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# Door-to-door waste collection: A framework for the socio – Economic evaluation and ergonomics optimisation

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A B S T R A C T

Waste collection is the first step of waste management, and its characteristics impact workers' health and safety. Arising out of the challenge for waste collection operators to design sustainable systems of work, the authors review the literature on ergonomics and socio-economic sustainability and design a theoretical framework for assessing the sustainability of waste collection. The framework quantitatively assess the impact of the door-to-door collection system on the health and safety of the workers to provide indications to waste collection operators on how the load carried by workers can be minimised and the economic and social sustainability can be improved. As a case study, this paper investigates the musculoskeletal disorders derived from the manual material handling of waste containers affecting the workers in charge of door-to-door sorted collection of paper waste with the goal of optimizing the workers well-being and overall waste collection system performance The research study was conducted in collaboration with a company which operates in solid waste collection for Italian municipalities. For this purpose, the ergo-quality level of two paper waste collection systems is evaluated. For each system, ten scenarios of door-to-door paper waste collection are considered. The analysis is complemented by an economic analysis, which estimates the costs associated with the collection system under consideration, and a social life-cycle assessment. Results suggest that using 120-litres capacity bins would effectively improve ergonomics and optimise the costs of the investigated activity. More specifically, due to mechanised collection, the more limited number of lifting and carrying operations would expose the workers to lower ergonomic risk.

## 1. Introduction

Municipal waste management (WM) is among the most complex systems to manage, and its characteristics impact the environment and human health (Eu, 2018a). Waste collection is the first step of WM, and source-separated waste collection has proved to be the most efficient method for returning high-quality materials suitable for high recycling efficiency (Di Maria et al., 2020, Laurieri et al., 2020) and a key success factor for enabling reuse and preparation for reuse (Degli Esposti et al., 2021). WM at the municipal level includes collection, transportation, treatment, and disposal of urban waste, and it involves legislative, urban planning and human aspects as well as the environmental, social, and economic dimensions of sustainability (Bamonti, 2012, Rodrigues et al., 2018).

In recent years, municipal solid waste management (MSWM) systems have been widely debated in several publications concerning the organization, planning, administration, engineering, financial, environmental and health aspects. They were lately reviewed particularly regarding the safety of the workers involved in managing of waste potentially contaminated by COVID-19 (Behera, 2021, Yousefloo and Babazadeh, 2020), and the effect of the COVID-19 pandemic on urban planning and management (Sharifi and Khavarian-Garmsir, 2020, Madsen et al., 2021). Together with street cleaning, waste collection is the most important service provided at the municipal level in terms of economic and environmental impacts on public health and citizens' quality of life and it is essential for achieving sustainable solid waste systems (Hannan et al., 2020, Benito et al., 2021). In this context, improper waste collection may lead to ineffective waste management:

*Abbreviations:* CR, Collection Route; DTD, Door To Door; LCA, Life Cycle Assessment; LI, Lifting Index; MMH, Manual Material Handling; MSD, Musculoskeletal Disorder; MSWM, Municipal Solid Waste Management; NIOSH, National Institute of Occupational Safety and Health; OD, Occupational Disease; RC, Reduction of Cost; sLCA, Social Life Cycle Assessment; SM, Sustainability Metric; WSL, Work Shift Length; WM, Waste Management.

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an improved approach to integrating social, economic, institutional, legal, technical, and environmental aspects is essential for planning the sustainable management of solid waste (Das et al., 2019). Although the literature is mainly focused on WM of specific waste streams (e.g., plastic, organic waste, waste from electrical and electronic equipment), with particular emphasis on public–private comparisons of efficiency in WM services (e.g., waste collection) (Bel and Warner, 2008, Bel, 2010), some authors also evaluate the performance of waste collection in terms of quality of the service (Bel and Sebo, 2021). In line with that, Bel and Sebo (2020) argue that evidence available on service quality is much scarcer than on other aspects, mainly due to the fact that measuring and monitoring quality is difficult and costly (Shrestha and Feiock, 2011).

Significant health issues also characterise the waste sector since its work activity involves, among other risk factors (e.g., weather, air, noise exposure), the manual material handling (MMH) of loads, i.e., receptacles: this can potentially cause musculoskeletal disorders (MSDs) (Thomas et al., 2021) which is defined by the International Encyclopedia of Public Health as a disease span, a range of ailments affecting the soft tissues of the musculoskeletal systems, including tendons, ligaments, cartilage, muscles, and nerves (Dennerlein, 2008).

Despite being a relatively small sector in terms of employment, waste collection records a significant fatal injury rate and its characteristics impact workers' exposure to non-fatal injuries due to the MMH of waste containers, and mainly the risk of developing work-related MSDs (Battini et al. 2018, Botti et al. 2020). A recent review on ergonomic interventions among waste collection workers cites 15 studies on occupational health developed in Europe (Emmatty et al., 2019). Specifically, questionnaires and medical examinations have globally reported MSDs and other diseases (liver disorders, Hepatitis A, Hepatitis B, respiratory problems, and cardiovascular diseases) (Engkvist et al., 2011, Jozwiak et al., 2013, Emmatty et al., 2019). National data from Italy show that MSDs are the main type of recognised Occupational Disease, and they have stabilised since 2012, after growing continuously over years (EASHW, 2019).

To the best of the authors' knowledge, a very limited number of studies focused on ergonomics to improve waste collection. None of these evaluates the ergo-quality aspects, along with the economic and social implications of a waste collection system. Regarding ergonomics, Botti et al. (2020) report very high ergonomics risk due to MMH when waste collectors empty the waste containers into the collection vehicle, suggesting some critical areas of improvement (e.g., avoiding torsion and awkward postures). Moreover, the same authors demonstrate that 2-wheeled containers with a capacity bigger than or equal to 120 L are safer and preferable than small standardized containers (with a capacity equal to 25 L). Similarly, Thomas et al., 2021 demonstrate that collection services using wheeled bins have lower MSD-related absence rates than those requiring bending and lifting operations. Thus, from an epidemiological perspective, the study's results identify a correlation between the collection methods and the prevalence of MSDs, concluding that systems comprising 4-wheeled and 2-wheeled bins appear to be consistently less hazardous for workers when compared to systems using sacks and boxes.

Only a few studies evaluated the socio-economic impacts of waste collection. Likewise, some studies are focused on the costs and the efficiency of local governments in managing waste collection (Benito et al., 2021), while others on the economic regulation of waste collection (Di Foggia and Beccarello, 2018, Magrini et al., 2021b). According to Campitelli and Schebek (2020), who reviewed 366 studies on waste management systems of cities or countries and focused on municipal solid waste, only 89 studies consider at least one social aspect. However, Mohsenizadeh et al. (2020) argue that some studies on MSWM incorporate the social dimension of sustainability, considering methods such as social life cycle assessment (sLCA), and social indicators (e.g., creation of job opportunities, visual pollution, amount of reused waste). Moreover, a recent review conducted by Hannan et al. (2020) shows that only 6 out of 21 studies on solid waste collection considered the social dimension of sustainability. Specifically, reviewing 162 selected papers, the authors conclude that there are ten most common constraints in sustainable waste collection. Narrowing down to the optimization constraints of the sustainable waste collection, the results show that only 2 out of those 6 studies evaluate the "labour constraint" in terms of human labour and job opportunities (Heidari et al., 2019, Hannan et al., 2020) and indirect social benefits in improving quality of life and human health (Mohsenizadeh et al. 2020, Hannan et al. 2020). As for "social and non-negative constraints", the authors consider the involvement of various stakeholder groups in the decision-making process and the impacts of social capital parameters (e.g., social network, social trust, social learning). Moreover, in designing a waste collection route (CR), the company in charge of waste collection service should consider both socio-economic implications and ergonomics aspects. In this context, the UK Health and Safety Executive has identified that the provision of appropriate guidance and tools represents a useful means of assisting Local Authorities, or organisations (including community organisations) that are responsible for delivering waste management services, to select the most appropriate systems to ensure that environmental targets are met with the least possible health and safety risk (Turner et al., 2008).

Thus, in this study, a technical-ergonomic evaluation complements a socio-economic analysis, which is not widely implemented for waste collection systems.

This study aims to quantify the impact of the DTD collection system on the health and safety of the workers involved in waste collection and to support waste collection operators in boosting the sustainable design of its service. For this purpose, firstly, a methodology for the assessment is proposed. Secondly, a framework to evaluate the sustainability of the service through the identification of the technical and economic factors, as well as the social impacts, is described. Finally, the designed framework is applied to the case study of DTD paper waste collection in an Italian Municipality to evaluate throughout the designed framework the ergonomic, technical, and socio-economic sustainability of a waste collection system from the workers' perspective. A technical intervention in a DTD collection scheme of paper waste was selected as a case study to provide indications to the operators on how the load carried by workers can be minimised and to improve the design as well as the sustainability of the paper waste collection system. The methodological approach used criteria indicating the ergo-quality level and technical, economic, and social performances of the selected collection systems (i.e., 40-litres and 120-litres capacity bins). The conversations with some waste operators confirmed that the analysis was not routinely used but might be helpful to decision-making in designing waste collection services (e.g., paper, glass, plastic).

The paper is structured in four sections. In Section 2, the authors describe the system and introduce the formulation of the mathematical modelling. Section 3 presents the case study. Section 4 discusses the results of the case study, while in Section 5, the authors draw some conclusions.

## 2. Materials and method

In this section, the authors detail the system of the study. Then, the method to calculate the sustainability metrics (SMs) and the mathematical modelling are described. Thus, the model used in section 3 to analyse the effects of socio-economic and ergonomics variables on the efficiency of waste collection is provided.

### *2.1. System description and sustainability metrics*

The literature agrees on selecting as indicators to monitor waste collection systems: i) the cost of the service, ii) the tons of waste collected in the municipality, iii) the number of containers per collection route (CR), iv) the frequency of collection (Emmatty et al., 2019, Botti et al., 2020, Benito et al., 2021). Therefore, the literature highlighted that the following aspects were globally considered to improve the sustainability of waste collection service: operating costs and collection time (Pires et al., 2019, Hannan et al., 2020).

This study proposes three sustainability metrics (SMs) for evaluating the sustainability of DTD waste collection service, based on the literature review described in Annex 1. Table 1 shows a brief overview of the designed system (i.e., object of the analysis, impacts, involved stakeholders and selected indicator) split into: i) technical and ergonomic, ii) economic, and iii) social aspects.

Once the three indicators for waste collection have been selected, within the designed framework, the authors explained the mathematical modelling to calculate the SMs using the method in Section 2.2.

### 2.2. Mathematical modelling

As depicted in Fig. 1, the authors designed a mathematical model to analyse and compare different collection systems in five steps with the following algorithm.

#### 2.2.1. Step 0: Selection of the collection systems and identification of the scenarios

Before evaluating the different collection systems, some selection criteria should be considered, to identify the most appropriate scenarios. Selection criteria are necessary to ensure the reliability of the analysis and the comparability among the collection systems. The authors designed a framework to analyse and compare collection systems which collect the same waste flow with the same frequency, operators, and vehicles. Besides that, other selection criteria are the applicability of the systems within the territory, their potential impacts on improving collection habits and the result of the ergonomics evaluation. According to Botti et al., (2020), Rossi et al., (2022), it is suggested conducting the ergonomics risk assessment using the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA (NIOSH, 1994). The selected scenarios should all have the same risk value (“low-risk related work”). Consequently, the selection criterion is the ergonomics evaluation, which classifies the collection system selected for the analysis as a “low-risk related work”.

#### 2.2.2. Step 1: Evaluation of the technical end ergonomics aspects

Technical and ergonomics analyses should focus on the feasibility and ergo-quality level of the waste collection service from the perspective of the waste operators and the workers in charge of waste collection.

The number of **manual handling operations (MHO)** includes the number of containers, as well as the load carried by the workers for each CR, and it can be calculated as follows (Equation (1)):

$$MHO = c \times u \tag{1}$$

**Table 1**
Overview of the technical and ergonomics, economic, and social aspects of the designed system.

| Aspects | Technical and ergonomic aspects | Economic aspect | Social aspect |
|---|---|---|---|
| **Object of the analysis** | Technical implications of reducing MMH of waste containers | Economic evaluation of the service | Social analysis of the collection workers |
| **Impacts** | Feasibility and ergo-quality level of the waste collection service | Cost of the service | Positive and negative impacts associated with the waste collection operators |
| **Stakeholders involved** | Workers<br>Waste operators | Inhabitants<br>Waste operators | Workers |
| **Selected indicators** | **Manual handling operations** as the number of operations needed to collect waste | **Reduction of cost** of the service | **Indicators included in the subcategory “workers** “(UNEP, 2011) |

Where:

c is the coefficient that represents the average number of collected bins per CR;

u is the user as the number of households which produce waste;

It was assumed that each user has got one bin which requires one MHO for waste operator. More specifically, given the deep complexity that characterizes the analysis - due to both multi-parameters’ assessments and to varying urban management settings – the coefficient “c” represents the uncertainty about the number of collected bins which is not always equal to the actual overall of the bins under study.

Where the coefficient c is calculated as follows (Equation (2)):

$$c = \frac{s_p \times k_b \times w}{l \times CR} \tag{2}$$

Where:

$s_p$ is the specific weight of collected waste (kg/litre)

$K_b$ represents correction coefficient for the cost unit (€/kg) and the generation of waste (kg/yr), which means that the generation of waste depends on the number of the members of each family under study (ARERA, 2020).

l is the litres capacity of the waste container

w is the amount of waste produced per year per household (kg/household)

CR represents the frequency of each collection route, which represents a parameter defined by the waste operator. It depends on several factors (e.g., the waste collection flow, the amount of waste generation, the population density).

#### 2.2.3. Step 2: Evaluation of the economic aspect

According to the literature, waste collection costs include the cost required to collect bins and containers for each CR. The potential **reduction of costs (RC)** considers the cost per inhabitant, and it can be calculated through Eq. (3):

$$RC(€/inhab.) = \frac{C}{u} \tag{3}$$

Where:

Costs (C) are calculated through Eq.4:

$$C(€/min) = \frac{cost}{wsl} \tag{4}$$

Where:

cost is intended to be the cost to collect the bins daily (€/day)

wsl is the work-shift length that includes the time required to collect each bin (t) multiplied by the number of containers for each CR (u), and it can be calculated as follows:

$$wsl(min/day) = t \times u \tag{5}$$

The purpose of the RC indicator is to communicate to all the citizens of the city the economic value of the reduction of cost refers to the waste collection service with a communicative approach based on easily understandable indicators (De Feo et al., 2019, Meriläinen and Tukiainen, 2020).

#### 2.2.4. Step 3: Evaluation of the social aspect

According to the literature, information on waste collection’s socio-economic aspects and waste collectors’ social performances has to be considered for decision-making. For this purpose, positive and negative impacts associated with the waste collection operator across the life cycle of its service should be assessed from the workers’ perspective. Likewise, social topics for workers are of interest to the authors because waste collection operators are the stakeholder group considered in the study.

For the design of the social analysis, the Social Life Cycle Analysis (sLCA) methodology is considered a useful tool to evaluate the social impacts of the selected waste collection system. According to Magrini

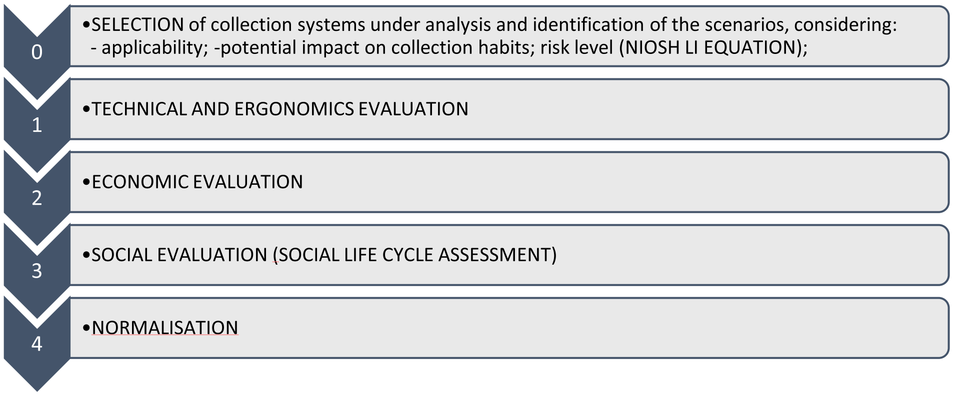


**Fig. 1.** Overview of the four steps of the designed framework.

et al. (2021a), the "Guidelines for Social Life Cycle Assessment of Products and Organizations 2020" (UNEP, 2020) should be used because they position sLCA in consonance with the SDGs and capture methodological developments lately implemented by the methodological sheets (UNEP, 2021). In this context, the Social Impact Assessment method described in the guidelines includes the following steps: i) selection of an impact assessment approach (i.e., reference scale, impact pathway); ii) definition of the social topics (stakeholder categories, children, and subcategories and/or impact categories); iii) identification of the reference scale to assess the impact; iv) possibly, choice of a weighting approach. Specifically, the stakeholder categories are the workers, the local community, the value chain actors, the consumers, the society, and the children. Hence, social sustainability has been evaluated based on the "workers" category and the following subcategories: i) freedom of association and collective bargaining, ii) fair salary, iii) working hours, iv) equal opportunities/discrimination, v) health and safety, vi) social benefits/social security. It should be noted that the subcategories "sexual harassment", "small holder including farmers", and "social benefits and/or social security" were not considered in this study, mainly due to the fact that they were out of the objectives of the study. Annex 1 details the assessment of the social analysis. The weighting approach was not applied in this study.

The "reference scale" for Social -Life Cycle Impact Assessment ranging from negative to positive performance is selected with only two scale levels (from −2 to + 2). Eq. 6 shows the final value of the indicator WS: $\sum_1^3 ws_i$ (Eq. 6)

Where:

$ws_i$ are the scores ranging from −2 to + 2 per each selected subcategory i of the category "workers".

See **Annex 1** for more information about subcategories.

### 2.2.5. *Step 4: Normalization of the results*

The fourth step refers to the normalization of the results, which were calculated through equations (1), (3), and 6. Driven by the experiences of Rigamonti et al. (2016), Wilson et al. (2015), Fernández-Braña et al. (2019), and Magrini et al. (2021a), as a first assessment, the present analysis is characterized by the same weight for each SM. The following mathematical formulae were applied to calculate the final score of each scenario:

$$Normalised\ value_{ijs} = \frac{SM_{ijs}}{\sum_1^3 SM_{ijs}}$$

$$Total\ score_j = \sum_{j=1}^{3} SM_{ijs}$$

Where:

$j$ represents the scenario (from 1 to 10);

$s$ represents the sustainability pillar (from 1 to 3, indicating ergonomics, economic and social aspects);

$SM_{ijs}$ is a sustainability indicator $i$, for scenario j, referred to the sustainability aspect $s$.

## 3. Case study

The research study focuses on DTD paper waste collection of small waste containers in an Italian Municipality (Argelato, Emilia-Romagna Region). Emilia-Romagna is a region in Northern Italy that extends inland westward from the Adriatic coast. The population of the Region is 4.459.477 inhabitants (2019), while the urban waste service is managed by 11 different providers (2019) (Magrini et al., 2021b). The street bin collection is the most common separated collection method in the Region: 33% of sorted waste is collected this way, while the DTD collection system covers 19% of separate collection waste. However, its diffusion rate has been growing for the past few years (ARPAE, 2019), and the municipalities have been promptly achieving the targets for separate collection of waste set by the European and national legislation (EU, 2011, Emilia-Romagna Region, 2015, EC, 2018a, EC 2018b). Moreover, in 2015 the Region established a fund to promote waste prevention and reduction among the Municipalities: the fund also aims to reduce the costs of changing the collection system for those Municipalities which want to implement a DTD collection system, including at least unsorted waste and biowaste (Magrini et al., 2021a; Emilia-Romagna Region, 2015). In this context, the DTD paper waste collection in Emilia-Romagna Region is mainly performed with bags and small standard waste containers, e.g. 40-litres capacity bins. Thus, it often requires MMH of bins and bags as lifting, pushing, and pulling operations.

The research study is divided into three phases: firstly, the ergonomics risk of two different DTD collection systems is evaluated by using the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA; secondly, ten scenarios for the DTD paper waste collection are considered. Further details on the relationship between the two different DTD collection systems are provided in Annex 2.

By considering the Municipality of Argelato, a situation in which paper waste collection is completely performed with 40-litre capacity bins (baseline scenario); a situation in which paper waste collection is completely performed with 120-litre capacity bins; 9 scenarios in which 40 L are partially substituted by 120 L. Finally, technical, economic, and social implications of the improved DTD paper collection system are provided. Further details on the ten scenarios are provided in Annex 2 and Annex 3.

### 3.1. *Step 0: Selection of the collection systems and identification of the scenarios*

As mentioned above, the preliminary step of the algorithm is the selection of the systems under analysis, based on the result of the ergonomics analysis and on other section criteria.

*3.1.1. Ergonomics analysis*

DTD waste collection activities include emptying bins and driving vehicles. As regards emptying bins, several risk factors affect the health and safety of waste collectors, such as lifting and carrying, pulling heavy loads, repetitive tasks, and long working hours. In that sense, these activities might cause work-related MSDs and might result in chronic injuries and ODs.

The ergonomics study focuses on the MSDs derived from MMH of waste containers in a DTD collection of paper waste. Data refer to urban waste collection performed by an Italian waste management operator reviewing its collection system in collaboration with the municipalities in the Emilia-Romagna Region. The ergonomics risk assessment includes the NIOSH Lifting Equation, developed by the National Institute for Occupational Safety and Health of the USA in 1994, to evaluate the risk of lifting and carrying, pushing, and pulling the selected waste containers (i.e., typology A and typology B). According to Thomas et al. (2021), each collection system has its specific combination of manual handling risks. In this context, paper waste is collected manually (in the case of 40-litre bins) and/or semi-mechanically (in the case of 120, 240, 360 L). As for the 40-litre capacity bins, the operator directly lifts small bins from the ground. Then, the operator lifts, carries and empty the bins into the vehicle hopper; and lowers the bins to the ground. Differently, for 120-litre and 360-litre bins, the workers pull and hook the 2-wheel containers to the vehicle. While pushing and pulling wheeled bins (120 – 360 L) affects the shoulders, elbows and back, handling baskets (30 – 45 L) affects the neck, shoulders, elbows and back (Thomas, 2005, Thomas et al., 2021).

As far as the ergonomics analysis of typology A is concerned, the analysis was conducted according to ISO 11228–1 standard (ISO 11228-1:2007). Considering typology B, the ergonomics analysis was performed by adopting wheeled containers for the DTD collection of paper waste. The methodology detailed in the ISO 11228–2 standard was applied to investigate the pushing and pulling forces during the manual handling of the 2-wheel containers, full of paper waste. The maximum capacity of the container is 120 L. Handles were positioned at 95 cm from the ground. Six pushing and pulling trials were performed. Trials consisted in pushing the container for 7.5 m, with a frequency of 1 push every two minutes. A digital force gauge equipped with two handles was used to measure the pushing force.

Table 2 shows the input data of the reference ergonomics study.

Table 3 shows the results of the NIOSH Lifting Index (LI). The green colour indicates the low-risk range (LI 0.85), the yellow the moderate risk range (LI > 0.85 and LI < 1), while the red one indicates the high-risk range (LI 2) and the purple the highest risk range (LI3). The LI was calculated for male workers since this type of works is expected to be performed only by them.

More details on the ergonomic risk assessment conducted by the NIOSH LI equation are shown in **Annex 4**.

*3.1.2. Selection of the scenarios*

Based on the results provided by the NIOSH LI, which has classified both the selected typologies as "low-risk related work" (section 2.3), an in-depth analysis was carried out of ten scenarios of DTD paper waste collection to evaluate the technical, economic and social benefits of the selected systems, in which the 40-litre containers (typology A) are totally or partially substituted with 120-litre bins (typology B).

The analysis of the ten scenarios was conducted according to technical, economic, and social indicators described in section 2.2. These indicators will assess the ergo-quality level related to the selected waste collection systems, the efficiency related to the organisation of the systems, socio-economic correlations, and effective implementations related to the improved scenarios.

**Table 2**
Characteristics of waste collection in an Italian non-urban area. Average value of 5 rounds for typology A and 2 rounds for typology B.

| Parameter / Typology of Bin | Unit | Typology A | Typology B |
|---|---|---|---|
| WSL | [min/day] | 480 | 440 |
| Breaks per day | [min/day] | 30 | 30 |
| Time to unload vehicle | [min/day] | 15 | 15 |
| Time to collect bins | [min/day] | 73 | 83 |
| Bin weight | [kg] | 5.67 | 17 |
| N. bins collected per day | [-] | 219 | 125 |
| Frequency of MMH operations | [-] | 0,5 | 0,5 |
| Total waste collected / worker | [kg] | 1,24 | 2,13 |

**Table 3**
NIOSH LI for each risk range related to the whole waste collection activity (Lifting, transport, pushing and pulling) of containers typology A and typology B.

| NIOSH results | Bins typology | |
|---|---|---|
| | Typology A | Typology B |
| Lifting operation | 0,59*<br>0,74** | – |
| Carrying operations | 0,42 | – |
| Pulling and pushing operations | – | 0.65*<br>0.79** |
| Colour indexing | GREEN | GREEN |

*male workers 18–45 years old **male workers < 18 or > 45 years old.

*3.2. Step 1, 2 and 3: Evaluation of the technical, ergonomics, economic, and social aspects*

The third phase of the research study aims to assess the scenarios' ergonomics, technical, economic, and social implications. The objective of the analysis was to support the waste collection operator in boosting its service's sustainable design by identifying the technical and economic factors and social impacts of the DTD paper waste collection systems.

Technical implications were evaluated based on the local context where the waste management operator provides its service. In that sense, the study involved many stakeholders, mainly the waste collection operator and its workers, the municipality of Argelato and its local authorities. In this context, the paper waste collection consists of two main tasks: emptying the bins and driving the vehicle to the transfer station, storage or sorting facility or recycling plant. The first task requires the workers to drive the waste collection vehicle to the bins and empty them into the vehicle hopper. The waste operator in charge of paper waste collection separately collects the containers on a tri-weekly arrangement using waste collection vehicles. In the early morning, waste collectors start the first CR. The work shift finishes at around 13, with a 30-minutes break per day. The kerbside collection requires about 80% of the total CR, while the average time to unload the collection vehicle at the recycling plant is about 75 min per day. Hence, the average time of MMH of waste containers is about 400 min per day. Both services are provided by a single crew which costs 0.89 €/min.

In the present case study, the assessment of technical implications was based on primary data on: i) specific characteristics of the collection system (e.g., local context, frequency, CRs), ii) analysis of paper waste (e.g., amount per inhabitants, quality of paper waste), and iii) inhabitants characteristics (e.g., number of users) and users' habits (e.g., typology of waste containers, production of paper waste). Considering paper waste generation (equal to 38.43 kg/cap/yr), paper waste weight (equal to 0.13 kg/l) and the number of household users, data are necessary to evaluate the feasibility and the design of the service (i.e., collection frequency, CRs, number of bins per round). As the collection frequency is 1/21 (time/day), the number of CRs per year is 16.

Table 4 shows the selected parameters for the collection systems.

As far as the economic assessment is concerned, the costs of the selected scenarios have been evaluated based on the cost of 0.89 Euro/min per day for each CR (Table 4)

**Table 4**
Description of the selected parameters of each collection system.

| Parameter | Scenario | | | |
|---|---|---|---|---|
| | **Unit** | **Scenario 0** | **Scenario 10** | **Scenario 5** |
| Average time to collect bin | [min/day] | 1 | 2 | 1 for 40-litre<br>2 for 120-litre |
| N. 40 L capacity bins | [-] | 313 | 0 | 157 |
| N. 120 L capacity bins | [-] | 0 | 313 | 157 |
| N. household users with 40 L | [-] | 727 | 0 | 367 |
| N. household users with 120 L | [-] | 0 | 727 | 367 |
| WSL | [min/day] | 437 | 403 | 420 |
| Cost | [Euro/min/CR] | 389 | 359 | 374 |

As for the assessment of social sustainability, the "reference scale" was selected as the impact assessment approach for sLCIA, ranging from negative performance to positive performance was selected with only two scale levels (from −2 to + 2).

## 4. Results and discussion

The present study evaluated the ergonomics and technical implications, as well as the economic factors related to the DTD collection of paper waste. Social sustainability was also assessed to identify the negative and positive impacts on collection workers, as a meaningful complement to the ergonomics case study.

Results show that the use of 120-litre capacity bins would significantly improve the ergonomics of the investigated activity (Table 4). The ergonomics study on 120-litre showed that the resulting pushing force was 15 kg and the pulling force was 11 kg. The ergonomics study on 360-litre showed that the pushing force was 17 kg and the pulling force was 13 kg. Hence, both observed values are lower than the limits for pushing force (23 kg) and pulling force (14 kg) suggested in ISO 11228–2 (International Standard Organization, 2007b). According to Battini et al. (2018), the main risk factor is due to the horizontal distance between the hand and the body of the worker as well as the vertical distance between the hands and the ground, and it impacts on the final risk index. Therefore, according to the authors lifting and pulling frequencies greatly impact the NIOSH LI. In this context, the use of typology B containers in scenarios 1 and 2 reduces the number of lifting and carrying operations. More specifically, due to the development of the semi-mechanised collection, the more limited number of lifting and carrying operations would expose the workers to less ergonomic risk in scenario 10. Scenario 5 gets a number of total ergonomic operations equal to 125, 94 of which are lifting, whereas 75 are pulling operations. Hence, the total amount of lifting and carrying operations is effectively reduced if compared to scenario 0 (235).

Therefore, the average work time of the improved mechanised collection (40 s per operation) is found to be higher than in the case of paper waste collection performed with the 40 L waste bins which require less time-consuming lifting operations (20 s). In that sense, while the average time of each bin is found to be twice for 120 L, the effective time of paper waste collection performed by 40 L for each CR is found to be the highest (Scenario 0). Interestingly, using 2-wheeled 120 L capacity bins reduce at the same time the MMH of loads and the effective time of the collection service. Hence, the best scenario with less lifting and carrying operations is the first one in which 120 L capacity bins completely substitute the 40 L bins. It should be noted that Scenario 5 shows the actual number of users with 120-litres capacity bins (60% of the users). Accordingly, 50% of the users did not have 120-litre bins by changing their habits.

Consequently, the costs of Scenario 1 and Scenario 5 were significantly reduced (see Table 4). Hence, by multiplying the cost of the service and the work shift length (see Table 3), the total costs of the services are an average of 6,220 €, 5,737 €, and 5,930 € for Scenario 0 and Scenario 10. The municipality accounts for an average of 7% of the total expenditure per year for paper waste collection. The results in Fig. 2 show that using 120-litres capacity bins would effectively reduce the total cost of the service for the citizens.

As for the social analysis, the sLCA results are shown in Table 5.

In six out of seven social topics, each scenario gets the same score. Since the collection service is managed by the same company (Brodolini, 2021), no significant differences have been evaluated for workers (Table 5). Scenario 0 was considered as the baseline scenario for the evaluation of the health and safety category, while scenario 10 has a positive impact on these topics based on the results of the ergonomic risk assessment. As a matter of fact, even if the NIOSH analysis evaluated the use of 40-litres and 120-litres capacity bins as "low risk related work", scenario 10 results in an ergonomic improvement for the workers when compared to the baseline scenario (scenario 0). More specifically, the safety of scenario 10 is increased by the fact that the MMH of loads would be significantly reduced, given that ergonomic interventions play an important role in developing waste collection services.

Moreover, the SMs have been evaluated for ten scenarios ranging from Scenario 0 to Scenario 10. Due to the semi-mechanised waste collection systems, It has been demonstrated that the MMH of waste containers has been significantly reduced, whereas the RC has been increasing due to the reduction of RC (Fig. 2). Consequently, the use of 120-litres capacity bins would expose the waste collection operators to fewer ergonomics risks, and the waste operators would undercharge households by 1.55 Euro for paper waste collection services. Social Life Cycle Assessment shows that the best scenarios in terms of social impact are scenarios 8, 9, and 10, whit a total score of 13 points (see Annex 5).

Finally, each SM was normalized (see Annex 5). Then, the total score of each scenario was calculated. Fig. 3 shows the results: the total score for each scenario is calculated as the sum of the scores of the sustainability dimensions. The total score results from the ergonomics, technical, economic, and social contributions. Scenario 10, whose total score is 45, ranks first.

## 5. Conclusions

The interest raised in waste collection is widely debated in several publications. The research study aims to shed light on designing efficient and effective collection schemes required to boost high-quality performances, particularly as regards separate waste collection. Waste collection characteristics impact the daily workers' exposure to the MMH of waste containers. In this context, ergonomics interventions are needed to reduce the risk of developing MSDs.

This study has the ambition to give a contribution to the waste collection field, quantifying the risk factors that might affect the health and safety of the workers involved in DTD waste collection, particularly considering its workloads and high repetitive tasks.

The literature highlighted that the risk factors vary depending on waste collection services (e.g., waste collection containers, collection frequency, collection rounds, collection vehicle) and on the postural assessment of the workers. Now, more than ever, social and economic sustainability is a critical part of our thinking, and targets on waste collection set by the European and national legislation are crucial.

An evaluation of social impacts complements technical and economic considerations to boost the sustainability of waste collection. sLCA methodologies have been applied, limiting the considered stakeholders to the workers. To evaluate the potential impacts on the improvement of the selected scenarios, in the assessment of technical and economic implications, some criteria have been selected to ensure the reliability of the analysis and the comparability among the selected collection system.

This case study demonstrates that using 120-litres capacity bins

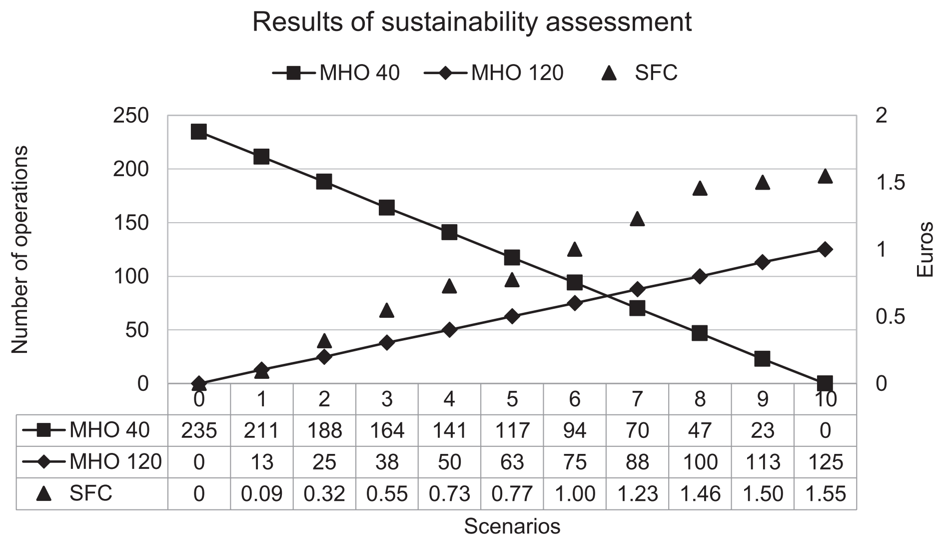


**Fig. 2.** Results of the technical and economic analysis for ten scenarios.

**Table 5**
Results of sLCA in terms of workers subcategory for ten scenarios.

| **Total sLCIA** | 11 | 11 | 11 | 11 | 12 | 12 | 12 | 12 | 13 | 13 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

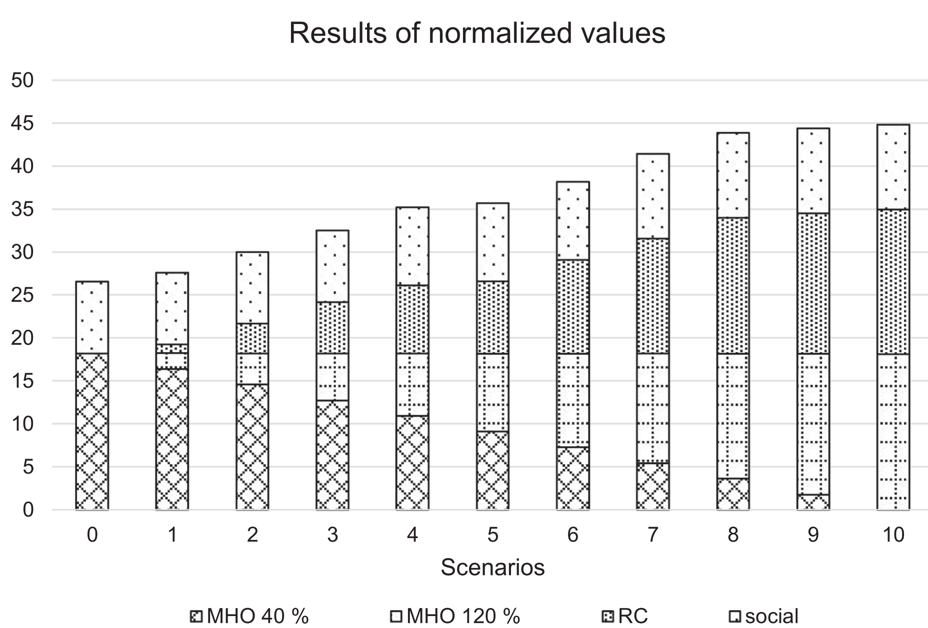


**Fig. 3.** Results of the normalized values of technical, economic, and s - LCA analysis for ten scenarios.

would improve the ergo-quality level of paper waste collection. As a result of the ergonomic risk assessment, it can be stated that using the 2-wheeled bins minimises the operator workload. Thus, the study confirms a cost and ergonomic optimisation in modifying the characteristics of the collection service by reducing the number of manual handling operations, such as lifting and carrying.

Future research studies might focus on other ergonomics aspects (e.g., high repetitive tasks, collection frequency, job rotations), environmental influencing factors (i.e., transportation, waste collection vehicles), socio-economic impacts on the users (e.g., household), and the applicability of the designed framework on other waste fraction as well as other bins typology (e.g., 240, 360, 4-wheeled). The application of the designed framework to different case studies (e.g., non-urban areas) will allow the authors to test and refine the process. A collaboration with other urban waste operators is encouraged to be disclosed.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.11.024.

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