Towards a framework to evaluate the life cycle sustainability performance of autonomous systems

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TOWARDS A FRAMEWORK TO EVALUATE THE LIFE CYCLE SUSTAINABILITY PERFORMANCE OF AUTONOMOUS SYSTEMS

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Abstract: Autonomous systems – such as self-driven tractors, cars, autonomous lawnmowers, or vacuum cleaner – seem to become increasingly attractive and operationally efficient. Yet, the environmental, economic, and social impacts of implementing autonomous solutions, as a substitution to conventional human-operated ones, still need to be quantitatively investigated. This piece of research questions whether existing methods and indicators are satisfactory to compare the performance of autonomous systems with human-operated counterparts through the lens of sustainability? Currently, few integrated approaches are linking environmental life cycle assessment (LCA), life cycle costing, and social-LCA. Also, additional conceptual and methodological issues arise in the case of autonomous systems assessment. As such, activity-based costing can be relevant complementary tool to integrate to ensure that the comparison in terms of sustainability performance of autonomous systems with their conventional counterpart is performed on a sound basis. In this line, this paper proposes the first elements of an integrated framework to guide and compare the life cycle sustainability performance between human-operated systems and newly developed autonomous alternatives.

Keywords: life cycle assessment, life cycle cost, activity-based costing, autonomous systems, guiding framework.

1 INTRODUCTION

1.1. Context and motivation

Autonomous systems bring intelligence to machines in the way they can spot and dynamically respond to a changing environment on their own. These newly developed solutions are promising as they could be used in almost any scenario, e.g., where it is dangerous or infeasible to send humans in, or simply by doing tasks more efficiently. In thinking how technology impacts us, today's society is facing important environmental challenges; greenhouse gases emissions increase the earth temperature, industrial pollution, and toxic emissions endanger ecosystems and clean water reserves, important metals needed for electronics and machines are becoming scarce and fossil fuels which society heavily depends on, are rapidly depleting [1]. Solving these environmental issues increasingly becomes a priority.

Life cycle assessment (LCA) is a quantitative method to environmental assessment according to the international ISO standards 14040-44 [2]. The ISO standards 14040-44 are quite generic – i.e. to be applied to a wide variety of traditional produces, process, and systems – and no further guidance is provided to define the appropriate system boundaries, functional unit, and indicators to assess the sustainability of the transition from human-managed to autonomous systems. For instance, the environmental impacts of a conventional system depend on the behavior and variability of users. In contrast, a fully autonomous system can perform the required function without any human intervention. This overall function is likely to be completed by other sub-functionalities and components that are neither initially included in the traditional system, nor possible to achieve during the operation of conventional systems. In this respect, the elements considered within the system boundary used to compare the sustainability performance of the two systems, satisfying the same need, are not systematically the same. In consequence, the system boundary used to compare the environmental impacts for the same required function are likely to be different for both systems.

On the economic side, life cycle costing (LCC) appears to be a suitable approach to compare the cumulative cost of each system, with still some methodological issues to solve. Firstly, the conventional system has different cost breakdown structures compared with the autonomous one. Secondly, the profitability of one system over another must be made under the same functional unit, which is key to compare product systems on a sound basis [2].

1.2. Research objectives and expected contributions

With this background, the present research work aims to provide a first framework to support the evaluation of the sustainable performance of autonomous solutions in comparison with traditional human-operated counterparts. The main goals of this study are therefore: (i) to highlight and discuss the gaps and challenges in the application of the LCA methodology to autonomous systems; (ii) to propose guidelines to assess and/or compare on a sound basis autonomous systems with human-operated counterparts; (iii) to identify or develop the appropriate environmental, economic, and social indicators to incorporate the possible hidden benefits or impact transfers from one solution over another. The methodological challenges to ensure a fair and scientifically sound comparison between autonomous solutions and human-operated ones are first exposed in this short essay. Several promising research leads to address these shortcomings are also discussed.

2 MATERIALS AND METHODS

The first step in this process was to investigate and discuss the application of the LCA methodology to autonomous systems, according to the ISO 14040/44 [2-3]. Particularly, separate LCA case studies on both human-operated and autonomous systems were used to better understand its deployment and practice. In parallel, a literature review was conducted to identify the challenges, gaps and opportunities to propose guidelines for assessing the environmental impact of autonomous systems. Recently, Kjaer et al. (2018) [4] proposed guidelines for evaluating the environmental performance of product/service-systems (PSS) applying the LCA methodology. The reason for introducing the PSS in this study is to highlight the assessment of intangible services that offers autonomous systems, compared to the way it is assessed in the PSS. As the authors mentioned, PSS are not necessarily environmentally benign compared to conventional systems [4] and provided guidelines to evaluate the environmental performance of PSS applying the LCA methodology. A more detailed analysis of these guidelines provided is detailed in the literature survey section.

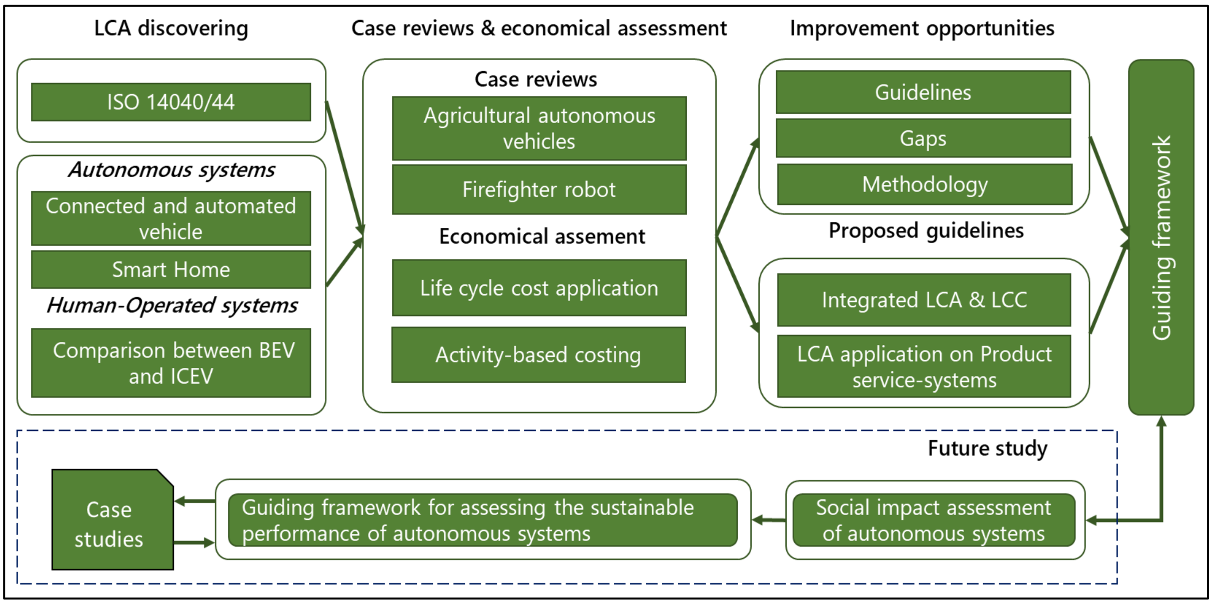

Figure 1. The process followed for the formulation of the framework.

Interestingly, the uptake of autonomous systems would contribute to transition from product-oriented design methods, that traditionally focus on physical elements, to the design of PSS. On this basis, activity-based costing (ABC) appears to be a relevant complementary tool to integrate to ensure that the sustainability assessment of autonomous systems is performed on a fair basis. For example, the ABC method can be deployed to calculate the cost of operating an autonomous system, and to compare it with the salaries of operators using the conventional system, in accordance with the functional unit and expected lifespan of both systems. A review of the few studies linking LCC and ABC approaches is carried out, in order to better incorporate the economic side of sustainability. With this background, the first elements of a guiding framework is proposed to support the sound environmental and economic impact assessment of autonomous systems, as summarized in figure 1.

3 LITERATURE REVIEW

3.1 *Methods and tools to evaluate the sustainability performance of product systems*

3.1.1. Comparison of LCA and LCC methodology

LCC methodology the internal and external costs associated with a product, process, project, or activity throughout its entire life cycle from raw materials acquisition to recycling/final disposal of waste materials [5]. LCC may be used as a systematic analytical process for evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources. The ultimate objective of the LCC of any product is to provide a framework for finding the total cost of design development, production, use, and disposal of the product with the intention of reducing the total cost [6]. In their integrated life-cycle cost assessment model, Warren and Weitz (2004) [5] defined three cost categories: conventional costs, liability costs, and environmental costs. This model for marking environmental and economic decisions may be an suitable model to inspire an idea of the framework, but such a model has the complexity of affecting environmental costs, and ecological impact, like air pollution, acid deposition and resource depletion cannot be measured with an economic indicator. Despite the similarity of their names, LCC and LCA have significant methodological differences as summarized in Table 1. For instance, LCC takes careful account of the timing of the cost flows, while LCA neglects flow timing. Also, the LCC scope often includes solely the processes imposing direct economic costs (or benefits) upon the decision maker [7].

Table 1. How LCA and LCC differ in purpose and approach, retrieved from Norris et al. (2001) [7]

Tool/Method	LCA	LCC
Purpose	Compare the relative environmental performance of alternative product systems for meeting the same end-use function, from a broad and societal perspective.	Determine the cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision-maker such as a manufacturing firm or a consumer.
Activities which are considered as part of the life cycle	All processes causally connected to the physical life cycle of the product; including the entire pre-usage supply chain; use and the processes supplying use; end-of-life and the processes supplying and-of-life steps.	Activities causing direct costs or benefits to the decision maker during the economic life of the investment, as a result of the investment.
Flows considered	Pollutants, resources, and inter-process flows of materials and energy.	Cost and benefit monetary flows directly impacting decision makers.
Units for tracking	Primarily mass and energy; occasionally volume, or other physical flow units.	Monetary units (e.g., dollars, euro).
Time treatment and scope	The timing of processes and their release or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impacts (e.g., a l00-year time horizon for global warming potential).	Timing is critical. Present valuing (discounting) of costs and benefits. Specific time horizon scope is adopted, and any fees or benefits occurring outside that scope are ignored.

3.1.2. Sustainability assessment of intangible services, example of application of LCA on PSS

Product-service systems (PSS) can be defined as the combination of tangible products and intangible services designed together so that they are jointly capable of fulfilling specific customer needs [8]. With the boom of artificial intelligence-equipped products and connected services, the PSS design method can be used to describe a new approach for interaction with intelligent systems, predominantly based on automation and services [9]. The recent literature on LCA applied to PSS contains guidelines for assessing environmental impacts with the application of LCA. The complexity of PSS lies in the intangible services, that make the application of LCA on PSS more challenging than on just product. Actually, the functional unit of PSS must describe the functionalities of the system, comprising both products and services [10]. On the one hand, Reap et al. (2008) [11] warned about the definition of a too narrow functional unit since it might not reflect the reality of the solution, thinking in a way that the autonomous system offers a range of functionalities compared to their counterpart. On the other hand, regarding the goal and scope definition, also Doualle et al. (2015) [10] argued the difficulty in comparing a PSS solution against a traditional offer are due to the fact that such a comparison can bring rebound effects that are difficult to be determined and cause situations of impact transfer. For example, using a firefighter robot instead of hiring firefighters may decrease costs in the long term, but might worsen social and environmental indicators. In their proposed guidelines, Kjaer et al. (2018) [4] added two steps to define the reference systems to be compared. Another interesting element they recommended to use is the flowchart, which gives an overview of the information and physical flows on which the system can visually be dissected, especially when it is an autonomous or complex system. All in all, based on the four steps of the LCA methodology described in the ISO 14040-44 [2-3], they added *ad hoc* sub-steps to properly pilot the application of LCA on PSS.

3.2. Sustainability performance of autonomous system in the literature

3.2.1. Application of LCA on autonomous systems and associated gaps

Table 2 provides an overview of the studies reviewed. For the LCA of connected and automated vehicles (CAV) [8], the life cycle phases included were the following: materials resources, production, manufacturing and assembly, use, and end of life management. The CAV indirect and exogenous effects at the mobility system level were excluded. Only the operational efficiencies due to direct effects on the vehicle level were included. Three additional key aspects were considered to assess the impact allocated to the use phase of autonomous vehicles [8] compared conventional ones [12]: (i) the specific CAV components, increasing the overall energy consumption; (ii) the exterior-mounted components on the CAV, increase the aerodynamic drag; and (iii), the burden of map data transmission over a wireless network. For the LCA of the home energy management system (HEMS), [13], the goal of the study was to assess the environmental load of an energy management system by modeling a 5-year energy management system in a 4-person house, with the aim of quantifying the negative environmental impact of smart home automation and balance them with their benefits during the life cycle of the HEMS. Each component of the HEMS was decomposed into sub-systems – namely, communication devices, management devices, field devices, smart meter, and computing devices.

Table 2. Overview of the selected articles of LCA applied to autonomous and human-operated systems.

	LCA of conventional and electric vehicles	**LCA of connected and automated vehicles (CAV)**	**LCA of home energy management system**
Reference	(Hawkins et al., 2013) [12]	(Gawron et al., 2018) [8]	(Louis el al., 2015) [13]
Type	Attributional LCA	Attributional LCA	Consequential LCA
Goal	Comparative LCA	Comparative and prospective LCA	Comparative LCA
System(s) considered	Conventional ICEV and a first-generation battery EV	Sensing and computing sub-system of CAV.	Home energy management system.

Functional unit	1 kilometer driven under average European conditions.	160 000 miles, rep 12 years of driving	5-year energy management system in a 4-person house

The review of the first studies covering the environmental impact assessment of autonomous systems helped us identifying several gaps and improvement opportunities for the main phases of the life cycle assessment:

- Manufacturing: The evaluation of material resources in these articles was based on the estimated weight of the sub-systems. Despite the efforts made, including, e.g., interviews with suppliers were to better evaluate material resources, the evaluation of material resources did not cover all resources, e.g., the materials used in the manufacture of the batteries for the CAV, as well as the transportation, packaging, and delivery of these resources.
- Use: In the long run, assessing the environmental impact allocated the use phase of autonomous systems could more accessible and more accurate than the current assessment of conventional systems, as these types of systems are equipped with advanced computers monitoring data. But currently, autonomous solutions are not yet operational to obtain data from their computers. Autonomous systems generate other/new types of impacts because they are connected (e.g., the environmental burden of map data transmission over wireless networks) and are equipped with sub-systems that can increase directly and/or indirectly the energy consumption.
- End-of-life: The end-of-life scenarios have not been detailed in these LCA studies, mainly due to the limitations of the LCA guidelines on that regard, combined with the complexity and end-of-life uncertainty of the systems studied.

3.2.2 Cost breakdown structure of autonomous systems: example of autonomous vehicles

Predicting the level of acceptance and the resulting competitiveness of future autonomous systems operational models requires knowledge of their cost structures. Due to the added parts and cost of artificial intelligence implementation, it is assumed that the necessary technology would increase vehicle prices by an average of 20% [14]. In the meantime, for the material extraction phase, the use of electrical energy as a source of energy for autonomous systems can increase the price because the battery is one of the main cost drivers of electric vehicles. As illustrated in Fig.2, the maintenance-related and cleaning costs for the autonomous taxi are the highest compared to the other solutions [15]. For the use phase, the autonomous system can perform the required function without human intervention, which can reduce personnel costs. Figure 2 illustrates the cost structure comparison between an autonomous system and its human-operated counterpart in the case of a private car and individual taxi. For instance, the taxi driver's salary takes up nearly 88% of the cost of the use phase, while there are no payroll costs in the case of a self-drive taxi.

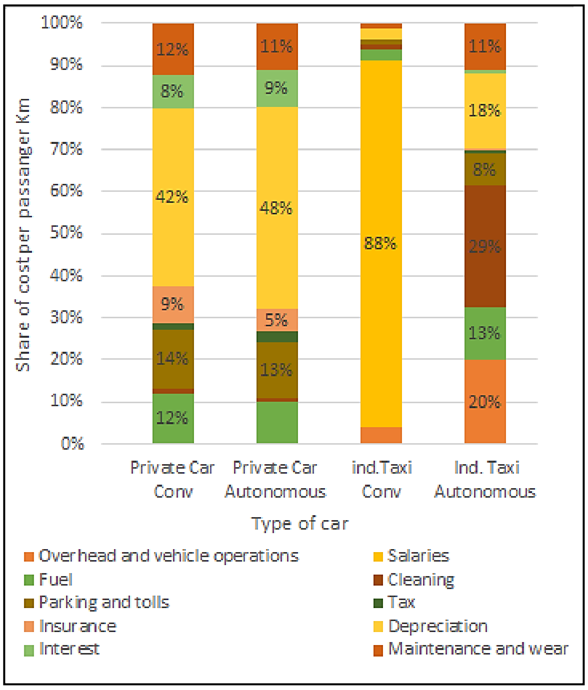

Figure 2. Cost structure comparison with (autonomous) and without (conventional) vehicle automation for private vehicles (private car) and taxi fleet vehicles without pooling (ind. taxi), retrieved from Bösch et al. 2017 [15]

4 FIRST RESULTS

4.1. Framework pillars

4.1.1. Focused assessment

Defining the type of assessment is a crucial and essential first step, as illustrated in Fig. 3. As such, the proposed framework aims to consider both attributional and consequential assessment, and is expected to provide recommendations on which type is commendable according to the goal of the study.

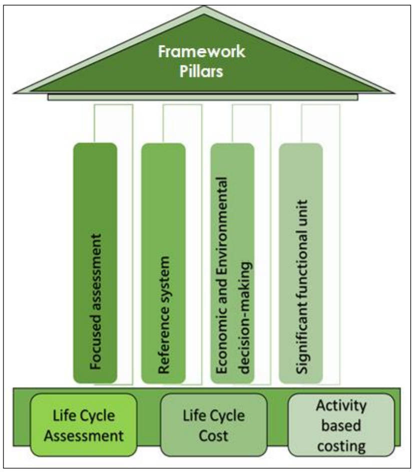

Figure 3. Proposed pillars of the framework

4.1.2. Reference system

Defining the right referential system(s) and systems boundaries for the evaluation of the sustainability performance of autonomous systems is also of the utmost importance meaningful, e.g., to compare different levels of automation.

4.2. Guided steps to assess the sustainability performance

This first version of this framework aims to combine and enhance LCA and LCC approaches to help decision-makers compare the environmental and economic performance between autonomous solutions and human-operated systems. As detailed in Fig. 4, the present framework contains seven sub-steps to support the goal and scope definition of LCA and the goal and purpose of the study of LCC. Then, for the life cycle inventory analysis, the evaluation of the development phase is added, because of its importance in the life cycle of autonomous systems, and the activity-based costing is added to support a thorough evaluation of the use and maintenance phase, as detailed in the next sub-section (4.3).

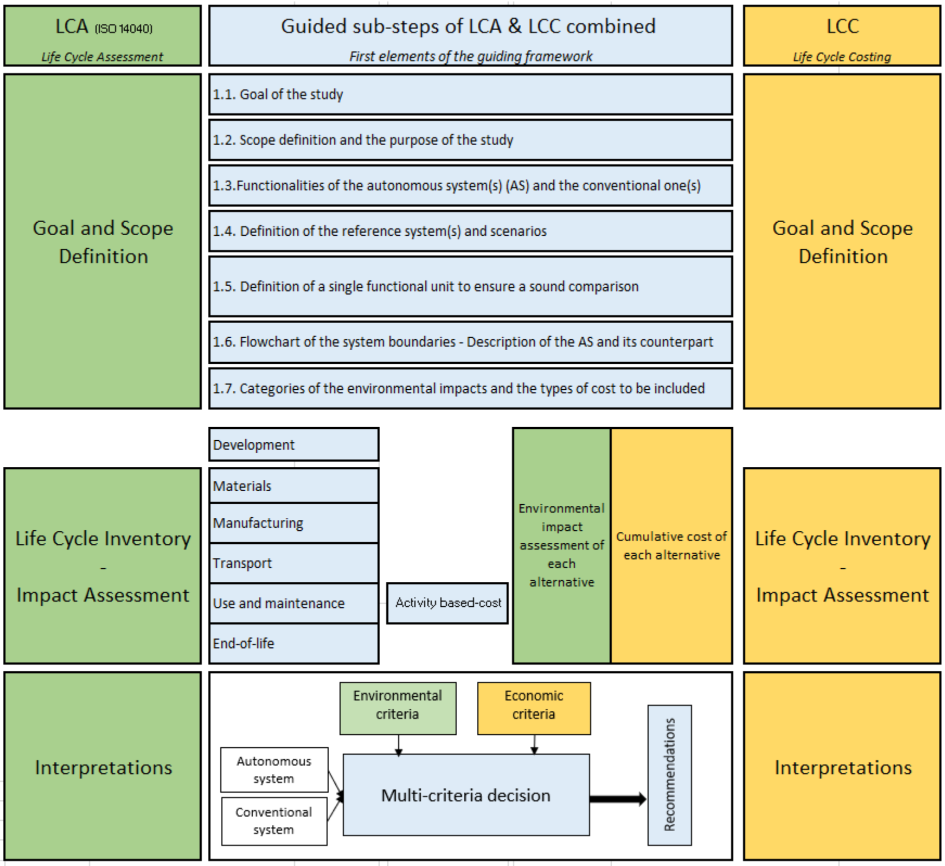

Figure 4. Combined guided steps for LCA and LCC application

4.3. Application of activity-based costing

The academic research on activity-based costing and its industrial applications has mainly focused on the industrialization process, which aims to quantify the cost of physical activities, due to the increase in indirect costs related to automation and the use of technologies. In the case of autonomous systems, where human operators are most often excluded, the application of the ABC method appears to be a relevant tool for quantifying the efficiency and profitability of such systems. First, the calculation of the cost of activity can enable manufacturers to compare the profitability of their high-tech equipment park with human-operated systems. Secondly, the application of ABC, combined with life cycle costing, makes the result of the life cycle cost inventory more complete by estimating the cost of service provided by autonomous systems. For example, the ABC method can be deployed to calculate the cost of operating an autonomous system, in accordance with the functional unit and expected lifespan of both systems. The ABC method is applied here on data from a real case study provided by Saidani et al. (2020) [16]. This study provides a case study on the environmental and economic comparison of an autonomous lawnmower and human-powered lawnmowers in various scenarios. The functional unit set was "maintaining the lawn of a 0.25-acre yard under a height of 2.5 inches, 26 weeks a year, for ten years in the U.S”. Therefore, the calculation of the ABC was done for an improved electric robotic mower in comparison with an operator using an electric push mower. Fig. 5 represents the global cost for both systems and the difference between these costs. On this basis, it was possible to determine the costs of an autonomous system per day for each year of its operation and compare this activity cost with the operators' salaries in the case of the lawnmower. Further details of the calculations, deploying the ABC methodology, are given in Table 3.

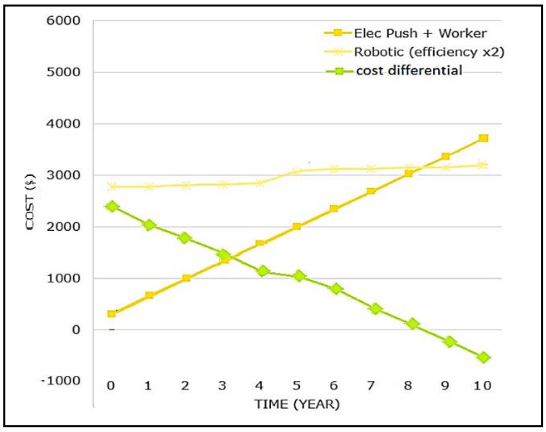

Figure 5. Total cost of ownership for both systems, over their 10-year lifetime

Table 3. Application of the ABC methodology, detail of the calculations

Year	0	1	2	3	4	5	6	7	8	9	10
Cumul cost of autonomous system (AS) - $	**2800**	**2855**	**2800**	**2900**	**3110**	**3180**	**3180**	**3200**	**3220**	**3220**	**3280**
Cumul cost of conventional system (CS) - $	**150**	**550**	**950**	**1350**	**1750**	**2150**	**2550**	**2950**	**3350**	**3750**	**4150**
Diff. Cost (As - Cs)	**2650**	**2305**	**1850**	**1550**	**1360**	**1030**	**630**	**250**	**-130**	**-530**	**-870**
Price of AS activity per week	**101.92**	**88.65**	**71.15**	**59.62**	**52.31**	**39.62**	**24.23**	**9.62**	**-5.00**	**-20.38**	**-33.46**
Price of AS activity per day	**14.56**	**12.66**	**10.16**	**8.52**	**7.47**	**5.66**	**3.46**	**1.37**	**-0.71**	**-2.91**	**-4.78**
Average of activity cost of AS ($ / per day)	**14.56**	**13.61**	**12.46**	**11.48**	**10.68**	**9.84**	**8.93**	**7.98**	**7.02**	**6.02**	**5.04**
Operator's salary - efficiency *2 ($ / per day)	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
AS versus CS ($)	**9.44**	**10.39**	**11.54**	**12.52**	**13.32**	**14.16**	**15.07**	**16.02**	**16.98**	**17.98**	**18.96**

The evaluation of activity-based costing shows that it is an relevant method for decision-makers in estimating the costs generated through the use of autonomous systems. In this case, the autonomous lawnmower with a double efficiency remains better to use in comparison to hiring two workers, from a life cycle cost perspective. When compared with a single worker, after three years, the activity cost of the autonomous lawnmower reaches the cost of hiring a worker. Within nine years, the activity cost of the lawnmower is reduced by half compared to the worker (see Fig. 6).

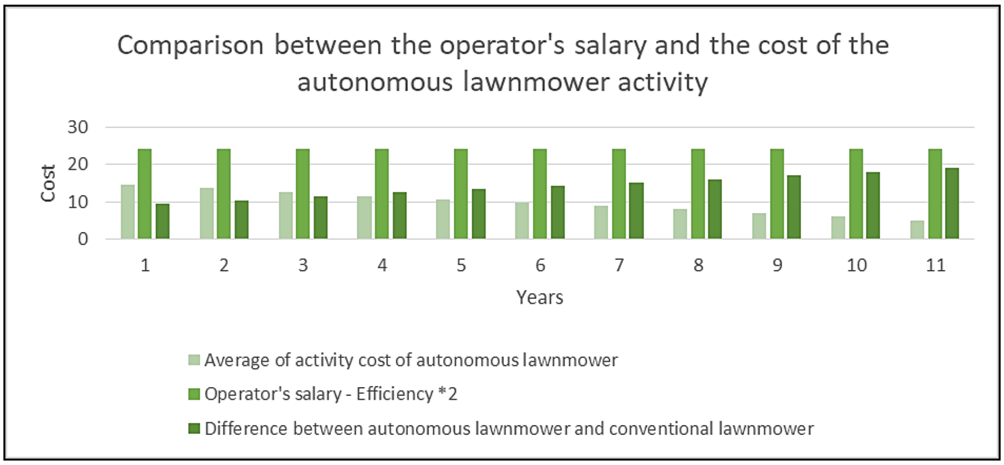

Figure 6. Activity cost of the autonomous lawnmower compared with the operator salary.

5 DISCUSSION AND PERSPECTIVES

5.1. Applying the proposed framework to a case study

The recently developed autonomous systems present a real open debate on their sustainable impacts, whether they can contribute and support human beings in mobility, household tasks, repetitive tasks or solving difficult problems. This paper provides the first elements of a guiding framework (under development) combining and augmenting the LCA and LCC methodologies for a sound sustainable impact assessment of autonomous solutions in comparison to human-operated ones. In order to quantify the intangible service provided by autonomous systems, the ABC approach was added and used to quantify this service and make the comparison fairer. It is necessary to note some limitations of this study, as it is a theoretical approach; until now, we have not applied it to real cases. To render the framework more pragmatic and practically applicable in assessing sustainable performance of autonomous system, it needs to be deployed and experimented on a real case study. the meantime, the application of this framework must be based on realistic data that provides a full life cycle overview with all aspects of sustainability.

5.2. Integrating social aspects

As social impact is an aspect of sustainability assessment, current research is aiming to integrate social impact by linking elements from social-LCA to develop a comprehensive and integrated framework for comparing the societal, environmental, and economic impacts of autonomous systems with their human-operated counterparts.

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