Door-to-door waste collection: analysis and recommendations for improving ergonomics in an Italian case study

Lucia Botti[1*]. Daria Battini[2]. Fabio Sgarbossa[3]. Cristina Mora[4].

[1] Interdepartment Research Center on Security and Safety (CRIS), University of Modena and Reggio Emilia, Modena, Italy (e-mail: lucia.botti@unimore.it)

[2] Department of Management and Engineering, University of Padua, Vicenza, Italy (e-mail: daria.battini@unipd.it)

[3] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway (e-mail: fabio.sgarbossa@ntnu.no)

[4] Department of Industrial Engineering, University of Bologna, Bologna, Italy (e-mail: cristina.mora@unibo.it)

[*]corresponding author.

Abstract

In the last decade, door-to-door waste collection methods have been largely applied by several municipalities in Italy, with the main purpose to achieve higher rates of sorted waste. This approach requires waste collectors to handle a high number of small waste containers during their work-shift, especially in urban areas and historic city centres. Workers may experience ergonomic issues during door-to-door waste collection ,due to the characteristics of the waste containers, the waste collection equipment, the work organization and citizens' behaviour. If not well planned and managed, this activity may expose waste collectors to ergonomic risk factors for musculoskeletal disorders.

This study proposes a detailed investigation of the door-to-door waste collection strategy operated in an Italian city centre for the collection of organic municipal solid waste, green

waste and residual waste. The aim is to investigate the impact of door-to-door waste collection strategies on the health and safety of the workers involved in this activity.
The results show that the lack of proper waste collection equipment determines poor ergonomics conditions during door-to-door collection of green waste. The poor design of operations and technology is the cause of ergonomic issues in the door-to-door collection of organic municipal solid waste and residual waste. Finally, work organization factors impact on the safety and health of all the waste collectors involved in this study.
A set of recommendations and suggestions are provided to managers, workers and citizens involved in door-to-door waste collection, showing that this activity can be sustainable if well designed and managed.

Keywords: Solid Waste Management; Waste collection; Door-to-door collection; Ergonomics; Human factors; Sustainability.

1. Introduction

Waste management is one of the key concepts at the core of sustainable development, together with environmental sustainability and ergonomics. Sustainable development promotes the integration of human development goals with the principles for sustaining and preserving the ecosystem and the natural resources upon which the economy and our society depend (Olawumi and Chan, 2018; Radjiyev et al., 2015). Sustainable organizations are encouraged to improve their environmental efficiency adopting effective waste management strategies, sustainable work practices and optimising the outcomes of human-system interactions. From this perspective, a sustainable organization delivers sustainable products and processes that meet environmental, organizational and ergonomics criteria, applying the sustainability knowledge in waste management (Olawumi and Chan, 2018; Siemieniuch et al., 2015).

Waste collection is the first part of the process of waste management, in which the waste is transferred from the point of grouping to the point of treatment. Separate waste collection is an essential requirement for sustainable waste management (Bartolacci et al., 2018). In the last two decades, the development of material and energy recovery technologies sustained the global efforts in supporting Municipal Solid Waste (MSW) management towards sustainability (Shekdar, 2009). In 2010, the greenhouse gas inventory of the European Union (EU-27) has stated that the waste sector accounted for around 3% of total direct greenhouse gas emissions in the EU-27 (Punkkinen et al., 2012). The positive effect of the urban per capita disposable income on carbon emissions was confirmed in China as well (Wang and Geng, 2015). More recently, an investigation on integrated waste management scenarios representative of the European situation evaluated possible trends in the net emission of greenhouse gases and in the required landfill volume. The results revealed that high level of separate collection is a critical factor for the success of integrated solid waste management systems, together with efficient energy recovery in waste-to-energy plants and very limited landfill disposal (Calabrò et al., 2015).

The European Union has encompassed an integrated approach to waste management, promoting the development of an integrated network of waste collection groups that manage recycling collection from the production phase to the recovery or final disposal. The European Waste Directive 2008/98/EC imposes to the EU members different mandatory recycling levels depending on the waste fraction. Citizens and companies are required to separate the MSW by type, e.g. food waste, green waste and recyclable materials (paper, glass, plastics, metals, etc.). Public authorities are strongly invited to comply with the collection requirements for different waste streams set in the waste legislation (Teerioja et al., 2012).

The choice of the waste collection system adopted by the municipality is strategic as waste collection cause a relevant part of the total MSW management costs (Sonesson, 2000). The 2019 Italian report on recycling and waste management reveals that the cost of waste collection and transport accounts for the 13.2% of the total cost of unsorted MSW management and the 23.4% of the cost of sorted MSW management (ISPRA, 2019).

MSW management is often performed with different modalities, depending on the agreement between the local municipality and the waste management companies. There are different collection systems, e.g. curbside bins, pneumatic systems and door-to-door. Specifically, door to door refers to the collection system where citizens place domestic waste close to the street in personal waste containers. Door-to-door collection allows higher results in terms of collected waste volume and quality of separation (Agència de Residus de Catalunya and Generalitat de Catalunya, 2017). A recent Finnish study has compared pneumatic and door-to-door collection systems. The results show that, compared with the pneumatic system, the economic performance of a vehicle-operated door-to-door waste collection system is higher (Teerioja et al., 2012). Furthermore, a recent study showed that the greenhouse gas emissions of pneumatic collection are three times higher than the values retrieved with door-to-door collection (Mora et al., 2013). Hence, the door to door collection system is suggested to replace the kerbside collection (Calabrò and Komilis, 2019).

The recent interest of institutions, public and private organizations and researchers in the role of ergonomics for supporting sustainable development is addressing new areas of research, aiming to understand and optimize the interactions between the human and the environment (Battini et al., 2011; Botti et al., 2017). Waste collection work is associated with a variety of physical, chemical, and biological hazards. Occupational accidents are frequent among waste collectors (Poulsen et al., 1995). The risk of fatal occupation injuries of waste collectors is higher than in general industry. Despite being a relatively small sector in terms of employment, the fatal injury rate in waste collection is relevant. The UK Health and Safety Executive (HSE) reports that the number of MSW workers fatally injured at work in the last year has more than doubled in comparison to 2015/16 (Slow Elisabeth, 2017). Specifically, the UK rate of fatal injuries in waste and recycling in 2016/2017 was the highest in comparison with other industries as construction, agriculture and manufacturing (see Figure A1 in Appendix A). The annual average fatal injury rate of waste and recycling, over the last five years, is around nine times higher than the construction industry rate. The ankle sprain while getting off the waste collection vehicle is a frequent non-fatal injury affecting waste collectors. Other common injuries are fractures, ocular trauma, and bites (Dorevitch and Marder, 2001). However, non-fatal injuries in waste collection are mainly Work-related Musculoskeletal Disorders (WMSDs) due to Manual Material Handling (MMH) of waste containers.

Waste collection requires MMH of loads, as lifting, lowering, pushing and pulling of collection bins, bags and carts. The weight of such containers is variable, depending on the waste typology, the container features, the collection frequency, the time of year and other variable factors. Such characteristics impact on the workers' exposure to the risk of MMH of waste containers and on the risk of developing WMSDs. In 2005, a research published by the Washington State's Department of Labor and Industries revealed that WMSDs account for 41 percent of the cost of workers' compensation claims (Silverstein et al. 2005). From 1994 to 2002, waste management industry caused 769,989 lost work days in the U.S. and $147,302,364 in claims costs. In 2006, the UK Health and Safety Laboratory (HSL) investigated the risks for developing WMSDs in door-to-door waste collection. The aim was to provide authoritative guidance on control measures to limit risk within the existing waste collection systems (Oxley et al., 2006). The HSL provided recommendations to waste collection employers and employees for safe manual handling of MSW containers, regardless the waste typology.

Waste collection is a challenging task due to, for example, varying topography, climatic conditions, and limited space for waste containers and transportation vehicles (Teerioja et al., 2012). In 2012, the University of Central Florida published the results of a comprehensive ergonomics study on waste collection, with focus on the waste collection technology. The research investigated three different modalities for waste collection, i.e. manual, semi-automated and automated. The results reveal that waste collectors are exposed to severe occupational injuries due to lifting, heavy load handling, repetition and awkward postures (Mccauley Bush et al., 2012). In 2014, a research on the ergonomics of waste collection investigated the interaction between waste collectors and collection vehicles for door-to-door waste collection (Attaianese, 2014). The study compared the collection vehicle features (e.g. platforms dimensions and height, handles, feet supports, etc.) and the anthropometric measures of waste collectors. Results show that waste collectors are forced to assume awkward postures of legs, back, arms and other articular segments because of the poor design characteristics of waste collection vehicles. Both the study from the University of Central Florida (2012) and the research from Attaianese (2014) focus on collection vehicles, giving useful information and insights for practitioners and designers. However, neither research study investigated other critical factors related to the design of waste collection strategies, that may impact on workers' safety and health, e.g. the features of waste containers and work organization.

In 2018, Battini et al. (2018) investigated the risk factors for WMSDs in door-to-door collection of organic MSW in the historic city centre of an Italian city, focusing on the characteristics of collection vehicles and equipment, e.g. the plastic containers provided to the citizens. The case study introduced by Battini et al. (2018) was characterized by high number of small waste containers that needed to be tipped into the waste collection vehicle. The results reveal that multiple factors of door-to-door collection strategies impact on waste collectors' safety and health, e.g. the characteristics of the collection vehicles, work organization and the features of waste containers.

Based on the results of such research, this paper shows a deeper investigation on waste management strategies and employees experiences during door-to-door waste collection. The door-to-door collection strategies adopted in an Italian historic centre for the collection of organic MSW, green waste and residual waste are introduced. The aim is to analyse the impact of the decisional variables for the design of door-to-door collection strategies on the health and safety of waste collectors.

The research questions addressed in this research are "Are door-to-door waste collectors exposed to ergonomic risk factors?", "Which is the impact of the decisional variables for the design of door-to-door collection strategies on waste collectors' health and safety?" and "Is it possible to prevent the presence of ergonomic risk factors during door-to-door waste collection?".

Four main categories of decisional variables have been identified:

Organization: the work organization, including the characteristics of the collection round, the duration of the work-shift and the number of workers in the collection crew;

Operations: the modalities adopted by waste collectors to perform the MMH of the waste containers (e.g. assumed postures and movements performed during door-to-door collection);

Technology: the characteristics of the collection vehicle, in terms of features of the collection truck;

Equipment: the characteristics of the waste collection equipment, in terms of features and weight of the waste containers.

An ergonomics analysis investigates the impact of such decisional variables on the exposure of waste collectors to the risk for developing WMSDs, due to the door-to-door collection of waste containers, in the reference case study. Results reveal that waste collectors experience ergonomic issues during door-to-door waste collection. Such issues are related to the poor design of door-to-door waste collection strategies, in terms of organization, operations, technology and equipment. Hence, door-to-door waste collection can be a sustainable activity if properly designed and managed.

The remainder of this paper is as follows. Section 2 introduces the characteristics of door-to-door collection, together with the collection schemes, the methods and the tools adopted in the reference case study. Section 3 shows and discusses the results of the ergonomics analysis, providing a set of suggestions for obtaining a sustainable and safe door-to-door collection system, even in Italian densely inhabited city centres. Finally, Section 4 concludes the paper, showing the future developments of this research study.

2. Methodology

This section introduces the materials and the methods adopted in this study. The door-to-door collection scheme investigated in this paper refers to the waste management strategy adopted in the historic centre of a city in northern Italy with 80,000 inhabitants. Door-to-door waste collection is operated by a waste management company, in collaboration with the local municipality. The municipality involved in this study is one of the most pro-active in Italy, i.e. it achieved the 88.5% rate of sorted waste collection in 2018 (the Italian mean national rate is 55.5 % according to www.csaimpianti.it/ispra) with less than 500 kg of waste per inhabitant per year.

This study focuses on the door-to-door collection schemes adopted by the waste management company for the collection of organic MSW, green waste and residual waste. The municipality requires the citizens to collect and separate the MSW in different types of containers, according to the waste fraction. The activities performed by waste collectors during a conventional work-shift include emptying the waste containers, driving between the waste collection points in the collection area and transporting the collected waste to the treatment plant or to the waste disposal.

2.1. The door-to-door collection scheme in the reference case study

Door-to-door collection in Italian urban areas is mainly performed with small standard waste containers, e.g. 25-30 l plastic bins, because of the difficulty to store and handle large containers in the narrow streets of the historic city centres. Residents are required to separate different materials in the containers and to expose them on the street, close to the point of production. The waste management company collects the containers on a weekly or bi-weekly basis, depending on the waste typology and on the season. Each residential area of the city is characterized by a collection round (CR). Following a defined CR, waste collectors reach each waste container and collect waste into a collection vehicle.

Specifically, 14 crews operate the door-to-door collection for a total of 28 CRs. Each crew is responsible for one CR per day. Door-to-door collection requires the waste collectors to handle the containers at the kerbside, performing manual movements to lift the plastic bins from the ground to the collection vehicle. The number of people in the crew depends on the waste typology, e.g. either a single or two-person crew typically manages the CR of organic and residual waste, while a three-person crew is necessary for the collection of green waste. In case of single-person crew, the same waste operator drives the collection vehicle and collects the waste containers on the kerbside. In the two and three-person crews, one worker typically drives the collection vehicle and the other one or two collect the waste containers. This collection strategy is preferred when the collection vehicle is a heavy truck and a special driving licence is required. Waste collectors do not rotate among different crews during the day. However, crew organization may vary during the year, i.e. the production of green waste and organic MSW is limited during winter, when garden maintenance is less intensive as compared to spring and summer, and the consumption of fruit and vegetables is more limited. Consequently, the citizens expose a limited number of waste containers on the kerbside.

2.2. Door-to-door collection of organic MSW

2.2.1. Organization

Organic MSW is the biodegradable waste material originated by the residuals of food and other biodegradable waste produced by the household. The waste management company in the reference case study collects the organic MSW on a bi-weekly basis.

Waste collectors' activity consists of two main tasks: kerbside collection and driving the vehicle to the waste treatment plant. The first task requires the workers to drive the waste collection vehicle to the bins and tip the waste into the truck hopper. This task requires about the 70% of the total time of MMH. One third of such 70% is necessary to drive the vehicle from bin to bin. The second task is performed for the remaining time (Battini et al., 2018).

The ergonomics analysis focuses on the worker of the single-person crew performing the door-to-door collection of the organic MSW. The worker starts the CR at about 5 am. The work-shift finishes at about 11.30 am. Two breaks of 15 minutes each are possible in the morning. Furthermore, workers stop collecting waste for about 50 minutes to reach the waste treatment plant and unload the vehicle hopper once a day (twice in summer, from May to July). The following Table 1 shows the characteristics of the door-to-door collection scheme for the organic MSW.

Table 1

Characteristics of the door-to-door collection scheme for the organic MSW. Average values of 28 CRs in summer, spring/autumn and winter seasons.

	Summer	Spring/Autumn	Winter
Average number of potential plastic bins in the residential area [bins]	813	813	813

Exposition rate [%]	70%	70%	70%
Collected waste [kg/day]	7024	3560	2853
Average weight of the plastic bin [kg]	7.99	3.47	2.76

The number of plastic bins in Table 1 refers to the average number of potential users in the residential area. Wheeled containers, e.g. waste containers provided to commercial activities as restaurants and grocery stores, are not included in this study.

The exposition rate is defined as the ratio between the actual number of waste containers exposed by the citizens on the kerbside and the total containers provided to residents. Statistics from the waste management company involved in this study reveal an exposition rate for organic MSW equal to 70% (Table 1), i.e. the actual number of plastic bins tipped by the waste collectors is lower than the potential bins in the residential area. Data used for the ergonomic risk assessment refer to the waste collection activity performed in the reference case study, in summer, spring/autumn and winter seasons (Table 1). Specifically, door-to-door collection of organic MSW containers in spring and autumn seasons show similar working and weight conditions, i.e. the following analysis includes average data for these seasons. Table 1 shows that the average weight of the plastic bin containing the organic waste in summer is more than twice the weight of the same container in spring or winter. The presence of fruit and vegetables residuals with high content of water that characterizes the summer season may explain such difference.

2.2.2. Operations

The waste collector lifts each bin, transferring the organic waste inside a truck container attached to the collection vehicle, then returns the empty bin to the citizen (Figure 1).

Fig. 1. On the left, the collection vehicle. On the right, two-handed tip of the plastic bin into the truck container on the back of a collection vehicle.

Each plastic bin is equipped with a plastic handle. Practice shows that waste collectors prefer to lift the bin from the upper edge, rather than using the plastic handle.

2.2.3. Technology

The collection vehicles are small size truck (from 5 to 7 m^3 of capacity) equipped with a rear hopper and a lifting equipment. Different types of truck containers are attached to the bin lifter where the operators unload the plastic bins. Figure 1 shows two types of collection vehicles. Automatic lifters are present on the vehicle to overturn the waste into the hopper. These lifting equipment are positioned on the back of the vehicle (Figure 1). The truck container is integrated in the collection vehicle on the left side of Figure 1. A wheeled container is attached to the lifting equipment in the collection vehicle on the right.

2.2.4. Equipment

The citizens collect organic waste in a 25-litre capacity plastic bin. The height of the upper edge of the plastic bin is 43 cm. The operation assumptions adopted for the ergonomics analysis are: the waste collector lifts and carries each plastic bin from the point of exposition to the truck container; the height of the hands at the origin of the lifting task is 43 cm; the horizontal distance of the hands from the body at the destination of the lifting movement is about 30 cm; the horizontal distance of the hands from the body at the destination of the lifting movement is about 55cm, i.e. the worker keeps the plastic bin distant from his body aiming to avoid splash and squirts of the organic MSW; some torsion (30°) is present at the destination of the lifting movement; the grip is poor, i.e. the waste collector lifts the plastic bin from the upper edge of the container; the waste collector is a man between 18 and 45 years old. The characteristics of the environment contribute to increase the critical conditions of organic MSW collection, e.g. extreme temperatures in summer and winter, and slippery and irregular paving.

2.3. Door-to-door collection of green waste

2.3.1. Organization

Green waste includes grass clippings, tree trimmings, shrubs and leaves. This waste is generated by pruning and leaf or other residuals of the maintenance activities performed in the green areas. The waste management company collects green waste and other pruning residuals on a weekly, bi-weekly or tri-weekly basis, depending on the residential area and on the season. The municipality defines the green waste collection program with the support of the waste management company. The average exposition rate of green waste, i.e. the number of exposed containers over the overall number of potential containers exposed by the citizens, is 17 %. Such value is the result of three investigations performed in the middle of the autumn season (between October and November 2018) in the reference urban area. The high presence of pruning residuals and leaf characterizes the autumn season in northern Italy. The average weight of green waste at the end of the work-shift is 3820 kg. Each served user may expose up to 3 waste containers.

2.3.2. Operations

A three-person collection crew operates the door-to-door collection of green waste in the reference case study. Specifically, one worker drives the collection vehicle and two workers collect the waste containers. The waste collectors lift the waste containers, transferring the green waste inside the hopper of the collection vehicle. Finally, waste collectors are required to return the empty containers to the citizens.

2.3.3. Technology

The collection vehicle adopted for door-to-door collection of green waste is a truck equipped with a rear hopper, in which the worker transfers the waste. In these trucks, no automatic lifters are present on the vehicle to overturn the waste into the hopper (see Figure A6 in Appendix A).

2.3.4. Equipment

The citizens collect green waste in different types of container, e.g. plastic bags, tubs, bundles and buckets (see Figure A2 in Appendix A). The municipality does not provide a standardized container for green waste, i.e. the choice of the container is up to the citizens. The following Table 2 shows the frequency of appearance of different types of waste containers used by the citizens to collect green waste.

Table 2.

Types of waste containers used by the citizens to collect green waste.

Waste container	Number of expositions	%
Plastic bag	42	38%
Tub	25	23%
Bundle	19	17%
Crate	11	10%
Bucket	9	8%
Other	4	4%
Total	110	100%

Data in Table 2 refer to a sample of 110 containers observed on the kerbside during an inspection in mid-autumn 2018. The citizens prefer to collect green waste in plastic bags (38%), followed by tubs (23%) and bundles (17%). Each container was weighted on site during multiple investigations, using a digital force gauge (IMADA ZTA-500N, sample rate 2000 data/s, accuracy +/-0.2%F.S.+/-1digit). This investigation allowed to determine the range of the Frequency Independent Lifting Index (FILI) values for all of the sampled lifts, for the ergonomics analysis (Waters et al., 2016, 2009). The 58% of the inspected waste containers was less than 7 kg (see Figure A3 in Appendix A). Waste containers under 3 kg were the 17% of the exposed containers. Weights under 3 kg are not included in this analysis as they do not contribute to increase the risk for manual lifting (Haslam and Waterson, 2013).
The operation assumptions adopted for the ergonomics analysis are: the composition of the exposed green waste, based on the weight of the waste containers, is in Figure A3; the workers keep the waste container close to the body during the lifting task; the height of the hands at the origin of the lifting task is variable between 20 cm and 110 cm; at the destination on the truck hopper, the height of the hands varies between 125 cm e 140 cm; the grip is poor since no handles are available; no torsions are performed while lifting the waste containers; waste collectors are men between 18 and 45 years old.
The characteristics of the environment contribute to increase the critical conditions of green waste collection, e.g. extreme temperatures in summer and winter, and slippery and irregular paving. Other critical characteristics are the presence of cutting extremes or edges, and the content instability of green waste containers.

2.4. Door-to-door collection of residual waste

2.4.1. Organization

Residual waste is the waste remaining after all recyclables have been collected. This waste typology is bound to landfills and its production should be limited. The citizens collect

residual waste in plastic bins provided by the municipality. Wheeled containers, e.g. waste containers provided to commercial activities, are not included in this investigation. The tasks performed for the door-to-door collection of residual waste are similar to the activities performed for organic MSW collection, i.e. the two main tasks performed by the waste collector are kerbside collection and driving the vehicle to the landfill. The first task requires about the 70% of the total time. One third of such 70% is necessary to drive the vehicle from bin to bin. The second task is performed for the remaining time (Battini et al., 2018).
The following Table 3 shows the characteristics of the door-to-door collection scheme for the residual waste.

Table 3.

Characteristics of the door-to-door collection of residual waste.

Parameter	Value
Average number of potential plastic bins [bins]	1907
Exposition rate	43 %
Collected waste [kg/day]	7730
Average weight of the plastic bin [kg]	9.4

The number of plastic bins in Table 3 refers to the average number of the users served by the waste management company for the door-to-door collection of residual waste in the reference case study. The exposition rate of the plastic bins containing residual waste is about 43 %. These data are from the waste management company involved in this study.

2.4.2. Operations

The kerbside collection modalities depend on the type of the collection vehicle adopted during the CR. Collection vehicles with the truck container require the waste collector to lift each bin and to transfer the residual waste inside a truck container attached to the collection vehicle. Then, the waste collector returns the empty bin to the citizen. In case of collection vehicles with no truck container, the waste collector transfers the content of the plastic bin inside the hopper of the collection vehicle, then returns the empty container to the citizen.

2.4.3. Technology

The collection vehicles are small size truck (from 5 to 7 m^3 of capacity) equipped with a rear hopper and a lifting equipment. Different types of containers are attached to the bin lifter where the operators can unload all the collected bins. When the container is full, the operator activates the automatic lifter on the vehicle to overturn the waste into the hopper (see Figure 1).

2.4.4. Equipment

The citizens collect residual waste in a 30-litre capacity plastic bin. The height of the upper edge of the plastic bin is 42 cm. The operation assumptions adopted for the ergonomics analysis are: all the exposed waste containers for residual waste are plastic bins; the height of the hands at the origin of the lifting task is 42 cm; the height of the hands at the destination of the lifting movement (i.e. the hopper, in case of collection vehicles with no truck container, or the truck container) varies with the typology of the adopted collection vehicle; the worker keeps the plastic bin close to his body at the origin of the lifting movement (30 cm); the horizontal distance of the hands from the body at the destination of the lifting movement is about 40 cm; no torsions are performed while lifting the plastic bins; the grip is poor since the waste collectors lift the plastic bins from the upper edge of the container; the collection worker is a man between 18 and 45 years old.

The characteristics of the environment contribute to increase the critical conditions of residual waste collection, e.g. extreme temperatures in summer and winter, and slippery and irregular paving.

2.5. Methodology for the ergonomics analysis

The ergonomics analysis in this study includes the risk assessment methodology based on the NIOSH Variable Lifting Index (VLI) for evaluating variable lifting tasks using the revised NIOSH lifting equation (Waters, 1993; Waters et al., 2016, 2009). The VLI method allows the assessment of highly variable manual lifting jobs in which the task characteristics, e.g. the geometry of the lifting task and the weight of the lifted objects, vary during the work-shift. Specifically, this method compares the actual weights lifted by waste collectors with the recommended values derived from the NIOSH lifting equation, for the actual lifting conditions. The reliability of the NIOSH VLI method relies on the epidemiological approach developed by its authors to investigate the association between the NIOSH VLI values and the health outcomes.

The postural assessment was performed with the OWAS method (Karhu et al., 1977). The observational technique for evaluating working postures was a wearable motion capture system consisting of 31 inertial sensors, placed on the whole body suit. In order to measure with precision the human body postures during the door to door waste collection activity under analysis, the authors applied the innovative full-body motion capture system (made up by a suit and a software) traditionally used for the real-time ergonomics evaluations in industrial environments as described in Battini et al. (2014) and Battini et al. (2018). This system allows the analysis of the body movements when all parts of the body are interested during the tasks execution. The system is based on inertial sensors with integrated compensation of magnetic interference and long wireless connection that permit its use in several kinds of industrial applications. When the operator wears the motion capture suit, the system collects and shows in real time a large set of full-body motion data, that are used to calculate the body posture parameters and the relative percentages required in several postural assessment approaches like OWAS, OCRA and TACOs.

3. Results and discussion

The following subsections 3.1 and 3.2 introduce and discuss the results of the ergonomics analysis, providing a set of suggestions and recommendations for improving ergonomics in door-to-door waste collection. The ergonomic risk assessment after the introduction of the proposed improvements is in Section 3.3. Punctual values of the resulting risk indices have been omitted for privacy reasons.

3.1. Ergonomics analysis

3.1.1. Door-to-door collection of organic MSW

The ergonomic risk assessment for the door-to-door collection of organic MSW with the NIOSH VLI investigates the ergonomic risks associated with the manual lifting and lowering of the waste containers (Waters, 1993; Waters et al., 2016). Such risk is analysed considering the average weight of the plastic bins. No punctual data on the weight of each plastic bin are available. The authors are aware that using an average weight value may underestimate the exposition of the workers to the risk of manual lifting. However, the aim is to investigate the potential exposure of workers to ergonomic risk factors. If the risk assessment based on the average weight of the plastic bins reveals the presence of some risks for the workers, then such situation is confirmed in real lifting conditions.

The following Table 4 shows the resulting NIOSH VLI risk ranges for each CR at the origin of the lifting task (lifting the plastic bin from the floor) and at the destination (tipping the plastic bin into the truck container). The NIOSH VLI green range indicates a low exposure of the workers to the risk of lifting and lowering, yellow indicates moderate risk, red indicates high risk range and purple indicates the highest risk range.

Table 4.

Percentage of CRs for each NIOSH VLI risk range, at the origin (O: lifting the plastic bin from the floor) and at the destination (D: tipping the plastic bin into the truck container), in each investigated season.

	Risk range				
	Green (% of CRs)	Yellow (% of CRs)	Red (% of CRs)	Purple (% of CRs)	Total (% of CRs)
Summer					
NIOSH VLI O	64%	21%	14%	0%	100%
NIOSH VLI D	0%	0%	64%	36%	100%
Spring/Autumn					
NIOSH VLI O	100%	0%	0%	0%	100%
NIOSH VLI D	53%	33%	13%	0%	100%
Winter					
NIOSH VLI O	100%	0%	0%	0%	100%
NIOSH VLI D	93%	0%	7%	0%	100%

Table 4 confirms the presence of the ergonomic risk for waste collectors due to the manual handling of the plastic bins, i.e. the NIOSH VLI is higher than 1 in several CRs. Specifically, the most critical values of the NIOSH VLI are at the destination of the movement, when the workers overturn the contents of the plastic bin into the truck container. The critical risk factor due to the characteristics of the adopted equipment and technology is the vertical distance of the hands from the ground (140 cm) when tipping the bin on the truck container, i.e. waste collectors lift the arms almost at the shoulder level. This risk factor impacts on the vertical dislocation of the lifting movement and on the final risk index. The critical risk factor due to the characteristics of the operations performed by the waste collectors is the horizontal distance between the hand and the body of the worker (55 cm), i.e. waste collectors keep the load far from the body while tipping the bin, aiming to avoid squirts and splashes. Trunk twisting and bad coupling contribute to increase the exposure of waste collectors to the risk of lifting and lowering. Finally, lifting frequency is an organizational risk factor with high impact on the resulting NIOSH VLI values.

The analysis reveals that summer is the most critical season, followed by spring/autumn and winter, i.e. no CRs appear in the green or yellow risk ranges at the destination of the lifting movement.

The OWAS method was adopted for identifying and evaluating working postures during door-to-door collection of organic MSW. The motion capture system described in Section 2 collected the data related to the body movements, in a testing environment. The aim was to reproduce the real case in which bins are located close to each other on both sides of the street, as described in Battini et al. (2018). The results of the postural assessment with the OWAS method reveal an acceptable risk range for neutral and bent forward postures during kerbside collection. A slightly harmful condition is present for the twisted posture. Finally, the bent and twisted postures reveal an extremely harmful condition (see Table A1 in Appendix A for the time fractions of each investigated back posture).

3.1.2. Door-to-door collection of green waste

The results of the ergonomic risk assessment for the door-to-door collection of green waste confirm the presence of the ergonomic risk, i.e. the NIOSH VLI values at the origin and at the destination of the lifting movement are higher than 1 (see Table A2 in Appendix A). Specifically, the NIOSH VLI value is in the yellow risk range (moderate risk) at the origin of the lifting movement. The most critical lifting conditions are at the destination of the movement, when the workers overturn the contents of the waste container into the truck hopper, i.e. the NIOSH VLI value is in the purple risk range (very high risk). The main risk factors are due to the characteristics of equipment and work organization. Waste collectors are required to return the empty containers to the citizen, after unloading the green waste into the collection vehicle. The absence of an ergonomic container for green waste is a critical issue. The collection of green waste requires the assumption of awkward postures of back and upper limbs. This activity requires the waste collectors to lift the arms at the shoulder level. In case of bulky waste containers, e.g. big plastic bags, the vertical distance of the hands of the workers from the feet level is 175 cm. This factor impacts on the vertical dislocation and on the final risk index. Furthermore, the shaking/emptying of the containers into the trucks may create injuries, respiratory and eye irritation problems for the waste collectors. An additional safety issue is the risk of injuries due to the contact with thorns and cutting branches.

The fact that plastic bags and other containers are emptied before being disposed slows down the collection process. Bad coupling contributes to increase the exposure of waste collectors to the risk of lifting and lowering. Finally, lifting frequency is an organizational risk factor with high impact on the resulting NIOSH VLI. Such lifting modalities reveal very high critical conditions and no additional postural assessment with the motion capture system is necessary to confirm the presence of the risk.

3.1.3. Door-to-door collection of residual waste

The results of the ergonomic risk assessment for the door-to-door collection of residual waste with the NIOSH VLI confirm the presence of the ergonomic risk for waste collectors due to the manual handling of the plastic bins (see Table A3 in Appendix A). The NIOSH VLI is in the yellow risk range at the origin of the lifting movement. The most critical values are at the destination of the movement, when the workers overturn the contents of the plastic bin into the truck container or into the truck hopper. The main risk factors are due to the characteristics of technology, operations and work organization. Specifically, the critical risk factor due to the characteristics of technology is the vertical distance of the hands from the ground when tipping the bin, i.e. waste collectors lift the arms almost at the shoulder level. This risk factor impacts on the vertical dislocation of the lifting movement and on the final risk index. Bad coupling contributes to increase the exposure of waste collectors to the risk of manual lifting and lowering. The critical risk factor due to the characteristics of the operations performed by the waste collectors is the horizontal distance between the hand and the body of the worker (40 cm), i.e. the waste collectors keep the load far from the body while tipping the bin. Finally, lifting frequency is an organizational risk factor with high impact on the resulting NIOSH VLI values.

3.2. Recommendations and suggestions for improving ergonomics in door-to-door waste collection

The results of the ergonomics analysis reveal that waste collectors are exposed to the risk of developing WMSDs, due to the manual handling of the waste containers. The postural assessment confirms a high exposure to postural risk factors for the back in standing posture while collecting the plastic bins. These results suggest critical areas of improvement that waste collection managers should address to improve waste collectors' health and safety. Table 5 shows the impact of the introduced decisional variables, i.e. organization, operations, technology and equipment, on the ergonomics of door-to-door collection, for each investigated waste typology. Specifically, the investigation of the NIOSH VLI allows to determine the impact of each parameter concurring in the calculation of the risk indices, e.g. lifting frequency and vertical distance. The decisional variables are related to these parameters, e.g. the lifting frequency refers to the organization, and the vertical distance of the hands from the ground at the origin of the lifting movement is related to the equipment. The marks in Table 5 describe such impact.

Table 5.

Impact of the decisional variables for the design of the door-to-door collection strategy, on the ergonomics of door-to-door collection of organic MSW, green waste and residual waste.

	Organic MSW	Green waste	Residual waste
Organization	++	++	++
Operations	++	+	++
Technology	++	+	++
Equipment	+	++	+

From an organizational point of view, an increment in the collection frequency of the bins during the week only in the most critical months, i.e. the summer time, for organic and green waste, could provide a beneficial effect towards the reduction of the risk indices reported in the ergonomics analysis. Moreover, results reveal that lifting frequency is an organizational risk factor with high impact on the results of the ergonomics analysis for residual waste collection. Using job rotation in the most critical months and adding a second worker to single-person crews that may expose the workers to high risk for manual lifting of the waste containers would reach a positive effect. The adoption of waste typology-based job rotation programs in the most critical months is also suggested.

The main risk factor due to the door-to-door collection of organic MSW and residual waste is the horizontal distance between the hands and the body of the worker, i.e. collectors keep the plastic bin far from the body while tipping the container, aiming to avoid squirts and splashes. Trunk twisting and bad coupling contribute to increase the exposure of waste collectors to the risk of lifting and lowering plastic bins. Such risk factors are related to the operations performed by waste collectors. Their reduction is possible by providing proper training. The safety managers of the waste management companies should inform waste collectors about the risks of incorrect lifting, and train their workers to lift the plastic bins keeping the load close to the body (less than 25 cm) in front position.

The results of the ergonomics analysis reveal that the main risk factors due to the door-to-door collection of residual waste are due to the characteristics of the adopted technology. These results suggest that similar solutions for organic MSW and residual waste may be adopted to reduce the impact of such risk factors. The vertical distance of the hands from the feet-level determines an high impact on the resulting NIOSH VLI for both such waste typologies. Waste collectors lift the arms almost at the shoulder level (140 cm) to tip the plastic bins into the truck container attached on the back of the collection vehicle. This risk factor is due to the characteristics of the adopted technology. The posture assessment with the motion capture system allowed to track the position of the workers' hands while tipping the plastic bins into the truck container, i.e. the results reveal that the adoption of a truck container with a lower height from the ground would reduce the vertical distance of the hands from the ground at the destination of the lifting movement (see Figures A4 and A5 in Appendix A). The vertical dislocation and the necessity to rotate and extend the back would reduce as well, leading to reduced fatigue and cycle time.

The poor design of equipment and work organization are the main cause of the ergonomic issues related to the door-to-door collection of green waste. The absence of a standardized waste container with a defined geometry and an ergonomic shape is a critical issue which largely increases the risks associated with this activity, e.g. the assumption of awkward postures of back and upper limbs, and the risk of injuries due to the contact with thorns and cutting branches (see Figure A6 in Appendix A).

An additional ergonomics analysis was performed adopting wheeled containers for the door-to-door collection of green waste. The methodology in the ISO 11228-2 (International Standard Organization, 2007) was applied to investigate initial and sustained pushing forces during the manual handling of a 2-wheels container with green waste. The maximum capacity of the container was 120 l. An handle was positioned at 97 cm from the ground. Sixty pushing trials were performed during a CR. Each trial consisted in pushing the container for 2 m. The observed pushing frequency during the CR was 0.55 pushes for minute. A digital force gauge equipped with two handles (IMADA ZTA-500N, sample rate 2000 data/s, accuracy +/-0.2%F.S.+/-1digit) was employed to measure pushing forces, as required by the ISO 11228-2 (International Standard Organization, 2007). The resulting initial pushing force was 6.5 kg and the sustained pushing force was 3.6 kg. Such values are lower than the recommend limits for initial (25 kg) and sustained (17 kg) pushing forces suggested in the ISO 11228-2 (International Standard Organization, 2007). Finally, a laboratory test was performed pushing a similar 2-wheels container with 120 l of residual waste for 10 m. The resulting pushing forces were lower than the recommended limits in the ISO 11228-2 (International Standard Organization, 2007) for the investigated pushing task. Specifically, the resulting initial pushing force was 16 kg and the sustained pushing force was 9 kg.

3.3. Ergonomic risk assessment after improvements

By applying the improvement solutions discussed in Section 3.2 for the collection of organic MSW, e.g. introducing a lower truck container and providing worker training about proper lifting practices, it is possible to calculate the new NIOSH VLIs after 3 months of analysis, as reported in Table 6.

Table 6.

Number of CRs for each NIOSH VLI risk range, at the origin (O: lifting the plastic bin from the floor) and at the destination (D: tipping the plastic bin into the truck container).

	Risk range				
	Green (% of CRs)	Yellow (% of CRs)	Red (% of CRs)	Purple (% of CRs)	Total (% of CRs)
Summer					
NIOSH VLI O	93%	4%	4%	0%	100%
NIOSH VLI D	93%	4%	4%	0%	100%
Spring/Autumn					
NIOSH VLI O	100%	0%	0%	0%	100%
NIOSH VLI D	100%	0%	0%	0%	100%
Winter					
NIOSH VLI O	100%	0%	0%	0%	100%

NIOSH VLI D	100%	0%	0%	0%	100%

Table 6 shows the resulting NIOSH VLI risk ranges at the origin of the lifting task (lifting the plastic bin from the floor) and at the destination, for the investigated CRs. These results describe a lower exposure of the workers to the risk of lifting and lowering the plastic bins, for all the CRs in spring/autumn and winter. Low exposure is confirmed in the 93% of the CRs in summer. Such results reveal a huge improvement of the safety conditions during manual lifting of the plastic bins with the proposed solutions. Minor adjustments would significantly improve the ergonomics of the investigated activity. Specifically, a limited number of CRs would expose the workers to high ergonomic risk due to lifting activity. Such risk could be additionally reduced by increasing the collection frequency during the week only in the summer time and by adopting specific job-rotation programs that ensure proper recovery for the workers during the work-shift. These corrections would positively impact on the results of the postural assessment, as well. The following Figure 2 gathers the precautions and the improvements demonstrated in this work.

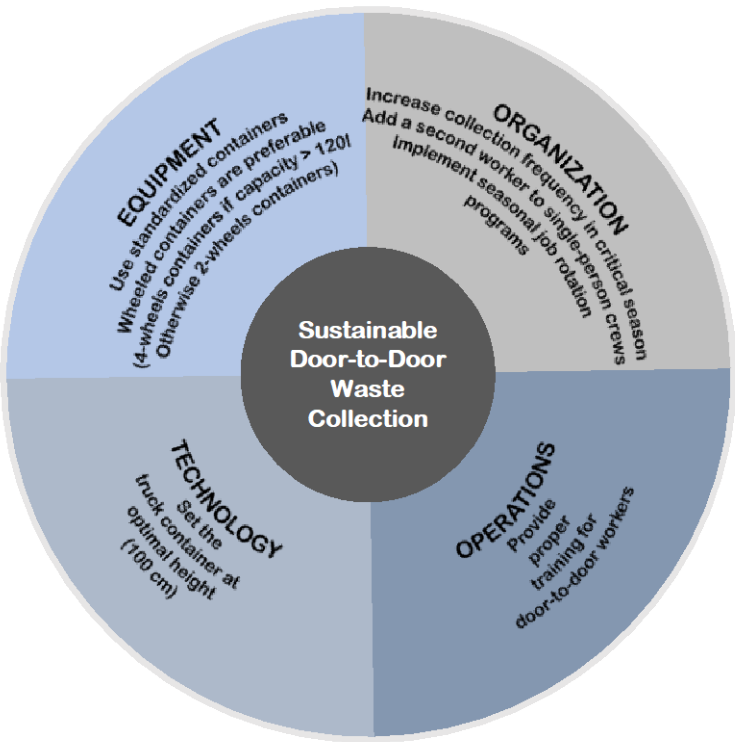

Fig.2. Guidelines for sustainable door-to-door waste collection.

Organization: increase the collection frequency of the bins during the week only in the most critical months, that is the summer season for organic waste bins; add a second worker to single-person crews that may expose the workers to high risk for manual lifting of the waste containers; use waste typology-based job rotation programs in the most critical months aiming to schedule the CRs that allow workers to alternate the waste typology to retrieve;

Operations: provide proper training to waste collectors explaining the correct working procedures and proper lifting practices, in order to avoid awkward postures, incorrect movements and person-dependent working approaches that can lead to person-dependent risk levels;

Technology: the collection truck should be equipped with lifting containers in order to permit an unloading height of bins equal to 100 cm.

Equipment: the municipality or the waste management company should provide the citizens with standardized containers for green waste. The wheeled containers have been demonstrated to be safe and preferable to the others. A second alternative includes the use of disposable containers, e.g. biodegradable bags with limited dimensions, which could be easily dumped in the collection vehicle.

A citizen aware of the risks for waste collectors due to the door-to-door collection activity may help in improving the working conditions and reducing such risk factors. A set of suggestions and directions for the citizens should include: do not expose the waste containers containing green waste to the weather conditions; do not leave the waste containers on the kerbside two or more days before the collection; use rigid containers for the collection of cutting and sharp brunches and thorns; do not expose bulky and heavy containers.

4. Conclusions

This paper provides the results of an investigation on the door-to-door collection modalities for organic municipal solid waste, green waste and residual waste, operated in an Italian historic city centre. An ergonomics analysis was performed, aiming to investigate the presence of ergonomic risk factors due to the manual lifting of the waste containers. Results confirm that waste collectors are exposed to ergonomic risk during door-to-door collection of the investigated waste typologies. The postural assessment revealed very high exposure to postural risk factors for the back in standing posture. The results here provided suggest that the door-to-door waste collection activity can become sustainable and ergonomic if a set of improvements and precautions are adequately and timely put in practice by the municipality and by the waste management companies.

Four areas of improvements have been identified: organization, operations, technology and equipment. In these areas, all the three major actors involved in the waste collection process are asked to make a step forward: the municipality, the collection companies and the workers are all involved and mutually linked each other towards the sustainability challenge. Even the citizens are not excluded: they need to be educated to behave in the most correct way in order to permit an efficient and sustainable door to door waste collection activity. The results of a behavioural survey conducted in 2019 in an Italian city revealed that citizens that practice door-to-door separation have a higher recycling conscience and are more satisfied with the city waste management system, compared with the ones that practice kerbside separation (Calabrò and Komilis, 2019). Hence, this research does not mean to question the benefits of door-to-door collection in terms of high amount of collected waste and quality of separation. The solutions proposed for reducing the exposure to the identified ergonomic risk factors, as collection vehicles with lower truck containers or wheeled containers for the collection of green waste, are present in other cities, both inside and outside the Italian territory. The waste management company involved in this study adopts some of the proposed solutions in other municipalities. However, no information are available about the decisional variables that lead such municipalities to prefer wheeled containers for green waste containers to plastic bags or other containers. This study aims to increase the sensitivity of decision makers, designers and researchers towards the design and the choice of safer alternatives that ensure safe and healthy work conditions during door-to-door waste collection. Ergonomics and human factors are critical decisional variables for the design of door-to-door waste collection strategies, in the same way as financial and economic parameters.

Finally, this is the first step of an ongoing research on ergonomics of door-to-door collection. Future developments of this research will integrate the introduced results with further investigations about other typologies of waste, e.g. plastic, paper, metal and glass waste, and additional guidelines for the design of safe door-to-door waste collection strategies.

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