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"Gheorghe Asachi" Technical University of Iasi, Romania

EXPLORING THE POTENTIALS OF APPLYING THE CIRCULAR ECONOMY FOR WASTE MINIMIZATION AT A REGIONAL SCALE BASED ON BIG DATA ANALYSIS

Reza Vahidzadeh[1]*, Ehsan Liaghati[1], Giorgio Bertanza[1], Silvia Sbaffoni[2], Mentore Vaccari[1]

[1]Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Via Branze 43, 25123, Brescia, Italy
[2]ENEA- Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Research Centre Casaccia, Via Anguillarese 301, 00123, Rome, Italy

Abstract

Although significant achievements have already been made in waste recycling, the quantity of material residues that annually end up in landfills is still regarded as an important environmental pressure at the global level. This paper presents the development of a methodology for studying the potentials of resource recovery for regions and provinces with a case study in the Province of Brescia. The provincial waste management database was used for mapping the wastes' origins and destinations. A Big Data Analysis approach was followed by developing two software packages. The first package is designed in the Powerbi environment to analyse waste management in each waste category, sector, and zone. The second tool was developed using R statistical software for preparing the mass-balance models in combination with spatial analysis. The two packages provide the possibility for planning interventive actions such as the circular economy and industrial symbiosis by identifying the most problematic points and targeting the improvement measures to minimize waste disposal.

Key words: circular economy, industrial symbiosis, recovery, waste management

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1. Introduction

Circular economy (CE) is becoming one of the main sustainability strategies among various nations, and it is also considered by international organizations such as the European Union (EU) as one of the focal points in the policy documents on sustainable development (Ignatyeva et al., 2021). One of the recent and frequently cited definitions indicates that "CE as a new model of economic development promotes the maximum reuse/recycling of materials, goods, and components in order to decrease waste generation to the largest possible extent. It aims to innovate the entire chain of production, consumption, distribution, and recovery of materials and energy according to a cradle-to-cradle vision" (Ghisellini et al., 2018). CE is represented in varying ways and through different conceptual models (Kirchherr et al., 2017). The references to reuse and recycling in these models demonstrate that achieving improved performance in waste management (WM) has a deep link to the CE (Pinter et al., 2021).

On the other hand, the concept of recovery in WM as an alternative for disposal (especially landfilling) may be linked to circularity (EPA, 1999). Moreover, several indicators have been proposed for measuring CE in different contexts (Geng et al., 2012; The Ellen MacArthur Foundation, 2019). In a study by

* Author to whom all correspondence should be addressed: e-mail: r.vahidzadeh@unibs.it; Phone: +39 3921263710

Sánchez-Ortiz et al. (2020), it was argued that among various indicators, those focused on WM could be more feasible to be measured in Europe. The indicators were *Waste diversion from landfills*, *Generation of waste* (*in production activities*), *Waste generation* (*in consumer activities*), and *Recycling rate for different types of waste/materials*. For the EU, these indicators are available in terms of total waste generation for economic activities (Eurostat, 2019, 2021). Ranjbari et al. (2021), in their thematic categorization of scientific publications about WM, have identified the above-mentioned indicators (i.e., waste generation, recycling rate, waste-to-energy, and recovery of secondary raw material) as subtopics under Municipal solid waste. This shows that the numerical studies for other types of wastes are still limited. Moreover, Kaza et al. (2018) has shown the current state of the recording of waste flows at the global level in different geographical contexts and the existing limits. Improvement and incentivizing of WM from recycling to the top of the waste hierarchy by the usage of IT tools is identified as an important future direction that can contribute to CE transition (Ranjbari et al., 2021). Therefore, it would be significant to develop and expand the current methods for the quantification of those fractions of generated waste that still end in landfills and to attempt to provide valorization solutions for them.

On the other hand, not only the general share of recovery for a detailed assessment of circularity is needed, but also the share of different valorisation options should be differentiated and weighed against each other. As a result of recently developed waste policies, the records related to WM in many national territories, including the EU, are collected and reported annually in aggregated forms. Due to the high amount of information in these databases, the current trend in their usage is focused on aggregations for national territories. Therefore, appropriate tools are required for disaggregating and presenting separated analyses for smaller regions or specific industrial sectors and to deal with the possible resulted uncertainties (Šomplák et al., 2019).

The flow mapping of waste streams is introduced in industrial symbiosis literature as "uncovering processes" (Chertow, 2007). However, flow mapping does not necessarily follow big data analysis since the movements of waste may be recorded by other tools such as directly visiting companies in small districts. In this case, it would be possible to characterize each waste stream by its precise physio-chemical composition, and further characterization may be asked from the owners (waste generators). However, in larger territories mapping the waste streams may be facilitated by using the local authorities' records. An application of this approach was published for industrial symbiosis study in Lisbon metropolitan area using coding systems for economic activities and waste categorization (Patrício et al., 2015). In Czech Republic, Šomplák et al. (2019) have studied some of the uncertainty problems from working with aggregated WM datasets in order to provide thematic maps for assessing each region's role in the production, recovery, and disposal of waste. Also, in Italy, coding systems were used for recording the possibilities of waste exchange among companies at regional scale (Cutaia et al., 2015a, 2015b; Luciano et al., 2016). The approach which was followed in these studies is based on engaging the interested companies for reporting their wastes (by-products) or potentially required resources in operative meetings for resource exchange. More recently, Van Capelleveen et al. (2021) considered the potential usages of waste classification tags to develop a matching procedure for industrial symbiosis by the provision of a thesaurus for the European Waste Catalogue (EWC) which may be a supplement tool for analysing WM databases. In vast areas a combination of statistical methods and spatial analysis may be useful in tracing the contribution of each sub-region unit to the whole system's performance and for programming the improvement actions (Richter et al., 2021). The following aspects can be regarded as areas for further scientific contribution:

- Provision of tools for analysing the regional datasets about WM considering the uncertainties in disaggregating procedures;
- Defining a set of parameters and indicators for analysing the potentials for developing CE initiatives;
- Assessing the limits of this approach and the data which should be exploited from other sources to have a comprehensive evaluation;

This paper presents a method for analysing the local WM systems and mapping the individual waste flows by defining a set of parameters which may be used as a framework for exploring the potentials for applying CE solutions. The provided tools and relevant metrics can support decision-makers at the regional and local scales to evaluate industrial areas' performance in the pathway toward circular economy.

2. Material and methods

2.1. Case study

The Province of Brescia covers an area of 4786 km^2 with 205 municipalities in the northern region of Lombardy (Italy). Brescia is an area historically known for its pioneer role in industrial recycling and recovery activities. Application of the symbiotic system for waste heat recovery from steel-making companies and also the treatment plant for recovery of energy from solid waste are important examples at the international level (Ramirez et al., 2017). In 2017, there were 119,972 companies in the province including large and medium industries, and also small artisanal units (Chamber of Commerce, 2017). In 2018, 9312 firms, mainly the larger and medium ones, reported their WM performances, with almost 40 % classified as manufacturers (ARPA Lombardia, 2020, 2021). The manufacturing system in the province of Brescia is mostly based on metal working and steel-making activities. Therefore, the main types of waste generated and managed in the province belong to these sectors. In Italy, the records of WM have been collected since the late 1990s in a system known as the Single Model of Environmental Declaration, in Italian as "Modello Unico di Dichiarazione ambientale", or MUD (ISPRA, 2019). The information derived from the database needs to become disaggregated to assess the performance of smaller geographic areas and evaluate the specific contribution from an industrial sector or a class of waste to the WM cycle.

2.2. Data collection procedure

In order to assess the data about WM for the study area, we first studied the data available in open-source platforms. The open-source data are generally available in the aggregated form at the regional scale. Some details may also be found about WM in provinces. For the municipalities as the smaller entities inside the province, it was impossible to find open-source data regarding their performance. This was also the case with smaller industrial districts. Moreover, the information about the performance of industrial sectors and various types of waste may only be found on aggregated scale. This means that the data about industrial activities was available for the first two digits of their ATECO 2007 codes (equivalent to European NACE codes). For waste categories, the information for larger waste families, the first two digits of CER codes (Catalogo Europeo dei Rifiuti) identical to ECW was available. Therefore, the first consideration for data collection was bringing more options for reconstructing the actual condition based on the following criteria:

- sector-based analysis
- zone-based analysis
- wastes type analysis

In each case, the limits and potentials in the usage of local databases and possibilities for improvement were assessed in collaboration with experts from local industrial associations. Following the preliminary assessment of the required information, the annual records on WM for the province of Brescia were requested from the regional environmental agency, ARPA Lombardia. In order to perform the analysis with better reliability, data for a 3-year period was collected. Each company, as a producer, transporter, recycler, or disposer of waste, is obligated to report its activities. Based on the content of the reports, the database is structured in five main sections with 30 interconnected lists of data (Ecocerved, 2020).

The main five sections include: (a) contact information of companies and their WM authorizations, (b) special wastes, (c) electrical and electronic equipments (WEEE), (d) packaging materials, (e) end-of-life vehicles. The section about special wastes contains seven lists which are coded as BA, BB, BC, BD, BE, Da, and DB. The mass flow model which is provided in this paper uses four files from this group. In order to provide a detailed example of the model structure, the contents of these files are introduced in Table 1.

2.3. Data analysis methods

Before disaggregating the collected data, a preliminary study was undertaken in light of insights from local authorities' annual environmental reports. A list of questions about the WM performance was prepared, which could not be answered with reference to aggregated data. This way, the targets of the data analysis were defined. These points were the followings:

- input-output mapping of the study area as a black box in order to show the relationship between the area and its surrounding regions
- mapping the WM network among the smaller elements such as sectors, districts, zones, etc. inside the area

Table 1. Characteristics of lists in MUD database which were used for the mass flow model (Ecocerved, 2020)

Lists	*Description*	*Types of presented data*
BA	Summary of individual companies' performance for each of their waste codes	Quantities of waste generation, delivery, transportation, or treatment carried out by the company on a specific waste code
BB	Delivery of waste between pairs of companies	Quantities of waste delivered between the two companies and their geographical location
BD	Disposal operations by treatment plants on each single waste code	Quantities of waste sent to disposal operations; D1-D15 (Eurostat, 2013)
BE	Recovery operations by treatment plants on each single waste code	Quantities of waste sent to recovery operations (R1-R13)

For this reason, it was decided to undertake these two targets by developing two software packages. The first package focuses on assessing the performance of the area as a black box with its input and outputs from the other regions. This will follow a mass-balance model with possibility of visualizing the same flows on geographical maps (Fig. 1). The second software package was developed for assessing WM in sub-systems such as municipalities and sectors to provide a user-friendly environment for supporting the first one in subsetting the bigger regional dataset (Fig. 2). For the first package, the collected information was imported to the R software for general data management and statistical analysis (Dayal, 2020). Data management was needed for preparing the data for further applications. Appropriate functions were defined, which provide the required flexibility for calculating the WM system's performance considering each study criterion.

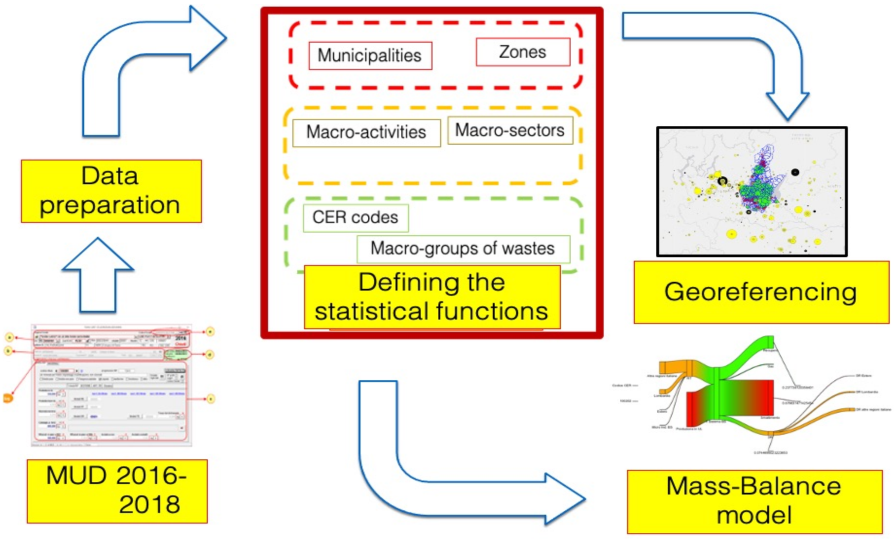


Fig. 1. The procedure for assessing the performance of the province of Brescia in waste recovery based on input-output analysis approach

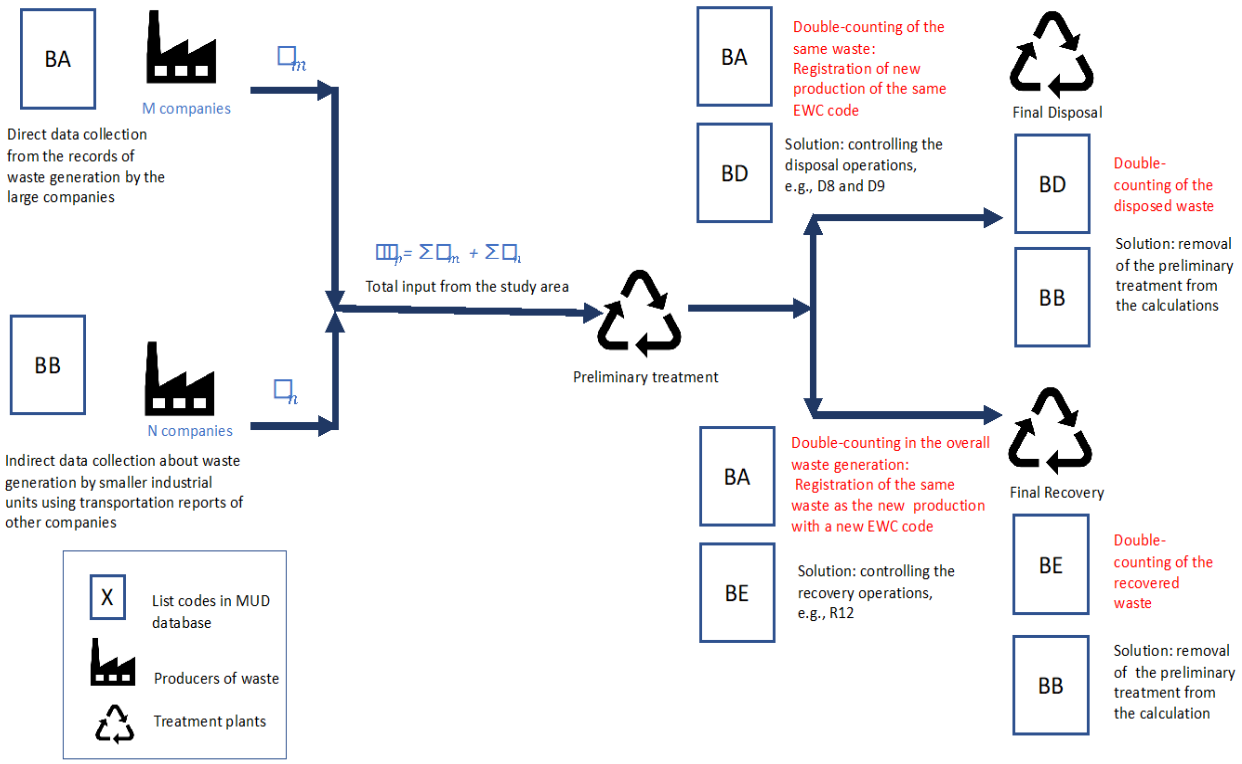


Fig. 2. Procedure for resolving uncertainty issues in the calculation of the total input of the system and assessing the destination of waste flows

The functions were defined in the form of input-out balance over the whole cycle of production, recycling and disposal. The mass flow model attempted to investigate the balance over the inputs and outputs of the WM network for each single EWC code. However, several potential sources of uncertainties existed in the database. Firstly, the treatment plant could transfer the waste after some initial treatment to a second plant. In these cases, if it underwent some changes in its physical and chemical state, the second flow may be reported as a new production by the treatment plant either with the same waste code (e.g., after a D8 operation for sludges) or with a new one (e.g., after R12 operations). Therefore, the second production report may cause a double-counting if it would be simply added to other productions. The same may occur in calculating the total treated waste if the intermediate treatments will be included in the output calculated by the model. Therefore, the model removes the double-counting cases. Moreover, there were small companies which had not to report their WM performance in the regional database according to law, while their share may be found in the BB records by waste transporters or by who received the waste for treatment. This amount of waste has also to be added as a part of the local input and differentiated from what is received from outside. An example is provided in Fig. 2, focusing on uncertainty issues and procedures for calculating input and output parameters.

The final output of the model (Fig. 4) was defined based on Sankey diagrams for evaluating the performance of the whole province as a system (Ruiz-Puente and Jato-Espino, 2020; Van Ewijk et al., 2018). The diagrams were generated by using the Sankey library of R software (CRAN, 2017). Fig. 4 shows that the total input (IN) of the system consists of two elements, waste production in the local companies and received waste from other producers (RT), which might be small artisanal units and non-industrial entities inside the province (Micro ind.). The sum of these quantities represents the system's inputs from the case study region (IN_p). The rest of the input ($IN – IN_p$) includes wastes received from companies in other provinces of the Lombardy region ($RT_{regional}$), companies in other Italian regions ($RT_{national}$), and companies outside the national territory ($RT_{internat.}$). Meanwhile, the total output (OUT) of the system consists of four main elements. Disposal (D_p), recovery (R_p), and temporal storage form the total management in the case study region (M_p). The rest of the output includes delivery of waste (DR) that may be sent to other provinces in the region (DR regional), other Italian regions ($DR_{national}$), or other countries ($DR_{internat.}$).

Comparing these parameters with the CE indicators proposed by Sánchez-Ortiz et al. (2020), four metrics were provided for assessing the CE transition in each sector or over each specific waste code:

(1) R_p/OUT = Material recovery inside the province

(2) D_p/OUT = Disposal of waste in the province

(3) $(DR_{national} + DR_{internat.})/OUT$ = Transportation of waste outside the regional boundaries

(4) IN_p/IN = Generation of specific waste in the province in total input

The presence of a potential scenario for recovery in the case study area ($R_p>0$) while the quantity of material recovery in the WM is minimal ($R_p << M_p$) can be investigated as an alerting sign from a non-technical barrier against CE transition which would need an in-depth study. For mapping the physical distances of waste exchanges, a spatial analysis was also supplemented using the open-source software tools in R and QGIS (Kaya et al., 2019). For this reason, all the industrial units in the database were georeferenced, and the records of exchange between them were translated to interactive geographical maps using libraries tmap and leaflet in R environment (Martorell-Marugán et al., 2021).

For the second part, the imported data from MUD dataset was prepared with Python. The cleaned data was then imported to a dashboard-base package in Powerbi. The software interface for this package is divided into eight main sections, i.e., (1) the hierarchical structure of activities, (2) the hierarchical structure of waste codes, (3) code search boxes, (4) text search boxes, (5) various graphical representations, (6) waste quantity, (7) geographical map, and (8) municipalities' slicers (Fig. 3).

The hierarchical structure of economic activities was used in this pocket for developing a user-friendly search tool for categorization of waste streams based on sectors. Therefore, this package provides an auxiliary tool for sub setting the data for geographical zones, industrial sectors, or waste codes of interest in a user-friendly environment (Fig. 6). The extracted data can then be imported as a small CSV file to the first tool for mass flow analyses and measurement of the WM circularity indicators.

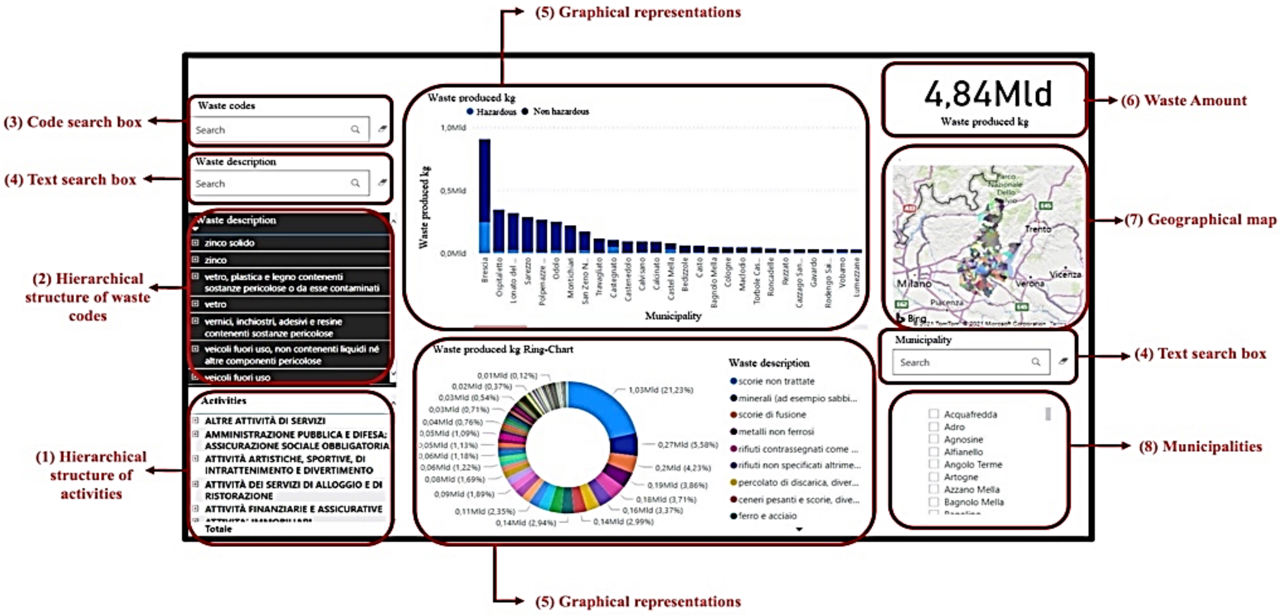


Fig. 3. The interface of the Powerbi-based tool for the analysis of WM network inside the boundaries of the province of Brescia

Validation of the proposed model was carried out following three steps. Firstly, a few specific waste streams were selected for which it was possible to get a reliable estimation for their generation based on the data about regional production or demand. For instance, considering the iron and steel production, it was possible to estimate the total generation of slags for the whole sector considering their current industrial technologies.

Regarding wastes with urban origins, such as sludge from urban sewage wastewater networks, it was possible to estimate the total generation of biological sludge by the number of inhabitants in residential areas (Rose et al., 2015; Strande et al., 2018). This way, for several cases, the numerical results obtained from the model were compared with primary evaluations in order to find the systematic errors in the software pockets.

Secondly, the results from the model were aggregated until reaching the same scale officially reported by the regional environmental agency. One of the study's objectives was to assess the current situation of the WM performance both regarding the generation of different waste codes in every single district and the treatments that those wastes received. It also became clear during the meetings with the experts of the regional environmental agencies that specific procedures were already developed for the correct interpretation of the database to obtain the relevant data for bigger aggregations. However, for smaller data fractions, it was necessary to see if the reaggregation can produce the same results.

Thirdly, in each case that the same result was not achieved, further collaboration was asked from experts of those specific sector. This opened the pathway, which includes a closer collaboration with environmental managers of single plants who gave clear descriptions of their waste types and their potential treatments and the procedure for recording relevant data. In cases that the improvement was not possible, the limitations of the approach and the requirements for further information were identified.

3. Results and discussion

The mass balance diagram for the top rank non-hazardous waste generated in the province is shown in Fig. 4. The model shows the share of material received from other regions in the total input of the system. Although the recovery parameter in this case (R_p/OUT) is smaller than the disposal, it indicates that for a significant amount of generated waste (almost 24 %), circular solutions have already been developed. Individual companies in the steel and iron sector which produced the same waste code could compare their performance to the overall performance of the relevant sector.

While for non-hazardous waste the province developed a considerable capacity in circular business models, the same diagram for hazardous waste shows little potential in recovery and respectively higher ($DR_{national}$ + $DR_{internat.}$)/OUT (Fig. 5). A comprehensive graphical description of the material flows was also prepared for following the circulation of each waste code toward and outward the province of Brescia. The map presented in Fig. 6 shows the geographical distribution of the elements of WM network for waste code 110105*.

The details of the current WM practices in different municipalities are presented in Fig. 7. The main types of waste produced in the province were also identified in a disaggregated manner. Therefore, it would be possible to find matching scenarios for their reuse in other symbiotic relations.

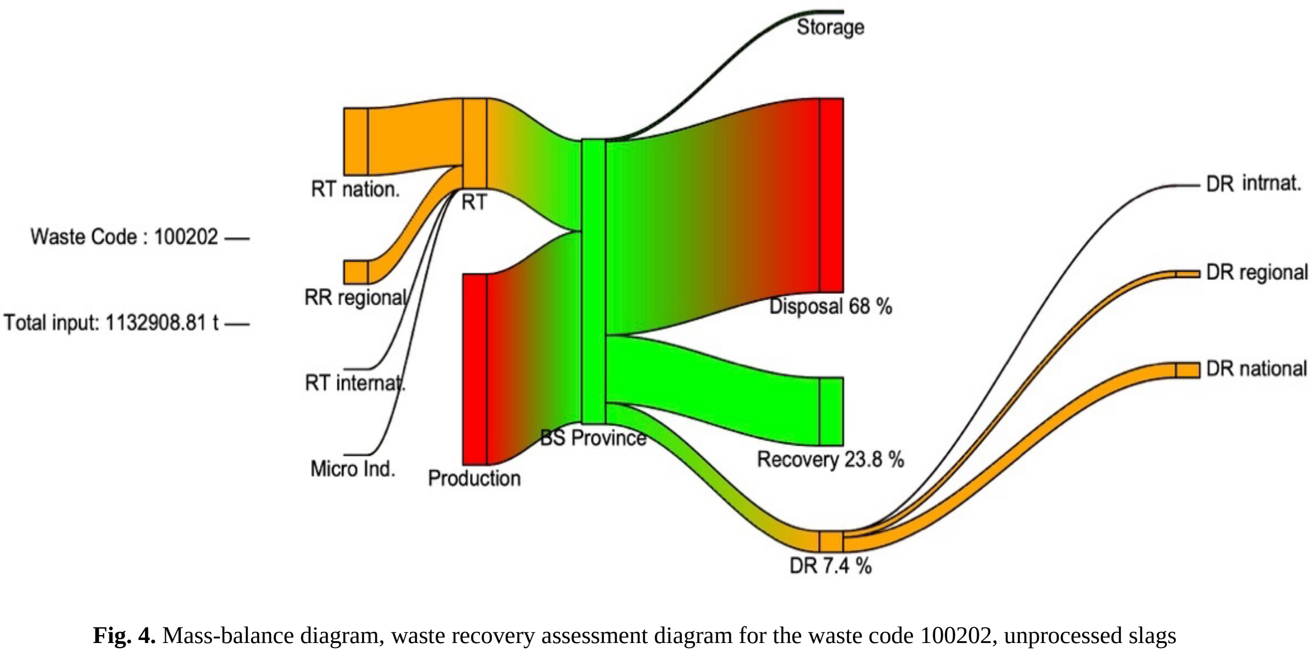


Fig. 4. Mass-balance diagram, waste recovery assessment diagram for the waste code 100202, unprocessed slags as the top rank non-hazardous waste produced in 2018 in the province of Brescia (BS)

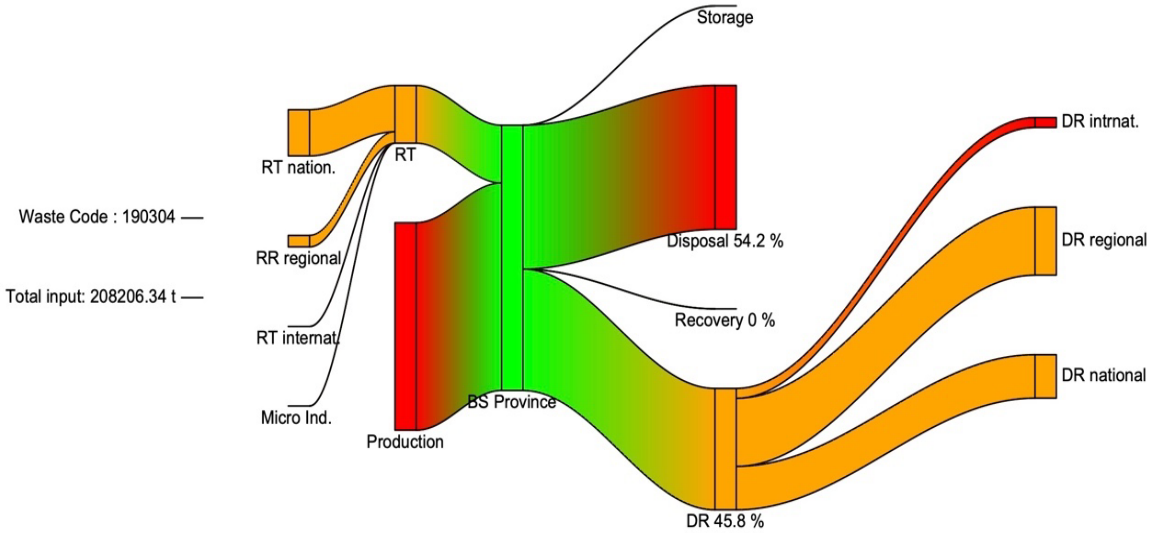


Fig. 5. Mass-balance diagram, Waste recovery assessment diagram for the waste code 190304*, as the top rank hazardous waste produced in 2018 in the province of Brescia

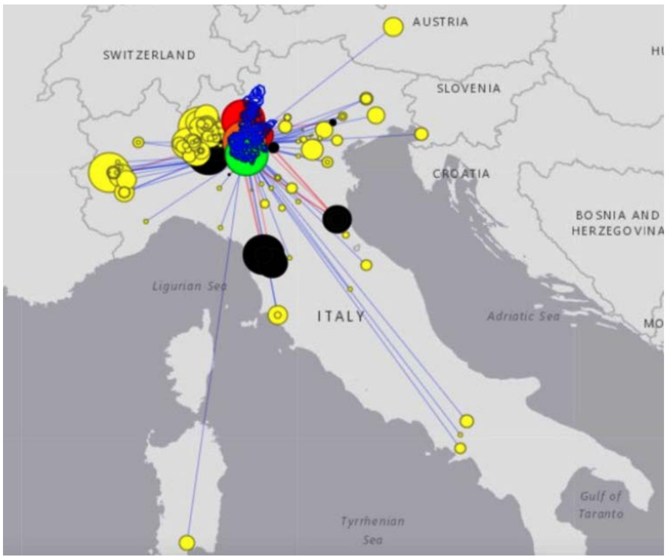


Fig. 6. Mapping the network of waste exchange for waste code 110105*

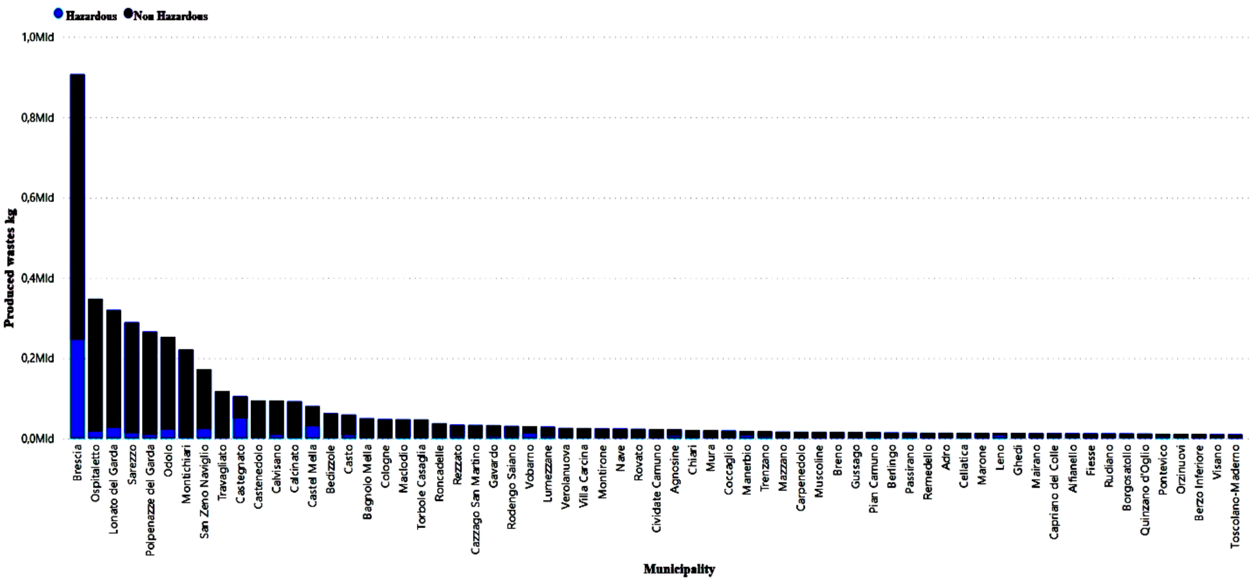


Fig. 7. Performance of the individual municipalities in the study area in generation of wastes

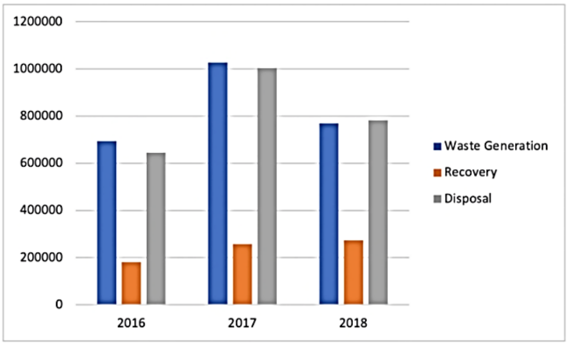
It was also found that other datasets should be integrated into the current model to make a more precise vision about the share of the companies out of the obligation for reporting waste generations, e.g., their NACE codes. Their total share in waste generation is relevant to the type of waste and may vary considerably from a code to another. However, these small firms' waste may be more suitable for recycling regarding the quality of material and purity. Therefore, the need for deepening the assessments for those industrial units is a limit of the current model even if their share has been estimated and reported as a separate group, as micro industries, based on the available information (Fig. 2).

Consideration must be made regarding some waste codes. The interpretation of the waste codes' content in terms of chemical composition and the origin of the wastes is not very simple. This is a totally different problem from the provision of verbal description for waste codes which has already been studied. For example, at present, a considerable amount of waste codes produced in the study area are those in CER families 19 and 17. However, these are mainly waste produced from secondary activities, or in other words, from the treatment of other waste codes; therefore, they may be very diverse in nature from one industrial unit to another. These groups of waste, in many cases, are landfilled or send to a farther destination for being treated. Therefore, from the environmental point of view, their recycling inside the province will result in significant benefits. However, the cost of their separation in the current situation would make it not feasible from the economic point of view. Therefore, the priority for symbiosis planning based on these results should be given to inert or non-hazardous codes and those with homogenous composition.

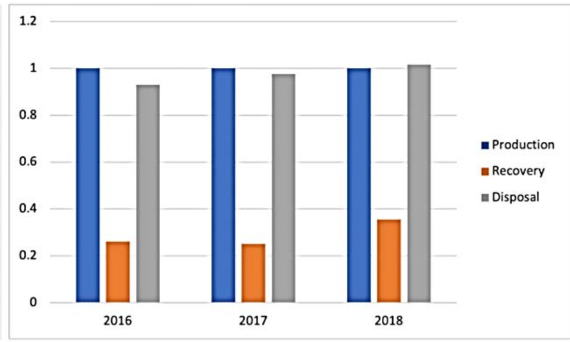
Another source of uncertainty is regarding the quantitative assessments based on annual studies. For this reason, the top-ten non-hazardous waste codes from the Powerbi-based data package were extracted and imported to the R studio mass-balance program. Comparing the performance of the study area for these waste codes in a three-year period shows little difference in the general trends of WM by normalizing the quantities for one unit of generated waste (Fig. 8b); however, the annual amount of generation and disposal may vary considerably (Fig. 8a).

This factor and the anomalies in waste amount was discussed further with the experts from the regional environmental agency and industrial experts in the province. One of the main reasons for this trend could be the entrance of unprecedented massive flows from temporary sources to the network, such as remediation activities in the ex-industrial sites. Therefore, such fluctuations in the input should be considered as a supply chain problem for CE businesses that want to consume the wastes as their principal resource.

A minimum baseline can be defined as the guaranteed amount of resource for symbiotic exchanges based on a historical study on waste generation and landfilling trends.



(a)



(b)

Fig. 8. Uncertainty analysis of WM performance for the first rank waste CER code, 100202 slags not treated, in the period 2016-2018 (a) the quantities of waste in tonnes (b) normalized situation based on one unit of waste generation

4. Conclusions

This study has provided tools for assessing WM at regional scale and parameters for evaluating CE transition by using big data analysis. The mass-balance model showed potentials for decision-making and identifying CE potentials such as industrial symbiosis by valorisation of specific waste streams to bring more effective environmental benefits to the whole system.

After removing double-counting cases and uncertainties, the output of the tools was used for assessing two parameters which already considered as relevant CE indicators, i.e., the share of the material recovery in total WM output (R_p/OUT), and the landfilling tendency (D_p/OUT) for specific waste flows and industrial sectors. The flows of non-hazardous wastes with minor recoveries ($M_p >> R_p > 0$) were also selected for conducting in-depth studies to understand the possible barriers against the expansion of CE. Moreover, using the NACE codes for aggregating the performance of similar units, it became possible to compare the circularity in the production for every single company against the overall performance of its relevant local sector.

The study area showed two main behaviours in applying CE solutions in WM. The considerably high amounts of (R_p/OUT) in managing non-hazardous wastes demonstrated promising potentials. However, the management of hazardous wastes still needs improvement since the ($DR_{national}$ + $DR_{internat.}$)/OUT and (D_p/OUT) were very high for this category.

It should also be noted that the concept of circular economy is broader than recycling, and the parameters which we reported covers partially this task. One of the important limits of this method is the uncertainty about the quality of waste streams with the same code which come from different treatment plants. Therefore, the homogeneity of waste streams needs to be evaluated and added as another indicator to the final analysis.

An essential element in the original dataset is the role of smaller companies and non-industrial entities whose generated waste enters the system. Further insights might be required for characterization of waste streams from this type of input, i.e., data provision from other sources.

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