Innovative VS. traditional: A framework to assess the sustainable trade-off of maintenance strategies

A.P. Pomè [1*], G. Orlandini [1], C. Tagliaro [1]

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, via Bonardi 9, Milan, Italty
*alicepaola.pome@polimi.it

Abstract: The European Union has the objective to make Europe the first zero-impact continent by 2050. The Green Deal has been issued specifically to encourage sustainable targets in the Architecture-Engineering-Construction-Operation (AECO) industry. Meanwhile, only 25% of the existing European building stock complies with the latest sustainability regulations. The environmental impact of real estate over the whole buildings' life cycle highly depends on the Operation and Maintenance (O&M) phase. Sustainable performance can be highly improved thanks to appropriate facility management (FM). Thus, it is urgent to introduce more effective sustainable practices by FM organizations, which may be possible with innovative maintenance, namely through the aid of digital technologies such as PropTech (property-technology) solutions. However, punctual assessments of the degree to which PropTech increases the sustainability performance of O&M are still missing. The present study aims to overcome this gap by outlining a framework of sustainability performance indicators for maintenance activities. This will allow future assessment of the impact of traditional maintenance practices compared to innovative ones, therefore boosting the adoption of supportive technology.

After defining the meaning of traditional and innovative building maintenance, the authors analysed the existing literature to collect a number of indicators suitable to assess the sustainable performance of maintenance activities. These indicators have been systematized based on the Environmental, Social, and Governance (ESG) assessment approach. A framework of 37 indicators was created, divided into five categories: environmental, social, economic, governance, and technical. A preliminary test for applicability of this conceptual framework to the activities included in the O&M phase was undertaken through discussion with an FM professional. The paper concludes by commenting on the future possible applications of this framework to evaluate the degree to which PropTech increases the sustainability of O&M, and, therefore, proves convenient to be adopted by FM companies.

1. Introduction

The advancement of digital technology impacted the way traditional industries perform daily operations. Thanks to digitalization, new perspectives to increase efficiency and sustainability are open. In the Architecture, Engineering, Construction, and Operation industry (AECO) this is commonly known as PropTech (abbreviation for Property and Technology). PropTech includes Building Information Modelling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI), among others, which have the potential to optimize the way operators plan, deliver, manage, operate, and maintain building assets [46]. As this revolution is recent, only few studies in the literature are available to date to explain the benefits of technological adoption, while many are still sceptic about the value for money of digital transformation.

AECO plays a central role in the sustainability triple-bottom line (i.e. environmental, social and economic impact). The built environment is responsible for around the 40% of global energy consumption and greenhouse gas emissions [1]. Especially, building operation and maintenance (O&M) have the highest sustainable impact (economic, environmental, and social), compared to other phases of buildings' life cycle [6]. The European Union has the ambition to make Europe the first zero-impact continent by 2050 [2]. To reach this objective, European countries have to optimize the emissions of their building stock, as only 25% of the existing buildings comply with the latest regulations [1].

Moreover, the interest in environmental, social and governance (ESG) indicators has recently increased in different economic sectors, promising to be effective for attracting tenants, reducing operations' expenditures, and improving investments [7]. ESG indicators are applied also in the AECO industry, with the aim to measure the sustainable performance and risks of investment and operations [8]. ESG reporting in AECO offers a practical and transparent instrument to assess the long-term impact of decisions and operations of sustainable projects [7]. An ESG approach can be valuable to integrate the sustainability principles expressed in the Agenda 2030 [3], known as Sustainable Developments Goals (SDGs) in the AECO industry. In this context, there is a large room for further relating ESG indicators to maintenance strategies. However, despite the interest expressed by the industry, a concrete strategy to measure the sustainability performance of O&M, based on ESG indicators, is still missing in the construction and real estate sector.

Thus, the present study aims to focus on building maintenance in order to understand the potential optimization towards sustainable development thanks to the aid offered by PropTech solutions.

After reviewing the adoption of digital technologies in the AECO industry, the study analyses the new perspectives for building maintenance and the potential benefits for a sustainable development of the strategies. Then, the

https://doi.org/10.1049/icp.2023.1739

methodology to implement a new framework for assessing sustainable performance of maintenance is presented. The last sections describe the framework, and discuss the limitations and future improvements of the present collection of indicators.

2. PropTech in the AECO industry

Digital technologies are generating a disruptive effect in all industries of the economy [4]. The technological wave is also increasing the efficiency of the AECO industry [9]. This digital innovation of the construction and real estate sector, defined as PropTech, is introducing several benefits in operations, such as, process improvements, advantages from market competitiveness, and operational efficiency [47]. Generally, PropTech represents the new approaches introduced into the industry [10], that push organizations to stay smart, sustainable, and inclusive [11]. Even if PropTech is still a new phenomenon, several networks around the world are trying to map the extent of innovation brought about by digital applications, by describing both the activities and business models of PropTech firms. The analysis of the scientific literature on PropTech shows two different ways in defining this innovation [46]. First, some authors describe "PropTech" as a supporting tool to help operators in the industry. Second, others describe "PropTech" as an approach to change the processes. Thus, PropTech seems to be applied as an innovator for processes, products, service, management, and business models of the AECO industry [6]. More generally PropTech affects the industry by introducing data-driven technologies in design, data assembly, and transactions [12].

Potential benefits in PropTech adoption are always counterbalanced by possible risks [13]. On one hand, innovation attracts more investors, and increases stakeholders' participation. On the other, the risk of failure is still high if not supported by performance maximization. A major benefit of PropTech solutions regards the improvement of transparency and connection among different clusters of operators, such as owner and tenants or building managers and building users [14]. Other benefits emerge in those solutions applied for the smart operation of buildings, such as energy and maintenance management [46]. By analysing the benefits of PropTech, several studies [13,14, 46, 48, 49] highlight two main aspects: (i) emerging technologies have the potential to improve competitiveness and productivity of AECO operations, (ii) innovation is always accompanied by the optimization of performances, which support the sustainable development of the industry. Thus, digital technologies are helping the AECO industry to reduce its environmental impact with the adoption of those technologies that optimize building operations and management, such as Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning (ML), and Digital Twin (DT).

Digital technologies represent a great opportunity to control, manage, and optimize buildings' consumptions during the O&M phase. For instance, Kim et al. [10] showed that the development of information technology, especially throughout the adoption of AI and ML, optimized the decision making process related to operations' management. Besides, [49] demonstrated that the use of an intelligent-BMS, an IoT network connected with an AI and ML platform, allows the reduction of energy consumption of 14 commercial buildings by 15% after one year of use. Another study [49] about the application of DT in O&M showed that the potential of this technology is the optimization of consumption, especially in energy and maintenance management. In all, all the authors confirm that predictive maintenance is only possible and fully applicable through the use of technology in the O&M phase of building life cycle.

3. New perspectives for building maintenance

The ways building assets are managed and maintained is constantly evolving over time. Building maintenance goes under the concept of facility management (FM), a discipline born in USA in the '80s. In 1993, the British Standard BS 3811 [51] described maintenance as the combination of administrative and technical activities to preserve and/or restore an item in a state in which it can execute the required function. More recently, UNI EN 15221 [50] defines facility management as the "*integration of processes within an organization to maintain and develop the agreed services with support and improve the effectiveness of its primary activities*".

So, the International Facility Management Association (IFMA) added enriched definition of FM by mentioning explicitly the relationship between the managed building asset with people, process, and technology [5]. Thus, by FM we mean the integration of multi-disciplinary activities for the built environment, which embraces the management of both services and users.

Encompassing many operations and functions, Allen [15] schematized building maintenance as the integration of strategy and process. The strategy should ensure both the value for money spent, and value protection for assets and resources. the maintenance process extends over subsequent phases: the maintenance audit, the maintenance plan, the maintenance program, and the collection of feedback. The maintenance practice pushed the international standardization bodies to better explain the concept of maintenance to highlight the relations among interventions and technical, administrative, and management activities. UNI EN 13306 [52] defined maintenance as *"the combination of all technical, administrative, and managerial actions during the life cycle of an entity to maintain or restore it to a state in which it can perform the required function"*. The combination of technical and administrative actions makes building maintenance a complex process to handle during the O&M phase of building life cycle. To support building managers and improve maintenance services, ISO 41001 issued a set of guidelines to monitor building maintenance practices. This standard proposes the Plan-Do-Check-Act cycle (PDCA) as the method to constantly monitor the quality of building maintenance. However, maintenance standards do not set up a system to verify the level of sustainability performance achieved by more efficient operations' management. Also, those standards that guide the impact assessment for the built environment (such as, BS EN 15978:2011 [53] and BS EN 15643:2021 [54]) are not explicit about how to measure the sustainability performance of maintenance activities. This is a limit of the ongoing discussion about improving sustainability performance in the O&M phase. In general, maintenance strategies are described in multiple ways. On the one hand, standards in the AECO industry tend to describe maintenance according to the type of plan used by managers.

On the other hand, studies from different industries describe maintenance throughout the evolution of the process over time. The two approaches are described in the following sub-chapters in order to highlight the ongoing shift from traditional to innovative maintenance, and support the argument about the relevance of digital technology to open up new perspectives for building maintenance.

3.1. Unplanned and planned maintenance

Strategy is a key aspect of maintenance activities. Generally, two main maintenance approaches are available, namely planned and unplanned maintenance [16], as showed in Figure 1. *Unplanned* maintenance is adopted to overcome problems, such as users' complaints, loss of control, and unexpected breakdowns [17]. *Planned* maintenance is performed to maximize a component performance while avoiding failures during operations [18]. Different strategies can be carried out both in planned and unplanned approaches. Unplanned maintenance follows a 'corrective' logic, whereas planned maintenance may use preventive and corrective strategies. BS 3811 [55] described *preventive* maintenance as the strategy *"carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item"*, which can be predetermined maintenance (carried out on a fixed time interval regardless of the item's conditions), condition-based maintenance (carried out with a continuous monitoring approach and according to the condition of the item), or predictive maintenance (carried out after the definition of the expected failure time of the component). BS 3811 [55] defined corrective maintenance as the strategy *"carried out after fault recognition and intended to put an item into a state in which it can perform a required function"*, which can be *deferred* maintenance (carried out without a determined schedule due to some limitations, such as costs, workforce, or materials), or *immediate* maintenance (carried out instantly to avoid other damage).

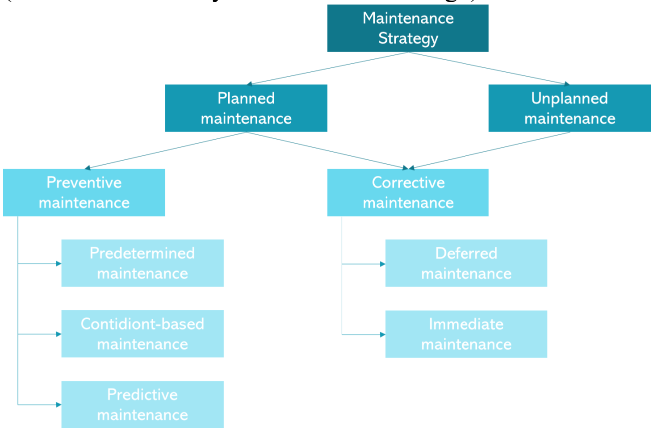

Figure 1 Types of maintenance strategies. Elaboration of the authors from BS 3811 standard.

3.2. Traditional maintenance VS. innovative maintenance

Maintenance strategies may be classified according to the evolution of the approach used in the industry. The drivers for choosing among different strategies are usually maintainability, reliability, availability, and cost optimization during the O&M phase with the objective to reduce downtime and maximize the activity [19]. The state of the art on the adoption of technology in the O&M phase shows that the transition from a traditional maintenance strategy to an innovative one may optimize the sustainable performance of buildings, as well as the sustainable performance of the maintenance activity itself. Eyoh and Kalawsky [20] ointed out that maintenance management has always been related to the change in technological innovation: from the control of simple machines and equipment to the monitoring of complex and sophisticated systems.

Even if focusing on engineering plants, the study [20] described the evolution of maintenance strategy (Figure 2), that can be applied to every industry. The first and most basic technique is the *primitive maintenance*, which matches most of the unplanned maintenance strategies, aiming to just react after a breakdown. The second technique is the *traditional maintenance*, which considers the reduction of maintenance costs while putting little attention to availability and reliability of systems. This is the classic strategy, basically corresponding to planned maintenance (as described also before), that can be differentiated into preventive maintenance and corrective maintenance. This technique trained maintenance managers to prevent and plan maintenance activities over the whole life cycle. This approach evolved into the *modern* technique, in which decisions are made according to the conditions of the item to be maintained [20]. According to the modern technique, maintenance programs are based on functional and operational information of systems. Thus, modern programs try to optimize traditional maintenance by incorporating historical information, best practices, and condition assessments. According to Eyoh and Kalawsky [20] these programs include five different techniques. (1) *Reliability maintenance* establishes the desired performance and the required functional standards. (2) *Risk-based maintenance* involves planned inspections. (3) *Condition-based maintenance* considers current degradation of the item. (4) *Productive maintenance* integrates breakdown information, reliability, and maintainability with respect to economic efficiency. (5) *Predictive maintenance* considers the real conditions of the item, using critical parameters and forecasts of future conditions.

Finally, thanks to the technological evolution, new technologies allowed the adoption of automation, which showed several weaknesses of modern maintenance techniques. On the whole, the development of effective maintenance strategies has been always aimed at reducing the risk of failures, maximize availability, sustainability, and reliability, while minimizing operational costs. *Innovative* maintenance can be considered as a novel technique, which uses technology to improve maintenance management [20]. Innovative maintenance may use two different maintenance approaches. *Intelligent maintenance* uses technology to monitor the condition of a system, diagnose possible failures, and predict the remaining useful life. *Condition-based Predictive maintenance* is an intelligent maintenance strategy that monitors conditions and performances, estimates future stages, and detects faults by using sensors and AI.

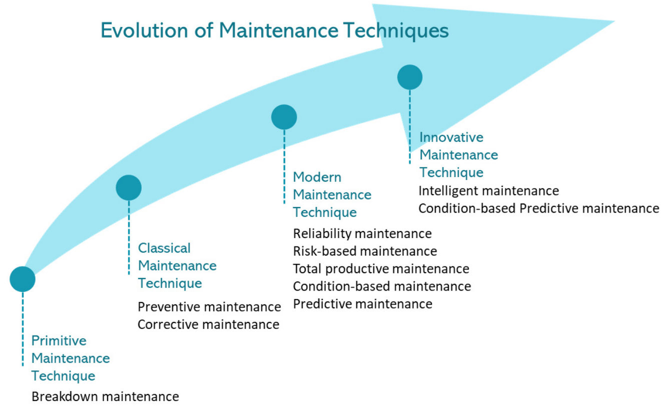

Figure 2 Evolution of Maintenance techniques over industrial systems. Elaboration of the authors from Eyon and Kalawsky, 2019.

Still trying to describe maintenance strategies, other studies explained the evolution of maintenance strategies by looking at the maturity level. Maturity comes from the ability of collecting, reviewing, and integrating more and more information in maintenance systems thanks to the integration of technology. Pushed by optimizing maintenance costs, maintenance managers introduce different approaches, which improve maintenance efficiency thanks to the adoption of knowledge-intensive strategies. According to Errandonea et al. [21] the evolution of maintenance strategies over time depends on the maturity level of systems. This study developed a maintenance maturity model defined by four levels of maintenance maturity: preventive, condition-based, predictive, and prescriptive. This last step represents the highest maturity level of maintenance, which can be reached thanks to better information available to the operators when systems adopt technology to analyse performance. Each level is described with three areas: assets, status, and maintenance. These areas are necessary to guide maintainers to gradually adopt more advanced maintenance strategies, starting with preventive and ending with prescriptive, which consists in using recommendation system for optimized and knowledge-based activities plan [22]. According to the present state of the art on the evolution of maintenance strategies, this study distinguishes two main categories of maintenance: traditional maintenance and innovative maintenance. *Traditional maintenance* includes preventive maintenance, with the main objective to assure regular operations. Conversely, *innovative maintenance* leverages on technology on top of preventive maintenance strategies with the goal to optimize costs and improve availability, reliability, and maintainability of the systems (Table 1). The concrete difference between traditional and innovative maintenance lays in the adoption of technologies.

3.3. Sustainability assessment of O&M

The integration of technologies may enable the improvement of buildings' environmental impact (Environment), the optimization of operations of building systems (Governance), and enhancement of users' well-being (Social). At the same time, technological innovation introduced by PropTech solutions has the potential to optimize the sustainable performance of O&M activities themselves [23, 46, 49]. Indeed, to manage existing buildings towards sustainability, a sustainable and effective approach must be taken into account, integrating the three spheres of sustainability (environmental, economic, and social) [24] while performing maintenance activities. For example, some traditional maintenance approaches, such as maintenance inspections, selection of maintenance materials, and maintenance waste disposal, are not sustainable and effective [25-27]. Moreover, the introduction of more sophisticated systems in buildings increase the complexity of building maintenance management [28]. Involving different processes (planning, tendering, execution, verification, and approval), a traditional maintenance strategy would lack in efficiency [24]. On the other hand, an innovative maintenance strategy would provide the opportunity to reduce emissions and waste, improve energy efficiency, and make a building more environmentally friendly [24].

Several studies suggest that there may be a significant correlation between digital technology adoption and the optimization of sustainability performance. However, the literature still misses an approach to measure the several opportunities generated by an innovative maintenance strategy in O&M. Therefore, the present study aims to outline a framework of indicators suitable to assess the level of sustainability of innovative maintenance compared to traditional maintenance.

4. **Methodology**

With the aim to implement a framework of indicators and evaluate the level of sustainability introduced by an

Source	Traditional maintenance	Innovative maintenance
Eyoh and Kalawsky, 2019	Primitive maintenance	Innovative maintenance
	Classical maintenance	
	Modern maintenance	
Errandonea et al., 2020	Preventive maintenance	Prescriptive maintenance
Definition	The routine maintenance that aims to ensure operations and reduce unplanned failures. The main goal is to keep the item operating at a peak of efficiency.	The implementation of technology (IoT, ML, and AI) helps to optimize maintainability, reliability and availability of the system. This maintenance can use condition-based, predictive, and reactive maintenance.

Table 1 Traditional maintenance VS. innovative maintenance. Elaboration of the authors.

innovative maintenance strategy, the present study follows subsequent steps:

i. A review of the literature on facility performance management helped understand which indicators has been used in previous applications to measure the sustainability of *traditional maintenance strategies*;

ii. Based on the existing indicators, a framework was created, divided into multiple sustainability categories, and was further integrated with indicators derived from *innovative maintenance strategies*, as suggested by facility management operators;

iii. A preliminary validation of the framework was conducted in order to verify its applicability in the daily operations of maintenance companies.

To proceed with the integration and preliminary validation of the framework, the authors interviewed the Chief Information Officer (CIO) and co-founder of an Italian PropTech company that introduced innovative maintenance in several projects. The company, Ekore[1], has been selected by convenience among those listed in the Italian PropTech Monitor of Politecnico di Milano.[2] Among the listed companies, only one is implementing IoT, AI, ML, and edge platform in the O&M phase to make maintenance activities more efficient. Ekore was founded in 2022 by ADHOX srl, a consultancy company in the BIM field, and BeanTech srl, an information and communication company. Ekore defines itself as a platform that uses technologies (especially, Digital Twin and Cloud environment) to optimize facility management of buildings. As Ekore proposes an on-demand technological structure for facility management to its clients, the authors found relevant to discuss the framework of indicators with this company, which has direct experience in guiding clients from a traditional to an innovative maintenance strategy. Two different talks on Microsoft Teams have been conducted with the company. The first, on May 5th 2023, explained the general logic behind the framework and was aimed specifically to complement it with new indicators. The second interview, on June 13th 2023, was a interview to further validate the final list of indicators, unit of measurements, and ways of data collections.

5. Results

5.1. Existing indicators for sustainability performance measurement

To develop a sustainability performance framework for maintenance we referred to the few available studies presenting some general discussion on the topic [29-32]. As reported in Table 2, we retrieved 14 scientific papers collected mainly through a snowball sampling method. The specific goal was to check which maintenance performance measurement perspectives were considered in each single study among three main categories: economic (cost effectiveness, quality, productivity), social (learning and growth, health and safety, employee satisfaction, customer satisfaction), and environmental.

Most of these studies agreed on the need to list a quantifiable and relatively easily list of indicators to evaluate performance in a holistic approach [33, 34]. According to

Table 2 Comparison of maintenance performance measurement indicators by different studies. Elaboration of the authors.

Reference		Performance indicators categories
Kutucuoglu et al., 2001	41	Equipment, task, cost, immediate customer impact, learning and growth-related performance.
Langston and Lauge-Kristensen, 2002	56	Strategic, Tactical, and Operational levels
Marquez & Gupta 2006	38	Strategic, Tactical, and Operational levels
Yasamis et al., 2002	43	Service as perceived by the owner; service as perceived by the end-user
Lützkendorf et al., 2005	31	Economic, Environmental, Social, Technical, Functional aspects
Parida & Chattopadhyay, 2007	44	Customer satisfaction, cost, plant/ process; maintenance task, learning and growth/Innovation, health, safety and environment; employee satisfaction related indicators
Pati et al., 2010	42	Hard indicators (maintenance policy and budget allocation) & Soft indicators (environment and behaviour)
Muchiri et al., 2010	39	Maintenance process (leading) and Maintenance results (lagging) indicator
Muchiri et al., 2011	40	Maintenance process (leading) and Maintenance results (lagging) indicator
Lavy et al., 2014a, 2014b	33 34	Financial, Physical, Functional and Survey-based indicators
Kylili et al., 2016	36	Economic, Environmental, Social, Technological performance + time, quality, disputes and project administration.
Sari et al., 2015	45	Economic, Environmental, Social aspects
Larsen, 2010	7	Economic, Environmental, Social aspects

Lützkendorf et al. [35] a performance approach has to consider simultaneously functional, design, technical, economic, environmental, and social aspects. Lavy et al. (2014a,2014b) grouped performance indicators into four

[1] Ekore: https://www.ekore.it/

[2] Italian PropTech Monitor:

categories: financial (cost and expenditures), physical (physical conditions of the facility), functional, and survey-based (mainly, qualitative indicators on users' satisfaction). Another approach, presented by Kylili et al. [36], proposed to include technological performance to measure sustainability, such as time, quality, disputes, and project administration. These indicators need to be quantitative, measurable, and applicable. To combine the indicators to maintenance strategy, Langston and Lauge-Kristensen [56], Marquez and Sànchez [37], and Marquez and Gupta [38] defined three levels: strategic (with the objective to transform business priorities into maintenance priorities), tactical (with the objective to determine the correct allocation of resources for maintenance performance), and operational (with the object to ensure the proper execution of maintenance work). Muchiri et al. [40] defined maintenance process (such as, equipment performance and cost performance) and maintenance result (such as, maintenance productivity and availability) as valuable categories to measure improvement in maintenance operations. With the objective to measure performance and efficiency, Kutucuoglu [41] identifies the added value given by learning and growing of maintenance workforce. Pati et al. [42] defined hard indicators, which evaluate maintenance policy (such as, budget allocation), and soft indicators, which are related to the environment and the behaviour. To suggest the quality of the building maintenance approach, Yasamis et al. [43] proposed a construction quality approach that looked at both service (as perceived by the owner) and product (as perceived by the end-users). To include users' perspective, Parida and Chattopadhyaya [44] listed specific indicators, such as customer satisfaction, cost, maintenance tasks, health, safety and environment, and employee satisfaction. Finally, an interesting approach came from another industry: automotive production. A literature review on the integration of maintenance performance measurement systems to measure, monitor, and improve production systems highlighted the need of an appropriate measurement framework to measure sustainable maintenance management [45].

Of note is that only the most recent articles, in particular those dating after 2015, formally start including indicators aimed at measuring economic, social and environmental impacts altogether, whereas the older ones tend to focus of costs and efficiency. This progression goes hand in hand with the development of regulations and standards, as described in the introduction of this paper. Interestingly, none of the most recent articles mentioned explicitly ESGs nor referred to the potential of innovative maintenance (i.e. digital technology) to feed the identified performance indicators.

5.2. A proposal for sustainable innovative maintenance assessment

From the analysis of the existing performance indicator categories, it was possible to identify five major impact categories that should be reflected by any new framework: economic, environmental, social, technical, and governance. To demonstrate the sustainability benefits of innovative maintenance strategy over traditional maintenance, we deemed it necessary to integrate the already available indicators with some new ones, that were gathered from the interview with a professional operator dealing with the transition from traditional to innovative maintenance, as described in the methodology section above. Thanks to the analysis of previous applications, we retrieved 30 items of the framework. Additional 7 new indicators derived from the interview. Overall, we obtained a comprehensive framework composed of 37 indicators.

As opposed to the most common approach found in the literature, which tends to attribute each indicator to a single impact, in our framework every indicator oftentimes impact two categories, as reported in Figure 3. The

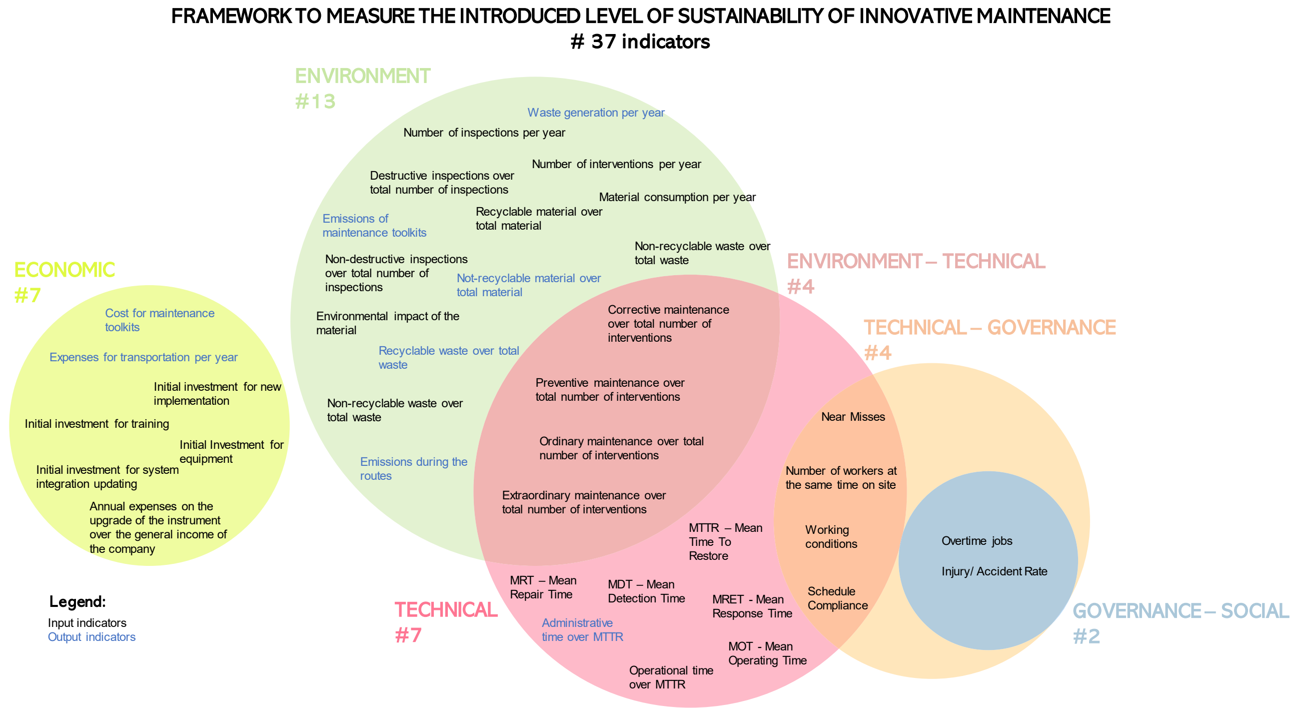

Figure 3 The framework of indicators to measure the introduced level of sustainability of an innovative maintenance over a traditional one. Elaboration of the authors.

combination of the different impacts, discussed in depth with the interviewee, would enrich the assessment of the sustainable performance of innovative maintenance strategies. In Appendix A, the entire framework is presented with the description and unit of measurement (UM) for each indicator. Moreover, all the indicators can be either input indicators or output indicators. Namely, input indicators are fed by primary data (e.g. through sensors, or different data collection method with each case company), whereas output indicators use input indicators' data to be calculated – respectively in black and blue colour in Figure 3).

5.3. Framework's validation

Ekore has not conducted any specific examinations to assess the degree of relation between maintenance and sustainability yet. However, Agostini agreed with our findings from the literature review about the importance and urgency of implementing a framework to evaluate the relation and the improved sustainability level of O&M. In particular, being able to demonstrate the increasing sustainability of innovative maintenance strategies could strongly boost the adoption of digital technologies in the sector by showing its value for money. According to the experience of Agostini, all the impact categories were considered fundamental even though, from the owner/buyer/investment company' point of view, the economic category would still remain the most relevant, followed by environmental, social, technical, and governance. All the indicators included in the final framework were considered relevant for assessing O&M's sustainable performance.

Generally, the interviewee gave a positive opinion regarding the scope of the implemented framework. Concerning the relations among technological adoption and potential sustainability, in his opinion the framework would better explain to building owners and/or facility managers the benefits of an innovative maintenance approach and the return obtainable by investing in digital technologies.

6. Conclusions

The present study aimed to overcome the current limitations of the facility management field in assessing the sustainability performance of maintenance operations. This is crucial to mitigate the global environmental degradation that the O&M phase of buildings' life cycle sadly contributes to. A structured way to evaluate the sustainability level of maintenance activities is still missing. However, the adoption of digital technology in O&M strategies opens up new avenues to monitor and manage the sustainable performance of maintenance operations. Therefore, the present study proposes a framework that integrate traditional and innovative maintenance indicators. The framework includes 37 items systematized in five impact categories (economic, environmental, social, technical, and governance).

The study represents a first attempt to create a sustainability assessment strategy. It needs further development to demonstrate the increased sustainability performance generated by an innovative maintenance strategy compared to a traditional one. The preliminary validation we ran through an interview with a professional operator was suitable to estimate a potential interest from operators in adopting the framework, and to partially estimate its applicability. Future developments of this study will use the framework to compare the maintenance strategy of real case study buildings.

Finally, the present study stimulates discussion in O&M, both from a scientific and practical point of view. Owners, managers, and users still need to understand the potential effect of implementing technologies for maintenance purposes. At the same time, research still fails to discuss in depth advantages and potential risks of technology adoption in the sector. The framework outlined in this paper contributes to systematising the potential sustainability gains of an innovative maintenance strategy.

7. Acknowledgments

The authors would like to thank Andrea Agostini, CIO and co-founder of Ekore.

8. References

8.1. Websites

[1] 'Verna S. - The crest of Renovation Wave: a toolkit to decarbonise the European building stock, Build', https://www.builup.eu/en/news/crest-renovation-wave-toolkit-decarbonise-european-building-stock, accessed 10 May 2023
[2]Green Deal. European Commission (2020), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN, accessed 10 May 2023
[3] Agenda 2030 for Sustainable Development (2015): https://unric.org/it/agenda-2030/, accessed 10 May 2023
[4] Feth, M.; Gruneberg, H. PropTech-The Real Estate Industry in Transition 2018. Available online: https://www.semanticscholar.org/paper/Proptech-The-Real-Estate-Industry-in-Transition-Feth-Gruneberg/031f93fbe1043e5bd343db3e15ff6c1230b85e5a, accessed 10 May 2023
[5] IFMA, What is Facility Management https://www.ifma.org/about/what-is-fm/ , accessed 10 May 2023
[6] G. Mattarocci, X. Scimone (2022). The New Era of Real Estate. An Analysis of Business Models in the Proptech Industry. Available online: https://link.springer.com/chapter/10.1007/978-3-031-16731-7_2 accessed 10 May 2023

8.1. Journal articles

[6] Chiang, Y.H., Li, J., Zhou, L., Wong, F.K.W., Lam, P.T.I. The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong, J. Clean. Prod., 2015, 109, pp. 326–335
[7] Larsen, T.. Implementing ESG in Private Real Estate Portfolios: The Case of U.S. and Pan-Europe Core Fund Managers. Journal of Sustainable Real Estate, 2010, 2(1): p. 249-267.
[8] Folqué, M., Escrig-Olmedo, E., Corzo Santamaria, T. Sustainable development and financial system: Integrating ESG risks through sustainable investments strategies in climate change context. Sustainable Development, 2021
[9] European Institute of Innovation & Technology (EIT). Digital transformation of European industry a policy

perspective full report digital transformation of European industry - A policy perspective, 2021.
[10] Kim, J.; Kim, J. An Integrated Analysis of Value-Based Adoption Model and Information Systems Success Model for PropTech Service Platform. Sustainability, 13, 12974, 2021
[11] Walsh C. Territorial agenda of the European union 2020: Towards an inclusive, smart and sustainable Europe of diverse regions. Planning Theory and Practice, 13:493–6, 2012
[12] Baum, A., Saull, A., Braessemann, F.PropTech 2020: The Future of Real Estate, University of Oxford, Said Business School, 2020.
[13] Lecomte, P. iSpace: Principles for a phenomenology of space user in smart real estate. Journal of Property Investment & Finance, 38(4), 271–290, 2020
[14] Bröchner, J., Haugen, T., & Lindkvist, C. Shaping tomorrow's facilities management. Facilities, 37(7/8), 366–380, 2019
[15] Allen, F. Strategic management and financial markets. Strategic Management, 14, 52, 1993
[16] Chanter, B., Swallow, P. Building Maintenance Management, John Wiley & Sons, 2008.
[17] Nur'afini D., Noor N.S., Izni S.I., Nur I.A., Fadzil M.Y., Nik Z.N.A. Review on maintenance issues toward building maintenance management best practices, Journal of Building Engineering, 44, 2021
[18] Ferreira, C., Silva, A., de Brito, J., Dias, I.S., Flores-Colen I. The impact of imperfect maintenance actions on the degradation of buildings' envelope components, Journal of Building Engineering, 33, 2021
[19] Swanson, L. Linking maintenance strategies to performance. International Journal of Production Economics, 70, 2001
[20] Eyoh, J., Roy S.K. Evolution of Maintenance Strategies in Oil and Gas Industries: The Present Achievements and Future Trends, 2019
[21] Errandonea, I., Alvarado, U., Beltrán, S., Arrizabalaga, S. A Maturity Model Proposal for Industrial Maintenance and Its Application to the Railway Sector. Appl. Sci., 12, 2022
[22] Bowen, G.A. Document Analysis as a Qualitative Research Method. Qual. Res. J., 9, 27–40, 2009
[23] GhaffarianHoseini, A., Zhang, T., Nwadigo, O., GhaffarianHoseini, A., Naismith, N., Tookey, J., Raahemifar, K. Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency. Renewable and Sustainable Energy Reviews, 72, 935-949, 2017
[24] Hauashdh, A., Jailani, J., Rahman I.A., AL-fadhali, N. Strategic approaches towards achieving sustainable and effective building maintenance practices in maintenance-managed buildings: A combination of expert interviews and a literature review. Journal of Building Engineering, 2021
[25] Fox, M., Coley, D., Goodhew, S., De Wilde, P.Time-lapse thermography for building defect detection, Energy Build. 92, 95–106, 2015
[26] Li, M., Yang, J. Critical factors for waste management in office building retrofit projects in Australia, Resour. Conserv. Recycl. 93, 85–98, 2014
[27] Jalaei, F., Zoghi, M., Khoshand, A. Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM), Int. J. Construct. Manag., 1–18, 2019
[28] Hauashdh, A., Jailani, J., Rahman, I.A. AL-fadhali, N. Structural equation model for assessing factors affecting building maintenance success, J. Build. Eng. 44, 2021
[29] Prior, J. and F. Szigeti. Why all the fuss about Performance Based Building? International Council for Research and Innovation in Building and Construction PeBBu Thematic Network, 2003.
[30] Sexton, M. and P. Barrett. Performancebased building and innovation: balancing client and industry needs. Building Research & Information Vol. 33 (2), 2005. pp. 142-148
[31] Lützkendorf, T., T.M.Speer. Alleviating asymmetrical information . Building Reasearch & Information Vol. 33 (2), 2004, pp. 182-195
[32] Hattis, D. B., Becker, R. Comparison of the Systems Approach and the Nordic Model and their Melded Application in the Development of Performance Based Building Codes and Standards. Journal of Testing and Evaluation. Vol. 29, No. 4, 2001, pp. 413–422.
[33] Lavy, S., Garcia, J.A., Dixit, M.K. KPIs for facility's performance assessment, Part I: identification and categorization of core indicators, Facilities 32, 2014a, pp. 256–274
[34] Lavy, S., Garcia, J.A., Dixit, M.K. KPIs for facility's performance assessment, Part II: identification of variables and deriving expressions for core indicators, Facilities 32, 2014b, pp. 75–294
[35] Lützkendorf, T., Speer, T., Szigeti, F., Davis, G., le Roux, P., Kato, A., Tsunekawa, K. A comparison of international classifications for performance requirements and building performance categories used in evaluation methods, Technical Research Centre of Finland, Association of Finnish Civil Engineers, Helsinki, Finland, 2005, pp. 61–80
[36] Kylili A, Fokaides P. A., Lopez Jimenez P. A. Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review, Renewable and Sustainable Energy Reviews, Vol. 56, 2016, pp. 906-915
[37] Marquez, A.C., Sánchez Heguedas A. Models for maintenance optimization: a study for repairable systems and finite time periods. Reliability Engineering and System Safety, 75, 3, 2002, pp.367–377
[38] Marquez, A.C., Gupta, N.D. Contemporary maintenance management: Process, framework and supporting pillars. Omega 34, 3, 2006, pp. 313-326
[39] Muchiri P., Printelon L., Martin H., De Mayer A. Empirical analysis of maintenance performance measurement in Belgian industries, International Journal of Production Research, 2010
[40] Muchiri P., Pintelon L., Gelders L., Martin H. Development of maintenance function performance measurement framework and indicators. International Journal of Production Economics, 131, 2011, pp. 295-302
[41] Kutucuoglu K.Y., Hamali J., Irani Z., Sharp J.M. A framework for managing maintenance using performance measurement systems. International Journal of Operations & Production Management, 21, 2001, pp. 173-94

[42] Pati D., Park C. S., Augenbroe G. Facility maintenance performance perspective to target strategic organizational objectives. Journal of Performance of Constructed Facilities, 24(2), 2010, pp. 180-187
[43] Yasamis F., Arditi D., Mohammadi J. Assessing contractor quality performance. Constr. Manage. Econom., 20(3), 2002, pp. 211–223
[44] Parida A., Chattopadhyay G. Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM). Journal of Quality in Maintenance Engineering. 13, 2007, pp. 241-258
[45] Sari E., Shaharoun A.M, Ma'aram A., Yazid A. M. Sustainable Maintenance Performance Measures: A Pilot Survey in Malaysian Automotive Companies, Procedia CIRP, Vol. 26, 2015, pp. 443-448

8.2. Conference Paper

[46] Pomè, A.P., Tagliaro, C., Celani, A., Ciaramella, G. 'Is Digitalization Worth the Hassle? Two cases of Innovation Building Operation and Maintenance'. OP Conference Series: Earth and Environmental Science, Trondheim, Norway, May 2023.
[47] Siniak N., Kauko T., Shavrov S., Marina N. The impact of PropTech on real estate industry growth. IOP Conf. Ser.:Mater. Sci. Eng., 2020
[48] Nikolai Siniak et al 2020 IOP Conf. Ser.: Mater. Sci. Eng. 869 062041, 2020
[49] Pomè, A.P., Signorini, M. Real time facility management: assessing the effectiveness of Digital Twin in the Operation and Maintenance phase of building life cycle. IOP Conference Series: Earth and Environmental Science, Trondheim, Norway, May 2023

8.3. Standard

[50] UNI EN 15221-1: 'Part 1: Terms and definitions', 2007
[51] BS 3811: 'Glossary of maintenance management terms in terotechnology', 1993
[52] UNI EN 13306: 'Maintenance/ Terminology', 2003
[53] BS EN 15978: 'Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method', 2011
[54] BS EN 15643: 'Sustainability of construction works. Sustainability assessment of buildings and civil engineering works', 2021
[55] BS 3811: 'Maintenance Strategy and Planning', 1993

8.4. Book, book chapter and manual

[56] Langston, C., Lauge-Kristensen, R.: 'Strategic Maintenance of Built Facilities' (Taylor & Francis Ltd, 1st edn. 2002)

9. Appendix A

Framework of indicators					
Indicators	**Input/Output**	**Description**	**U.M**	**Category**	**Source**
Number of interventions per year	Input	Counts the number of interventions (the fieldwork conducted to keep the asset in good condition) in a year	nr/yr	Environment	Gonzalez et al. 2017
Corrective maintenance over total number of interventions	Input	Represents the ratio over the all number of intervations of maintenance activities conducted after a failure is detected in a year	%	Environment/ Technical	Rediske et al. 2022
Preventive maintenance over total number of interventions	Input	Represents the ratio over the all number of intervations of maintenance activities conducted to reduce the risk of failures in a year	%		
Ordinary maintenance over total number of interventions	Input	Represents the ratio over the all number of intervations of maintenance activities planned in a year	%	Environment/ Technical	Interview to Ekore
Extraordinary maintenance over total number of interventions	Input	Represents the ratio over the all number of intervations of maintenance activities not planned in a year	%	Environment/ Technical	
Number of inspections per year	Input	Counts the inspections in a year	nr/yr	Environment	Hauashdh et al. (2022)
Destructive inspections over total number of inspections	Input	Represents the number of distructive inspections (that implies the creation of waste) over the all inspection in a year	%		
Non-destructive inspections over total number of inspections	Input	Represents the number of non-distructive inspections (that implies only control of the item) over the all inspection in a year	%		
Material consumption per year	Input	Represents the total material used in a year for maintenance activities	kg/yr	Environment	Interview to Ekore
Recyclable material over total material	Input	Represents the amount of used materials in a year that is recyclable	%		
Not-recyclable material over total material	Input	Represents tha amount of used materials in a year that is not-recyclable	%		
Environmental impact of the material	Input	Represents the impact of the used materials in a year for maintenance activities	$kgCO_2/yr$		
MRT – Mean Repair Time	Input	Represent the average time required to perform the maintenance activity	hours	Technical	Normativa ISO
Waste generation per year	Output	Counts the amount of waste generated by interventions	kg/yr	Environment	Hauashdh et al. (2022); Martinez-Rocamora et al. 2017
Recyclable waste over total waste	Output	On the total waste, represents the recyclable one	%		
Not-recyclable waste over total waste	Output	On the total waste, represents the not-recyclable one	%		
Emissions of maintenance toolkits	Output	Counts the total emission generated by interventions	$kgCO_2/yr$	Environment	Martinez-Rocamora et al. 2017
Cost for maintenance toolkits	Output	Counts the total cost of interventions	€/yr	Economic	
MTTR – Mean Time To Restore	Input	Represents the average time of restoration	hours	Technical	UNI EN 15341:2007
MDT – Mean Detection Time	Input	Represents the average time for detecting anomalies	hours		
MRET - Mean Response Time	Input	Represents the average time to activate the operational part	hours		
Administrative time over MTTR	Output	Represents the average administrative time over MTTR	%		
MOT - Mean Operating Time	Input	Represents the average operating time (approval, schedule, suspension, intervention)	hours		
Operational time over MTTR	Output	Represents the average operational time over MTTR	%		
Traveled distance per year	Input	Represents the average distance taken by maintenance operators for intervention	km/yr	Environment	Martinez- Rocamora et al. 2017; Romano et al. 2015
Emissions during the routes	Output	Represents the average emission of travels	$kgCO_2/yr$	Environment	
Expenses for transportation per year	Output	Represents the average expenditures of travels	€/yr	Economic	
Schedule Compliance	Input	Represents the ration between scheduled maintenance tasks completed over time (and, total number of tasks)	%	Technical/ Governance	Gonzalez et al.2017, UNI EN 15341:2007
Overtime jobs	Input	Represents the ration of overtime works over planned hours: represents the effectiveness of maintenance planning, worker health, or ideal number of employees	%	Social/ Governance	
Injury/ Accident Rate	Input	Represents the ration between injury and accident over interventions	%	Social/ Governance	Al-Turki et al. 2014; Heinrich, 1931
Near Misses	Input	Represents the ration of missed accident over interventions	%		
Working conditions	Input	Represents the quality of working conditions of maintenance workforce	From 0 to 5		
Number of workers at the same time on site	Input	Represents the necessity of workforce for intervention	Nr	Governance/ Technical	Interview to Ekore
Initial investment for new implementation	Input	Represents the initial economic cost	€	Economic	U.S Department of Energy 2010
Initial investment for training	Input	Represents the cost of training program for maintenance workforce	%		
Initial Investment for equipment	Input	Represents the cost of the infrastructure to manage maintenance	%		
Initial investment for system integration updating	Input	Represents the cost for updating the already-existed system	€	Economic	Interview to Ekore
Annual expenses on the upgrade of the instrument over the general income of the company	Input	Represents the average of annual costs for maintaining the control infrastructure	%	Economic	U.S Department of Energy 2010

Table 3 Framework of indicators. Elaboration of the authors.