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1 **BIM can help decarbonize the construction sector: life cycle evidence from**

2 **Pavement Management Systems**

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11 **ABSTRACT**

12 Transforming the construction sector is key to reaching net-zero, and many stakeholders expect its
13 decarbonization through digitalization, but no quantified evidence has been brought to date. This article
14 proposes the first environmental quantification of the impact of Building Information Modeling (BIM) in the
15 construction sector. Specifically, the direct and indirect greenhouse gas (GHG) emissions generated by a
16 monofunctional BIM to plan road maintenance – a Pavement Management System (PMS) - are evaluated using
17 field data from France. The related carbon footprints are calculated following a life cycle approach, using
18 different sources of data – including ecoinvent v3.6 – and the IPCC 2013 GWP 100a characterization factors.
19 Three design-build-maintain pavement alternatives are compared: scenario 1 relates to a massive design and
20 surface maintenance, scenario 2 to a progressive design and pre-planned structural maintenance, and scenario 3
21 to a progressive design and tailored structural maintenance supported by the PMS. First, results show the
22 negligible direct emissions due to the PMS existence – 0.02% of the life cycle emissions of scenario 3's
23 pavement, e.g. 0.52 t CO₂eq for 10 km and 30 years. Second, the base case and two complementary sensitivity
24 analyses show that the use of a PMS is climate-positive over the life cycle when pavement subgrade bearing
25 capacity improves over time, neutral for the climate otherwise. The GHG emissions savings using BIM can
26 reach up to 14 and 30% of the life cycle emissions respectively compared to scenario 2 and 1, and resp. 47 and
27 65% when restraining the scope to maintenance and rehabilitation and excluding original pavement
28 construction. Third, the neutral effect of BIM in case of a deterioration of the bearing capacity of the subgrade

1 may be explained by design practices and safety margins, that could in fact be enhanced using BIM. Fourth, the
2 decarbonization potential of a multifunctional BIM is discussed, and research perspectives are presented.

3

4 **Keywords:** BIM, Pavement Management Systems, decarbonization, digitalization, LCA,
5 construction.

6 **1 Introduction and background**

7 Construction is a key sector that must be transformed to reach a net-zero society, and many
8 stakeholders expect its decarbonization through digitalization, but no quantified evidence has
9 been shown to date. In Canada, construction is the second most carbon-intensive sector,
10 accounting for 12% of the national emissions, 59% of them coming from infrastructure (de
11 Bortoli and Agez, Under review). To decrease this burden, many green construction practices
12 have been appraised using Life Cycle Assessment (LCA) - for buildings (e.g. Anand and
13 Amor, 2017; Vilches et al., 2017) or infrastructure (e.g. AzariJafari et al., 2016; Saxe et al.,
14 2020) - while the environmental consequences of digitalization such as the use of Building
15 Information Modelling (BIM) for buildings have been presented positively as a way to
16 automatize environmental quantifications and optimizations (Soust-Verdaguer et al., 2017).
17 BIM is defined as the “use of a shared digital representation of a built asset to facilitate
18 design, construction, and operation processes to form a reliable basis for decisions”
19 (International Organization for Standardization, 2018). Its direct and indirect environmental
20 impacts – those due to resp. the amortization of BIM’s hardware, equipment and
21 infrastructure, their operation, and the usage of BIM’s software, and the consequences of
22 BIM on construction processes and management - have never been quantified to date. In the
23 meantime, the environmental impact of digital services has been increasingly studied

1 (ADEME, 2016) and shown to be significant: Information and Communication Technologies
2 (ICT) would emit between 1.8 and 3.9% of the global anthropogenic greenhouse gas (GHG)
3 (Freitag et al., 2021). Thus, it cannot be inferred that the direct environmental impact of BIM
4 is negligible, nor that its potential indirect environmental benefits overcome its direct costs.
5 This paper aims to offer a first life cycle quantification of these aspects.

6 The impact of infrastructure construction exceeding those of buildings (de Bortoli and Agez,
7 Under review), this paper will focus on infrastructure. Moreover, among the different kinds
8 of infrastructure, roads support the most emitting mean of transportation (Our world in data,
9 2020). Their decarbonization is thus a priority to reach a net-zero pathway. However, BIM
10 for infrastructure is less advanced than BIM for buildings (Malagnino et al., 2021). “I-BIM”,
11 “Infra-BIM”, or BIM for infrastructure, started to be implemented in 2013 in the rail
12 construction sector of developed countries (Matejov and Šestáková, 2021). Since then, it has
13 been shown to help design road elements thanks to visualization – e.g. pavement sections,
14 roundabouts, tunnels (Vignali et al., 2021) -, planning airport maintenance (Abbondati et al.,
15 2020), and in general improving infrastructure (Costin et al., 2018). I-BIM-based
16 environmental assessments would also increase sustainability awareness within design teams
17 (van Eldik et al., 2020), but the direct and indirect environmental impacts of I-BIM have not
18 been quantitatively investigated. The difficulty in assessing these impacts lies both in the
19 versatility of I-BIM and its novelty. It started to be punctually used one decade ago, and 47
20 categories of usages have been classified, including automations, pricing, monitoring, failure
21 detection, and maintenance planning (Costin et al., 2018).

22 Pavement Management Systems (PMS) are common software programs analyzing road
23 condition data to plan maintenance. These PMSs allow to adopt different strategies in the
24 design-build-maintain sequence related to a pavement life cycle, compared to a non-digitally
25 helped pavement management. They are thus equivalent to a monofunctional I-BIM

1 dedicated to road maintenance and used for decades by road operators. As ex-post
2 assessments generally present a lower degree of uncertainty than prospective assessments, a
3 case study will be conducted to quantify on field data the consequence of using this
4 experienced BIM function on a pavement life cycle carbon footprint, compared to alternative
5 ways to design and maintain this pavement.

6 Two main schools of thought exist to design roads and schedule their maintenance: empirical
7 vs mechanical-empirical (ME) methods. The American continent mainly used the AASHTO
8 empirical method (AASHTO, 1993), before switching progressively to a ME version
9 (AASHTO, 2008; US DoT - FHWA, 2019a, 2019b, 2019c, 2019d). In France and Africa, the
10 LCPC-Setra ME method is widely used (LCPC-Sétra, 1994). A catalogue of standard
11 solutions has been made available (Corte et al., 1998), while design and maintenance plans of
12 strategic pavements are usually tailored using the match ME software “Alize”. As they carry
13 a substantial portion of the traffic (around 20%) on a short portion of the national road
14 network (1%) (de Bortoli 2018), high-traffic roads present strategic socioeconomic
15 importance, and more design-build-maintain alternatives. Thus, this case study will focus on
16 high-traffic roads.

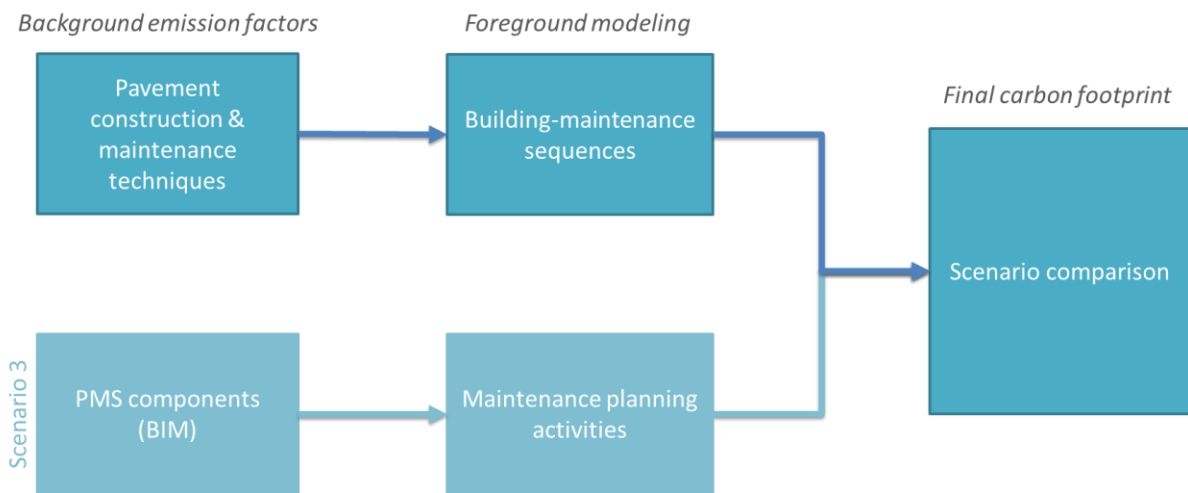
17 The objectives of this study are to quantify the carbon footprint of (1) the PMS function of an
18 I-BIM based on field data, and (2) three design-build-maintain alternatives for a high-traffic
19 road in France over its entire life cycle, (3) to understand the potential impact of the PMS
20 function of a BIM on climate change, and (4) discuss the environmental consequences of a
21 multifunctional BIM.

1 **2 Method**

2 **2.1 Overview of the method**

3 A method is developed to quantify the carbon footprint of the most common ways to design,
4 build and maintain high-traffic roads in France, including an option where maintenance is
5 digitally helped using a PMS, to compare the GHG emissions related to these different
6 practices and seize the consequences of using digital tools for maintenance operation
7 planning that could be included in an I-BIM. This method consists in developing three
8 design-build-maintenance scenarios to compare their life cycle carbon footprint, calculated
9 based on foreground and background inventories (or emission factors) from the literature,
10 road maintenance operators, and their suppliers. The quantification method is based on LCA,
11 applied consistently with Standards ISO 14040 and 14044 (International Organization for
12 Standardization, 2006a, 2006b), and the characterization factors chosen are IPCC 2013 GWP
13 100a, the most recent factors when this study was conducted (mid-2021). The system
14 boundaries include production, maintenance, and use stages. The functional unit is “building
15 and maintaining in good condition over 30 years a 10 kilometer-long and 7-meter-wide
16 section of highway in France, under a traffic of 500 heavy vehicles per day”.

17 In this method section, the foreground modeling will be first presented, i.e. the scenarios of
18 design-build-maintenance operations and related PMS activities as well as the equations to
19 calculate the carbon footprint of the pavement over its life for each scenario. The scenarios
20 are detailed in the following section developed with pavement construction companies and
21 highway concessionaires in France. Second, the background data and emission factors (EF) to
22 quantify this carbon footprint will be detailed. An EF is the carbon footprint of any unitary
23 activity occurring during the pavement lifespan.



1

2 **Figure 1 Calculation method overview**

3 **2.2 Case study scenarios**

4 **2.2.1 A theoretical representative French highway**

5 The case study is conducted on a theoretical representative French highway, with two lanes in
6 each direction, bearing a traffic of 500 heavy vehicles per day and direction (the “T1” French
7 class of Average Annual Daily Traffic (AADT)), with a traffic rate assumed at 0%. A 10-
8 kilometer-long section designed to last 30 years is considered, with a width of 7 meters per
9 direction (excluding shoulders), and a class « PF2qs » subgrade at the commissioning stage.
10 Subgrades are classified in France based on the French standard NF P 94-117-1 (AFNOR,
11 2000), the “SETRA-LCPC” guides on pavement subgrade design (Corte et al., 2000a,
12 2000b), and a national complement on PF2qs class subgrades (CEREMA, 2017). A PF2qs
13 subgrade corresponds to a “Plate Test Static Deformation Module” (EV2) between 80 MPa
14 (included) and 120 MPa (excluded) (CEREMA, 2017). Ten years after commissioning, this
15 bearing capacity is assumed to decrease toward a “PF2” subgrade class ($50 \text{ MPa} \leq \text{EV2} < 80$
16 MPa) over 25% of the linear and increase toward a “PF3” subgrade ($120 \text{ MPa} \leq \text{EV2} < 200$
17 MPa) over 25% of the section as well, respectively due to drainage issues deteriorating the

1 subgrade and traffic compacting the soil. Fifty percent of the linear will maintain a PF2qs
 2 subgrade overtime.
 3 This evolution has been arbitrarily estimated by Eurovia, a leading road construction
 4 company worldwide, and sensitivity analyses will be conducted, respectively over a restricted
 5 and an extreme range of subgrade evolutions. This problem presents three parameters –
 6 respectively %PF2, %PF2qs and %PF3 the average percentage of each subgrade class length
 7 over the pavement lifespan. The sum of these parameters equals 100% but can vary
 8 independently. Thus, there is no continuous representation showing all the possibilities of the
 9 subgrade evolutions. For this reason, arbitrary values are chosen for these sensitivity
 10 analyses. Table 1 presents the parameters' values that will be tested for the restricted range
 11 sensitivity analysis (SA), while Table 2 presents the parameters' values for the extreme
 12 range SA.

13 **Table 1 Parameters' values for the “restricted range” sensitivity analysis**

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f - base</i>	<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>	<i>k</i>
%PF2	0.5	0.4	0.3	0.2	0.1	0	0	0	0	0	0
%PF2qs	0.5	0.6	0.7	0.8	0.9	1	0.9	0.8	0.7	0.6	0.5
%PF3	0	0	0	0	0	0	0.1	0.2	0.3	0.4	0.5

14

15 **Table 2 Parameters' values for the “extreme range” sensitivity analysis**

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f - base</i>	<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>	<i>k</i>
%PF2	1	0.8	0.5	0.5	0.4	0.25	0.1	0.1	0	0	0
%PF2qs	0	0.2	0.5	0.4	0.5	0.5	0.5	0.4	0.5	0.2	0
%PF3	0	0	0	0.1	0.1	0.25	0.4	0.5	0.5	0.8	1

16 **2.2.2 Massive vs progressive designs and maintenance**

17 Two ways of designing pavements can be considered in France: a massive vs a progressive
 18 design. We call massive design (Scenario 1) an approach that consists of designing a
 19 pavement to last till the end of its life without structural reinforcement under the traffic

1 expected. In that case, maintenance operations are only performed to keep the pavement
2 surface in good condition: ensuring waterproofness, a skid resistance suiting safety
3 thresholds, and good riding conditions. In France, massive design is guided by the LCPC-
4 Setra catalogue for pavements (Corte et al., 1998).

5 Alternatively, a progressive design (Scenarios 2 and 3) is performed when a pavement is not
6 originally designed to mechanically resist the traffic expected over its entire service life and
7 needs structurally-reinforcing maintenance operations that will at the same time restore good
8 surface condition. This second approach requires to use a ME design software and may be
9 selected by road concessionaires to optimize discounted cash flows and reduce traffic risk.
10 This risk management practice is particularly attractive under an ever more uncertain future,
11 due to climate change consequences on pavement conditions and changes in behaviors related
12 to cultural standards evolutions, economic crises, and else.

13 Then, two approaches allow for managing the maintenance of progressively-designed
14 pavements: theoretical mechanical planning (scenario 2) or data-supported adaptative
15 planning (scenario 3). The maintenance in scenario 2 is planned during the design process
16 using a ME design software considering traffic forecast and can be further modified with
17 traffic data. Scenario 3 consists of data-supported maintenance management: it relies on
18 traffic data but also pavement condition data collected and monitored over time, stored, and
19 analyzed in a PMS. This is the most tailored maintenance approach existing, as it adapts to
20 the real evolution of traffic, climate, and thus pavement mechanical conditions. It thus avoids
21 premature pavement failures as well as structural oversizing.

22 *2.2.3 Design and maintenance sequence by scenario*

23 **Description**

1 The pavement design and maintenance sequences of the three scenarios are illustrated in
2 Figure 2, with a theoretical risk of failure of 5%. It means that, over the pavement's lifespan,
3 with the original subgrade class and under the traffic expected, 5% of the surface will have
4 experienced bottom-up cracking calling for rehabilitation (=full-thickness reconstruction).
5 The thickness and material type of each layer are presented over the 30-year service life in
6 Figure 2. The different materials and techniques used are cold micro asphalt concrete
7 surfacing (CMACS, called "enrobés coulés à froid" (ECF) in French), semi-coarse aggregate
8 asphalt concrete (overlays) (SCAC(O), called "béton bitumineux semi-grenu" (BBSG) in
9 French), Road base asphalt (RBA, called "grave-bitume" (GB3) in French), (very) thin
10 asphalt concrete overlays ((V)TACO, called "béton bitumineux (très) mince (BB(T)M) in
11 French). Scenario 1 is extracted from the French LCPC-Setra Catalogue (Corte et al., 1998).
12 SCAC M&F corresponds to mill (M) a former surface layer before filling (F) it with SCAC.
13 Scenario 2 is designed with ODIN, Eurovia's ME design software based on the same physics
14 as the standard Alizé's software. In Scenarios 1 and 2, the road manager does not have data
15 on the evolution of the road condition and is thus unaware of the evolution of the subgrade
16 bearing capacity. This results in subsections of the pavement failing prematurely. The
17 cumulated section's portion likely to fail over time is calculated with Odin and provided in
18 the supplementary material. Finally, scenario 3 is also managed with Odin but with perfect
19 knowledge of the pavement evolution, including the subgrade's modulus, and maintenance is
20 optimized accordingly.

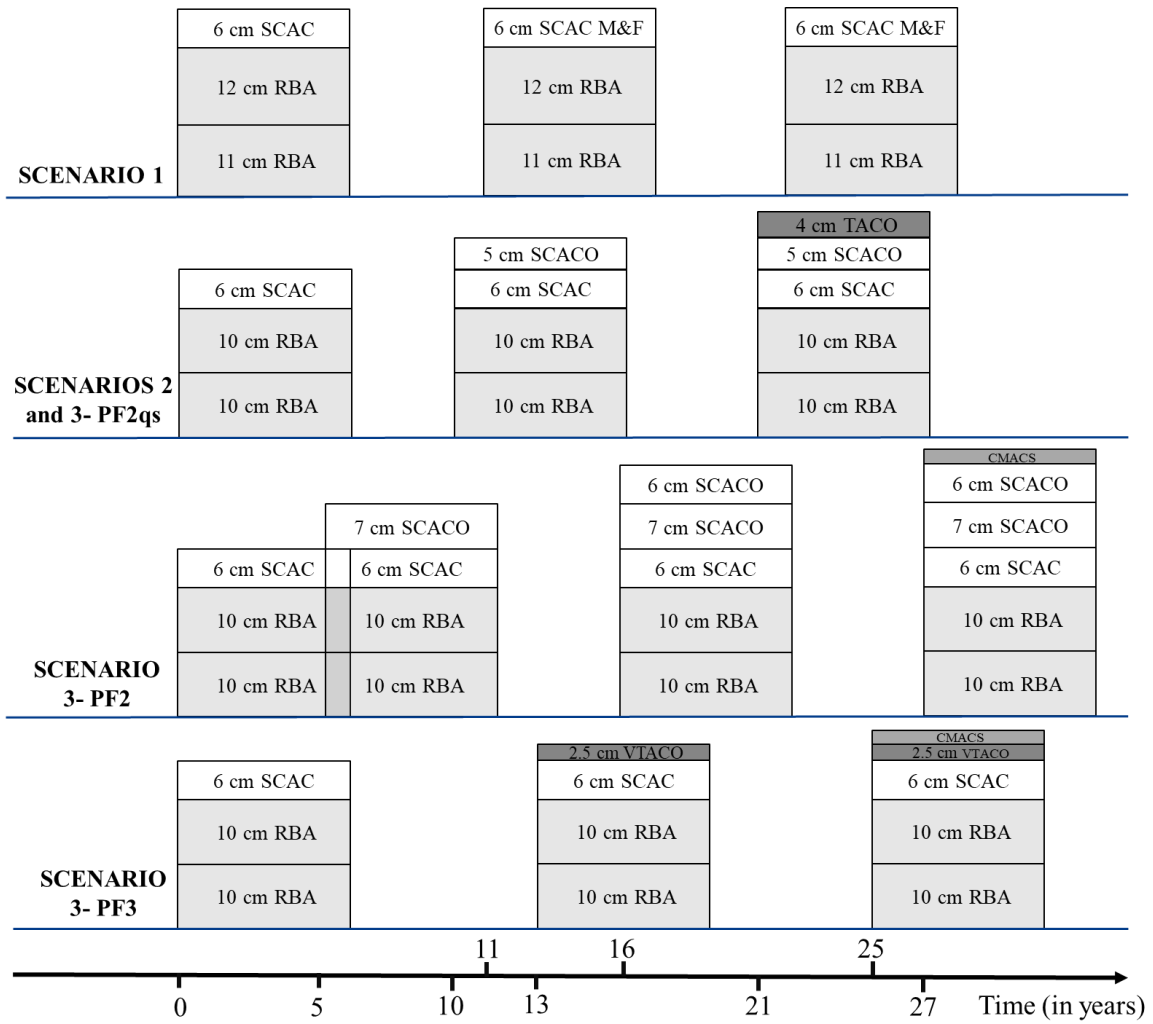


Figure 2 Design and maintenance sequence of the different scenarios

Carbon footprint

The carbon footprint CF of the built-maintained pavements over 30 years will be calculated following equation (1), where $W_{section}$ is the width of the pavement studied (in meters), $L_{section}$ the length (in meters), and EF_i the emission factor of the construction operation i occurring during the pavement lifespan (in $kgCO_2eq/sm$), this operation being related to original construction or maintenance.

$$CF(\text{built} - \text{maintained pavement}) = \sum_i W_{section} \times L_{section} \times EF_i \quad (1)$$

1 2.2.4 *Pavement Management*

2 **Modeling scenarios**

3 In scenarios 1 and 2, premature pavement failures are identified by regular patrolling, i.e. via
4 visual surveying performed by trained staff, often from the pavement management company.

5 As scenario 3 also comes with this patrolling, these operations will be removed from the
6 system boundaries for all scenarios, following ISO 14044 guidelines (International
7 Organization for Standardization, 2006b). On the other hand, scenario 3 requires pavement
8 monitoring by an equipped truck which measures the evolution of the bearing capacity of the
9 highway pavement. This data is therefore collected and then stored in a database. A pavement
10 asset management team will then analyze them to plan the maintenance operations.

11 To model this PMS's features (illustrated in Pavement Management System use casesFigure
12 3), a "SysML Use cases" diagram is used. this formalism describes use cases and external
13 actors' interactions in a concise way. Three external system users are considered: external data
14 (that need to be collected), an external database (that is used to store data), and the user of the
15 PMS (that is a member of the pavement asset management team). Four use cases are
16 considered: collecting external data, storing internal data, running a local task, and
17 transferring internal data. The last two use cases constitute the PMS's maintenance operation
18 planning. To be more efficient, only the main use cases are represented, and the
19 extend/include relationships are omitted. For example, collecting data may be extended to
20 storing.

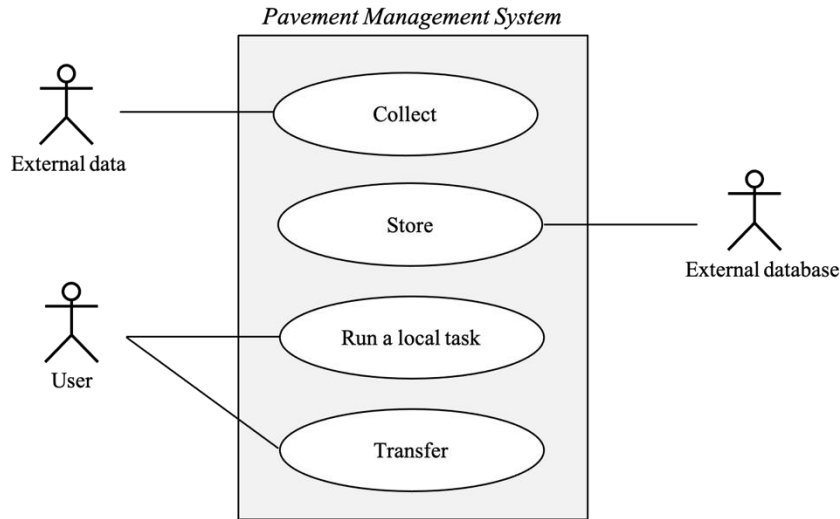


Figure 3 Pavement Management System use cases

PMS carbon footprint

The Global Warming Potential (GWP) of a PMS for a pavement section, $I_{PMS}^{section}$, can be calculated using the generic equation (2):

$$I_{PMS}^{section} = I_{PMS}^{data} + I_{PMS}^{storage} + I_{PMS}^{maintenance} \quad (2)$$

Where:

- The section is defined by a length and a maintenance period
- I_{PMS}^{data} is the GWP to collect the data related to the section
- $I_{PMS}^{storage}$ is the GWP to store the data related to the section
- $I_{PMS}^{maintenance}$ is the GWP to plan the maintenance operation related to the section

Data collection of the pavement condition

In France, we use different types of deflectometer to measure pavement deflection. In this case study, a curviameter is used, i.e. an instrumented truck weighted with 13 tons on its rear axle to record the deformation under this axle. According to ecoinvent's truck classification, this vehicle is considered as a 16-32 ton truck, and a EURO6 emissions standard is

1 considered. French national roads are standardly monitored every three years in each
2 direction (Lorino et al., 2006), but some strategic roads can be monitored more often, such as
3 once a year.

4 The GWP of the data collection, I_{PMS}^{data} , is defined by equation (3):

$$5 \quad I_{PMS}^{data} = n_{round} * P_m * L_{section} * F_m \quad (3)$$

6 Where:

- 7 - P_m is the maintenance period in years
- 8 - $L_{section}$ is the length of the studied section in km
- 9 - n_{round} is the number of monitoring rounds per year
- 10 - F_m is the emission factor of the vehicle used to collect road condition data in kg
11 CO_2eq per km

12 We choose the worst-case scenario, in which the monitoring round is conducted every year.
13 The emission factor of the instrumented truck, F_m , is calculated from the 16-32 ton EURO6
14 Transport freight process from Ecoinvent 3.4 process (see Table 4). To estimate the carbon
15 footprint of such a truck per kilometer traveled, we multiply the freight transportation process
16 based on the ton-kilometer functional unit by the average load considered by ecoinvent – i.e.
17 5.79 tons (Spielmann et al., 2007).

18 **Data storage**

19 The PMS's database is composed of several pieces of hardware: 3 servers (ProLiant BL460c
20 Gen10 and ProLiant BL460c Gen9 models), 1 storage bay (3PAR 8200 model), and 1 backup
21 bay (StorOnce 5500 model). The GWP of the data storage related to the studied
22 section, $I_{PMS}^{storage}$, is defined by equation (4):

$$23 \quad I_{PMS}^{storage} = \frac{P_m * L_{section}}{L_t} * k_{database} * \left(\frac{I_{hard}}{\Delta_{hard}} + I_{yrun} \right) \quad (4)$$

24 Where:

- 1 - L_t is the total section's length informed in the database in km
- 2 - $k_{database}$ is the allocation coefficient considering the proportion of the database used
- 3 for the PMS
- 4 - I_{hard} is the GWP of the PMS's database hardware in kg CO₂eq
- 5 - Δ_{hard} is the depreciation period of the hardware database in years
- 6 - I_{yrun} is the GWP of a one-year run of the database in kg CO₂eq

7 In this case, the entire database is dedicated to PMS: $k_{database} = 1$. Δ_{hard} and L_t are given
 8 by an internal expert (see Table 3). I_{hard} and I_{yrun} are provided by the manufacturer (see
 9 Table 4).

10 **Data analyses**

11 Data are analyzed by the pavement asset management team to plan the maintenance. The
 12 evolution of the bearing capacity of the subgrade is extrapolated from the pavement
 13 deflection. Then, the need for further structural reinforcements or delaying operations is
 14 estimated. The digital activities of the team are composed of local tasks, with a computer, and
 15 data transfer from the PMS's database. More specifically, two types of users, and thus
 16 computers, are involved: standard and advanced stations. The GWP of the maintenance
 17 operation planning, $I_{PMS}^{maintenance}$, is defined by equation (5):

$$18 \quad I_{PMS}^{maintenance} = n_{operation} * P_m * L_{section} * (k_t * F_{transfer} + F_{adv} + F_s) \quad (5)$$

19 Where:

- 20 - $n_{operation}$ is the number of maintenance planning during one year
- 21 - k_t is the data volume transferred per PMS planning operation per km and year
- 22 - $F_{transfer}$ is the emission factor to transfer data
- 23 - F_s and F_{adv} are the emission factors of the amortization of the two types of computing
- 24 stations

1 According to an internal expert, maintenance operation planning is carried out every 15
 2 years: $n_{operation} = 1/15$. This internal expert considers, in a worst-case scenario, that three
 3 maintenance planning conducted on a 100 km section over 50 years require 50 gigabytes
 4 (GB) of data transfer. Thus, k_t is calculated from this estimation.

5 F_{adv} and F_s are calculated with equation (6):

$$6 \quad F_{adv} = k_{adv} * \left(\frac{I_{adv_device}}{\Delta_{adv_device}} + 24 * P_{adv_device} * F_{elec} \right) \quad (6)$$

7 Where:

- 8 - k_{adv} is the number of days spent on the PMS software on the advanced station, per
 9 PMS planning operation, per km, and per year
- 10 - I_{adv_device} is the GWP of the advanced computing station's manufacturing in kg
 11 CO₂eq
- 12 - Δ_{adv_device} is the depreciation period of the advanced computing station
- 13 - 24 is the number of hours per a day
- 14 - P_{adv_device} is the electrical power in watts, daily weighted
- 15 - F_{elec} is the emission factor of the electricity consumption

16 The internal expert considers, in a worst-case scenario, that three maintenance operation
 17 planning conducted on a 100 km-long section for 50 years require 40 days on the PMS
 18 software on the standard station and 15 days on the PMS software on the advanced station.
 19 This allows calculating k_{adv} and k_s (see Table 3). A standard computer is composed of a
 20 laptop and two display screens while an advanced computer uses a computer desktop with
 21 two display screens, a pointing device, and a keyboard. This allows calculating I_{adv_device}
 22 and I_{s_device} from the ecoinvent database (see Table 3). Δ_{adv_device} and Δ_{s_device} correspond
 23 to 5 years, converted to 1825 days.

1 We assume, in agreement with the internal expert, that a display screen operates for 8 hours
2 per day at 90 W and stays on stand-by at 1 W for the remaining time. A laptop also operates 8
3 hours per day at 65 W but is turned off the rest of the time. Finally, a desktop computer
4 operates all day, i.e. 24 hours, at 300 W. Those assumptions allow us to determine P_{adv_device}
5 and P_{s_device} (see Table 3). The emission factor of the electricity consumption F_{elec} is also
6 given (see Table 4).

7 **Table 3 Foreground data of PMS carbon footprint**

<i>Data</i>	<i>Value</i>	<i>Unit</i>
n_{round}	1	
$k_{database}$	1	
Δ_{hard}	5	years
L_t	2737	km
$n_{operation}$	1/15	
k_t	$3.33 \cdot 10^{-3}$	$GB \cdot (\text{operation} \cdot \text{year} \cdot \text{km})^{-1}$
Δ_{adv_device}	1825	days
Δ_{s_device}	1825	days
k_{adv}	10^{-3}	$(\text{operation} \cdot \text{year} \cdot \text{km})^{-1}$
k_s	$2.6 \cdot 10^{-3}$	$(\text{operation} \cdot \text{year} \cdot \text{km})^{-1}$
P_{adv_device}	330.67	W
P_{s_device}	83	W

8 **2.3 Background emission factors**

9 **2.3.1 Road construction and maintenance operations**

10 Life cycle inventories (LCI) for road construction and maintenance operations have been
11 developed by de Bortoli et al. (2018; 2022a) in the French context. They are the most
12 representative LCIs within the existing LCIs for the context of this study (de Bortoli, 2020) in
13 terms of asphalt binder, aggregates, asphalt mixing, building machines, material
14 transportation, and else. These cradle-to-laid LCIs are based on the functional unit of one
15 square meter of pavement built over a certain thickness, in centimeters, or milled. As these
16 LCIs were specifically developed to study resurfacing strategies, some of them have been re-

1 scaled to model the original construction of the pavement, over a thicker layer, consisting of
 2 more material per square meter but also sometimes more compaction operations. The
 3 compaction of the subbase and base layers has been modeled based on Eurovia practices
 4 depending on the layer's thickness. The detail can be found in the supplementary material
 5 (excel spreadsheet).

6 2.3.2 Pavement management system

7 Data storage

8 I_{hard} and I_{yrun} are provided by the manufacturer to the internal expert (see Table 4).

9 Data analyses

10 F_{elec} is the emission factor of the electricity mix. The electricity is mainly consumed in
 11 France and we use the French *Base carbone* emission factor (ADEME, n.d.). $F_{transfer}$ is
 12 calculated based on the worst energy intensity of Internet transmission reported by Coroama
 13 and Hilty, i.e. 1.8 kWh/GB (2014), and F_{elec} . To calculate I_{adv_device} and I_{s_device} , we use
 14 the following global market ({GLO}) processes from ecoinvent v3.4: “Computer laptop” and
 15 “Display liquid crystal 17 inches” for the standard station, and “Computer, desktop, without
 16 screen”, “Keyboard” and “Pointing device optical mouse with cable” for the advanced
 17 station.

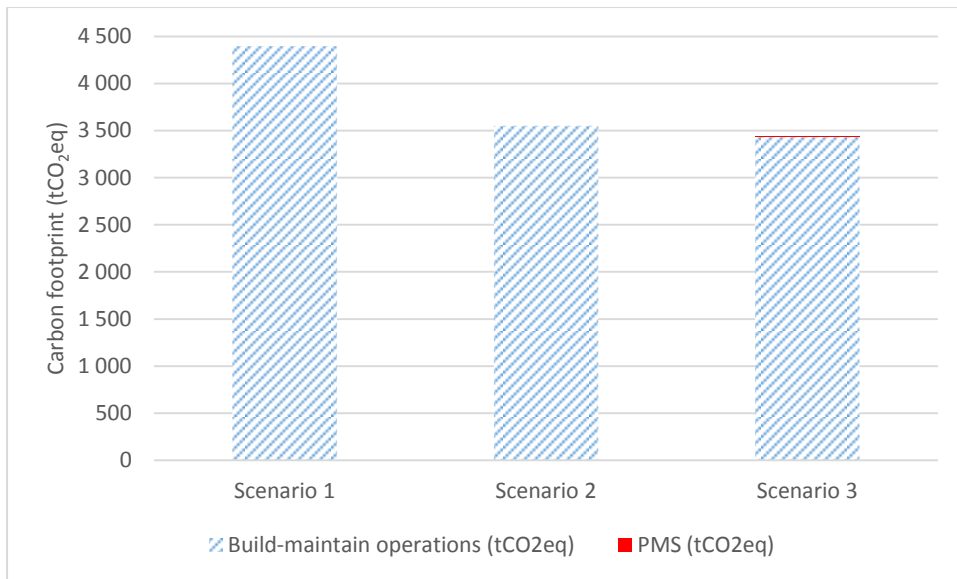
18 **Table 4 Background data to calculate the PMS's carbon footprint**

<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
F_m	0.92	kg CO ₂ eq * km ⁻¹
I_{hard}	167	kg CO ₂ eq
I_{yrun}	1165	kg CO ₂ eq * year ⁻¹
F_{elec}	59.9*10 ⁻³	kg CO ₂ eq * kWh ⁻¹
$F_{transfert}$	107.82*10 ⁻³	kg CO ₂ eq * GB ⁻¹
I_{adv_device}	1052.43	kg CO ₂ eq
I_{s_device}	942.31	kg CO ₂ eq

1 **3 Results and interpretation**

2 *3.1 Comparison of the three design-build-maintain practices*

3 Figure 4 shows the carbon footprint of the pavement over its 30-year-long lifespan depending
4 on the scenario. Scenarios 2 and 3 emit less than scenario 1, respectively by 19 and 22%. This
5 means savings of respectively 961 and 1076 t CO₂eq for the 10 km-long section over 30
6 years. Thus, massive GHG savings occur from the transition from massive to progressive
7 pavement design. But tailored maintenance thanks to the PMS in scenario 3 reduces by an
8 additional 3% the GHG emissions of the pavement over its life cycle compared to a non-data-
9 driven maintenance scheme (scenario 2). If not considering the original construction
10 emissions, BIM generates 11% GHG savings on the maintenance and rehabilitation of the
11 pavement over its service life. The direct impact of the PMS usage – e.g. manufacturing of
12 the digital hardware, infrastructure and data collection vehicle as well as their operation and
13 the use of the software - is highlighted in red (Figure 4): it accounts for 0.52 t CO₂eq over the
14 pavement section life cycle, e.g. 0.02% of scenario 3's carbon footprint, for one data
15 collection per year. If the pavement condition data is collected every three years instead, the
16 PMS direct impact is even lower, decreasing to 0.33 t CO₂eq. The carbon footprint of the
17 PMS is negligible compared to the pavement construction and maintenance emissions. On the
18 contrary, it might be surprising to get more emission gains limited to 3.4% from the tailored
19 maintenance.



1

2 **Figure 4 Carbon footprint of the pavement life cycle depending on the scenario**

3 **3.2 Roadworks' contributions**

4 To understand better why the PMS does not bring more substantial gains (-3.3% emissions),

5 Figure 5 presents the impact contribution of each stage of the pavement life cycle. The use of

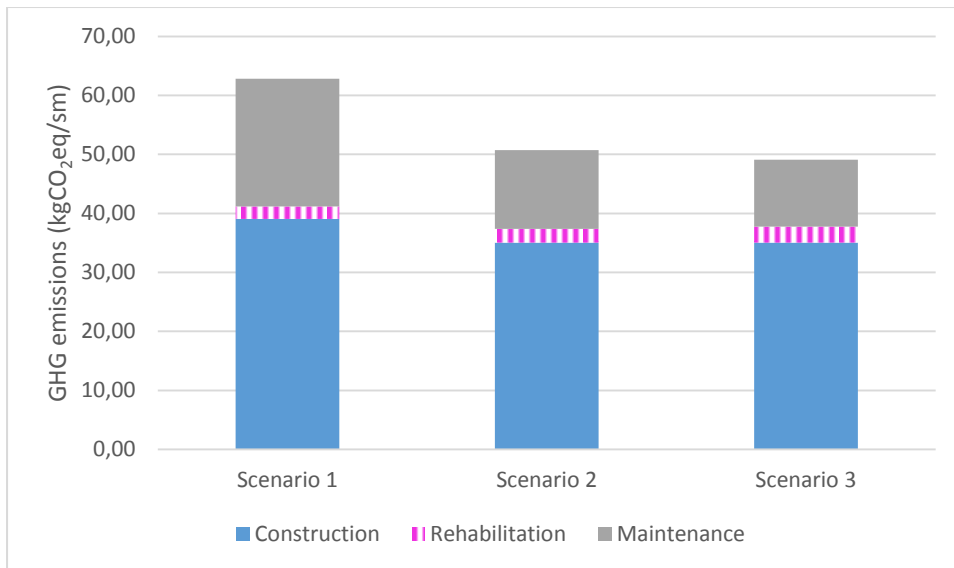
6 the PMS allows to reduce the probability of pavement damage and thus the length to rebuild:

7 scenario 2 presents a reconstruction stage emitting 2.37 kg CO₂eq/sm when it represents 2.74

8 kg CO₂eq/sm for scenario 3. The effects of the PMS on maintenance operation gains are a bit

9 more important: the maintenance stage emits 13.3 kg CO₂eq/sm in the case of scenario 2,

10 against 11.3 kg CO₂eq/sm for scenario 3.



1

2 **Figure 5 GHG emissions of the pavement life cycle for each stage of its life cycle, per square meter**

3 **3.3 PMS contributions**

4 All results, presented in Table 5 and Figure 6, relate to the 10 km-long section over 30 years.

5 The GWP of the PMS is 520.7 kg CO₂eq. It is divided in 241.1 kg CO₂eq (46.3%) for data

6 storage, 277.9 kg CO₂eq (53.4%) for data collection activities and 1.7 kg CO₂eq (0.3%) for

7 maintenance planning activities, e.g. the usage of the PMS by asset managers. Data collection

8 is the biggest contributor to PMS's carbon footprint, with 53.4% of the total impact. Data

9 storage is almost equally contributing, with 46.3% of the total GWP, while the PMS's usage

10 itself is responsible for a negligible amount of GHGs (0.3%). The GWP due to data storage is

11 largely due to the database running, i.e. electricity consumption (97.3%). The amortization of

12 the database's hardware manufacturing represents only 2.7% of the total GWP. The GWP of

13 maintenance planning activities comes from the local tasks (87.5%) and data transfer tasks

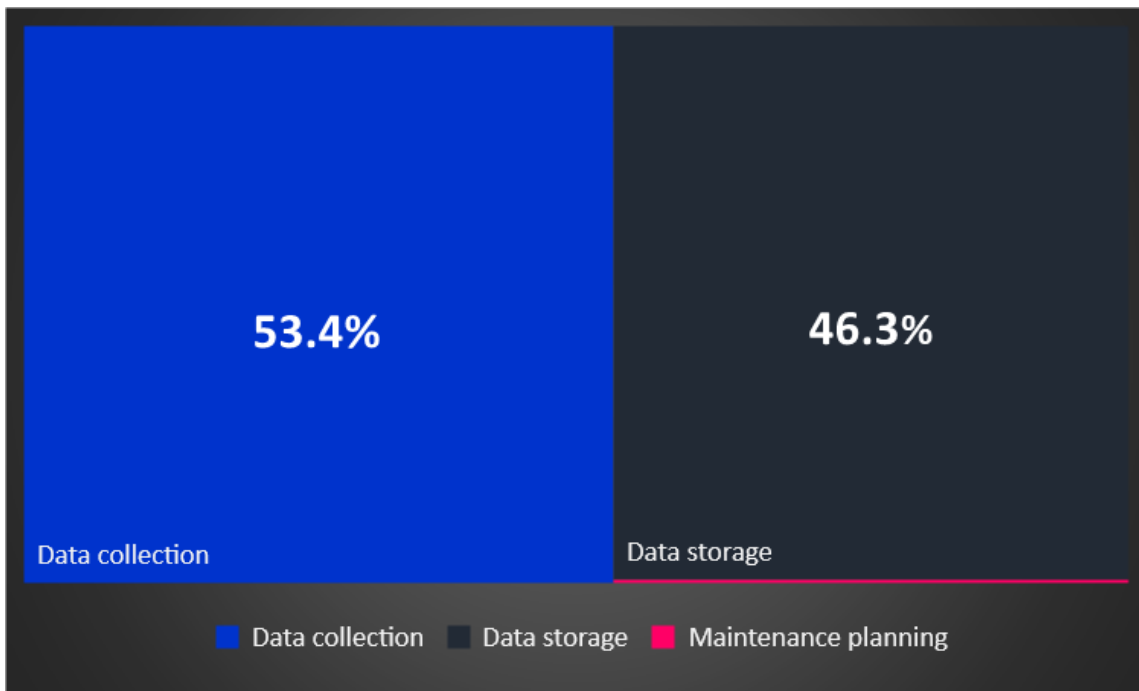
14 (12.5%).

15 **Table 5 PMS's carbon footprint and contributions to total**

	<i>GWP (kg CO₂eq)</i>
PMS total	520.8

Data storage	241.1	46.3 %	
<i>Of which: hardware</i>	6,5		2.7 %
<i>Of which: running</i>	234.5		97.3 %
Data collection	277.9	53.4 %	
Maintenance planning	1.7	0.3 %	
<i>Of which: local task</i>	1.5		87.6 %
<i>Of which: transfer task</i>	.2		12.4 %

1



2

3 **Figure 6 The GWP distribution of data storage, data collection, and maintenance operation activities**

4 **3.4 Sensitivity analyses**

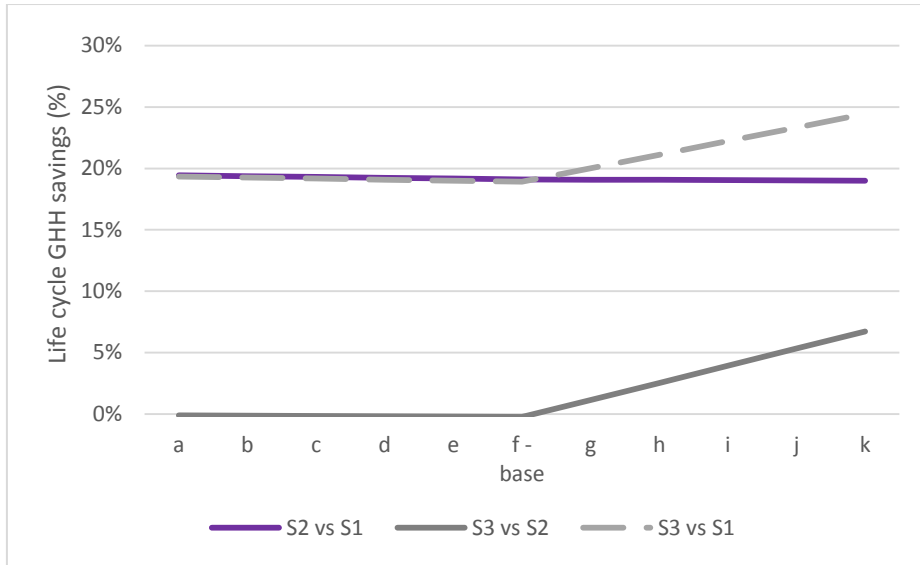
5 In the base case, the subgrade is considered to evolve from PF2qs to respectively PF2 and
6 PF3 over 25% of the section’s length each. While this assumption has been proposed based
7 on a road constructor’s expertise, no national statistics can be used to validate its national
8 representativeness. The sensitivity of the results to this evolution is tested based on a
9 “restricted range” (Figure 7) and an “extreme range” (Figure 8) of subgrade class evolutions.

1 The second sensitivity analysis can be considered as extreme or rather unlikely, as up to the
2 entire length of the subgrade is tested to be either upgraded or downgraded.

3 The two figures show that, if the subgrade's bearing capacity deteriorates over time (scenarios
4 a to e), the structural reinforcement of the complete section classically carried out to respect
5 the pavement design reliability is globally environmentally equivalent to minimal
6 maintenance consisting of crack filling to delay alligator cracking, or rehabilitating short
7 pavement sections with premature damage due to the worst-performing materials over the
8 section. In this case, the advantage of using a PMS to tailor maintenance overtime may be
9 masked by the safety margins taken in the design process due to the spatial heterogeneity of
10 the pavement's behavior.

11 On the contrary, if the bearing capacity of the subgrade improves, which may occur with the
12 compaction of the pavement under heavy traffic (scenarios g to k), the results highlight that it
13 is environmentally beneficial to know the condition of the pavement to adjust the
14 maintenance with structural reinforcement. The PMS shows all its potential in these
15 scenarios, as it allows to delay maintenance operations where they are not needed.

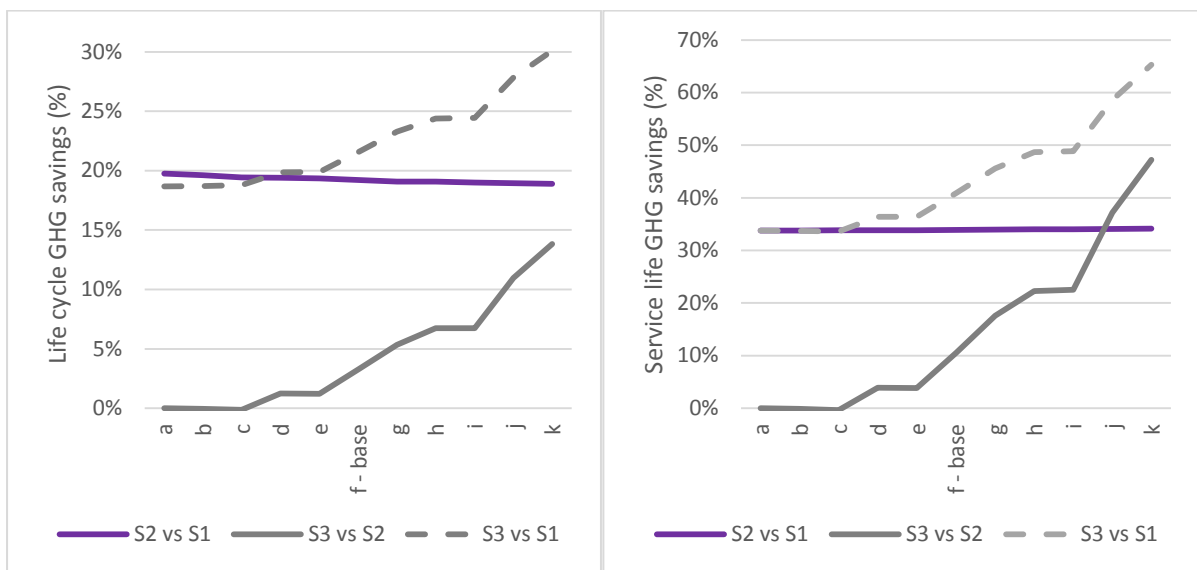
16 Quantitatively, results show that savings of up to resp. 7 and 25% of the pavement life cycle
17 GHG emissions can be reached using BIM to tailor maintenance (scenario S3) compared to
18 resp. classic progressive or massive design and maintenance approaches (scenaris S1 and S2)
19 on a restricted range of subgrade bearing capacity evolutions (Figure 7). When considering an
20 extreme range of psubgrade bearing capacity evolutions, these gains reach up to resp. 14 and
21 30% over the pavement life cycle. If we restrain the scope to the service life and exclude the
22 emissions from the original construction, these gains skyrocket to 47 and 65%.



1

2 **Figure 7 GHG savings of the different pavement management scenarios over the life cycle “restricted**

3 **range” sensitivity analysis**



4

5

(a)

(b)

6 **Figure 8 GHG savings of the different pavement management scenarios - over the complete life cycle (a)**

7 **and on the service life (b) - depending on the evolution of the subgrade bearing capacity – “extreme**

8 **range” sensitivity analysis**

1 **4 Discussion**

2 In this case study, we calculated the impact of using a PMS – the equivalent of a
3 monofunctional I-BIM for pavement maintenance planning – on a high-traffic road life cycle
4 carbon footprint. Nevertheless, I-BIM can provide 47 different types of technical support
5 defined by Costin et al. (2018), and a multifunctional I-BIM would necessarily have different
6 impacts. For instance, we estimated that an equivalent amount of GHGs is emitted over the
7 pavement lifespan with a progressively designed pavement that is maintained with the
8 support of a PMS when the bearing capacity of a subgrade deteriorated. But these results may
9 only reflect French maintenance practices that could be too strict from the point of view of
10 the mechanical maintenance of the structure. Thus, I-BIM could be used to break free from
11 established rules and optimize structures over time according to desired criteria, for example,
12 carbon emissions minimization. Indeed, monitoring the condition of pavements in real-time
13 through instrumentation and using these data in an I-BIM to simulate the structural evolution
14 over time would greatly advance maintenance management compared to what current
15 structural simulation software programs allow. The big data generated and stored on the
16 condition of the pavements and their environment could seed the development of algorithms
17 based on artificial intelligence (AI) allowing for better simulate the behavior of road
18 structures. Indeed, road design methods have gone from an empirical approach to a
19 combination of mechanical physics and empiricism ("ME" methods) in the face of the
20 inability of empiricism to capture the unlimited heterogeneity of pavement behavior due to
21 limited data. The road sector has then turned to ME methods to reduce the errors of the
22 physical models thanks to calibration coefficients. But ME methods are still limited to
23 forecast pavement evolutions, and one might think that behavior models generated thanks to
24 machine learning - and especially artificial neural networks - would perform better. Yet, AI

1 algorithms are known to potentially consume a massive amount of electricity, and particular
2 electronic elements whose environmental impact could be heavy (Strubell et al., 2019).
3 Future studies should look into these aspects to ensure the development of a climate-positive
4 I-IBM.

5 Moreover, we have shown that, although the carbon footprint of the PMS itself is negligible
6 compared to construction operations, half of its emissions are due to the collection of data
7 and the other half to their storage. Instrumenting the roads with sensors rather than surveying
8 them with internal combustion engine (ICE) vehicles could help reduce the impact of the
9 "maintenance planning" function of an I-BIM, but the sensors would also generate impacts,
10 despite these impacts need to be investigated further (Pirson and Bol, 2021). In addition, the
11 data generated could be much more massive and its storage could thus generate substantial
12 GHG emissions. Thus, it would be appropriate in the future to assess the carbon footprint of
13 multifunctional I-BIMs and to study the risk associated with the profusion of data.

14 Finally, the impact of road construction has been proven to be very limited compared to its
15 usage (de Bortoli et al., 2022a; de Bortoli and Agez, Under review; Wang et al., 2012), and I-
16 BIM could help optimize the management of pavements to reduce their environmental impact
17 over their entire life cycle, including through their surface condition and geometry that
18 impact vehicle consumption and aging (de Bortoli et al., 2022a; Chatti and Zaabar, 2012;
19 Wang et al., 2012; de Bortoli et al., 2022b).

20 In any case, a multitude of different I-BIMs could be developed. And according to Bellman's
21 principle of optimality, the sum of the optima of subsystems is different from the optimum of
22 the system (Bellman, 1952). Also, optimizing recursively subsystems - each I-BIM's
23 subsystem corresponding to one specific function - will be necessary to get close to the
24 systemic optimum of the I-BIM over time. Depending on how I-BIM is used and in which
25 technologic conditions, its impact will vary. For example, the environmental impact of the

1 elements of the technosphere such as electricity (Alderson et al., 2012; Wolfram et al., 2016),
2 metals (Watari et al., 2021), electronic components, and else, varied and will keep on varying
3 in time and space. Forward-looking assessments are uncertain but necessary to project the
4 potential consequences of I-BIM on climate. Additionally, we only considered GWP in this
5 study. However, burden-shifting should be monitored and controlled. According to the
6 Information Communication Technology scope published by ADEME, freshwater
7 eutrophication and metal resources' would be the first two key burdens shifted with
8 digitalization (Bio Intelligence Service, 2011), and they should be assessed closely when it
9 comes to planning the development of BIM.

10 **5 Conclusions**

11 This article evaluates for the first time the environmental impact of the use of a BIM for
12 infrastructure. More specifically, the carbon footprint of two road designs and three
13 maintenance management approaches are compared: massive design accompanied by surface
14 maintenance (scenario 1), progressive design combined with structural maintenance without
15 monitoring of the bearing capacity of the subgrade (scenario 2), and the same progressive
16 design with optimized maintenance thanks to a PMS recording the deflection of the
17 pavement, the PMS being equivalent to a monofunctional I-BIM. This case study shows that
18 the direct carbon footprint of I-BIM is negligible compared to the carbon footprint of
19 pavement construction and maintenance operations over 30 years. In addition, the indirect
20 effect of PMS, i.e. its consequences on emissions from construction operations taking place
21 during the life of the pavement, are rather positive. Nevertheless, I-BIM is still novel,
22 transitioning, and thus knowledge is limited: I-BIM can become a drag as a climate asset, and

1 further and continued research will be needed to ensure its development serves the transition
2 to carbon neutrality.

3

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15

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21 REFERENCES

- 22 AASHTO, 2008. Mechanical-empirical pavement design guide. American Association of
23 State Highway and Transportation Officials, Washington D.C.
24 AASHTO, 1993. AASHTO guide for design of pavement structures. American Association
25 of State Highway and Transportation Officials, Washington, D.C.
26 Abbondati, F., Biancardo, S.A., Palazzo, S., Capaldo, F.S., Viscione, N., 2020. I-BIM for
27 existing airport infrastructures. *Transp. Res. Procedia* 45, 596–603.
28 <https://doi.org/10.1016/j.trpro.2020.03.052>

- 1 ADEME, 2016. Potentiel de contribution du numérique à la réduction des impacts
2 environnementaux : état des lieux et enjeux pour la prospective. (Rapport final),
3 Temis.
- 4 ADEME, n.d. Base carbone® [WWW Document]. URL [https://bilans-](https://bilans-ges.ademe.fr/fr/basecarbone/donnees-consulter/choix-categorie)
5 [ges.ademe.fr/fr/basecarbone/donnees-consulter/choix-categorie](https://bilans-ges.ademe.fr/fr/basecarbone/donnees-consulter/choix-categorie)
- 6 AFNOR, 2000. NF P 94-117-1 : Portance des plates-formes, Partie 1 : Module sous
7 chargement statique à la plaque (EV2).
- 8 Alderson, H., Cranston, G.R., Hammond, G.P., 2012. Carbon and environmental footprinting
9 of low carbon UK electricity futures to 2050. *Energy* 48, 96–107.
10 <https://doi.org/10.1016/j.energy.2012.04.011>
- 11 Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research
12 directions in LCA of buildings: A critical review. *Renew. Sustain. Energy Rev.* 67,
13 408–416. <https://doi.org/10.1016/j.rser.2016.09.058>
- 14 AzariJafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements:
15 reviewing research challenges and opportunities. *J. Clean. Prod.* 112, 2187–2197.
16 <https://doi.org/10.1016/j.jclepro.2015.09.080>
- 17 Bellman, R., 1952. On the Theory of Dynamic Programming. *Proc. Natl. Acad. Sci.* 38, 716–
18 719. <https://doi.org/10.1073/pnas.38.8.716>
- 19 Bio Intelligence Service, 2011. Analyse comparée des impacts environnementaux de la
20 communication par voie électronique (Volet courrier électronique : Synthèse).
21 ADEME.
- 22 CEREMA, 2017. Dimensionnement des épaisseurs de couche de forme pour PF2qs -
23 Complément au GTR et au GTS (ISBN 978-2-37180-152-3 No. Note d'information
24 Chaussées-Plates-forme-Assainissement n°2).
- 25 Chatti, K., Zaabar, I., 2012. Estimating the effects of pavement condition on vehicle
26 operating costs, NCHRP report. Transportation Research Board, Washington, D.C.
- 27 Coroama, V.C., Hilty, L.M., 2014. Assessing Internet energy intensity: A review of methods
28 and results. *Environ. Impact Assess. Rev.* 45, 63–68.
29 <https://doi.org/10.1016/j.eiar.2013.12.004>
- 30 Corte, Fevre, Havard, Joubert, Perrot, Morel, Quibel, Schaeffner, Veysset, 2000a. Réalisation
31 des remblais et des couches de forme - Fascicule I - Principes généraux. Sétra-LCPC.
- 32 Corte, Fevre, Havard, Joubert, Perrot, Morel, Quibel, Schaeffner, Veysset, 2000b. Réalisation
33 des remblais et des couches de forme - Fascicule II - Annexes. Sétra-LCPC.
- 34 Corte, Guidoux, al., 1998. Catalogue des structures types de chaussées neuves. Sétra-LCPC.
- 35 Costin, A., Adibfar, A., Hu, H., Chen, S.S., 2018. Building Information Modeling (BIM) for
36 transportation infrastructure – Literature review, applications, challenges, and
37 recommendations. *Autom. Constr.* 94, 257–281.
38 <https://doi.org/10.1016/j.autcon.2018.07.001>
- 39 de Bortoli, A., 2020. Asphalt pavement resurfacing: a review toward a better selection and
40 representativeness of LCI, in: *Pavement, Roadway, and Bridge Life Cycle*
41 *Assessment 2020*. CRC Press, Taylor & Francis Group, London, pp. pp12-23.
- 42 de Bortoli, A., 2018. CHAPTER 5 – Regionalization and construction of specific Life Cycle
43 Inventories [in French], in: *Toward Sustainable Road Maintenance: Taking into*
44 *Account Vehicle-Pavement Interactions into the Decision-Making Process -*
45 *Illustration by a French Highway Case Study [in French]*. University Paris East -
46 Ecole des Ponts ParisTech.
- 47 de Bortoli, A., Agez, M., Under review. EEIO efficiently sketches large-scale environmental
48 transition plans: illustration by Canada's road industry.

- 1 de Bortoli, A., Féraille, A., Leurent, F., 2022a. Towards road sustainability – Part II: applied
2 holistic assessment and lessons learned from French highways resurfacing strategies.
3 Sustainability Under review.
- 4 de Bortoli, A., Féraille, A., Leurent, F., 2022b. Towards Road Sustainability—Part I:
5 Principles and Holistic Assessment Method for Pavement Maintenance Policies.
6 Sustainability.
- 7 Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G.S., Friday, A., 2021. The
8 real climate and transformative impact of ICT: A critique of estimates, trends, and
9 regulations. *Patterns* 2, 100340. <https://doi.org/10.1016/j.patter.2021.100340>
- 10 International Organization for Standardization, 2018. ISO 19650-1:2018 - Organization and
11 digitization of information about buildings and civil engineering works, including
12 building information modelling (BIM) — Information management using building
13 information modelling — Part 1: Concepts and principles.
- 14 International Organization for Standardization, 2006a. ISO 14040:2006 - Environmental
15 management -- Life cycle assessment -- Principles and framework.
- 16 International Organization for Standardization, 2006b. ISO 14044:2006 - Environmental
17 management -- Life cycle assessment -- Requirements and guidelines.
- 18 LCPC-Sétra, F., 1994. Conception et dimensionnement des structures de chaussée. LCPC ;
19 SETRA, Paris; Bagneux.
- 20 Lorino, T., LEPERT, P., Riouall, 2006. Application à la campagne IQRN des méthodes
21 statistiques d'analyse de l'évolution des chaussées. *Bull. Lab. Ponts Chaussées* 25–41.
- 22 Malagnino, A., Montanaro, T., Lazoi, M., Sergi, I., Corallo, A., Patrono, L., 2021. Building
23 Information Modeling and Internet of Things integration for smart and sustainable
24 environments: A review. *J. Clean. Prod.* 312, 127716.
25 <https://doi.org/10.1016/j.jclepro.2021.127716>
- 26 Matejov, A., Šestáková, J., 2021. The Experiences with utilization of BIM in railway
27 infrastructure in Slovak Republic and Czech Republic. *Transp. Res. Procedia* 55,
28 1139–1146. <https://doi.org/10.1016/j.trpro.2021.07.084>
- 29 Our world in data, 2020. Cars, planes, trains: where do CO2 emissions from transport come
30 from? Our World Data. URL <https://ourworldindata.org/co2-emissions-from-transport>
31 (accessed 5.26.22).
- 32 Pirson, T., Bol, D., 2021. Assessing the embodied carbon footprint of IoT edge devices with a
33 bottom-up life-cycle approach. *J. Clean. Prod.* 322, 128966.
34 <https://doi.org/10.1016/j.jclepro.2021.128966>
- 35 Saxe, S., Guven, G., Pereira, L., Arrigoni, A., Opher, T., Roy, A., Arceo, A., Von Raesfeld,
36 S.S., Duhamel, M., McCabe, B., Panesar, D.K., MacLean, H.L., Posen, I.D., 2020.
37 Taxonomy of uncertainty in environmental life cycle assessment of infrastructure
38 projects. *Environ. Res. Lett.* 15, 083003. <https://doi.org/10.1088/1748-9326/ab85f8>
- 39 Soust-Verdaguer, B., Llatas, C., García-Martínez, A., 2017. Critical review of bim-based
40 LCA method to buildings. *Energy Build.* 136, 110–120.
41 <https://doi.org/10.1016/j.enbuild.2016.12.009>
- 42 Spielmann, M., Bauer, C., Dones, R., 2007. Transport services: Ecoinvent report no. 14 -
43 road transport, EcoInvent report. Swiss Centre for Life Cycle Inventories, Dübendorf.
- 44 Strubell, E., Ganesh, A., McCallum, A., 2019. Energy and Policy Considerations for Deep
45 Learning in NLP. <https://doi.org/10.48550/ARXIV.1906.02243>
- 46 US DoT - FHWA, 2019a. Summary Report Midwest Region Peer Exchange Minneapolis,
47 MN July 18–19, 2019. US Department of Transportation - Federal Highway
48 Administration.

- 1 US DoT - FHWA, 2019b. Summary Report Northwest Region Peer Exchange Portland, OR
2 June 13–14, 2019. US Department of Transportation - Federal Highway
3 Administration.
- 4 US DoT - FHWA, 2019c. Summary Report Southeast Region Peer Exchange Atlanta, GA
5 March 14–15, 2019. US Department of Transportation - Federal Highway
6 Administration.
- 7 US DoT - FHWA, 2019d. Summary Report Southwest Region Peer Exchange Lakewood,
8 CO May 21–22, 2019. US Department of Transportation - Federal Highway
9 Administration.
- 10 van Eldik, M.A., Vahdatikhaki, F., dos Santos, J.M.O., Visser, M., Doree, A., 2020. BIM-
11 based environmental impact assessment for infrastructure design projects. *Autom.*
12 *Constr.* 120, 103379. <https://doi.org/10.1016/j.autcon.2020.103379>
- 13 Vignali, V., Acerra, E.M., Lantieri, C., Di Vincenzo, F., Piacentini, G., Pancaldi, S., 2021.
14 Building information Modelling (BIM) application for an existing road infrastructure.
15 *Autom. Constr.* 128, 103752. <https://doi.org/10.1016/j.autcon.2021.103752>
- 16 Vilches, A., Garcia-Martinez, A., Sanchez-Montañes, B., 2017. Life cycle assessment (LCA)
17 of building refurbishment: A literature review. *Energy Build.* 135, 286–301.
18 <https://doi.org/10.1016/j.enbuild.2016.11.042>
- 19 Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., Kim, C., 2012. Life cycle energy
20 consumption and GHG emission from pavement rehabilitation with different rolling
21 resistance. *J. Clean. Prod.* 33, 86–96. <https://doi.org/10.1016/j.jclepro.2012.05.001>
- 22 Watari, T., Nansai, K., Nakajima, K., 2021. Major metals demand, supply, and environmental
23 impacts to 2100: A critical review. *Resour. Conserv. Recycl.* 164, 105107.
24 <https://doi.org/10.1016/j.resconrec.2020.105107>
- 25 Wolfram, P., Wiedmann, T., Diesendorf, M., 2016. Carbon footprint scenarios for renewable
26 electricity in Australia. *J. Clean. Prod.* 124, 236–245.
27 <https://doi.org/10.1016/j.jclepro.2016.02.080>
28