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Waste hierarchy index for circular economy in waste management

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ABSTRACT

The aim of current European Union waste management directives is to promote prevention of waste and the application of a waste management hierarchy: preparing for reuse, recycling, other recovery, and disposal. The Waste Framework Directive only measures the waste operations recycling, incineration, and landfill individually, not measuring the implementation of the waste hierarchy principle in Member States of the European Union. The present study proposes a waste hierarchy index (WHI) to measure the waste hierarchy within a circular economy context, applied to municipal solid waste. In developing the WHI, recycling and preparing for reuse, as defined by Eurostat, were considered as positive contributors to the circular economy, and incineration and landfill as negative contributors. The WHI was applied at different geographic scales (local and national levels) to verify its potential and limitations. The WHI is a direct and concise indicator that provides a holistic perspective on how waste is being managed. The WHI is more than a source of waste statistics; it is the beginning of a real discussion about how waste statistics should be managed to reach a circular economy through the implementation of waste hierarchy.

1. Introduction

The waste hierarchy principle has existed for approximately 40 years. According to van Ewijk and Stegemann (2016), the concept originates in prioritizing reduction, recycling, and reuse of waste over treatment or disposal, having been started in the United States by the private company 3M (Overcash, 2002) and in Europe by the Dutch politician Ad Lansink, who proposed it in the Dutch Parliament in 1979 (Parto et al., 2007). In 2008, the waste hierarchy principle was included in the Waste Framework Directive 2008/98/EC (WFD) (European Parliament and Council, 2008) and was subsequently transposed into the national law of European Union (EU) Member States. The European WFD defines the waste hierarchy as the priority order of operations to be followed in the management of waste: prevention, preparing for reuse, recycling, other recovery (including energy recovery), and disposal. In 2015, the Circular Economy Strategy from EU COM/2015/0614 (EU Commission, 2015) defended the role of waste management based on a waste hierarchy as the way to lead to the best overall environmental outcome and to get valuable materials back into the economy. Hultman and Corvellec (2012) reinforce the same potential of waste hierarchy, highlighting the ability of recycling sites to transform material that can be recovered, and circulated, performing the "unblackboxing" of material management. In 2016, waste hierarchy was included in the 12th Sustainable Development Goals (SDG) of the 2030 Agenda for Sustainable Development adopted by the 193 United Nations countries (UN, 2016) named "Responsible consumption and production": "by 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse".

Waste hierarchy has been contemplated in the international and national regulations, although there is no indicators for its implementation. The existing indicators were intended to quantify the performance of specific waste operations: source separate collection and recovery and recycling rates, with targets defined in European Union waste directives. According to Price and Joseph (2000), the recycling rate is the most widespread indicator, being straightforward to quantify and capable of demonstrating movement up (or down) the hierarchy. Recycling rate issues and limitations have been pointed out in the literature. Haupt et al. (2017) highlighted that national recycling rates of European countries do not share the same definition; this concern was pointed out in the Circular Economy Action Plan (EU Commission, 2015) where the EU intends to harmonize the definition of recycling rate. The recycling rate fails for not being calculated to address closed-loop recycling (re-recycling, up-cycling) from open-loop recycling (down-cycling). This is problematic because open-loop recycling

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is applied to situations where recovered secondary material is used in products of lower quality (Haupt et al., 2017), reducing products lifetime in the economy. The circular economy (CE) requires intensive and constant products cycles (as occurs in up-cycling as opposed to down-cycling (Dieterle et al., 2018) which are not being addressed by the current recycling rate. Another issue with the recycling rate is that it can be of high level, but the way that the rest of the waste operations are handled is not clear. Waste management systems can be built to have high recycling rates and, simultaneously, high incineration rates or high landfill rates. This is not in accordance with what is expected from applying the waste hierarchy principle. Iacovidou et al. (2017) pointed out that the recycling rate alone is not capable of measuring the overall waste management quality, efficiency, and sustainability. The recycling rate can show the waste re-entering the economy, although it is incomplete. The recycling rate is a segmented indicator, requiring other indicators related to other waste operations to give a clearer view of waste hierarchy implementation. The missing holistic view in the recycling rate does not allow to measure the level of the waste hierarchy, and is not capable of giving the performance of waste sector in promoting CE. As has also been pointed out, the recycling rate cannot assess CE in waste sector, being considered a misleading indicator that has contributed to poor decision making and to poor innovation in the industry (Di Maio and Rem, 2015). Prevention of waste is the most important waste management step and should be monitored, however, that is not the case, due to the difficulty in measuring something that it is not there (Zorpas and Lasaridi, 2013). An indicator for reuse has also been proposed by Fortuna and Castaldi (2018) to assess the impact of reuse organizations to waste prevention in New York City, named Reuse Impact Calculator. The difficulty in measuring waste prevention and reuse is a possible justification to indicators being focused on recycling rate. The Material Circularity Indicator developed by Ellen MacArthur Foundation and Granta Design (2015) is an attempt to include the waste hierarchy in the development of products by including the amount of recycled materials and reused components, as well the destination after use and the recycling efficiency, although is not applicable for waste management systems.

A recent attempt to measure waste hierarchy implementation has been made through the use of the Ternary Diagram method (Pomberger et al., 2017). The Ternary Diagram method is only a visual tool to allow the simultaneous observation of three rates: recycling rate, incineration rate, and landfill rate. The method is not capable of influencing European waste legislation as an indicator could, which is to be included in regulation documents. Neither can the Ternary method give indications that the waste hierarchy applied is also respecting the mass conservation concept inherent in the Circular Economy Action Plan (EU Commission, 2015): CE occurs when "the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized" in such a way so as to "develop a sustainable, low carbon, resource efficient and competitive economy."

In this study, it is argued that existing indicators do not lend themselves to determining waste hierarchy implementation levels in quantitative and holistic ways, and one of the aims here is to close this gap. To do so, the waste hierarchy index (WHI) is presented, an indicator developed to reflect the waste hierarchy using CE principles that are comparable and quantifiable. The WHI considers all waste operations, as well as different types of recycling and incineration processes, supporting the mission and purpose of CE. The WHI was tested at national and local geographic levels, in European countries and in Portuguese municipalities, respectively. A broad discussion of the implications of the indicator to waste operations is presented based on the results.

2. Materials and methods

2.1. The waste hierarchy index formulation

When considering how the implementation of the waste hierarchy principle could be measured, the available data was analyzed to identify what was possible to be quantified. The question asked was the following: looking at the definition of the waste hierarchy principle and the order of the operations, can a formula be proposed to measure waste hierarchy implementation in the light of the CE? The challenge was unique, and to do it was applied the methodology in Fig. 1.

2.1.1. Selection of waste operations

Different waste hierarchy operations make different contributions to CE: preparing for reuse, up-cycling, re-recycling, down-cycling, composting/anaerobic digestion from source-separate collection, biological treatment from mixed collection, waste-to-energy (WtE), incineration without energy recovery, and landfill. The selection of waste operations considering the different role in promoting CE is done in this step.

2.1.2. WHI formulation

In this step of WHI formulation, the intention was to propose an index that could relate available waste operations and in which their potential to empower CE is considered in the formulation. The methodology to measure the waste hierarchy in the light of the CE was to consider as "pure" CE the preparing for reuse, up-cycling, re-recycling, composting and anaerobic digestion, the last two from source separation. The resulting products that were re-introduced into the economy were assumed to be quality products. In cases of down-cycling, biological treatment from mixed waste and WtE, the formula considered that it can only partially contribute to CE, and that partial contribution is represented by coefficients that are put into the formula on those waste operations. Incineration and landfill were considered as not being CE operations, because once materials are sent to those destinations, they cannot be reintroduced into the economy as materials to be applied in other products. These assumptions are in line with van Ewijk and Stegemann (2016), where the backbone of the CE is 'reuse and recycle' to ensure closure of materials and energy loops

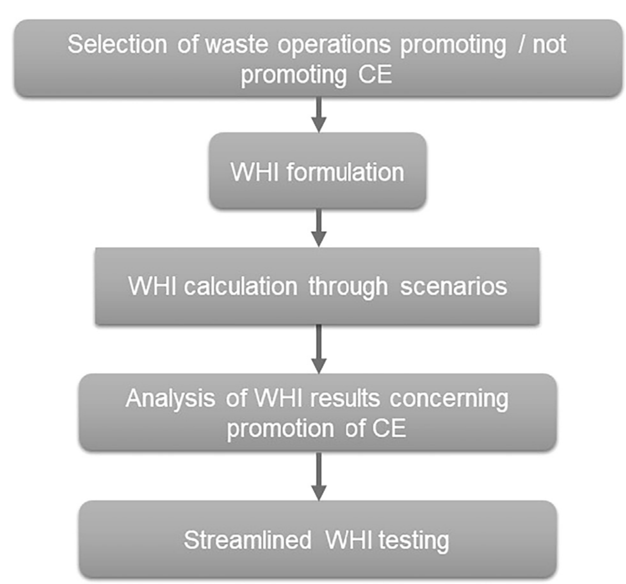

Fig. 1. Methodology used to develop the WHI.

(cycles), to provide regenerative use of resources, with incineration and landfill being undesired because they represent leakage from the industrial system. MacArthur (2015) also affirms that incineration of waste gives no additional benefits for CE. Potting et al. (2017) mentions that incineration with energy recovery should be the lowest priority in a CE, because materials are no longer available to be used again in products. Municipal solid waste (MSW) incineration contributes to metal recycling, which reintroduces metal into the economy, and WtE technology provides energy to the economy (Haupt et al., 2017). However, the energy recovered by incineration can only be used once, which limits the circularity of materials in the economy. Incineration (with and without energy recovery, dedicated or in co-incineration) kept as contrary to the CE needs to be discussed to avoid situations such as that of Denmark, which has an overcapacity of incineration installations and is importing waste to keep these units running (Cimpan et al., 2015). The treatments promoting the CE have a weighting factor of '1', whereas all the others that do not support CE are weighted as '−1'. With this weighting, the WHI can affect negatively the operations that provide little or no material reintroduction into the economy, and which are not promoting a CE. The formula used to calculate the WHI applied to MSW is

$$WHI = \frac{[(1((PR + UpR + RR + CAD) + aDR + bBT + cWtE)) + (-1((1-a)DR + (1-b)BT + (1-c)WtE + I + L))]}{Total\ \ waste\ \ treated} \times 100,$$

where *PR* is preparing for reuse; *UpR* is up-cycling; *RR* is re-recycling; *CAD* is composting and anaerobic digestion from source separation; *DR* is down-cycling; *BT* is biological treatment of mixed/residual MSW; *WtE* is incineration with energy recovery (in accordance with WFD efficiency level); *I* is incineration without energy recovery (in accordance with WFD efficiency level); *L* is landfill; *a* is the contribution level of down-cycling to the CE (varies between '0' and '1'); *b* is the contribution level of BT to the CE, and it ranges between '0' and '1'; and *c* is the contribution level of WtE to the CE (ranges between '0' and '1'). Incineration includes dedicated incineration and co-incineration. The data used was for waste mass, wet basis. In this formula, total waste treated is used instead of total waste generated, to ensure that the balance is closed. The waste generated may not be totally treated, not having both the same amount in the Eurostat; the amount of waste treated corresponds to the total amount of waste sent for the different treatments. Although Eurostat may refer to recycling as "material recycling," such definition does not exist in the Eurostat glossary (Eurostat, 2018), which uses the term "recycling." The definition of "preparing for reuse" cannot be found in the Eurostat glossary (Eurostat, 2018), and the corresponding data are missing from the Statistics Portugal (Statistics Portugal, 2018) and Eurostat databases. The existing definition occurs in the WFD: " 'preparing for reuse' means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing" (European Parliament and Council, 2008). For some waste streams, as is the case of waste electrical and electronic equipment (WEEE), "preparing for reuse" is included in the targets for recovery and recycling, but the term is not statistically defined. Without a specific definition, there are no data available to characterize it. The values of the WHI vary between −100% and 100%. A WHI of −100% reflects that the waste hierarchy is not being implemented in a way that could promote a CE, while a WHI of 100% represents the opposite case, when all MSW is sent to CE operations exclusively.

2.1.3. WHI calculation through scenarios

There is no information available at Eurostat, which is the database of reference for waste operations for EU, to calculate WHI for each Member State and also at European level. For these reasons, two scenarios were considered to examine the WHI:

Scenario 1. Variables *a*, *b*, and *c* are all equal to 0.5; WtE, down-cycling and BT recycling operations have a moderate contribution to CE.

Scenario 2. Variables *a* and *b* are equal to 0.8, and *c* is 0.2; the input of down-cycling and BT increases slightly; and WTE makes a small contribution to the CE.

Using Eurostat data, the "material recycling" was divided into three types: up-cycling, re-recycling and down-cycling. Composting/anaerobic digestion was split in two, considering half from source-separated and half from mixed collection. Preparing for reuse was considered zero, not being removed from the recycling amount.

2.1.4. Analysis of WHI results

The developed scenarios were tested using Eurostat data to assess the WHI in European countries. The indicator used by European Commission to assess how waste is being managed is recycling rate. A comparison will be conducted between WHI (scenarios 1 and 2) with recycling rate. The data used were sourced from Eurostat (https://ec.europa.eu/eurostat/web/environment/waste). WHI was compared to the recycling rate, and implications to the several waste operations were addressed.

2.1.5. Streamlined WHI testing

The WHI could not be applied using the available data from Eurostat because data is not available to fill all the waste operations defined in the formula. Scenarios would be needed, however, scenarios are not always an adequate procedure in practical situations. The stakeholders of waste management might question the CE considerations made to waste operations and the coefficients assumed. For these reasons, and to make the data available for use without adaptations to individual situations, a streamlined WHI was proposed:

$$WHI = \frac{[(1 \times (Preparing\ \ for\ \ reuse + Recycling + Composting/Digestion)) + ((-1 \times (Incineration + Landfill)))]}{Total\ \ waste\ \ treated} \times 100$$

where definitions of "recycling", "composting", "incineration", and "landfill" are the ones used by Eurostat. The streamlined WHI was adapted to use data available in Eurostat (https://ec.europa.eu/eurostat/web/environment/waste) for European countries and data available at Pordata database (https://www.pordata.pt) for the municipal level in Portugal. Pordata is a Portuguese database devoted to publish statistics on Portuguese society, where waste management is included. Data available at Eurostat and Pordata was for composting/digestion together, which includes anaerobic and aerobic decomposition resulting in a product used on land or for growing media or substrate, recycling (any recovery option through which waste is reprocessed into products), incineration (includes WtE and combustion processed with and without energy recovery), and landfill (the disposal of waste at land and specific sanitary landfills). The streamlined WHI was tested to verify its effectiveness comparatively to the WHI.

3. Results and discussion

3.1. Descriptive analysis of the results

3.1.1. Waste hierarchy index: European countries case study

The WHI was calculated for the 28 Members States of the European Union (EU-28), and Iceland, Norway, and Switzerland, using Eurostat data, year 2014 (see A1). The calculation results are presented in Table 1 and Fig. 2 (example of calculation is presented in A2). In general, the EU-28 has a WHI between −4% and −9%, a negative index, indicating that the waste hierarchy is not being implemented correctly in a way that could promote the CE. Only 11 countries have a positive WHI (above 10%) at least in one scenario (alphabetically): Austria (29%), Belgium (31%), Denmark (26%), Estonia (16%), Germany (29%), Luxembourg (14%), the Netherlands (27%), Norway (23%), Slovenia (12%), Sweden (30%), and Switzerland (32%). The reason for this result is the high recycling rates (Eurostat, 2019) that those countries presents (above 42%), being Estonia and Slovenia two exceptions. The other countries have low or negative indexes, at east in one scenario, with the most extreme values of the WHI belonging to Greece (−74%), Malta (−86%), Romania (−74%), and Slovakia (−74%), countries with low recycling and high landfill of MSW (landfill rates are presented in A1).

Not all countries with high recycling rates have high WHI. Italy and United Kingdom (UK) presents recycling rates of 42% and 43%, similar to Denmark, although the WHI are negative for both scenarios. This is explained by the amount of waste sent for landfill in the both countries presented in A1, 34% and 29% respectively, whereas Denmark has a landfill rate of 1%, being most of waste in Denmark send to WtE.

The results indicate that WtE affects waste hierarchy implementation. Countries perform better in scenario 1 (where WtE, DR, BT have the same contribution to CE, 0.5) except Slovenia and Germany which are better in scenario 2 (where WtE has a low contribution to CE comparatively to the other options, 0.2). The result is justified by the amount of waste sent for recycling by both countries comparatively to incineration and landfill (in respect of the total waste treated, the recycling rate of both countries is 66% for Germany and 61% for Slovenia, presented in A1). In scenario 2, the countries with WHI above 10% are 7 of the previous 11 countries: Austria (22%), Belgium (18%), Germany (31%), the Netherlands (12%), Slovenia (12%), Sweden (11%) and Switzerland (17%), which reflects the Member States that are sending most of the waste for recycling, although the different types of recycling are considered. The considerable reduction of WHI (above 15% of reduction from scenario 1 to scenario 2) to the Netherlands, Denmark, Estonia, Norway, Sweden and Switzerland shows their

Table 1
Scenarios to calculate the WHI and streamlined WHI (year 2014).

Country	WHI Scenario 1	WHI Scenario 2	Streamlined WHI	Recycling rate (Eurostat, 2019)
Germany	29%	31%	32%	66%
Slovenia	−1%	12%	21%	36%
Austria	29%	22%	17%	56%
Belgium	31%	18%	9%	54%
Netherlands	27%	12%	2%	51%
Sweden	30%	11%	−1%	50%
Luxembourg	14%	3%	−5%	48%
Denmark	26%	4%	−10%	45%
Italy	−7%	−9%	−10%	42%
United Kingdom	−2%	−8%	−11%	43%
Ireland	5%	−7%	−16%	40%
France	−2%	−13%	−20%	40%
Estonia	16%	−9%	−26%	31%
Finland	2%	−20%	−35%	33%
Hungary	−39%	−38%	−38%	31%
Lithuania	−41%	−39%	−38%	31%
Spain	−39%	−39%	−38%	31%
Portugal	−31%	−36%	−39%	30%
Latvia	−54%	−49%	−46%	27%
Poland	−45%	−46%	−47%	27%
Czechia	−40%	−28%	−49%	25%
Bulgaria	−58%	−54%	−51%	23%
Cyprus	−70%	−66%	−64%	17%
Croatia	−72%	−68%	−66%	17%
Greece	−74%	−71%	−69%	15%
Romania	−74%	−72%	−70%	13%
Slovakia	−69%	−74%	−77%	10%
Malta	−86%	−85%	−84%	7%
EU-28	−4%	−9%	−11%	43%
Switzerland	32%	17%	7%	54%
Norway	23%	1%	−14%	42%
Iceland	−52%	−45%	−41%	30%

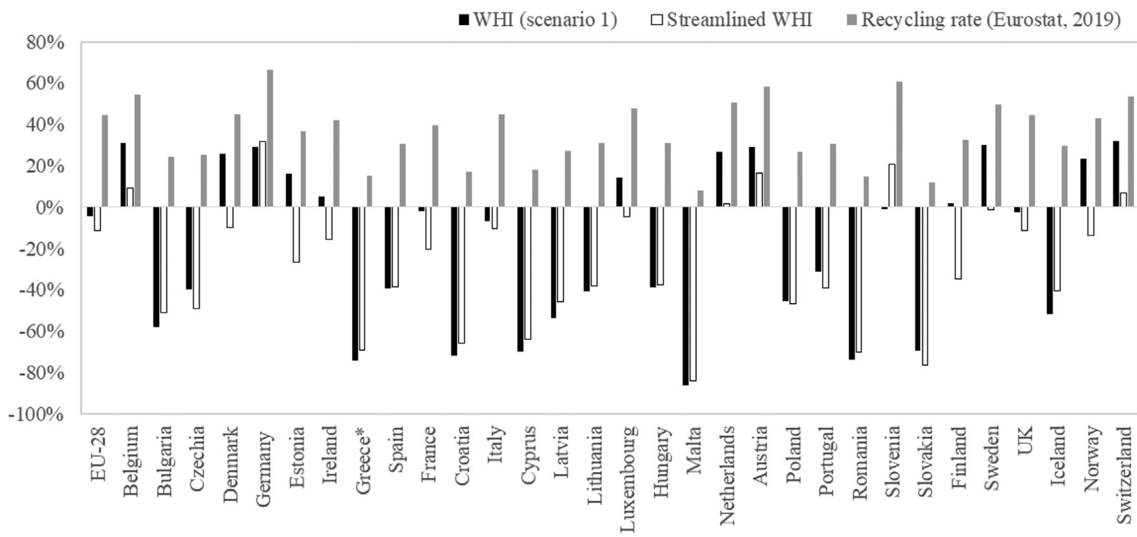

Fig. 2. Comparison of WHI (scenario 1), streamlined WHI and recycling rate (year 2014).

dependence from WtE (at least 46% of incineration rate as presented in A1), which is not in accordance with the waste hierarchy principle of WFD.

3.1.2. Streamlined waste hierarchy index: case study from European countries

Looking at Table 1, in general, the EU has a streamlined WHI of −11%, indicating that the waste hierarchy is not implemented correctly in a way that could promote the CE (the calculation of streamlined WHI is on A3). Only six countries have a positive streamlined WHI: Germany (32%), Slovenia (21%), Austria (17%), Belgium (9%), Switzerland (7%), and the Netherlands (2%). The positive results are mostly related to a high amount of waste going to recycling and moderate incineration. The other countries have negative indexes, with the most extreme values of the streamlined WHI belonging to Malta (−84%), Slovakia (−77%), and Romania (−70%), all countries with low recycling and high landfill of MSW.

By comparing streamlined WHI with recycling rates, it can be seen that the recycling rates are higher (and more positive) than the values of the streamlined WHI, so decision-makers may interpret their performance as adequate, which is not the case for implementation of the waste hierarchy principle. The streamlined WHI reflects better the missing waste materials that are not reintroduced into the economy, revealing more information about how waste is being managed than would the recycling rate alone. The streamlined WHI and recycling rate indicators have similarities, as proven by Pearson coefficient 0.957 (p = 0.000) and Spearman Rank coefficient 0.965 (p = 0.000), and justified by use of the same data in the calculation (amount of waste sent for recycling).

The streamlined values reveal the massive contribution of incineration (including WtE) to the management of waste, which constitutes a threat to the CE becoming a reality. The recycling rate indicates that the amount of waste reentering the economy, but not the waste that is left behind by landfill and incineration. The countries with the highest recycling rates are Germany, Austria, Belgium, Switzerland, the Netherlands, Sweden, Luxembourg, Denmark, and the UK, whose recycling rates are all above or equal to the EU-28 recycling rate of 43% (Eurostat, 2019). Slovenia, which has a high streamlined WHI, is excluded from this group (Eurostat uses waste generated in the denominator of recycling rate formula and not waste treated, the one used for WHI (scenarios and streamlined)), and the options taken by Slovenia to avoid incineration can only be highlighted by the WHI and the streamlined WHI. In countries with high recycling rates, namely Belgium, Denmark, Luxembourg, and Netherlands, the presence of massive incineration is only indicated by the WHI and streamlined WHI, which reflects the negative choices of these countries relative to promoting a CE.

3.1.3. Streamlined waste hierarchy index: Portuguese municipalities case study

The calculation results of the streamlined WHI for Portuguese municipalities are presented in Fig. 3 for 2002 and 2015 (data is presented in A4, from Pordata (2018)). The scale presented in Fig. 3 was made at the web platform where the WHI is working (https://www.pordata.pt). One of the main findings are the negative results of the streamlined WHI for both years, highlighted by the negative scale, meaning that the waste is mostly sent to destinations for action at the bottom of the waste hierarchy: incineration and landfill.

In 2002, the WHI was −84.6%, mostly due to MSW going to landfills; in 2015, the WHI rose to −37.9% (Pires and Martinho, 2016). The improvement is notable, although Portugal cannot be classified as a country implementing the waste hierarchy in practice. The evolution from 2002 to 2015 is due to a decrease of the waste going to landfill through the increasing amount of MSW going to composting, anaerobic digestion and to recycling. The composting and anaerobic digestion are done in existing units performing composting/anaerobic digestion in the mechanical biological treatment (MBT) units. In continental Portugal 17 MBT units exist, four composting plants and one anaerobic digestion plant (the four composting plants and the anaerobic digestion plant receive source-separated biodegradable municipal waste or green waste). The Autonomous Region of Madeira has a composting plant for source-separated biodegradable municipal waste, and the Autonomous Region of the Azores operates nine composting plants for mixed MSW, one of them being a vermicomposting plant (RAA, 2018). In 2002, the amount of MSW sent for composting or anaerobic digestion was 134,714 t, and in 2015, was 745,506 t (Pordata, 2018). The recycling amount was also significant, being mostly from source separation of packaging waste: in 2002, the recycling amount was 212,665 t, and in 2015, 677,771 t (Pordata, 2018). Looking to the municipalities, the highest streamlined WHI reached in 2002 was 9.2% for Porto Moniz (Autonomous Region of Madeira), where a small composting plant is located, followed by zero for the Setúbal municipality, where one MBT is located. The lowest streamlined WHI (−100%) occurred in nine cities located in the northern region of the country and the Autonomous

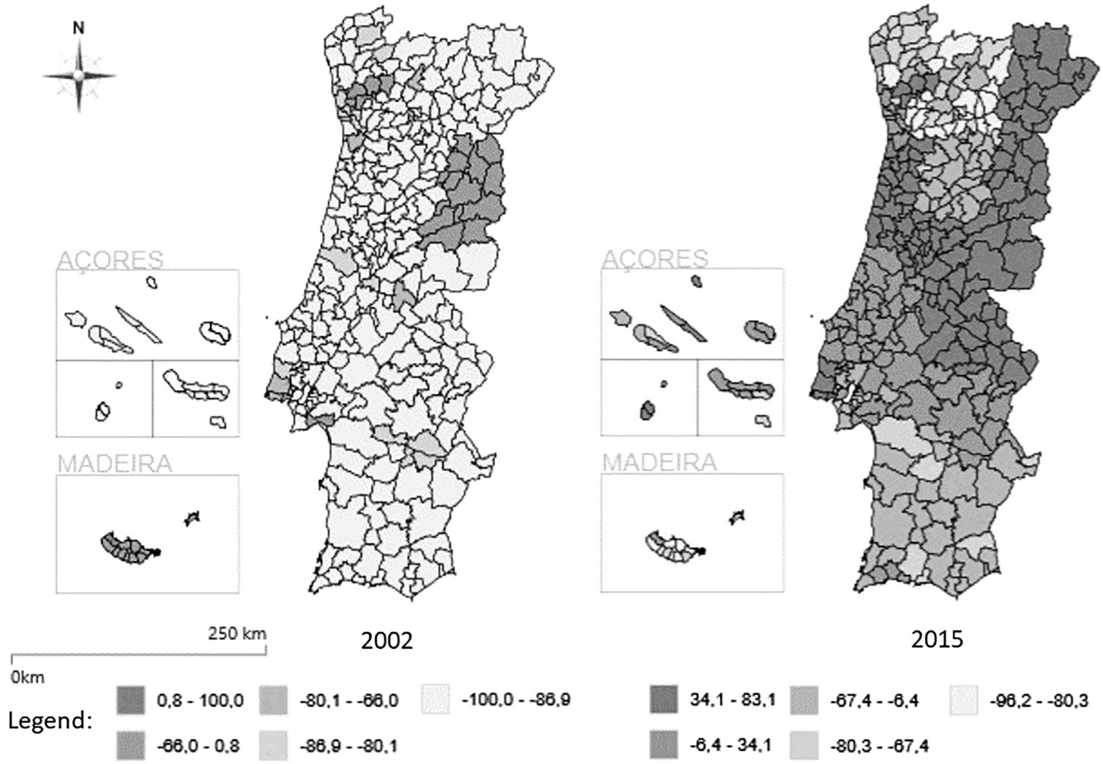

Fig. 3. WHI for Portuguese municipalities in 2002 and 2015 Source: adapted from Pires and Martinho (2016).

Region of the Azores. MSW sent to landfills led to a WHI of −100% in these cities.

In 2015, the cities Lajes das Flores and Santa Cruz das Flores (the Autonomous Region of the Azores) and the Vizela municipality (northern region) had the highest streamlined WHI (83.1%, 73.3%, and 71.6%), mostly due to sending waste for composting treatment and using source separation of packaging waste. The cities with the lowest WHI were Câmara de Lobos (Autonomous Region of Madeira), Mesão Frio, and Murça (northern region), with values of −96.2%, −96.1%, and −95.2%, due to sending of MSW to landfills.

Comparing the results from 2015 to the indicator recycling rate, the three Portuguese municipalities with the highest recycling rates are the same ones as those with the highest values of streamlined WHI and in the same order: Lajes das Flores (92%), Santa Cruz das Flores (87%), and Vizela (86%), showing that the resolutions to manage waste were based on recycling operations. In the cases where incineration occurs—Lisbon, Oporto, and Funchal cities—the streamlined WHI is low compared to their recycling rates. Lisbon presents a recycling rate of 24% and a streamlined WHI of −52%; Oporto has a recycling rate of 33% and streamlined WHI of −33%. Funchal already has a low recycling rate of −3%, which validates the result of the streamlined WHI of −94%. If those municipalities had opted for MBT instead of incineration, their streamlined WHI would be 67% for Lisbon, 100% for Porto, and 97% for Funchal. The streamlined WHI considered alone is capable of correcting the bias of the recycling rate, reflecting correctly the level of waste hierarchy implementation in the municipalities.

3.2. Final remarks on the WHI and streamlined WHI

The usefulness of the WHI is dependent on three factors: data availability, importance of waste operations contributing to CE, and waste streams in the municipal waste. The data availability depends on the rules established by Eurostat concerning the waste operations to be reported, and those rules are dependent on EU waste Directives. If there is no legal interest in defining targets for preparing for reuse and the different levels of recycling (upcycling, re-recycling and down-cycling), the application of the WHI can be limited. Testing the streamlined WHI helped to reduce the issue of data availability, while keeping the conclusion the same as with the WHI— higher WHI results from higher amounts of waste sent to operations that could improve CE (recycling, composting and anaerobic digestion). The data available from Eurostat and Pordata could also be improved, thereby meliorating the results reached so far by the streamlined WHI.

Concerning the importance of waste operations (types of recycling, biological treatment and incineration) from the waste hierarchy that are contributing to the CE, a question arises: how will those operations be evaluated? A possible method could be by the number of times that waste can be recirculated in the economy, which reflects the quality of recyclables and energy recovery issues.

In the case of the quality of recyclables (compost, plastic, paper), the quality of those materials from source-separated collection is higher than that from mixed/residual waste because the contamination occurring during collection is avoided. A higher quality will increase circularity of materials in the economy. Materials quality difference is highlighted in the Best Available Techniques Reference Document for Waste Treatment in the section on MBT (JRC, 2017), where it is mentioned that the quality of output (from mixed/residual waste) is generally not acceptable for widespread use because of its heavy metals and inert contents. For this reason, the European Commission Guidance on Municipal Waste Data Collection (EU Commission, 2017) defines that only biological treatment of separately collected organics shall be reported under composting (i.e., under recycling). The circularity of waste in the economy is dependent on the nature and composition of waste, which depends on the type of collection (source separated or mixed) and on the technology available for treatment. For collection, the WHI can improve the source separation of waste by highlighting the preparing for reuse, up-cycling, re-recycling, and biological treatment based on such waste collection. Its relevance is based on the findings of Feil et al. (2017), who showed that the quality of the Polyethylene terephthalate (PET) bottle fraction is affected by other plastic bottles that contaminated the separated PET fraction, and that the quality of the plastic film is affected by the high amount of organic waste, which reduces the price for the product. In the meantime, a proposal for the classification of the different recycling options is presented, based recyclability and substituion of virgin materials potential, used in life cycle assessment: (1) up-cycling refers to glass and metal recycling from source separation because both materials are infinitely recyclable (Tonn et al., 2014); (2) re-recycling can be paper/cardboard recycling, PET and Polyethylene packaging waste, and compost/digestate resulting from source separation since they are recyclable but do not have an infinite recycling potential or do not replace in a 1:1 proportion the virgin material (Rigamonti et al., 2009); (3) down-cycling can be recycling of laminated plastic packaging or carton liquid packaging since its recycled material has a less market value product (Fortelný et al., 2004), and down-cycling also for all previous materials from mixed/residual waste; and (4) biological treatment is for biodegradable municipal waste treatment of mixed/residual waste using MBT.

In the case of the energy recovery, the material circularity is reduced. When waste is only sent for energy recovery, the material will recirculate once; all waste, even in down-cycling, has at least the option for energy recovery (if a calorific value is present). WtE supplies energy for the economy, with the potential to bridge and enhance resource and energy efficiency improvements for waste materials that cannot be reused or recycled (Malinauskaite et al., 2017). If the energy value is too high, there is the risk of WtE be implemented without respecting waste hierarchy principle and conservation of resources. A better discussion of the role of WtE in CE is needed, to ensure that the waste sector is the source of secondary raw materials to the economy, as predicted in CE, and not a secondary source of energy. In fact, the WHI could have implications for how CE is being considered in waste management. The dichotomy recycling or incineration is one of the most important questions when managing waste. A study conducted on behalf of the European Parliament by Hollins et al. (2017) concluded that countries with high waste incineration (e.g., Denmark, Sweden, the Netherlands, and Belgium) should divert waste from incineration to recycling if they want to reach the 65% recycling target of the CE strategy. These are countries with high recycling rates at the EU-28 level. If a streamlined WHI target was established for 65%, no country would be capable to accomplish now, even Germany that presents a recycling rate of 66% but only a streamlined WHI of 32%. The WHI validates such conclusion, by helping the EU decision-makers to identify which countries, regions, and municipalities should restrict incineration to ensure that faster achievement of a CE is not compromised.

The WHI allows development of a focus on municipal waste, depending also on the definitions of Eurostat for the waste streams considered or not. The WHI does not give different weights to the different waste streams (and materials) that compose municipal waste, assuming that all have the same importance. Many other materials need to be considered in the municipal waste, namely WEEE, textiles, bulky waste, hazardous waste, and construction and demolition waste from a domestic source. To include them, the details of data collected from Eurostat, national entities and municipalities must improve. The step toward improved data collection was taken in 2017 with clarification on MBT in the Guidance (EU Commission, 2017), but the definition of the waste hierarchy terms, and to what they correspond in practice, need to be clarified and discussed. The WHI can accommodate any type of waste, including a mixture of waste streams (as is given in the present case) and can also be used for specific waste streams, as long as data is available.

4. Conclusions

The goal of this study was to develop an indicator that could measure waste hierarchy implementation, having the CE concept as its background. The WHI allows calculation of the level of implementation of waste hierarchy considering different types of recycling and incineration, where different weights are attributed to them dependent on the ways that the waste operations contribute to CE. With WHI the use of recycling rate, incineration rate, and landfilling rate can be dismissed from EU waste directives. The streamlined version of WHI allows its application at the moment, being valid to be applied with existing data from European countries reporting to Eurostat. The improved clarity that WHI provides, because all waste hierarchy operations are aggregated into a single number, can help policymakers to define targets based on this index, as well as helping them to provide adequate incentives or disincentives around waste operations, and to determine the waste operations to be enhanced and the ones to be abandoned to reach a CE, at any geographic scale. Application of the WHI could be made for specific materials and waste streams, which would require data to be available and testing. The WHI considers only the operations that occur after waste is generated, and it does not include prevention. The absence of waste prevention is needed when calculating the WHI because the definition of waste in the WFD and the formula also require that the mass balance of the waste treated be closed. The CE and waste hierarchy principle from the WFD looks differently at waste prevention. WFD proposed that waste prevention can be reached by reuse, reducing adverse impacts of waste and thereby reducing the presence of harmful substances in the waste generated. In contrast, the CE waste prevention concept includes the material flow: as long products are reused, refurbished, and remanufactured, waste prevention is occurring. Further research and policy development are needed to merge these waste prevention concepts, allowing the improvement of WHI to include waste prevention.

The implications of the use of WHI for European waste policies are significant: the indicator reveals that Europe is not a recycling society. This conclusion should be the beginning of a real discussion about waste statistics and waste management to reach a CE through implementation of the waste hierarchy principle. The inclusion of prevention in WHI will require further research development, as well the inclusion of waste operation efficiencies. The coefficients that now can only be assumed need to be defined as constants in a formula valid throughout Europe, which constitutes another future research development. Although the purpose of the WHI is not to measure the CE of a national system (not replacing existing CE indicators for such purpose), the approach followed to develop the WHI can be used as an indicator of the CE applied to the waste management sector, filling the gap of missing indexes for the CE, as pointed out by Elia et al. (2017).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.06.014.

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