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How much do choices impact environmentally the maintenance activities? A measurement framework based on Ecological Footprint

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Abstract: The Architecture-Engineering-Construction-Operation (AECO) industry is responsible for a very high environmental degradation. In this context, the Operation and Maintenance (O&M) phase of building life cycle is recognized as the highest influencer of the industry's environmental impact.

Even if sustainable constructions refer to improve the efficiency of buildings throughout more sustainable processes, such as waste-generation reduction and resource-use optimization, most efforts have focused on improving energy efficiency during O&M. Especially, being maintenance a critical activity to optimize building management, a framework to measure the effects on environmental sustainability seems to be missing in the facility management field.

The present research introduces a framework for measuring the environmental impact of maintenance activities to support facility managers to (i) calculate the effectiveness of maintenance choices, (ii) guide the maintenance activities over times, (iii) optimize the environmental effect of maintenance activities. After selecting the Ecological Footprint as the best methodology for these purposes, the authors implement the calculation model, and test it on four case study buildings.

Results highlight the potential of such a model to guide facility managers throughout different maintenance strategies. Measuring the potential gains over a time span of 50 years, the total impact of predictive maintenance approach is the 5% higher than the corrective one. However, future improvements need to collect more data about the maintenance activities to better specify the calculations. Digital technology, such as a network of IoT for maintenance monitoring, would help the data collection and better test the model and its impact on the maintenance procedure.

1. Introduction

The building stock plays a central role in reaching long-term sustainable goals. On one hand, the overall building sector consumes around 30-40% of energy [4], and generates around 1/3 of the total greenhouse gas emissions [5]. On the other, buildings are linked to human life by contributing to wellness, productivity, satisfaction, security, and behaviour of building occupants [6].

The urgency of integrating sustainable principles to the building sector increases when focusing on Europe. The European Union (EU) has the objective to make Europe a emission-neutral continent by 2050 [1]. However, European building stock is far from being emission-neutral. Including highly energy-intensive buildings, the European built environment is a major cause of wasted energy and CO_2 emissions [4]. The Building Performance Institute of Europe [2] reports that over 97% of EU existing building stock needs to be requalified in order to comply with European standards by 2050. The data came from an analysis of the age of European building stock, which showed that only buildings built after 2010 can be consider efficient (with a U-value of 0,49 W/m^2K for the envelope). As stated by the Global Status Report [3], working on the envelope and plants of buildings at least 25% of the total energy demand could be reduced by implementing energy performance measures on existing buildings.

Sustainability is not just a matter of energy demand. The transition of Europe towards a sustainable development deals with a combination of environmental, economic, and social challenges [7]. Renovation and maintenance activities of the existing building stock are ones of the most attractive and low cost options to optimize energy consumption and emissions of the Architecture, Construction, Engineering and Operation industry (AECO) [43]. This also affects the wellbeing and indoor comfort of users, generating a positive effect on social sustainability [7]. Operation and maintenance strategies are strongly related to the optimization of sustainability performance of in-use buildings. However, before taking action to optimize Operational and Maintenance (O&M), impacts have to be measured in order to understand which strategies adopt.

Therefore, the present research aims to measure the environmental impact of activities in the O&M phase of building life cycle. After introducing the state of the art of the O&M impact on buildings' sustainable performance, the study introduces a model, based on Ecological Footprint index (EF), to measure the environmental impact of O&M activities. Finally, the results of some case study buildings are reported to discuss potentials and limitations of the model.

2. Environmental impact of Operation & Maintenance phase (O&M)

Although AECO is integrating the concept of environmental sustainability with the reduction of energy demand and material consumptions [8], the industry still represents a key element in the economy to translate in a sustainable development society. Among different phases of building life cycle, the most resource-consuming is the O&M [9]. Operations and maintenance activities demands the 80-90% of the total energy consumed in all phases of building life cycle [10]. The basic goal of sustainability in

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AECO focused on reducing energy consumption, safeguarding the ecosystem, enhancing health and safety of users, and improving productivity [40]. The energy optimization is not sufficient, as energy represents only one component of buildings' environmental impact [11]. A study [12] on energy usage in Japanese offices revealed that the acquisition of energy savings necessarily does not contribute to an improvement of building sustainable performance. [13] concluded that the building performance finally depends on users' behaviours. Moreover, even if studies still confirmed that O&M is the largest contributor (around 90%) of building life cycle energy consumption, buildings are evolving towards a lower operational consumptions [14]. In the future, the environmental impact of O&M will depend always more on other sources, such as materials and manpower during maintenance operations. Thus, a smart sustainable building should integrate actions for the reduction of energy demand and strategies to optimize O&M.

Building maintenance aims to preserve minimum conditions that fulfil the purpose for which a building has been built for. Over the years, several studies and reports emphasized the challenges in ensuring good maintenance activities in support of building performance [15]. However, most stakeholders (including, facility managers and property developers) contend that the lack of money and expertise is the main barrier to reach out the carbon-efficiency and cost-effectiveness in O&M [16]. Although the improvement involves not only buildings conditions (especially, durability and reliability), but also leads to energy savings, building maintenance is an expensive process, in economic, timing, and environmental impact perspectives [17]. Studies highlighted the direct link between building performance and building condition [18], and its impact on the sustainable principles [19]. Supported by multidisciplinary approaches, building performance is based on property and facility management [15]. To improve the adoption of sustainable strategies in buildings, Hwang and Tan [20] pointed out that facility management teams are the key promoter of sustainable building processes. The team can incorporate the sustainable objectives in their operations (planning, designing, construction, and management). In this complex management, the role of facility manager becomes important as maintenance activities deal with numerous variables, such as construction maintenance, information validation, logistic dependency, workforce's competence, and schedule coordination [21]. Facility managers control and coordinate various tasks, such as the proper functioning of installations, maintenance activities, cleaning activities, economic expenditures, and environmental performances [22, 23]. However, the facility management field still needs a supporting tool to measure building towards sustainability [39]. Such a tool would help facility managers to guide building policies, measure impacts, and improve the sustainability performance. Thus, focusing on maintenance activities, the present study aims to elaborate a calculation model to measure the environmental impact.

3. Methodology

From the literature review, it is clear the need of assessing environmental impact of O&M operations to adjust the sustainable performance of buildings. This study intents to garner attention to the environmental impact of maintenance strategies adopted for optimizing the sustainable performance of in-use buildings.

In order to implement an evaluation framework, the study applies the following steps:

i. Selection of a sustainable indicator: the Ecological Footprint Index (EF) is selected as the best sustainable indicator to measure environmental impact of maintenance strategies;
ii. Definition of the calculation model: the calculation model is defined by improving previous applications of EF in the O&M phase of building life cycle;
iii. Test of the calculation model: two different tests are implemented. First, a comparison among three case study buildings is conducted in order to test the effectiveness of the calculation model. Second, a simulation comparison between different maintenance strategies is performed to test the reliability of the calculation model.

After reviewing EF and presenting the calculation model, the present study discusses results. Finally, limitations of tests and future improvements of the calculation model are presented into the conclusions.

4. Ecological Footprint Index

In the past decades, many models have been developed to assess the environmental impact of buildings. Several reviews discuss these studies, that used different indicators, especially Life Cycle Assessment [24-27]. Even if the growing number (and, application) of sustainable indicators has been defined as a "spreading indicator culture" [41], the decision making process needs to be guided by a set of sustainable indicators able to represent the complexity of the impact generated on the Earth [28]. Agreeing in the complexity of implementing a calculation model for the O&M phase, these reviews found out a good option to assess the environmental impact of in-use buildings, namely the Ecological Footprint indicator. An indicator is a communication tool that simplifies the high complexity of the human-environment relationship [29]. EF is a valuable variable that provides information on the environmental impact of systems, and supports to policy makers in setting environmental goals [28]. The message provided by EF is clear, single, and unambiguous, telling policy makers how far the system is from sustainability [30]. Thus, to overcome the general perception that maintenance is not significant with respect to the consumption of materials and energy in the O&M phase, brought researchers in breaking down the maintenance operations and founding all impact sources of maintenance activities [14].

The Ecological Footprint methodology has been selected due to its relevance in the sustainable performance measurement field [31]. EF is a resource accounting method to measure the sustainable development of a population or an economy in a quantitative way [14]. The main strengths of EF are its scalability (from humanity to single processes), and the unit of measurement used to express results, global hectare per year (gha/yr), easily understood also by no experts [32].

EF has been implemented by Wackernagel and Reel in 1990's with the objective to measure the pressure of human demand on the Earth [33]. EF uses, as a reference, the Earth, which is considered as a finite and closed system. The boundaries imposed by the Earth represent the biophysical limit of human expansions, which is the key aspect for sustainable development [32]. Thus, EF compares the demand of resources to the ecosystems' ability to reproduce those. To make demand comparable with the supply (the natural capacity of the system – the Earth), EF aggregates the consumed resources (materials and energy) together. Finally these consumptions are translated into global hectares and allocated to the productive lands (built-up, cropland, grazing land, CO_2 sink, fishing land, and forest land).

Previous studies have used EF to assess environmental impact of buildings. [32] used the service life of materials with an added extra 5% of energy consumed by machineries to calculate the embodied energy of O&M. [34] applied EF to study the building impact by energy retrofitting, such as thermal insulation or air conditioning systems). [35] applied EF to calculate the complete life cycle environmental impact of an exhibition hall. In O&M, they included energy and water as impact sources. [14, 23] applied EF for the calculation of O&M operations, including three clusters of impact sources: manpower (consumption of food and water), materials (consumption of energy and construction materials), and machineries (consumption of fuel and energy). Finally, a study conducted by Pomè et al. [31] tried to collect previous applications of EF on the AECO industry in order to implement a complete calculation model. With the objective to assess the environmental impact of in-use buildings, this study presents a model of nine impact sources: built-up, energy consumption, water consumption, material consumption, food & drink, mobility, waste generation, recycle potential, and occupant. The building users demand, defined by the nine impact sources, is converted into global hectares and compared with the supply, the productive lands available on Earth to regenerate the consumed resources. The application of the general model on a case study building allowed the authors to understand the potential and limitation of a model based on EF [31]. The model can express the over-consumption of resources and may encourage a more sustainable culture. On the other hand, the study presents several limitations in the calculation.

First, the study did not implement a standard procedure to collect data from facility managers. By affecting the results, this don't allow a comparison among different case study buildings. A standard procedure for data collection will help cross-company comparison and the implementation of benchmark analysis.

Second, the model failed in measuring the environmental impact of some impact sources. Especially, looking at the material consumption addendum, the study considers the amount of hours spent in the building by workers and multiply them by an average trolley, which represents the average amount of materials used for maintenance activities. This limits facility managers to provide real data on maintenance consumption, as they aren't aware of the amount of hours spent in the building by operators.

Third, calculations are performed by applying an average trolleys of consumptions. A further analysis must be implemented in order to best describe different strategies used in building management. Especially, looking at the material consumption impact sources, Pomè et al. [31] didn't consider the different maintenance strategies that facility managers can adopt.

Therefore, the present study aims to focus on measuring the environmental impact of maintenance activities by adopting the Ecological Footprint indicator, and reviewing the application of previous studies.

5. Maintenance Ecological Footprint Assessment

A main limit of the study implemented by Pomè et al. (2021) is about the measurement of the environmental impact of maintenance activities by asking the amount of hours used per single material. The study listed the maintenance consumption (MC) into the impact source called material consumption, which also measured impact of cleaning activities. The calculation proposed in this study multiplied the total hours per year of utilization per the emission factor of the material and the equivalent factor for the CO_2 sink land (1):

$$\begin{aligned} MC = {} & Hours\ per\ use\ of\ material\ i\ \left(\frac{h}{year}\right) \\ & * Emission\ Factor\ of\ material\ \left(\frac{tCO_2}{m^3}\right) \\ & * CO_{2\ sink\ factor} (\frac{gha}{tCO_2}) \end{aligned} \tag{1}$$

The emission factor of materials came out by considering three different aspects: manufacturing, transport, and waste. This is why it is based on the embodied energy of materials [14, 23, 31]. While, the CO_2 sink factor is calculated on the five equivalent productive lands, reported by the Global Footprint Network[1], which provides annual worldwide estimations of EF [31].

In order to improve calculations, the present study eliminates the hours per use of material and considers the expenditures for maintenance activities. As facility managers can only review year expenditures from maintenance contracts, the calculation used the costs of ordinary and extraordinary maintenance to assess the environmental impact. By ordinary maintenance the authors mean those activities that have been planned in the maintenance plans; while by extraordinary those unplanned activities that follow inspections. According to Molinari (2002), maintenance costs can be split up in materials costs and manpower costs. Especially, for ordinary maintenance the 20% of total costs is allocated to materials, 80% to manpower; on the other hand, for extraordinary maintenance the 80% of total costs is allocated to materials, and 20% to manpower.

A second limit of the previous applications was the average trolley for emission factors. The present study defines two type of trolleys. One for ordinary and extraordinary activities, and the other for other maintenance operations, such as the specific replacement of components and systems. Both the trolleys use several sources to access components and embodied energies to use in the calculation. [23] and "The Whitestone Facility Maintenance and Repair Cost Reference 2009-2010" are the two main references for defining the list of activities performed during maintenance activities. Then, to access the overall costs, the authors used

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[1] Global Footprint Network: https://www.footprintnetwork.org/

the “Regional Price List of Public Works (Lombardy) - volume 2.1”, the “Unit Costs and small civil maintenance and urbanization, 2021 edition”, and “Electrical and mechanical systems, 2021 edition”. Finally, OpenLCA, which is an open source database of environmental impact of elements, is used to list embodied energies of components. Thus, the present study changes the formula as follow:

$$(2) \qquad MC = Cost\ of\ maintenance\left(\frac{€}{year}\right) * Material\ quantity\left(\frac{kg}{€}\right) * Emission\ Factor\ of\ material\left(\frac{tCO_2}{kg}\right) * CO_{2\ sink\ factor}\left(\frac{gha}{tCO_2}\right)$$

The final table of activities, costs, and embodied energies is reported in Appendix A.

Third, the previous application of EF describe environmental impact of maintenance activities with a static measure. By assessing single information of the case study building, [31] were able to measure the impact of the analysed year without providing further information to facility managers. Thus, a second objective of the present study is to make the calculation a dynamic model in order to make facility managers aware of different maintenance strategies. Representing how far the system is from sustainability [28], the EF model must allow facility managers to evaluate sustainable performance of different policies and maintenance actions over time.

To make the model dynamic, the authors need to access the different probabilities of maintenance activities performed over an year of activity. In particular, two maintenance cases are analysed: preventive-predictive maintenance, and corrective maintenance. As reported by [44], preventive maintenance is carried out in pre-defined intervals or according to prescribed criteria; while corrective maintenance is carried out after a fault has been recognized. Preventive and predictive maintenance activities are considering together because both have the objective to optimize the efficiency of the system by anticipating failures [38]. On the other hand, corrective maintenance is based on the prevention of possible failures of a system with the objective to prevent failure costs [38]. The prevention of costs follows the given equation (2):

$$(2)\ Min\ \ C_M + [C_f * p_f * (C_M, t_M)]$$

Where:

- C_M: is the discounted future maintenance costs;
- C_f: is the discounted failure costs;
- p_f: is the probability of failure that depends on the scheduling of maintenance (C_M).

In corrective maintenance the state of the system is usually unknown, however when a breakdown occurs the information is registered. So [38] described the two types of corrective maintenance. One, defined condition-based, is characterized by a system-condition model; the other, defined time-based, suggest a time period in which it is necessary to carry out the maintenance activity for a defined component of a system. Moreover, the maintenance costs are a function of the reaction time of the maintenance activity, which is based on (i) the reliability of workers and resources, and (ii) the delay of the maintenance activity, that may cause several consequential failures [38]. Thus, in order to subdivided the activities according to the maintenance costs, the quality of the item, expressed through the concept of deterioration, is used [42]. This deterioration function is used to evaluate the costs of extraordinary maintenance, calculate the amount of materials used, and measure the footprint. While for ordinary maintenance, the cost of maintenance is considered unchanged for the overall life cycle of the system. Then, the deterioration function [14, 42] is defined as follow:

$$(3)\ Y = e^{-t/k^{0,5}}$$

Where:

- Y: is the quality of the analysed item; and
- t: is the time [year].

This function is used to define the percentage of failure, which depends on the probability of failure of a given item, defined as follow:

$$(4)\ Probability\ of\ failure = 1 - e^{-t/k^{0,5}}$$

In order to estimate the future maintenance condition of the analysed system, the probability function is used to estimate the cost of extraordinary maintenance for the overall building life cycle. Thus, some further assumptions are defined by the present study. First, the building life cycle is assumed of 50 years from the end of construction [42]. Second, the restored quality obtained after a maintenance activity is defined as half of the quality value the item had in the previous year [42]. Thus, given the cost of extraordinary maintenance of the analysed year, the simulation of the future probable costs and activities of extraordinary maintenance is conducted throughout Excel sheets.

To calculate the environmental impact of maintenance activities, the present study implements all calculations throughout Excel. The data entry, asked to facility managers, requests few information on the adopted maintenance strategy. In addition to maintenance information, facility managers need to report costs of maintenance, age of the building, and which refurbishment/replacement items has been changed in the analysed year.

TYPE OF DATA	DATA
Maintenance type	Preventive/ Predictive Corrective
Cost of ordinary maintenance	… €
Cost of extraordinary maintenance	… €
Year of construction	…
Age	…
Refurbishment or Replacement	HVAC Radiator Copper HVAC pipes Electrical panel Electrical wiring Incandescent lighting Switch Sanitary equipment Copper water pipes Gas tank Gas oil/tank Copper gas pipes Steel gas/oil pipes

	Fire extinguisher PVC sewage pipe Lift

Table 1 Input data for assessing the environmental impact of maintenance activities – elaboration of the authors.

6. Results

To test calculations the authors have measured the environmental impact of three case study companies. The data has been collected for the year 2020 of three office buildings located in Milan, Italy (Table 2).

Building A, built in 2000, is leased to a multinational company, that occupied all the 10 floors of the building. Building B, built in 2003, is leased to a commercial information company, which started to occupy the all 9 floors of the building in 2017. Finally, Building C is an historical building located in the city-center of Milan. The company opened a coworking spaces, closed to companies, in 2020, after a full renovation. Thus, this is the only case study building certified LEED Gold.

	TYPE OF DATA	CASE STUDY DATA
BUILDING C	N employees	450
	Average occupancy	450
	Age	1
	Location	Milano
	Total SQM	33.972,00
	Type of building	Coworking space
	Ownership/Tenant	Owned
	Green Certifications	LEED Platinum
	Maintenance strategy	**Preventive**
	Maintenance costs	**Ordinary: € 50.000** **Extraordinary: € 10.000**
	Refurbishment or replacement	**NO**
BUILDING B	Average occupancy	100
	N employees	850
	Age	16
	Location	Milano
	Total SQM	23.920,00
	Type of building	Office
	Ownership/Tenant	1 Tenant
	Green Certifications	-
	Maintenance strategy	**Preventive**
	Maintenance costs	**Ordinary: € 100.000** **Extraordinary: € 40.000**
	Refurbishment or replacement	**NO**
BUILDING A	N employees	693
	Average occupancy	224
	Age	19
	Location	Milano
	Total SQM	22.511,00
	Type of building	Office
	Ownership/Tenant	1 Tenant
	Green Certifications	-
	Maintenance strategy	**Preventive**
	Maintenance costs	**Ordinary: € 277.000** **Extraordinary: € 48.000**
	Refurbishment or replacement	**NO**

Table 2 Data of the three case study buildings – elaboration of the authors.

The data of the three case study companies have been plot in the Excel file in order to measure the environmental impact of the maintenance strategy adopted in 2020 (Table 3).

DATA	RESULT
BUILDING C	
Years	2020
Maintenance Type	Predictive
Cost for ordinary maintenance	€ 50.000,00
Cost for extraordinary maintenance	€ 10.000,00
Year of Construction	2020
Age	1
Total impact (tCO₂/year)	**7,82**
gha/year	**3,21**
Refurbishment or replacement?	NO
BUILDING B	
Years	2020
Maintenance Type	Predictive
Cost for ordinary maintenance	€ 100.000,00
Cost for extraordinary maintenance	€ 40.000,00
Year of Construction	(2003) - 2017
Age	4
Total impact (tCO₂/year)	**16,04**
gha/year	**6,58**
Refurbishment or replacement?	NO
BUILDING A	
Years	2020
Maintenance Type	Predictive
Cost for ordinary maintenance	€ 277.000,00
Cost for extraordinary maintenance	€ 48.000,00
Year of Construction	2000
Age	20
Total impact (tCO₂/year)	**26,1**
gha/year	**10,21**
Refurbishment or replacement?	NO

Table 3 Results of the three case study buildings – elaboration of the authors.

As expected, the environmental impact of maintenance activities is lower for a new building, as Building C. In order to compare the three results, the gha/year has been divided per total square meters of the office building and per the average occupancy of workers (Figure 1).

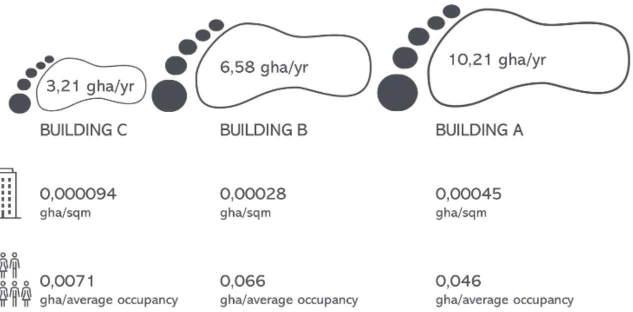

Figure 1 Results of the environmental impact of maintenance activities for the three case study buildings (year 2020) – elaboration of the authors.

Even if it is not possible to find a correlation between the environmental impact of maintenance strategies and the square meters of the building or the average occupancy, Building C still performs better compared to the others. On the other hand, Building B has an average occupancy of 100 workers, which makes the indicator of EF over average occupancy higher than Building A (with an average occupancy of 224 workers), which has the greatest environmental impact. Thus, maintenance strategies of the case study buildings do not involve other conditions, such as average people or total square meters of the building, but perform only activities mandatory by law.

After having calculated and compared the environmental impact of maintenance strategies of three office buildings, the authors have tried to use the Excel model to simulate different scenarios. The simulation started with the cost of maintenance of the three scenarios (Table 4):

- Predictive maintenance without any substitution in the time considered during our test;
- Predictive maintenance with the substitution of one element
- Corrective maintenance under reaction

For simulating the environmental impact of different maintenance strategies, the authors have considered a case study building with an age of 22 years. For the two cases of predictive maintenance, a total cost of ordinary maintenance has been considered equal to € 1.350.000 and of extraordinary to € 100.000. While for the third case of corrective maintenance – under reaction, the cost of € 1.350.000 has been allocated to extraordinary maintenance (Table 4). In addition to ordinary and extraordinary maintenance, case 2nd and case 3rd considered the substitution of an HVAC. Thus, the impact of this substitution, usually allocated to the year 25, has been considered for the two cases in the year 22.

Simulation	CASE 1	CASE 2	CASE 3
Year	2021	2021	2021
Maintenance Type	Predictive	Predictive	Corrective – under reaction
Cost for ordinary maintenance	1.350.000 €	1.350.000 €	- €
Cost for extraordinary maintenance	100.000 €	100.000 €	1.350.000 €
Year of Construction	2000	2000	2000
Age	22	22	22
Total impact (tCO_2/year)	84,61	111,13	287,60
gha/year	**34,69**	**45,57**	**117,92**
Refurbishment -replacement	NO	SI	SI
Quantity of materials substituted	0 kg	780 kg	780 kg

Table 4 Simulation case studies: data and results – elaboration of the authors.

Considering a total building life cycle of 50 years, in the year 22, the simulated case study building generates an environmental impact different according to the different maintenance strategies adopted. With a predictive maintenance without refurbishment/replacement, the impact equals 34,69 gha/year; with refurbishment/replacement, the impact equals 45,57 gh/year; and, with a corrective maintenance under reaction, the impact equals 117,92 gha/year. Thus, it seems that the adoption of a strategy performs better in terms of environmental impact. However, if the environmental impact is plotted over the 50 years (Table 5), considering the substitutions of the HVCA in the year 25 for the first case of predictive maintenance, and in the year 22 for the other two, the average environmental impact seems lower for the corrective maintenance – under reaction. Predictive maintenance has a constant impact over the building life cycle, while the environmental impact of corrective maintenance under reaction fluctuates over the life cycle with unexpected picks. The low impact of the first years increases over the life cycle due to the increase of the percentage of failure of the system, which loses reliability.

Year	**ENVIRONMENTAL IMPACT [gha/yr]**		
	1st case	**2nd case**	**3rd case**
1	26,96	26,96	2,72
2	27,16	27,16	5,33
3	27,35	27,35	7,84
4	27,53	27,53	10,26
5	27,70	27,70	12,59
6	27,67	27,67	12,45
7	27,85	27,85	14,84
8	27,99	27,99	17,13
9	28,15	28,15	19,33
10	28,31	28,31	18,82
11	28,08	28,08	21,11
12	28,28	28,28	23,38
13	28,14	28,14	22,89
14	28,30	28,30	25,01
15	28,44	28,44	27,06
16	28,25	28,25	26,46

Year	ENVIRONMENTAL IMPACT [gha/yr]		
	1st case	2nd case	3rd case
17	28,42	28,42	28,43
18	28,58	28,58	30,33
19	28,74	28,74	32,16
20	28,92	28,92	33,96
21	28,50	28,50	33,07
22	**34,69**	**45,56**	**117,92**
23	28,78	28,78	34,24
24	29,01	29,01	33,33
25	40,26	29,39	35,46
26	27,95	27,95	23,72
27	28,13	28,13	25,58
28	28,30	28,30	27,39
29	28,46	28,46	29,15
30	28,85	28,85	28,46
31	27,70	27,70	19,62
32	27,88	27,88	21,49
33	28,02	28,02	23,31
34	28,18	28,18	25,09
35	28,37	28,37	26,85
36	27,97	27,97	23,39
37	27,88	27,88	25,04
38	28,00	28,00	26,72
39	28,17	28,17	28,36
40	28,33	28,33	27,36
41	28,00	28,00	28,95
42	28,14	28,14	30,54
43	28,30	28,30	32,09
44	28,46	28,46	33,61
45	28,63	28,63	35,10
46	28,32	28,32	36,53
47	28,45	39,33	46,24
48	28,69	28,69	36,87
49	28,58	28,58	38,20
50	40,11	29,23	26,91
AVERAGE	28,80	28,80	27,45
SUM	1439,92	1439,92	1372,68

Table 5 Simulation case studies: plot of the environmental impact over the building life cycle (50 years) – elaboration of the authors.

7. Conclusions

The present study represents an advancement in the ongoing topic of changing O&M operations toward a sustainable development. The EF index is reviewed and a more detailed analysis on materials is conducted in order to develop a dynamic model, usable for evaluation of possible conditions. Indeed, the adoption of a calculation model to assess the environmental impact of different maintenance strategies help facility managers in adopting more sustainable and efficient policies.

The discussion of the results with the facility managers of the three case study companies highlighted the potential of using the EF indicator to express environmental impact of O&M. All the facility managers found clear and well expressed the unit of measurement (gha/year), because it can also be understood by no-experts. Unfortunately, results couldn't be commented on further as no actions had been taken. The calculations have been performed in 2020, in the middle of the Covid-19 pandemic, which especially effected office buildings. In this period, facility managers had to deal with workers returning to the offices, ensuring minimum distances between desks, and taking all precautions to avoid contagion. Thus, little interest was generated by performing maintenance strategy. In the future further discussion will be conducted to measure the impact of ordinary, extraordinary, and refurbishment activities.

Simulations on different strategies adopted to substitute the HVCA element shows that the environmental impact of a corrective maintenance under reaction is less compared to a predictive maintenance. In this condition, the impact increases over time with picks. This test does not consider other boundary conditions, such as the rate at which the system would fail if not maintained over the years. Future developments of the methodology will consider digital technologies (especially, artificial intelligence) to improve the quality of the test and simulate several conditions.

8. References

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9. Appendices

Item	Cost [€]	Emission Factor [$kgCO_2/kg$]	Item/year [qu/yr]	Cost/year [€/yr]	Annual cost [€/yr]	kg/item [kg]
Cleaning product	5,00	0,029889	10	50	2.986,60	0,8
Lubricant	10,00	1,741156	2	20		0,52
Filter	40,00	6,227	2	80		2,5
Descaler	10,00	0,868	2	20		0,52
Lubricant oil	20,00	1,271	2	40		0,52
Anti-mold	50,00	2,58	1	50		15
Silcion	23,80	3,167	2	47,6		1,5
Batteries	250,00	87,63	2	500		1,15
Gaskets	134,00	5,589	3	402		2,5
Lamps	3,00	1,0362	100	300		0,015
Switch	2,51	2,137	10	25,1		0,03
Cables	26,00	3,093	5	130		3,3
Fuse	1,15	4,238	80	92		0,01
Paints	70,00	8,44	2	140		6,8
Bolts	0,50	1,9	200	100		0,002
Screw	0,25	4,86	300	75		0,002
Differential switch	361,55	2,137	2	723,1		3,2
Plaster	16,90	0,236	2	33,8		25
Handles	11,00	4,362	4	44		0,6
Tubes	4,00	5,589	6	24		0,02
Fire Extinguisher	45,00	5,089	2	90		18

Table 6 Maintenance trolley: ordinary maintenance and extraordinary maintenance – elaboration of the authors.