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The application of life cycle assessment (LCA) in municipal solid waste management: A comparative study on street sweeping services

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ABSTRACT

Street sweeping services are integral to municipal solid waste management systems. The environmental impact of municipal solid waste management has been widely debated in the literature, but the specific impact of street sweeping services has not been fully studied. The aim of this study is to fill this literature gap by applying the life cycle assessment (LCA) methodology to compare the effects of different types of street sweeping services provided in two medium-sized Italian cities. The results show that fuel consumption is by far the largest contributor in all environmental impact categories, followed by the material consumption of the equipment. The study provides managerial and policy implications. The results can enable managers to lessen the environmental impact of sweeping services, and the findings can be applied by policy makers through Green Public Procurement procedures.

1. Introduction

Life cycle assessment (LCA) methodology has been used to assess the environmental impact of products and services in many different sectors, including municipal solid waste management (Geng et al., 2010; Yay, 2015). LCA enables a comparison of different management systems in the sector and, through the identification of the most impactful phases, to provide suggestions for improving environmental performance. Comparative LCA studies of alternative municipal solid waste management systems in the literature include using LCA to compare street and door-to-door waste collection systems (Gilardino et al., 2017) and a comparison of the environmental effects of incineration and landfill as waste disposal scenarios (Nabavi-Pelesaraei et al., 2017).

Street sweeping is an integral part of urban hygiene services and, consequently, of the municipal solid waste management (MSWM) system. In this framework, the service can be considered environmentally relevant from both positive and negative perspectives. On one side, studies have focused on the positive environmental impact of the service, with authors highlighting how it could reduce dust emissions from paved roads and thus contribute to better air quality in urban settings, in terms of concentration of particulate matter (Amato et al., 2010; Karanasiou et al., 2012). On the other side, probably we cannot retain to it as a service with high environmental impact. However, considering how widespread and frequent the service is in most large and medium cities worldwide, its cumulative environmental impact may be particularly significant.

Although scholars have widely discussed the application of LCA to different services in the field of MSWM, few analyses of the environmental impacts of street sweeping services can be found in the academic literature. To the best of our knowledge, no scholars have to date assessed this service by taking an LCA approach. The justification to adopt a LCA perspective in the assessment of this service is also related to the fact that street sweeping is usually assigned through public tenders. Previous scholars in the field of Green Public Procurement (GPP) highlighted that the environmental requirements of public tenders are too often focused on the adoption of an environmental certification of the service provider more than the inclusion of “technical specifications” linked with the most pollutant phase or materials used in the service (Testa et al., 2012).

To fill this gap in the literature, the aim of this study is to apply LCA to a street sweeping service, identify the phases that have the most impact on the environment, and to quantify this impact. We present a comparative case study of the sweeping services in to two

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medium-sized Italian cities: Pisa and Livorno. Although these are similar to many other cities in Italy, the case study is not intended to be representative of all Italian urban contexts. The research allows us to highlight similarities and differences between the environmental impacts of the two street services and identify their strengths and weaknesses. The paper proceeds as follows. The next section briefly illustrates previous studies in the literature. Section 3 describes the applied methodology in conducting the LCA analysis. In Section 4 the results are outlined and discussed. The last section summarizes the main findings of the study.

2. Literature review

2.1. LCA and municipal solid waste management

LCA can be applied in many areas of waste management, as it is able to consider the whole life cycle – and each single phase – of alternative systems, and the related environmental impacts (Ghose et al., 2017; Daddi et al., 2017). The extensive literature concerning LCA confirms it to be a valid instrument for supporting decisions and investments in municipal solid waste management (MSWM) systems (Rigamonti et al., 2010). As Dong et al. (2014) illustrated, LCA combined with a Life Cycle Costing (LCC) analysis can enable the most energy-efficient, environmentally friendly and economically affordable system to be chosen from three different MSW treatment technologies: landfill; landfill with biogas conversion to electricity; and incineration with energy recovery. Evangelisti et al. (2014) also used LCA to compare the environmental impacts of anaerobic digestion in energy and organic fertiliser production with two alternative approaches: incineration for energy production and landfill for electricity production.

Other authors have focused on the methodology of using LCA for integrated MSWM (Finnveden, 1999; Clift et al., 2000; Ekvall et al., 2007), or on the use of LCA as a tool for comparing different waste management systems and selecting the solution with the lowest environmental impact (Cherubini et al., 2009; Manfredi and Christensen, 2009; Iriarte et al., 2009; Zorpas, 2016).

LCA has been used as a tool to compare alternative MSWM systems in specific urban areas. For example, Mendes et al. (2004) used LCA to compare three incineration scenarios with different ash treatment systems in the city of São Paulo, Brazil, and two landfilling scenarios, with and without energy recovery. They concluded that incineration with ash disposal in a landfill site has the lowest impact value of all categories.

According to Buttol et al. (2007), LCA is not widely used as a tool in the planning of integrated MSWM in Italy, but they demonstrated its potential by applying it to a case study of Bologna District, in which it supported the development of a new waste management plan. Similarly, Liamsanguan and Gheewala (2008) utilized a life cycle perspective to compare two methods used for MSWM in Phuket, a province of Thailand: landfilling without energy recovery and incineration with energy recovery. Their results, which were focused on energy consumption and greenhouse gas emission, demonstrated that incineration performed better. LCA has also been used to compare alternative scenarios in the field of MSWM (Zhao et al., 2009; Erses Yay, 2015; Liu et al., 2017).

The environmental impact of food waste has recently been evaluated using LCA, enabling the most sustainable options to be identified (Righi et al., 2013; Abeliotis et al., 2016; Brancoli et al., 2017; Zorpas et al., 2018). The anaerobic co-digestion of dewatered sewage sludge in small plants and home composting were found to be most effective. In other studies LCA has been applied to waste water treatments, to quantify and compare their environmental impact, and to identify potential methods of improvement (Ortiz et al., 2007; Pasqualino et al., 2009). Focusing on waste collection activities, Pérez et al. (2017) applied LCA to compare the carbon footprints of waste collection vehicles under different scenarios, and revealed the impact of different fuels in MSWM vehicles on climate change.

2.2. Street sweeping waste service studies

Street sweeping waste services are generally examined from a technological point of view. One branch of the literature focuses on the service's effectiveness in reducing dust emissions, particularly concentrations of particulate matter, in urban areas through cleaning the roads, (Chow et al., 1990; Fitz and Bumiller, 2000; Tobin and Brinkmann, 2002). As mentioned in the introduction, these studies highlight the beneficial effect of street sweeping services on the air quality of urban areas, and their contributions to reductions in the emissions that originate from vehicles circulating on paved roads (Amato et al., 2010; Karanasiou et al., 2012).

Other studies deal with the technical features of street sweepers. Abdel-Wahab et al. (2011) conducted experimental tests to determine the ability of road sweeping gutter brushes to remove various debris types. Similarly, Vanegas-Useche et al. (2015) investigated the performances of two oscillatory gutter brushes in removing street sweeping waste, and Wang et al. (2015) developed a model to analyse brush deformation and predict brush characteristics with the aim of improving sweeping efficiency and assisting the controller design. Besides focusing on technological aspects, few studies address the environmental impacts of street sweeping waste services. The pollutants in the waste collected by the service have been analysed (Jang et al., 2009) and possible waste recovery actions have been explored (Zamhöfer and Schmidt, 2001). This review of the theoretical framework highlights that although LCA is widely used in the field of municipal waste management studies, the literature still lacks research into the overall environmental impact of street sweeping waste services, and no authors have studied the service with an LCA approach.

3. Method

As defined by the International Organization for Standardization, LCA is a methodology to better understand and assess the potential environmental impacts associated with a product or a service throughout its life cycle. The International Standards EN ISO 14040-14044 of 2006 require a definition of the functional unit and system boundaries (goal and scope definition), an input-output inventory (inventory analysis), an evaluation of the associated potential impacts (impact assessment) and ultimately an explanation of the results (impact interpretation) (EN ISO 14040-14044, 2006). Through LCA it is possible to compare different alternatives and guide companies and public institutions towards more environmentally sustainable decisions (Daddi et al., 2015). The results of LCA enable the most significant environmental indicators to be selected, which can then inform consumers by means of green marketing tools.

3.1. Case study profile: AVR street sweeping services in Pisa and Livorno

AVR is an Italian multitasking company operating in street maintenance and environmental sectors.

In the environmental sector, AVR provides MSWM integrated services. The main activities are separate waste collection, waste transportation, street sweeping and cleaning, and management of collection centres. In this case study we applied a life cycle assessment approach to the street sweeping services carried out by AVR in the Italian cities of Pisa and Livorno, to quantify and compare their environmental impacts. Pisa and Livorno are two cities located in the Tuscany region of central Italy, with populations of 89,158 and 159,219, respectively.

AVR provides different street sweeping service systems in these two urban contexts according to their urban layouts and population features. The service in Pisa includes the use of sweepers and cleaning machines (mechanical street sweeping) in addition to the traditional manual activities, such as basket emptying and manual street sweeping with brooms and dustpans. In Livorno the service only consists of the latter two manual activities. The environmental impacts of the two complete services are thus evaluated and compared, so the total contributions of the different operations can be analysed along with the basic manual sweeping services that are carried out in both cities. The resulting differences due to local service organization and implementation can then be investigated.

3.2. Functional unit

The functional unit provides the reference value for all the identified environmental impacts and describes quantitatively and qualitatively the function of the product/service (i.e. to provide the suitable cleaning standard quality of the tendered service). It must be a reference parameter commonly used to measure companies' performance and to assess the size of the street sweeping service. The functional unit selected in this study is thus '1 h of street sweeping service as carried out by one worker to provide suitable quality of the service'. The total number of hours required and the number of workers hired are the two parameters used to assess the size of the street sweeping service during the tendering process and in the service organisation. The total worked hours for all street sweeping service workers during the reference period were obtained from the ministerial tables in the employment contracts (Ministry of Labour and Social Policies). Table 1 shows the total amount of worked hours applied in this case study. The service in Livorno refers only to the first semester of 2016 as it was only recently activated, while the service in Pisa refers to the whole year of 2015.

3.3. System boundaries, cut-off and allocations

Figs. 1 and 2 illustrate the system boundaries and the life cycle stages included in the analysis of the two street sweeping services.

The service in Pisa includes manual and mechanical street sweeping, while the service in Livorno only includes manual street sweeping. Utilities are present in both cases and specifically include the consumption of electricity, natural gas, water and diesel fuel for generators used on the local company premises.

The system boundaries include only the activities related to the sweeping services and therefore the inputs and outputs only refer to these. For example, the output 'Waste' includes the waste produced by AVR in providing the street sweeping service (broken brooms and dustpans, AVR office waste, etc.), while the urban waste collected during the street sweeping activity is excluded from the system boundaries.

Table 1
Total amount of worked hours in the study periods.

Pisa workers (N°)	Total hours (jan. 2015–dec. 2015)	Livorno workers (N°)	Total hours (jan. 2016–june 2016)
74	111.964	82	57.133

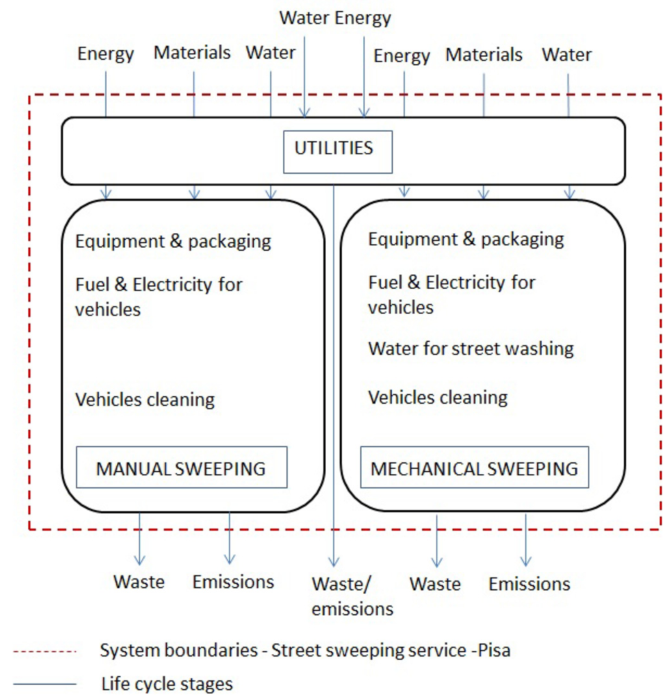

Fig. 1. System boundaries of the street sweeping service in Pisa.

In Pisa, manual and mechanical street sweeping includes the following inputs: equipment, (brooms, dustpans, bin liners, work uniforms, etc.) and related packaging, fuel for the vehicle pool, electricity for recharging electric vehicles and, only for mechanical sweeping, water and soap for street cleaning. In both services,

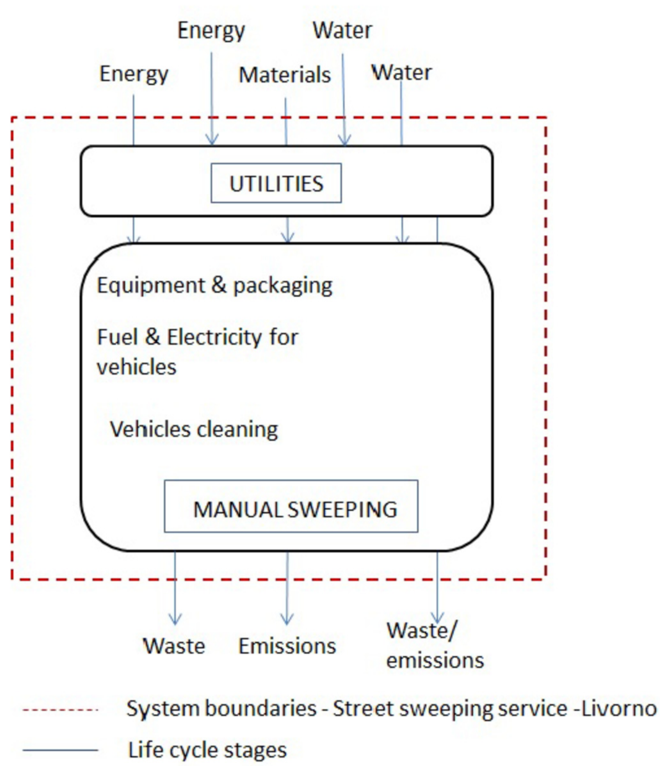

Fig. 2. System boundaries of the street sweeping service in Livorno.

vehicles are used to reach a specific city area and to carry the equipment and the collected waste. Their cleaning operations, with specific soap use, water and electricity consumption and waste production, have been included. The utilities include the consumption of electricity, gas and water on the local premises.

The AVR site in Pisa is the operating base for other services, so we applied an economic allocation method to estimate the share of utility inputs and outputs related to the street sweeping service. The revenue percentage of the street sweeping service in the total revenues of the Pisa site for 2015 (58%) is used to attribute the impacts from waste production and the consumption of electricity, natural gas, water and diesel fuel for generators on this service. As the street sweeping revenues are reported for the whole service, it was not feasible to provide a specific revenue allocation to manual and mechanical services, respectively. So the waste and utilities impacts are allocated to the whole street sweeping service.

The manual street sweeping in Livorno includes the inputs of equipment (brooms, dustpans, bin liners, work uniforms, etc.) and related packaging, fuel for the vehicle pool and electricity for recharging the batteries of fuel-oil mixture vehicles. The utilities include the consumption of electricity and water of the local premises. Vehicles are also used in Livorno's manual street sweeping service to reach a specific city area and to carry equipment and collected waste. However, in this case, vehicle washing is not conducted at the AVR site and so it was not possible to collect the related inputs and outputs. The process is thus excluded from the system boundaries.

In both scenarios, vehicle maintenance operations—such as replacement of tyres, clutches, manifolds and other vehicle components—have been excluded from the system boundaries, as these activities are carried out by an external mechanical workshop.

3.4. Life cycle inventory analysis

All input and output data for each process included in the system boundaries are collected in the life cycle inventory.

Data used in this study are primary and context-specific, and were collected at the premises of Pisa and Livorno or at the headquarters of AVR in Rome, using the company data bank, questionnaires and direct observation. Background data were obtained from the Ecoinvent 3.1 database (Ecoinvent database).

The data is derived for the following life cycle stages.

Manual street sweeping. This includes the fuel consumption of vehicles and the electricity for vehicle recharging, equipment (brooms, bin liners, dustpans, working clothes, etc.) and related packaging, and inputs for periodic vehicle cleaning, waste and emissions.

Mechanical street sweeping (Pisa service only). This includes the fuel consumption of vehicles and the electricity for vehicle recharging, equipment (brooms, bin liners, dustpans, working clothes, etc.) and related packaging, and inputs for periodic vehicle cleaning, water and soap for street cleaning, waste and emissions.

Utilities (office inputs and outputs). This includes electricity, natural gas for heating, water and waste.

Section I in the Supplementary Information (SI) provides a detailed inventory of the investigated services in Pisa and Livorno, and the specific Ecoinvent datasets used for the analysis.

3.5. Life cycle impact assessment

Life cycle impact assessment provides an evaluation of the potential environmental impacts starting from the inventory input and output data. The assessment method chosen is the ILCD 2011 Midpoint+, which is the recommended method for the Product Environmental Footprint (PEF). PEF is the multi-criteria measure of the environmental performance of goods or services throughout their life cycle, introduced by the EC and described in the EU Recommendation 179/2013/EU.

The method includes 16 impact categories: Climate change (kg CO_2 eq.), Ozone depletion (kg CFC-11 eq.), Human toxicity - Cancer effects (CTUh), Human toxicity - Non-cancer effects (CTUh), Particulate matter (kg PM2.5 eq.), Ionizing radiation HH (kBq U235 eq.), Ionizing radiation E (interim) (CTUe), Photochemical ozone formation (kg NMVOC eq.), Acidification (molc H+ eq.), Terrestrial eutrophication (molc N eq.), Freshwater eutrophication (kg P eq.), Marine eutrophication (kg N eq.), Freshwater ecotoxicity (CTUe), Land use (kg C deficit), Water resource depletion (m^3 water eq.), and Mineral, fossil and Renewable resource depletion (kg Sb eq.)

In this study we obtained all the impact assessment results and carried out normalization and weighting steps to select the most relevant impact categories, which were then further analysed. The SimaPro 8.1.0 software was used for the analysis.

4. Results and discussion

Life cycle impact assessment enables an evaluation of the environmental impacts of the street sweeping services investigated in this case study, with the relative contribution of each single stage included in the system boundaries. For each scenario, data regarding energy and material consumption, emissions and waste are converted into environmental impacts over numerous categories and detailed for each life cycle stage.

The results were analysed by first referring to the total sweeping service to determine the specific contributions of each stage and process, and then to manual sweeping services only, which are conducted in both cities. This last analysis enables a direct comparison, to determine the differences in environmental performance due to different organizational and efficiency levels in the services.

4.1. Life cycle impact assessment of total street sweeping services

Table 2 gives the absolute values of the environmental impacts of the total service for all the impact categories in the two services, referring to the functional unit (i.e., 1 h of street sweeping service carried out by one worker), and their relative percentage difference.

To facilitate an evaluation of the results, we focused on the impact categories most relevant after the normalization and weighting steps. We excluded Human toxicity and Ecotoxicity impact categories, as these are considered less reliable (level II/III) in the ILCD classification (EC, 2012) (Fig. 3).

The following most relevant impact categories (i.e., those with more than a 5% contribution to the single point indicator) are considered for further analysis:

- Climate change
- Particulate matter
- Photochemical ozone formation
- Acidification
- Terrestrial eutrophication
- Mineral, fossil and Renewable resource depletion

As expected, the environmental impacts of the service in Pisa

Table 2
Life cycle impact assessment results of the total street sweeping services in Pisa and in Livorno, referring to 1 h of street sweeping service performed by one worker.

Impact category	Unit	Total service Livorno	Total service Pisa	Δ PI-LI
Climate change	kg CO_2 eq	1.78	5.79	69.20%
Ozone depletion	kg CFC-11 eq	1.9E-07	8.4E-07	77.03%
Human toxicity, non-cancer effects	CTUh	6.0E-08	2.4E-07	75.59%
Human toxicity, cancer effects	CTUh	2.0E-08	7.0E-08	74.80%
Particulate matter	kg PM2.5 eq	8.56E-04	2.77E-03	69.08%
Ionizing radiation HH	kg U235 eq	0.07	0.31	76.10%
Ionizing radiation E (interim)	CTUe	5.4E-07	2.23E-06	75.97%
Photochemical ozone formation	kg NMVOC eq	0.023	0.033	30.22%
Acidification	mol H+ eq	8.1E-03	0.03	70.40%
Terrestrial eutrophication	mol N eq	0.02	0.08	76.66%
Freshwater eutrophication	kg P eq	4.48E-05	2.41E-04	81.41%
Marine eutrophication	kg N eq	1.92E-03	9.95E-03	80.69%
Freshwater ecotoxicity	CTUe	1.36	9.71	85.74%
Land use	kg C deficit	3.76	23.95	84.32%
Water resource depletion	m3 water eq	6.66E-03	5.58E-02	88.06%
Mineral, fossil & ren resource depletion	kg Sb eq	1.14E-04	5.29E-04	78.49%

are higher than those of Livorno for all categories, due to the presence of the mechanical service. For Climate change, the impacts are higher in Pisa by about 69%, with 5.79 kg CO_2 eq. for the service in Pisa and of 1.78 kg CO_2 eq. in Livorno.

For Particulate matter, the difference is also 69%, with 2.77E-03 kg PM2.5 eq. in Pisa and 8.56E-04 kg PM2.5 eq. in Livorno. Fuel consumption, which is obviously higher in Pisa due to the use of vehicles for the mechanical service, contributes to these categories.

For Acidification the difference is about 70%, with 0.03 mol H+ eq. for the service in Pisa and 8.1E-03 mol H+ eq. in Livorno, while for Terrestrial eutrophication, the difference is about 77%, with 0.08 mol N eq. for the service in Pisa and 0.02 mol N eq. in Livorno. These impacts are mainly due to the vehicle fuel emissions.

For Mineral, fossil and renewable resource depletion, the difference is about 78%, with 5.29E-04 kg Sb eq. in Pisa and 1.14E-04 kg Sb eq. in Livorno. This difference is not only due to the higher fuel consumption but also because more equipment is used in the Pisa service.

The difference is smaller at 30% for Photochemical ozone formation, with 0.033 kg NMVOC eq. in Pisa and 0.023 kg NMVOC eq. in Livorno, as the fuel/oil mixture used in Livorno, instead of the LPG and diesel used in Pisa, has a considerable effect on ground-level ozone formation. A contributional analysis of the total service environmental impacts allows us to identify the stages and processes with the most impact in the two scenarios. In Pisa, the effects are mainly due to the manual and the mechanical street sweeping stages, which have the major inputs of equipment and fuel for the vehicle pool. Specifically, mechanical street sweeping contributes over 50% to each category, manual street sweeping contributes an average of 37% to all categories, while utilities and waste contribute 1% and 0.05%, respectively (Fig. 4).

The details in Table 3 show that the main impact of the process unit contributions is due to the fuel consumption in the vehicle pool, which contributes over 80% to all the impact categories, with over 90% to Photochemical ozone formation and Mineral fossil and renewable resources. This confirms the importance of evaluating the environmental impacts of the vehicle pool, as previously stated by Pèrez et al. (2017), who calculated the impact on climate change associated with the MSW collection and transport fleet, and observed that their Diesel scenario yielded emissions 18.5% higher than those of the Compressed Natural Gas scenario.

In our scenario, the equipment impact is on average less than 10% (8.75%). Electricity, mainly used for vehicle recharging, contributes on average less than 2%. Finally, packaging, water, waste, natural gas and supply transport contribute less than 1% to all the impact categories.

In Livorno, the majority of the impact is due to manual street sweeping, which accounts for an average contribution of 84% for all categories. This stage has in fact the greatest number of inputs in terms of equipment and fuel for the vehicle pool (Fig. 5).

The details of the process contributions analysis shows that the predominant impact is due to the fuel consumption in the vehicle pool, which contributes about 93% to Mineral fossil and renewable

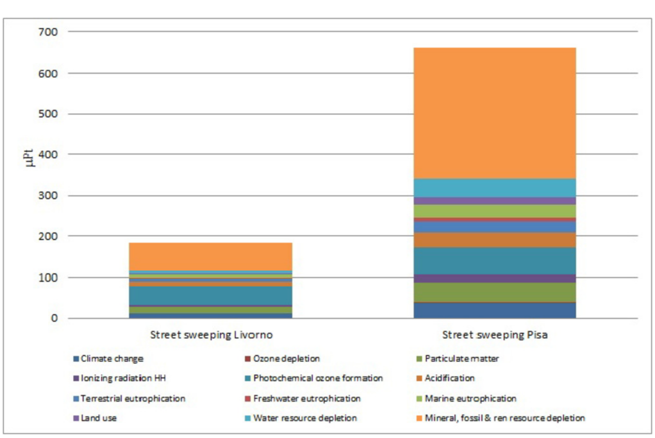

Fig. 3. LCA impact assessment results after weighting and normalization steps.

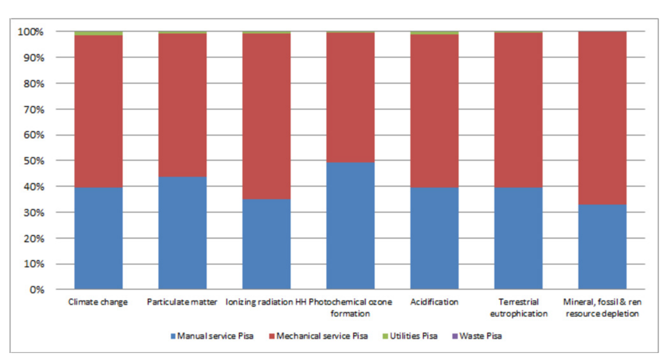

Fig. 4. Contributional analysis of the total street sweeping service in Pisa.

Table 3
Main process contributions to impact assessment results of the service in Pisa.

Impact category	Unit	Total	Equipment (%)	Packaging (%)	Water (%)	Electricity (%)	Waste (%)	Fuel (%)	NG (%)	Transport (%)
Climate change	kg CO_2 eq	5,35E+00	8,84	0,19	0,08	2,55	0,20	87,98	0,43	0,11
Particulate matter	kg PM2.5 eq	2,85E-03	15,88	0,46	0,10	1,81	0,05	81,47	0,15	0,09
Photochemical ozone formation	kg NMVOC eq	3,23E-02	6,42	0,17	0,04	0,90	0,03	92,32	0,07	0,06
Acidification	molc H+ eq	2,61E-02	11,88	0,29	0,11	2,62	0,03	84,70	0,29	0,09
Terrestrial eutrophication	molc N eq	7,80E-02	9,61	0,19	0,05	1,21	0,04	88,76	0,06	0,08
Mineral, fossil & ren resource depletion	kg Sb eq	4,79E-04	4,98	0,06	0,20	0,14	0,00	94,44	0,01	0,17

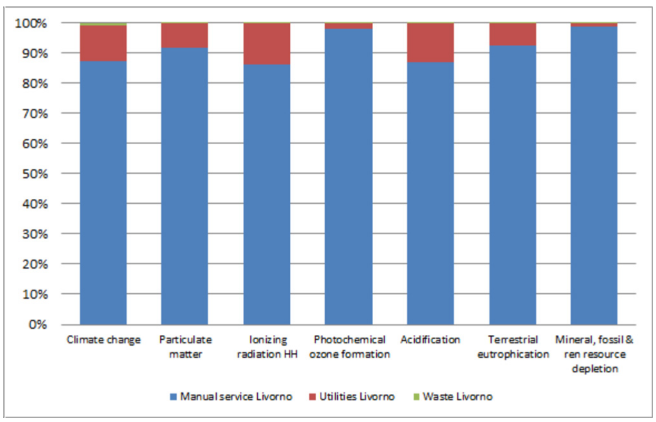

Fig. 5. Contributional analysis of the total street sweeping service in Livorno.

resources, 89% to Photochemical ozone formation, 64% to Terrestrial eutrophication, 59% to Particulate matter, 55% to Climate change and 51% to Acidification. The analysis also shows a relevant contribution of equipment impact, with an average of 22% on all the categories. Electricity, used mainly for vehicle recharging, contributes on average less than 10%, while packaging, water, waste and transport of the equipment contribute less than 1% to all impact categories (Table 4).

In both scenarios it is evident that fuel consumption by vehicles has by far the largest impact, particularly if the service includes the use of mechanical vehicles. In fact, the service in Pisa including the mechanical component has a fuel consumption of 1.23 L fuel/hr. service while in Livorno, which only has a manual component, consumption is 0.31 L fuel/hr. service, resulting in a difference of 75%. This leads to an increase in the environmental impact in all the impact categories. Climate change, for example, is 4.7 kg CO_2 eq. in Pisa and 0.935 kg CO_2 eq. in Livorno.

Equipment consumption is similar with 0.18 kg equipment/hr. service in Pisa and 0.22 kg equipment/hr. service in Livorno. This leads to a similar contribution in terms of absolute value for all the impact categories. The impact on Climate change, for example, is 0.473 kg CO_2 eq. in Pisa and 0.547 kg CO_2 eq. in Livorno. Utilities and waste, however, have a very low contribution to the total impacts, but for utilities the absolute value of the impact in Pisa is higher than in Livorno, and vice versa for waste. We suspect that these differences are related to the data quality, as explained in the previous section, but unfortunately we have no alternative data available for our study.

4.2. Life cycle impact assessment of manual street sweeping services

Focusing on the manual service, Table 5 shows the total impacts for the two services on the relevant categories, referring to the functional unit (i.e., 1 h of street sweeping service performed by one worker) and giving their relative percentage difference.

The comparison between the two manual sweeping services still shows higher impacts for Pisa, although the difference is about 41% when considering the average for all categories.

For example, in the Pisa scenario the impact is about 30% higher for Climate change, with 2.23 kg CO_2 eq. for the service in Pisa and 1.55 kg CO_2 eq. in Livorno. For Mineral, fossil and renewable resource depletion the difference is about 32%, with 1.68E-04 kg Sb eq. in Pisa and 1.13E-04 kg Sb eq. in Livorno. For Particulate matter and Acidification, the difference is about 35%, with 1.21E-03 kg PM2.5 eq. in Pisa and 7.80E-04 kg PM2.5 eq. in Livorno, and 1.08E-02 mol H+ eq. in Pisa and 6.98E-03 mol H+ eq. in Livorno, respectively. For Terrestrial eutrophication the difference is about 46%, with 3.14E-02 mol N eq. in Pisa and 1.69E-02 mol N eq. in Livorno.

The only exception is the category Photochemical ozone formation, for which the service in Livorno has a greater impact than in Pisa of about 28%, with 1.61E-02 kg NMVOC eq. in Pisa and 2.25E-02 kg NMVOC eq. in Livorno.

The contributional analysis reveals the processes with the highest impact in the two scenarios. In the Pisa manual street sweeping service, fuel consumption for the vehicle pool contributes an average of about 82% to all categories, with over 90% for Photochemical ozone formation and Mineral, fossil and renewable resource depletion. Equipment contributes an average of about 12%. Electricity consumption for recharging electric vehicles contributes an average of 2% to all impact categories, while vehicle cleaning, packaging and transport of materials contribute less than 1% (Fig. 6 and Table 6).

Table 4
Main process contributions to impact assessment results of service in Livorno.

Impact category	Unit	Total	Equipment (%)	Transport (%)	Fuel (%)	Waste (%)	Packaging (%)	Electricity (%)	Water (%)
Climate change	kg CO_2 eq	1.69E+00	32.39	0.37	55.36	0.67	0.67	11.85	0.03
Particulate matter	kg PM2.5 eq	8.61E-04	31.12	0.34	58.98	0.07	1.24	8.22	0.03
Photochemical ozone formation	kg NMVOC eq	2.27E-02	9.29	0.10	88.67	0.02	0.16	1.76	0.01
Acidification	molc H+ eq	7.66E-03	34.24	0.34	51.50	0.05	0.79	13.04	0.04
Terrestrial eutrophication	molc N eq	1.77E-02	26.72	0.40	64.69	0.09	0.67	7.39	0.03
Mineral. fossil & ren resource depletion	kg Sb eq	1.05E-04	4.61	0.82	93.33	0.01	0.24	0.89	0.10

Table 5
Life cycle impact assessment results of the manual street sweeping services referring to 1 h of street sweeping service carried out by one worker.

Impact Category	Unit	Manual service Livorno	Manual service Pisa	Δ PI-LI
Climate change	kg CO_2 eq	1.55E+00	2.23E+00	30.39%
Particulate matter	kg PM2.5 eq	7.80E-04	1.21E-03	35.42%
Photochemical ozone formation	kg NMVOC eq	2.25E-02	1.61E-02	−28.46%
Acidification	mol H+ eq	6.98E-03	1.08E-02	35.55%
Terrestrial eutrophication	mol N eq	1.69E-02	3.14E-02	46.31%
Mineral, fossil & ren resource depletion	kg Sb eq	1.13E-04	1.68E-04	32.93%

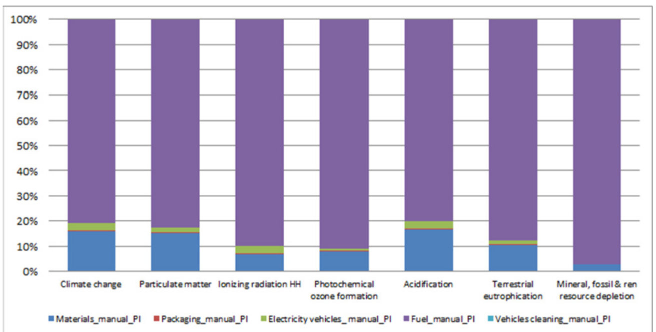

Fig. 6. Contributional analysis of the manual street sweeping service in Pisa.

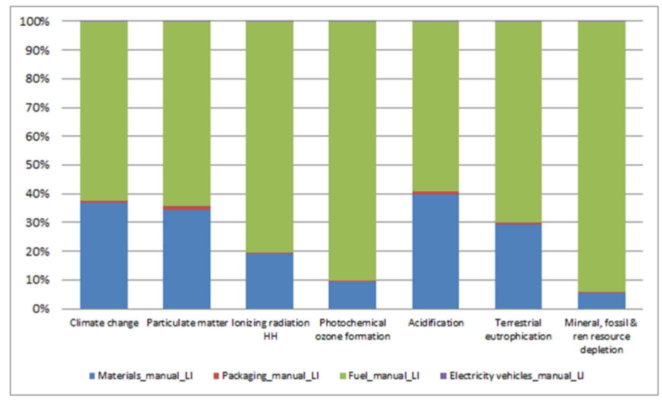

Fig. 7. Contributional analysis of the manual street sweeping service in Livorno.

For Livorno's manual street sweeping, fuel for the vehicle pool contributes an average of 70% to all the categories, with over 90% for Photochemical ozone formation and Mineral, fossil and renewable resource depletion. Equipment contributes on average 28%, ranging from 39% for Acidification and 36% for Climate change to less than 10% for Photochemical ozone formation (9.45%), and Mineral, fossil and renewable resource depletion (4.65%).

Packaging and transport of materials both contribute less than 1%, while the electricity consumption for recharging electric vehicles has almost a nil contribution (Fig. 7 and Table 7).

The comparison between the two manual services shows that the Pisa service has higher environmental impacts due to the higher contribution of fuel per functional unit (0.5 L fuel/hr. service) than in Livorno (0.31 L fuel/hr. service). In the Climate change category, for example, the fuel impacts are 1.71 kg CO_2 eq. in Pisa and 0.936 kg CO_2 eq. in Livorno. In Pisa the frequency of the service and the larger extent of the street sweeping routes may be responsible for the higher fuel consumption. Indeed, a deeper knowledge of this territorial context reveals that the frequency of street sweeping in Pisa has been increased, as it is particularly challenging in the urban areas that include the city market and nightlife zones.

Conversely, the impact due to equipment in Livorno (0.22 kg equipment/hr. service) is greater than that in Pisa (0.12 kg equipment/hr. service) for most of the impact categories. Climate change, for example, is 0.547 kg CO_2 eq. in Livorno and 0.33 kg CO_2 eq. in Pisa. Livorno has a higher number of workers and thus they consume more working clothes and bin liners. The only exception is the category Photochemical ozone formation, for which the service in Livorno has a greater impact than in Pisa by 28.46%, which is due to the different fuel used in the vehicle pool: a fuel/oil mixture in Livorno and diesel or LPG in Pisa. Electricity consumption is also more relevant in Pisa, where it is used for recharging electrical vehicles, while in Livorno the only electricity consumption is due to the recharging of batteries of vehicles powered by the fuel/oil mixture. As for other processes, the Pisa manual service also includes vehicles cleaning; however, this contributes only 0.51%.

5. Conclusions

The findings of this study have managerial and policy implications.

Managers of the street sweeping services should consider the extensive environmental impact of the vehicle pool and thus reduce fuel consumption. They could also adopt management practices such as constant and structured planning and monitoring

Table 6
Main process contributions to the impact assessment results of the manual service in Pisa.

Impact category	Unit	Total man_PI	Material man_PI	Packaging man_PI	Electricity man_PI	Fuel man_PI	Transport man_PI	Vehicles cleaning man_PI
Climate change	kg CO_2 eq	2.12E+00	3.33E-01	4.83E-03	6.28E-02	1.71E+00	3.64E-03	3.97E-03
Particulate matter	kg PM2.5 eq	1.25E-03	1.86E-04	7.87E-06	2.22E-05	1.03E-03	1.67E-06	2.36E-06
Photochemical ozone formation	kg NMVOC eq	1.59E-02	1.25E-03	2.90E-05	1.25E-04	1.44E-02	1.26E-05	1.25E-05
Acidification	molc H+ eq	1.03E-02	1.70E-03	4.58E-05	3.14E-04	8.22E-03	1.50E-05	2.34E-05
Terrestrial eutrophication	molc N eq	3.08E-02	3.17E-03	8.79E-05	4.12E-04	2.71E-02	4.14E-05	4.27E-05
Mineral. fossil & ren resource depletion	kg Sb eq	1.58E-04	3.59E-06	1.79E-07	2.95E-07	1.53E-04	4.97E-07	7.17E-08

Table 7
Main process contributions to the impact assessment results of the manual service in Livorno.

Impact category	Unit	Total man_LI	Material_man_LI	Transport material_man _LI	Fuel_man_LI	packaging_man_LI	Electricity_man_ LI
Climate change	kg CO_2 eq	1.50E+00	5.47E-01	6.30E-03	9.36E-01	1.14E-02	5.78E-05
Particulate matter	kg PM2.5 eq	7.90E-04	2.68E-04	2.89E-06	5.08E-04	1.07E-05	2.04E-08
Photochemical ozone formation	kg NMVOC eq	2.23E-02	2.11E-03	2.19E-05	2.01E-02	3.66E-05	1.15E-07
Acidification	molc H+ eq	6.66E-03	2.62E-03	2.60E-05	3.95E-03	6.03E-05	2.89E-07
Terrestrial eutrophication	molc N eq	1.64E-02	4.74E-03	7.18E-05	1.15E-02	1.18E-04	3.79E-07
Mineral. fossil & ren resource depletion	kg Sb eq	1.04E-04	4.86E-06	8.62E-07	9.84E-05	2.58E-07	2.72E-10

of the street sweeping's routes, or technological innovations such as the gradual introduction of vehicles with lower environmental impact. In addition, a better focus on logistics systems could improve the environmental impact, for example enabling fewer trips to provide the same street sweeping service.

The findings suggest managers should also take into account the environmental impact of equipment. In both manual street sweeping services, bin liners have the greatest impact due to the large quantities used, with an average percentage in all impact categories of 60% in Pisa and 71% in Livorno. Avoiding wastage is therefore important; bin liners should be replaced only when necessary, and quality products that do not damage easily should be used. In mechanical street sweeping services, soap for street cleaning was the material with the highest incidence of waste. Currently, an average of 3 g of soap is diluted in 1 L of water. The recommended dilution ratio is from 2 g to 10 g per litre of water, depending on the level of dirt. Hence, in our case studies the use of a lower rate of dilution (2 g/L) would provide only a marginal improvement. An alternative could be to replace the product currently used with an eco-label soap that has environmental effects certified as below a certain threshold and thus may provide a significant improvement.

The findings of our paper have policy implications at local as well as European level.

At the local level, the public authorities in charge of assigning the municipal street sweeping service can validate the results by drafting public tenders that go beyond the ordinary practices of Green Public Procurement, such as requesting environmental certification for the service providers (Testa et al., 2012; Günther and Scheibe, 2006). To seriously consider reducing the environmental impacts of their services, we suggest introducing specific requests into street sweeping public tenders concerning vehicle fuel, logistics management and the equipment and materials used. This case study provides a specific LCA application to assess and compare the environmental impacts of two different street sweeping systems, underlining the importance of evaluating the effects of this service in the waste management sector. The LCA study has identified the highest impact areas, specifically fuel consumption, and correlates them with possible inefficiencies and incorrect designs of street sweeping routes. The implemented methodology has thus permitted a more thorough evaluation of the service along with other efficiency parameters.

At the EU level our study can contribute to the policies about the urban environment. The European Commission has, in recent years, been increasing its focus on urban contexts, also taking into account that by 2020 it is estimated that almost 80% of EU citizens will be living in cities. The 7th Environmental Action Programme of the European Commission dedicated the priority objective n.8 "To enhance the sustainability of the Union's cities". Among other suggested actions, it invites to "set of criteria to assess the environmental performance of cities" based on quantitative studies and data. Also other technical publications of European Commission highlight the importance of street sweeping service as for example source of street dust. In particular, a recent report on the Best Environmental Management Practices describes an initiative adopted by the city of Helsinki to reduce the environmental impact of street cleaning activities (European Commission, 2015). The focus of the study is mainly related to air quality and the effects of street cleaning on PM_{10} emissions. However this report lacks of quantitative data related to the environmental impacts of street sweeping service. Also in this case, our study can contribute to this policy debate with a comprehensive look to all environmental impacts of the sweeping service, providing data collected in our case study.

Our study has certain some limitations. First, the two time periods taken as reference for data collection may limit the representativeness of the results. As indicated in Table 1, data for the Pisa service were collected throughout 2015, while in Livorno, the sweeping service only began in 2015. We thus collected data in the first semester of 2016, when we assumed that the implementation of the service had achieved a standard operation level. Data from the whole year are more likely to average out the requirements and the consumption due to seasonal changes and are thus more accurate, while data only over six months may produce a different result. However, data collected in Livorno for this study are from January to June and thus include several seasons, so we consider this to provide representative values and not to significantly affect the final results.

Another limitation is the replicability of the study findings. Pisa and Livorno are two medium cities and the environmental impacts, particularly those related to logistics, of the street sweeping services could depend on the urban structures of the towns. We are fully aware of the low replicability of the study, but it should be regarded as an initial case study in the field of LCA of street sweeping services, and the results should not be considered as fully representative of similar services carried out in other cities.

Finally, we suggest that scholars focus future research on LCA and waste services in general, and street sweeping services in particular. The findings can be verified in larger or smaller cities. Our hope is that this study can offer an initial insight to prompt further discussion on this topic. In future research, an in-depth study of possible solutions should also be conducted, to improve the impact in the categories identified in our study. Representatives of municipalities in charge of municipal solid waste management services can then be involved. Finally, we invite scholars who are researching the beneficial effects of street sweeping, in terms of the dust concentrations in urban contexts, to use our data in comparisons of the positive and negative environmental impacts of these services.

Appendix

Detailed inventory for the street sweeping services in Pisa and Livorno. Additional details on Ecoinvent process used and relevant modifications are given in Table S-2.

Table S-1
Life cycle Inventory analysis street sweeping service in Pisa and Livorno.

	Input and outputs	Pisa	Livorno	Unit
	Manual street sweeping			
Equipment				
Brooms and dustpans	Wood; PP; Aluminium; PVC	422	349	kg
Bin liners	HDPE	12500	11640	kg
Working clothes	Cotton; PET; Aluminium; ABS; PVC; Wool; PP, Nylon 6-6	556	372	kg
Equipment packaging				
	Cardboard; LDPE film; PP; Steel;	846	658	kg
Fuel for vehicle pool				
	Liquid gas	25307	5840	l
	Diesel	30351	907	l
	Fuel/oil mixture	–	10912	l
Electrical vehicle recharge				
	Electricity	12775	6	kWh
Vehicle cleaning				
	Soap	30	–	l
	Water	200	–	m^3
	Electricity	665	–	kWh
	Waste	400	–	kg
	Mechanical street sweeping			
Equipment				
Brushes	Steel, PP	1582	–	kg
Soap	Soap	4469	–	l
Working clothes	Cotton; PET; Aluminium; ABS; PVC; Wool; PP, Nylon 6-6	1323	–	kg
Equipment packaging				
	Cardboard; LDPE film; PP; Steel;	872	–	kg
Fuel for vehicle pool				
	Liquid gas	2401	–	l
	Diesel	79400	–	l
Electrical vehicle recharge				
	Electricity	562	–	kWh
Vehicle cleaning				
	Soap	270	–	l
	Water	1800	–	m^3
	Electricity	5981	–	kWh
	Waste	3600	–	kg
Water for street cleaning				
	Water	3346	–	m^3
	Utilities			
	Electricity	7250	20759	kWh
	Water	382	208	m^3
	Natural gas	2594	–	m^3
	Waste	5704	1380	kg

Table S-2
Ecoinvent processes used for the street sweeping services inputs and outputs.

	Input/output materials	Ecoinvent processes	Modifications (remarks)
Equipment	Wood; PP; Aluminium; PVC; Steel; Soap	Sawnwood, softwood, air dried, planed {RER}; Sweet sorghum stem {GLO}; Polypropylene, granulate {RER}; Injection moulding {GLO}; Aluminium, primary, ingot; Sheet rolling, aluminium {GLO}; Polyvinylchloride, bulk polymerised {GLO}; Steel, unalloyed {GLO}; Sheet rolling, steel {GLO}; Soap {GLO}	
	HDPE	Polyethylene, high density, granulate {RER}; Extrusion, plastic film {RER}	
	Cotton; PET; Aluminium; ABS; PVC; Wool; PP, Nylon 6-6	Cotton fibre {GLO}; Spinning, bast fibre {GLO}; Polyethylene terephthalate, granulate, amorphous {RER}; Aluminium, primary, ingot {UN-OCEANIA; Sheet rolling, aluminium {GLO}; Acrylonitrile-butadiene-styrene copolymer {GLO}; Polyvinylchloride, bulk polymerised {GLO}; Injection moulding {GLO}; Sheep fleece in the grease {RoW}; Nylon 6-6 {GLO}; Polypropylene, granulate {RER}; Injection moulding {GLO}	
Equipment packaging	Cardboard; Cardboard; LDPE film; PP; Steel	Core board {GLO}; Packaging film, low density polyethylene {GLO}; EUR-flat pallet {GLO; Polypropylene, granulate {GLO}; Injection moulding {GLO}; Steel, unalloyed {GLO}; Sheet rolling, steel {GLO}	
	Liquid gas	Transport, passenger car, large size, natural gas, EURO 5 {RER}	Modified with actual fuel consumption
Fuel for vehicle pool	Diesel	Transport, freight, light commercial vehicle {CH}; Municipal waste collection service by 21 metric ton lorry {CH}; Transport, freight, lorry 16–32 metric ton, EURO5 {RER}; Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RER}	Modified with actual fuel consumption
	Fuel/oil mixture	Transport, passenger, motor scooter {CH}	Modified with actual fuel consumption

(*continued on next page*)

Table S-2 (*continued*)

	Input/output materials	Ecoinvent processes	Modifications (remarks)
Electrical vehicle recharge	Electricity	Electricity, medium voltage {IT}	
	Soap	Ethoxylated alcohol (AE3) {GLO}	
Vehicle cleaning	Water	Water, well, in ground, IT	
	Electricity	Electricity, medium voltage {IT}	
	Waste	Municipal waste collection service by 21 metric ton lorry {GLO}	
Water for street cleaning	Water	Tap water {CH}	Modified for Italy
	Electricity	Electricity, medium voltage {IT}	
Utilities	Water	Tap water {CH}	Modified for Italy
	Natural gas	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas,	
	Waste	Municipal waste collection service by 21 metric ton lorry {GLO}; Municipal solid waste {IT}| treatment of, incineration	

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