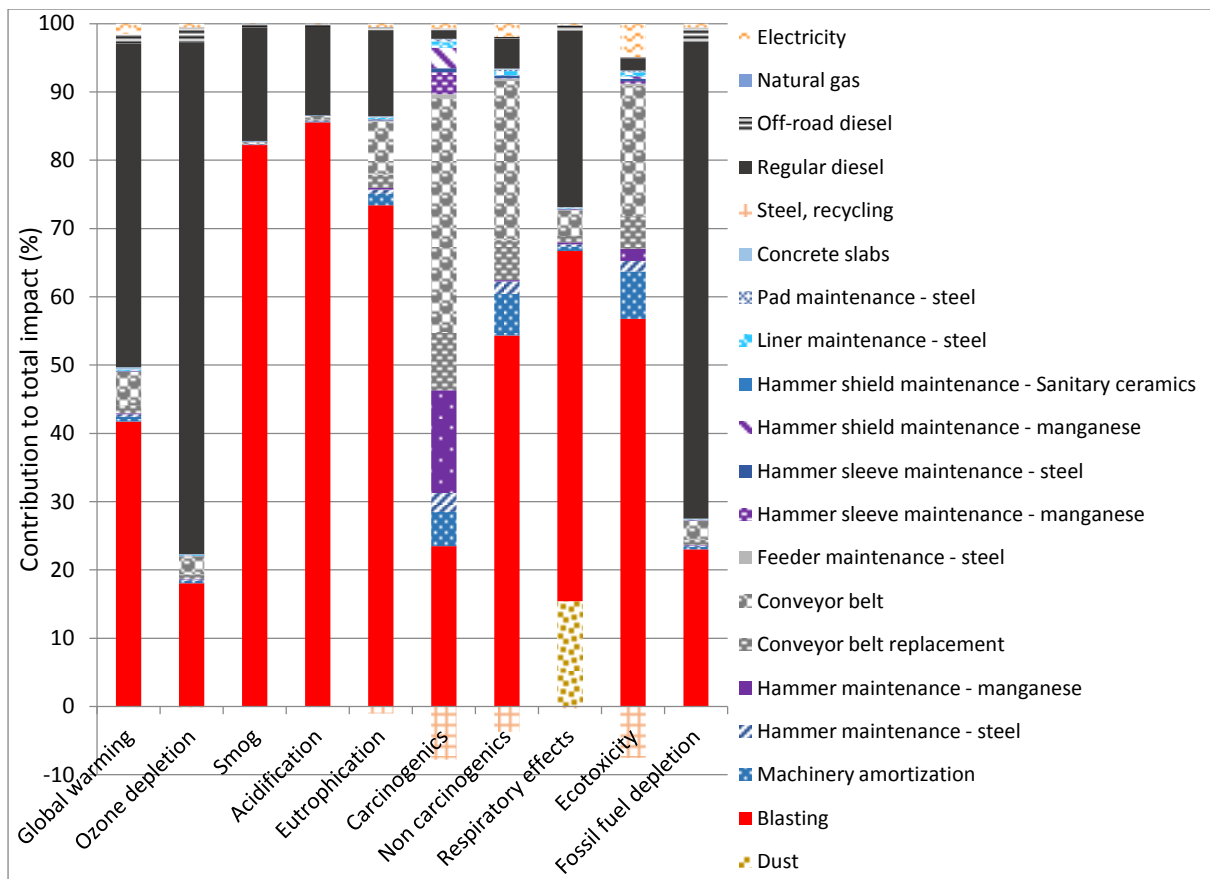


Figure 3 Hotspot analysis of aggregate production activities for Eurovia Quebec in 2021, for fixed production

Mobile production

Figure 4 presents the hotspot analysis of the average 2021 mobile aggregate production of Eurovia in Quebec. The blasting (in red), with 25 to 90% of the impact contribution, is again the most important contributor on most indicators, excluding ozone depletion, carcinogenics, and fossil fuel depletion. Then, the regular diesel, generally burned in the crusher generator, is the second biggest contributor (13-46%) on all the indicators, to the exclusion of health impacts and ecotoxicity. The ORD, either used by the mobile crushers or on-site trucks, then brings the most important impacts (0-25%), while the contribution was very low in the case of fixed production. The carcinogenics impact category displays very specific contributions: 65% of the impact is explained by the machinery amortization and maintenance, mainly by

the manganese production for the maintenance of the hammer and its sleeve (51%, in purple), and the rest by the manufacturing of steel (in blue). While the crusher's spare parts are only made of 18% of manganese and 82% of steel, manganese brings the biggest contribution due to its high impact. Steel still brings a substantial impact on non-carcinogenic health impacts and ecotoxicity, with resp. 21 and 19% of the total impact.

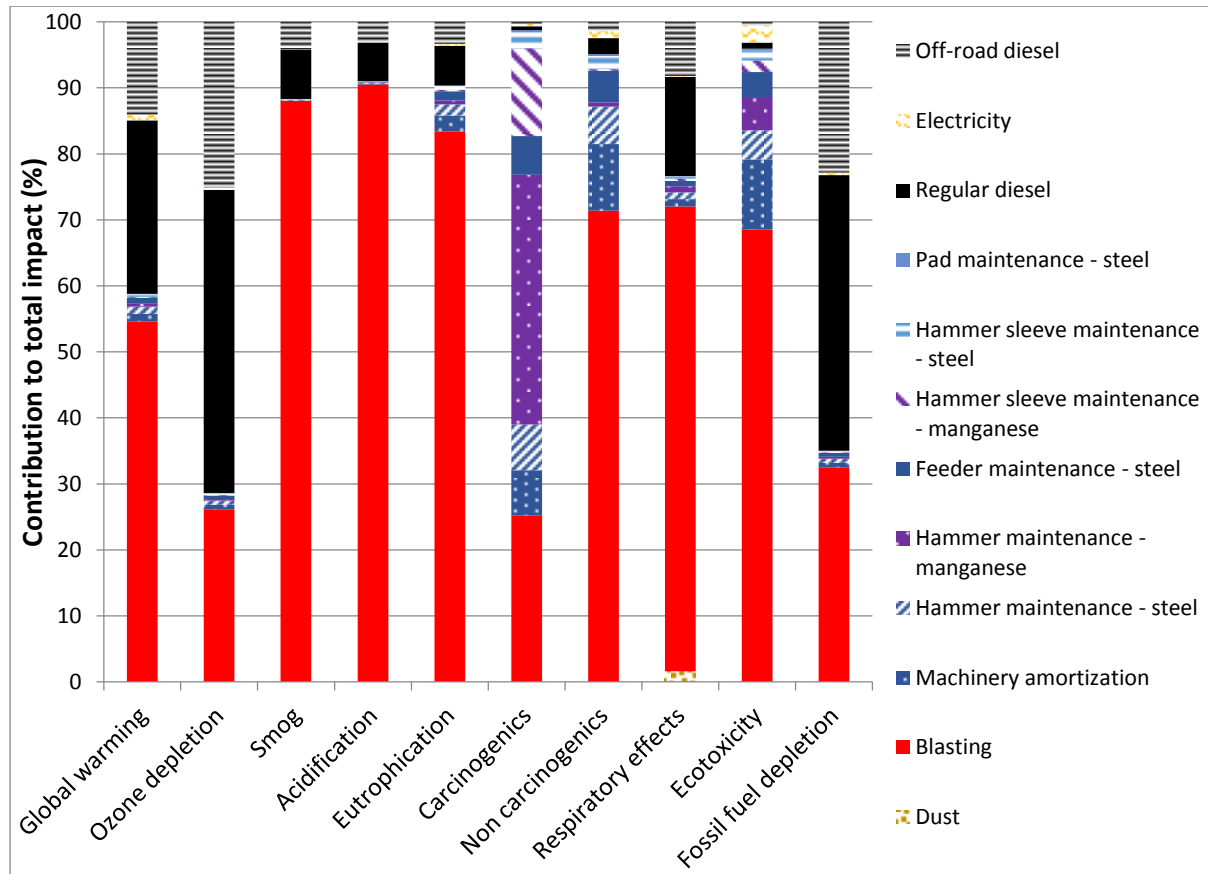


Figure 4 Hotspot analysis of aggregate production activities of Eurovia Quebec in 2021, for mobile production

3.2. Quebec's aggregates impacts

The environmental impacts of different aggregates produced in Quebec by Eurovia are presented in Table 13 for each TRACI's impact category. Their comparison is shown in Figure 5. Eurovia's aggregates produced in Quebec emitted on average 2.97 kgCO₂eq/t in 2020 and 3.03 kgCO₂eq/t in 2021. This slight increase can be explained because the rocks

mined in 2021 that were a bit harder than in 2020, and to the larger part of fixed-produced aggregates in 2021, these aggregates being more impacting than mobile-produced aggregates. Site-specific LCAs show a range in the carbon footprint of the aggregates of 2.28-3.59 kgCO₂eq/t. The aggregates produced with the SBE unit have the lowest impact overall, mainly due to the low consumption of explosives in 2020 related to the nature of the rock exploited. St Bruno quarry's aggregates show the highest impact on many indicators including climate change, due to its high explosive consumption and high consumption of gasoline and ORD.

On a multicriteria approach, the most impacting aggregates are from Saint Bruno quarry and/or SDE unit production. The less impacting aggregates are globally from St-Philippe and/or SBE. A factor of two exists between the most and the less impacting aggregates on most of the impact categories: smog, acidification, eutrophication, non-carcinogenic health impacts, and respiratory effects. Let's note that the use of filters on crushing units – in the case of Laval's crusher, and mobile units – does not mainly explain the respiratory effects, as aggregates from SDE are slightly more impacting than the average aggregates in 2020 and 2021. The impact range is more restricted on other categories, especially on global warming (-37% impacts between the most and the less impacting aggregate), ozone depletion (-32%), and fossil fuel depletion (-31%). Inter-site variation is thus quite important when it comes to the environmental impacts of aggregate production on a cradle-to-gate perimeter, even more than what has been shown in previous studies such as the one by Jullien et al. on three different French quarries (2012).

Table 13 Environmental impacts of different aggregates in Quebec by impact category

<i>Impact category</i>	<i>Unit</i>	<i>Average. 2021</i>	<i>Average. 2020</i>	<i>St Bruno</i>	<i>St Philippe</i>	<i>Laval</i>	<i>SBE</i>	<i>SDE</i>
Global warming	kgCO ₂ eq	3.03E+00	2.97E+00	3.59E+00	2.51E+00	2.86E+00	2.28E+00	3.07E+00

Ozone depletion	kgCFC-11eq	4.24E-07	4.13E-07	4.58E-07	3.89E-07	4.60E-07	3.26E-07	3.76E-07
Smog	kgO ₃ eq	2.83E+00	2.82E+00	3.58E+00	1.85E+00	1.94E+00	2.15E+00	3.48E+00
Acidification	kgSO ₂ eq	1.18E-01	1.18E-01	1.51E-01	7.60E-02	7.90E-02	8.95E-02	1.47E-01
Eutrophication	kgNeq	1.11E-02	1.10E-02	1.43E-02	7.75E-03	8.16E-03	8.31E-03	1.32E-02
Carcinogenics	CTUh	4.78E-07	4.80E-07	5.53E-07	3.94E-07	4.20E-07	4.64E-07	6.19E-07
Non carcinogenics	CTUh	6.91E-07	6.79E-07	9.41E-07	5.58E-07	5.93E-07	5.02E-07	7.48E-07
Respiratory effects	kgPM2.5eq	7.14E-03	6.97E-03	9.06E-03	5.95E-03	2.09E-04	4.95E-03	7.30E-03
Ecotoxicity	CTUe	5.45E+01	5.40E+01	7.21E+01	4.21E+01	4.54E+01	4.31E+01	6.41E+01
Fossil fuel depletion	MJsurplus	4.06E+00	3.96E+00	4.47E+00	3.64E+00	4.27E+00	3.11E+00	3.71E+00

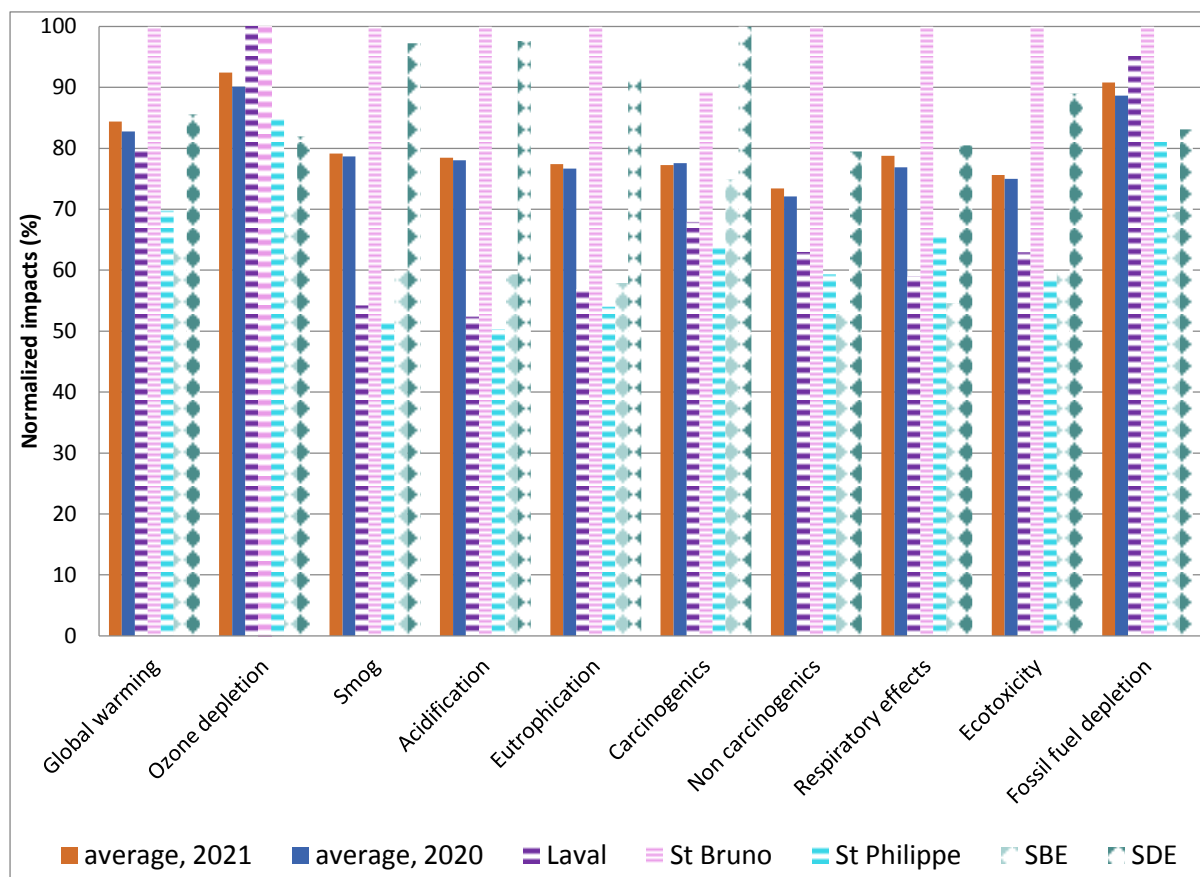


Figure 5 Comparison of the environmental impacts of Quebec's average and site-specific aggregate productions

3.3. Sensitivity analyses

3.3.1. Nature of rocks

Figure 6 presents the sensitivity of the impacts of the 2021 fixed production of aggregates to the consumption of explosives, depending on the nature of the rocks exploited. These impacts have been normalized based on the most impacting aggregate. It shows an important sensitivity of the impact to the consumption of explosives – with a reduction of 13 to 49% of the impact between volcanic and sandstone rocks (in blue) and limestone rocks (in purple), which respectively impact the most and the less the environment. The sensitivity of the results is particularly striking in air pollution-related impact categories. In particular, the consumption of explosives explains a difference by a factor of two in terms of smog, acidification, and eutrophication, due to the pollutants released by blasting. Let's note that the sensitivity of the results to the consumption of explosives would be even higher if assessed on the aggregate mobile production, as blasting is a more important contributor for this type of site in our sample.

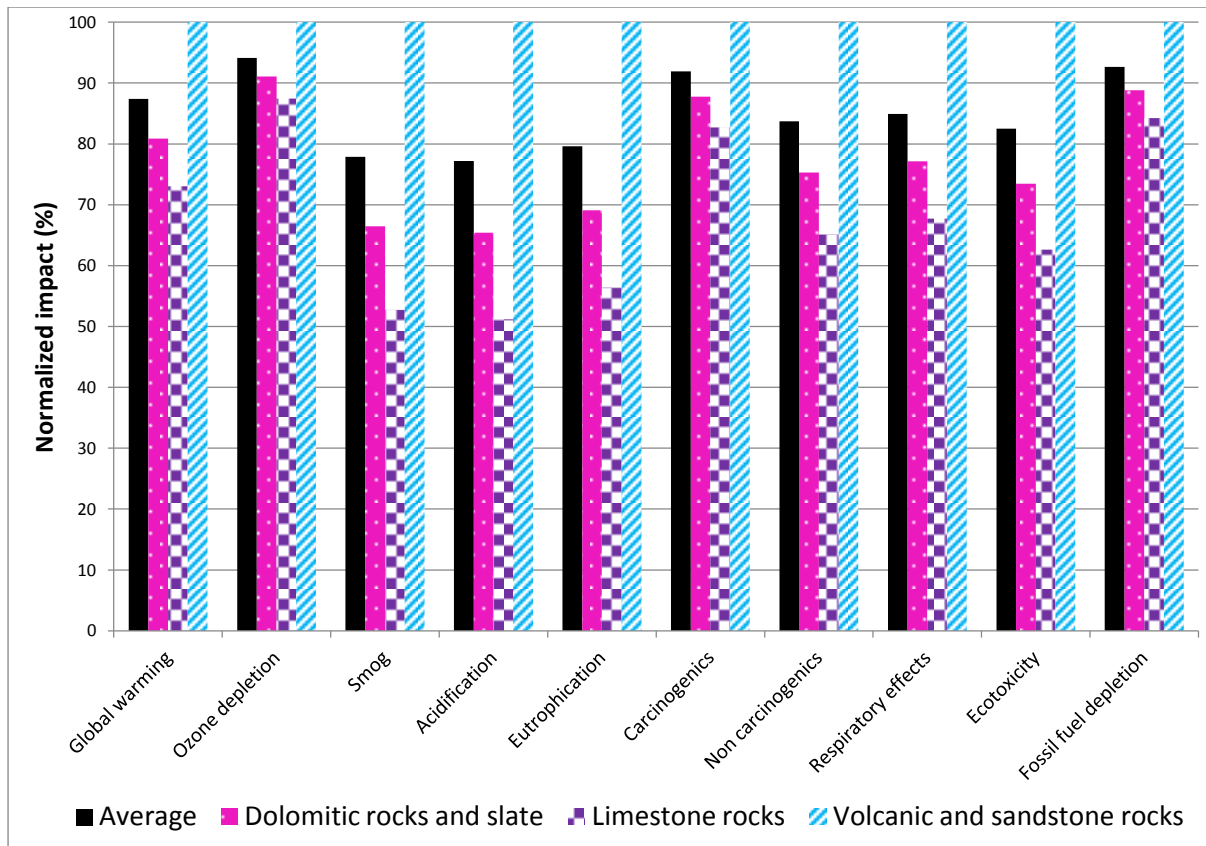


Figure 6 Normalized comparison of 2021 aggregate fixed production impacts depending on the nature of rocks

3.3.2. Electricity mix

Figure 7 and Table 14 show the results of a scenario analysis where, based on the LCA model for the 2021 average Eurovia’s fixed production in Quebec, the electricity mix is changed. In other words, I calculated the environmental impact of the same production as if it happened in other provinces of Canada – Ontario, Alberta – or with the average Canadian electricity supply, in some regions of the United States – the northeast part (NPCC electricity, for Northeast Power Coordinating Council), the western part (WECC electricity, for Western Electricity Coordinating Council) and the Midwest (MRO electricity, for Midwest Reliability Organization) -, with the average European mix, or with the average Chinese mix. Results show an important sensitivity of the aggregate impact to the electricity mix for global

warming (less impacting aggregates emit -37% of GHG than most impact ones), eutrophication (-68%), non-carcinogenics emission (-50%), and respiratory effects (-45%). On other impact categories, the decrease ranges from 5 to 32%, resp. for smog and carcinogenics. The carbon footprints of these aggregates range between 3.28 and 4.98 kgCO₂eq/t in resp. Quebec and China. Although our system boundaries are more complete than those of any study done so far – including blasting and capital goods manufacturing and maintenance, the first one being a main contributor to the carbon footprint of aggregates -, our carbon footprint range is consistent with the literature, and especially with the study of Ghanbari et al. which finds a carbon footprint range of 2.30-4.45 kgCO₂eq/t (2018), and Korre and Durucan's study that reported carbon footprints between 0.29 and 4.02 kgCO₂eq/t (2009). Canada's provinces present very variable impacts, with Alberta's aggregates displaying the worst consequences for the environment, due to a 90% fossil-based electricity mix. Alberta's aggregates have the highest impacts on eutrophication, health effects, and ecotoxicity, while China's aggregates are the worst on global warming, smog, and acidification. On the other impact categories, each of the three zones from the US alternatively presents the highest impacts. US productions rather rank in the highly impacting aggregates, except northeast production on some indicators (global warming, eutrophication, health impacts). Quebec's aggregates are always the less impacting thanks to the very high share of hydroelectricity in its mix (94%), the rest mainly coming from wind turbines (4%) (Canada Energy Regulator, 2022).

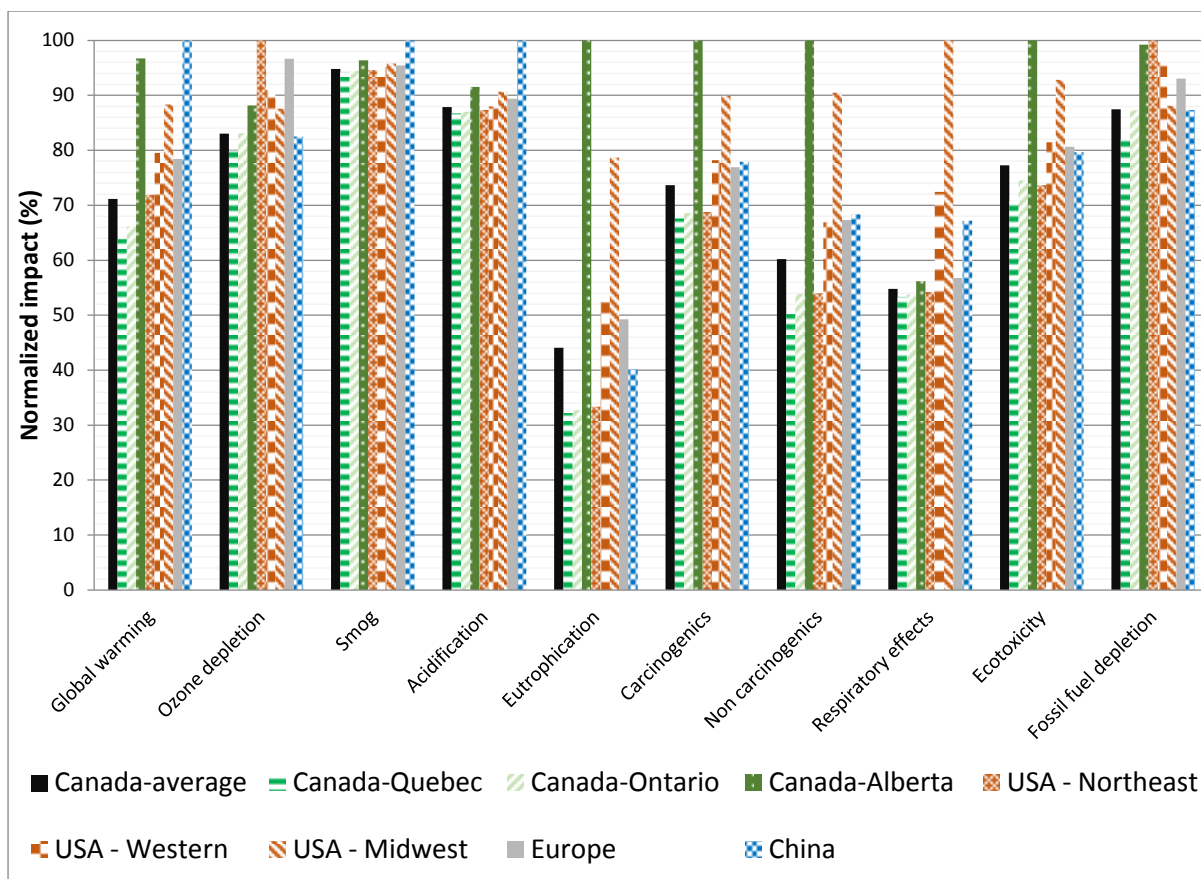


Figure 7 Sensitivity of the aggregate’s impacts to the electricity mix: comparison of Canadian provinces, US zones, Europe, and China

Table 14 Impact of aggregates depending on the electricity mix

Impact category	Unit	Canada-Alberta	Canada-average	Canada-Ontario	Canada-Quebec	China	USA - Midwest	USA - Northeast	Europe	USA - Western
Ozone depletion	kg CFC-11 eq	5.25E-07	4.95E-07	4.95E-07	4.76E-07	4.91E-07	5.22E-07	5.95E-07	5.76E-07	5.42E-07
Global warming	kg CO2 eq	4.98E+00	3.66E+00	3.40E+00	3.28E+00	5.15E+00	4.55E+00	3.70E+00	4.04E+00	4.10E+00
Smog	kg O3 eq	2.90E+00	2.85E+00	2.84E+00	2.84E+00	3.01E+00	2.89E+00	2.85E+00	2.87E+00	2.87E+00
Acidification	kg SO2 eq	1.24E-01	1.19E-01	1.18E-01	1.18E-01	1.36E-01	1.23E-01	1.19E-01	1.21E-01	1.20E-01
Eutrophication	kg N eq	3.53E-02	1.55E-02	1.15E-02	1.14E-02	1.42E-02	2.77E-02	1.18E-02	1.74E-02	1.85E-02
Carcinogenics	CTUh	6.85E-07	5.05E-07	4.70E-07	4.63E-07	5.34E-07	6.16E-07	4.71E-07	5.27E-07	5.36E-07
Non carcinogenics	CTUh	1.47E-06	8.88E-07	7.94E-07	7.40E-07	1.01E-06	1.33E-06	7.96E-07	9.92E-07	9.86E-07
Respiratory effects	kg PM2.5 eq	8.28E-03	8.08E-03	7.93E-03	7.87E-03	9.91E-03	1.47E-02	8.00E-03	8.37E-03	1.07E-02

<i>Ecotoxicity</i>	CTUe	7.85E+01	6.06E+01	5.85E+01	5.56E+01	6.25E+01	7.28E+01	5.78E+01	6.33E+01	6.39E+01
<i>Fossil fuel depletion</i>	MJ surplus	5.47E+00	4.83E+00	4.82E+00	4.52E+00	4.82E+00	4.86E+00	5.52E+00	5.13E+00	5.30E+00

3.3.3. Nature of the installation: mobile or fixed

Figure 8 compares the impact of average, fixed, and mobile productions of aggregates by Eurovia in 2020 and 2021. First, the inter-annual variation is very low: it never exceeds 3%, whatever the indicator. Based on our models, mobile production is overall more efficient than fixed production, excluding on ozone depletion, smog, and eutrophication. It especially reduces by 25% the impacts compared to the fixed production in terms of GHG emissions, around 10-15% in terms of carcinogenic emissions, around 20% in terms of non-carcinogenic emissions, and around 25% in terms of fossil fuel depletion. Yet, the consumption of explosives has been more important for the mobile industry – resp. 2.97 and $2.93 \cdot 10^{-4}$ kg/kg in 2020 and 2021, against 2.67 and $2.75 \cdot 10^{-4}$ kg/kg for the fixed industry – due to the nature of the rocks blasted in mobile sites. But lower fossil fuel consumptions are reported on mobile sites. On the health impact categories, the higher impact of the crushing unit maintenance in the case of mobile productions compared to fixed productions is explained by the exploitation of more abrasive rocks in the case of mobile production, which is not intrinsically related to the type of installation. But as the production and maintenance of conveyor belts on fixed production sites generate significant impacts, mobile production is ultimately less impactful on these two indicators.

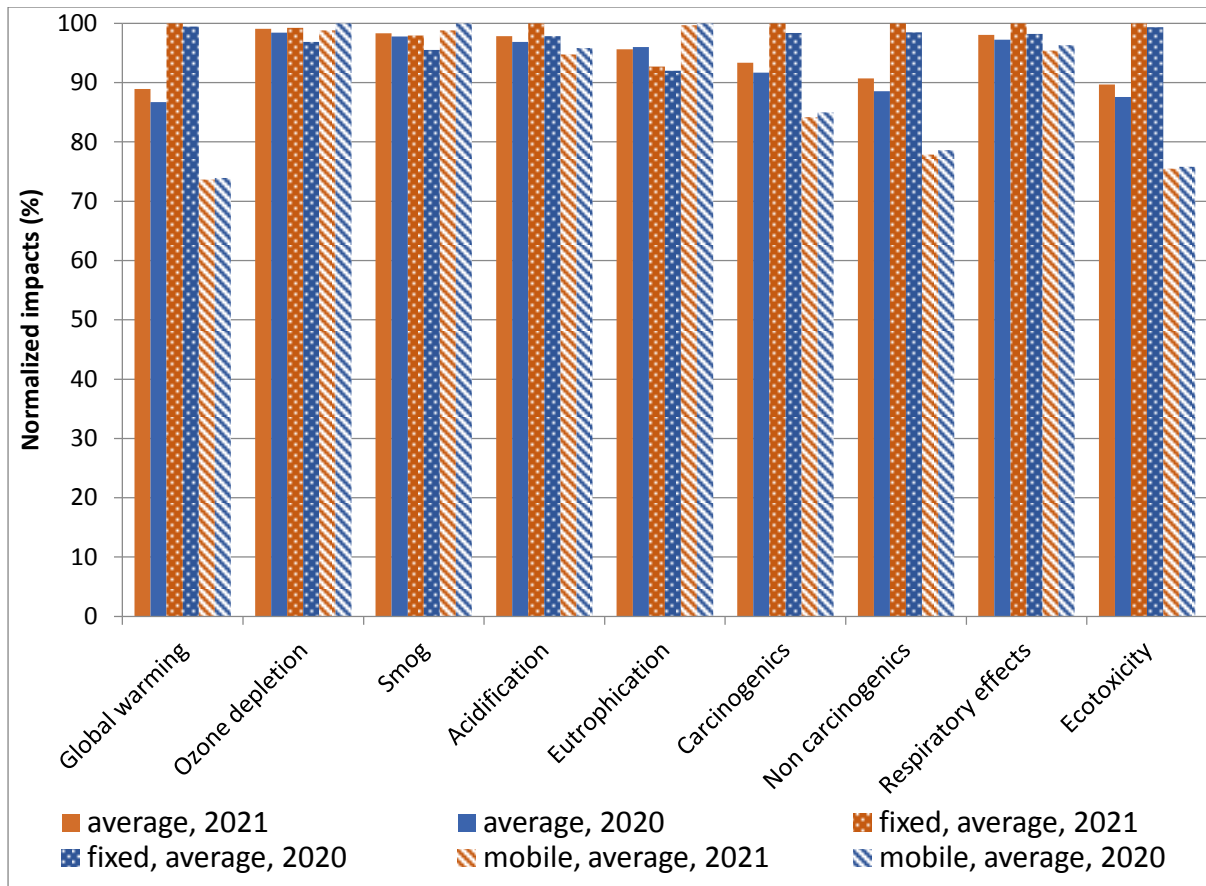


Figure 8 Comparison of the environmental impact of average Quebec’s aggregate productions with fixed versus mobile units.

Finally, the energy consumption reported by external crushing service suppliers must be questioned. Indeed, fuel consumption reported by Eurovia in its fixed sites is higher than fuel consumption reported by suppliers on mobile sites. Yet, fixed sites tend to be more electrified, normally implying a lower fuel consumption. The difference could partly be explained by shorter transportation distances from the basting site to the crusher on mobile sites, but this explanation seems still unsatisfying.

3.3.4. Transportation to consumer

Two kinds of trucks can be used to transport the aggregates to the consumer: the most common trailer trucks, or smaller 12-wheel trucks. Moreover, distances between quarries and

customers regionally vary widely in Quebec. Figure 9 presents the variability of aggregate carbon footprints, from cradle-to-consumer, depending on the distance from the quarry's gates to the customer, the truck used, and the transportation model. I developed the 12-wheel truck and trailer truck models (see methodological section), and compared their results to the results using the default truck transportation model from ecoinvent ("*market for transport, freight, lorry 16-32 metric ton, euro5 {RoW}*"), with doubled average distances to account for empty returns. The carbon footprint of the different options and models per ton of aggregates transported over one kilometer (tkm) is provided in the supplementary material and shows that 12-wheel trucks emit less than trailer trucks. Final results (Figure 9) show that transport to the customer can more than double the carbon footprint of the aggregate going out of the quarry, in the case of the region where transportation distances are the longest (i.e. Gaspésie's region). In the case of the shortest distance (i.e. Northern Materials area), with 12-wheel trucks, the extra emission due to transportation only represents 14% compared to the carbon footprint at gate. On average, transportation adds 46% to the carbon footprint at gate. Nevertheless, results show that the ecoinvent by-default model overestimates by a factor of two the emissions due to transportation. This is due to the feeble average load considered in the trucks by ecoinvent: a bit less than 6 tons on average, against three times more for the trailer trucks loaded with aggregates in Quebec on average (35.5 tons, full load, divided by two to account for empty returns). As ecoinvent transport processes calculate the impact per ton transported over one kilometer, the lower the load considered, the higher the impact per ton-kilometer. Tailoring the transport models in construction LCA is thus critical not to overestimate the impacts from this stage.

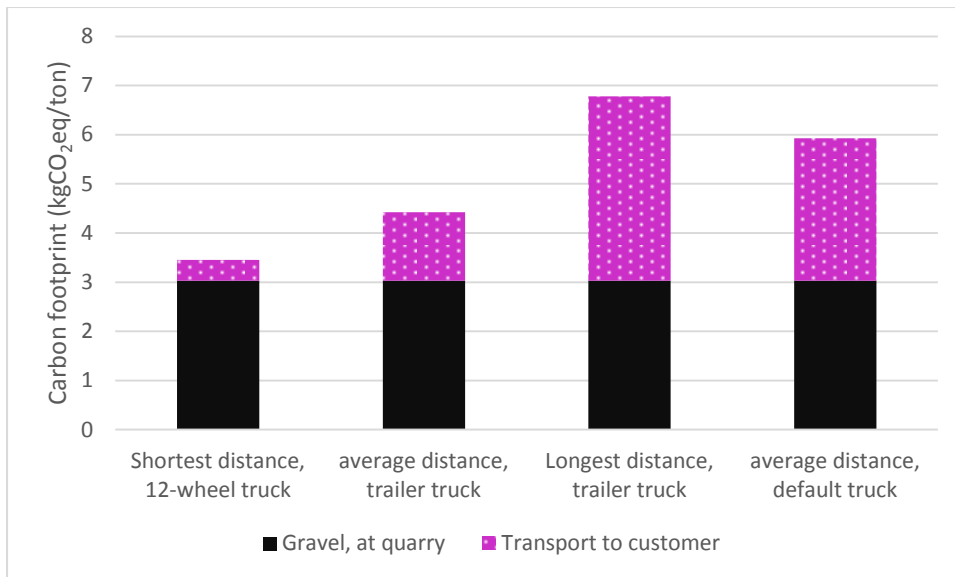


Figure 9 Aggregate carbon footprint from cradle-to-customer, from production (in black) and transportation (in magenta)

4. Discussion

4.1. Explaining carbon footprints

I will thus discuss my results through a comparison of my models with ecoinvent models based on real data collections in Switzerland, Brazil, and India. The models in ecoinvent display various carbon footprints: 3.4 kgCO₂eq/t in Switzerland, 4.9 kgCO₂eq/t in Brazil, and 7.3 kgCO₂eq/t in India (with TRACI characterization factors, see Table 15 and Figure 10). The Swiss inventory displays the lowest diesel consumption of all the models compared – 14 MJ/t against 27 MJ/t for the Brazilian inventory and 30 MJ/t for the Indian inventory – while our fixed-produced aggregate inventory reports 19 MJ of diesel consumed by ton of aggregate produced. As the Swiss inventory does not account for blasting, which is the top two contributor to the carbon footprint along with diesel in my models, its carbon footprint must then be even lower than the carbon footprint range that I get in this Canadian study. But the rough machinery and building amortization model, accounting for a substantial part of the

carbon footprint, explains this slightly higher carbon footprint, as well as higher consumption of LFO accounting for 8% of the Swiss carbon footprint. This quite high consumption of LFO (used in theory to heat buildings) seems unlikely based on current practices. This comparison also shows that our diesel consumption data, although in the lower range of existing LCI's diesel consumption, are consistent.

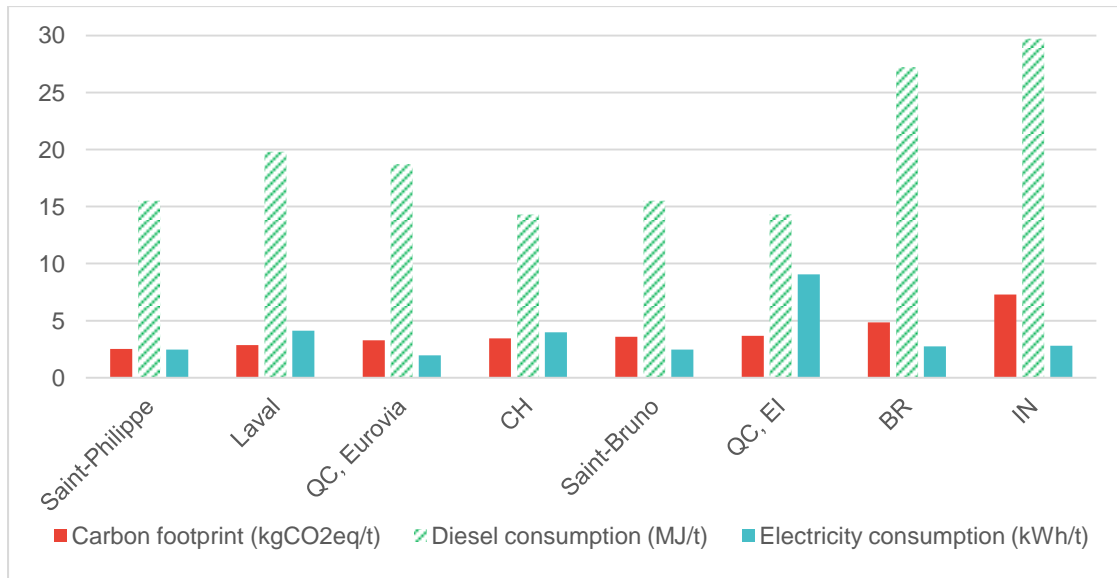


Figure 10 Comparison of carbon footprints, diesel, and electricity consumption in various aggregate LCA models and results

Table 15 Comparison of carbon footprints, main consumptions, and type of rocks in various aggregate LCA models and results

Source	Geography	Carbon footprint (kgCO ₂ eq/t)	Diesel consumption (MJ/t)	Electricity consumption (kWh/t)	Explosive consumption (g/t)	Type of rock	Comments
This study	Saint-Philippe	2.51	15.5	2.47	167	Limestone	
This study	Laval	2.86	19.8	4.11	167	Limestone	
This study	QC, Eurovia	3.28	18.7	1.95	275	Mixed	"gravel, fixed, average, 2021"
ecoinvent	CH	3.44	14.3	3.98	0	?	"gravel, crushed"
This study	Saint-Bruno	3.59	15.5	2.47	370	Volcanic (hard rock)	
ecoinvent	QC, EI	3.68	14.3	9.06	0	?	

ecoinvent	BR	4.86	27.2	2.74	370	Granite (hard rock)	
ecoinvent	IN	7.28	29.7	2.79	70.9	Granite and black trap stone	Basting emissions excluded

4.2. Nature of rocks matters

Jullien et al. did not find any consumption difference considering the nature of rocks: crushing requested 10.51 MJ/t (18.5 MJ/t in total) for the hard rocks they analyzed, while soft rocks requested 6.3 MJ/t on one site and 12.4 MJ/t on the other site. On average, the consumption of diesel and electricity represent 28.3 MJ of primary energy consumed per ton for the French aggregates studied in this article, against a range between 24.4 and 34.6 MJ/t in our study, and 28.6 and 46.9 MJ/t in ecoinvent. However, the comparison in Table 15 based on ecoinvent and my Canadian models shows that explosive consumption is one of the best explicative variables of the carbon footprint of aggregates, i.e. the nature of rocks. Thus, hard rock aggregates tend to present higher impacts than softer rock aggregates, which has not been shown in the French models developed by the UNPG syndicate, due to their restricted system boundaries (UNPG 2011a, 2011b). Let's recall that the Indian model from ecoinvent presents a surprising explosive consumption, 5 times lower than quantities usually used to extract the hard rocks modeled in this process. Let's also note that the aggregate carbon footprint is then mainly explained by diesel consumption, but that it can also substantially be explained by electricity consumption in countries where electricity mixes have high carbon intensity such as in India. Indeed, around 35% of the carbon footprint from the Indian aggregates can be explained by electricity consumption in the ecoinvent process.

5. Conclusions

My article presents the most advanced aggregate LCA models to date, allowing a better understanding of the environmental impacts of production and transport of the most used material in the world. It shows the importance of modeling blasting and machinery (crusher unit and conveyor belt): they are major contributors to several categories of environmental impact. I also demonstrated for the first time the high sensitivity of environmental impacts to the nature of the rock exploited. First, the harder it is, the more explosive it requires, which increases the impact. Second, the more abrasive the rock, the faster it degrades crusher wear parts, whose maintenance especially generates tensions on health impacts (carcinogenics, non-carcinogenics, respiratory effects), as well as ecotoxicity. I showed the pronounced sensitivity of the impacts to the electricity mix, by evaluating the case of several Canadian and American areas, Europe, and China : up to a factor of 3 between the less and the most impacting aggregate. Finally, I showed that truck transportation must be modeled based on construction-specific data sinceecoinvent's generic model overestimates the impacts of aggregate truck transportation by a factor of two. With tailor-made models, the average environmental cost of transporting the aggregate to the consumer increases the impact of the aggregate leaving the quarry by nearly 50%, with strong regional variability (+14 to +96%). In terms of perspectives, the development of new explosive and equipment LCIs, the monitoring of diesel consumption, machinery lifespan and wear depending on the nature of rocks, as well as on-site dust emission measures, are the next steps to improve aggregate LCI models. But in the short term, I call for completing the existing aggregate LCA models in the reference databases, especially with blasting and machinery wear, as well as customizing truck transport LCIs for construction, to more accurately assess the environmental impacts of aggregate consumption.

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