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DOCTORAL THESIS - SUMMARY

THE MANAGEMENT OF MUNICIPAL SOLID WASTE IN EU UNDER A CIRCULAR ECONOMY PERSPECTIVE

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1. INTRODUCTION

This **Elena Cristina RADA**'s PhD research concerns the future management of municipal solid waste (MSW) in the territory of the European Union (EU). The 4Rs paradigm (reduce – reuse – recycle – recover energy) must change. Waste management must be re-organized under a Circular Economy (CE) perspective.

In order to understand the context where the present research is located, it must be underlined that in 2015 the European Commission issued a few important documents on CE**.** They concern some revised legislative proposals on waste management. The official aim was the stimulation of an EU transition towards a CE. An expected consequence is a global competitiveness with advantages for a sustainable economic growth.

If we consider the priority in waste management in EU, the above mentioned "package" on CE underlines the relevance of reuse and recycle before recovery of energy. The target is to close the loop. Product lifecycles must change favoring their re-use. This target is seen also in terms of positive balances for environment and economy.

After 2015, the EU issued additional documentation setting deeper targets compared to the past. For instance in the 2018 CE packaging a target for 2030 has been set concerning plastic: by 2030, all the plastic packaging should be recyclable. Moreover, additional interest is demonstrated towards monitoring actions to be sure about the obtained results in the EU countries.

At national level, Romania is following the directives set by the EU as demonstrated by the "*Hotărârea Senatului nr. 3/2016"* (MO), that is the package *"Pachetul privind Economia Circulară: COM (2015) 614 final"* named also *"închiderea buclei"*.

A resume of the Chapters characterising the PhD research thesis are reported as follows. The document consists on nine Annexes too, developed to deepen a few aspects of the CE and waste management topic. A list of 144 references completes the PhD thesis.

The present document is a 16 pages summary of the overall work.

2. OPTIMISING THE METHODOLOGY OF CHARACTERISATION OF MSW IN EU UNDER A PERSPECTIVE OF CIRCULAR ECONOMY

The methodology of characterisation of MSW in EU showed an important evolution. That was seen in form of efforts made by the local Authorities of management in zooming on MSW composition. In parallel, in the territories of the best managed regions, the trend of the collected vs generated MSW rate went towards 100%. This Chapter dealt with the methodology of MSW characterisation. That concerns specifically the characterisation of residual MSW (RMSW). This is the waste that remains after source separation. That separation, called also selective collection (SC), is compulsory in the EU. The methodology must go over the present necessities of information in a specific region. It must look at the aim of a correct planning for future scenarios of MSW management. For sure, these scenarios must be based on a high efficiency of SC. As demonstrated in the Chapter, if we take into account the target of a CE we must accept a characterisation based even on more than 20 fractions and sub-fractions (a fraction of MSW is a class of materials like glass, paper, etc.). An original proposal was set in the thesis.

An important aspect in the design of treatment plants and in the biodegradable waste process control is the biological stability of the biomass of interest. This parameter points out the degree of decomposition of the biodegradable organic matter. Thus, measurements of biological reactivity have become more and more important in the sector of MSW. They allow classifying treated MSW, untreated MSW and derived products, before their disposal in a landfill or their use (e.g. in form of compost). A parameter widely used for biological stability quantification is the respirometric index (RI). The specialized literature demonstrated a high interest on it. The present research will base a part of the original proposed RMSW characterization model on the adoption of RI. Indeed, it is a parameter suitable for generating a useful information on the biodegradability of the waste, not available in the conventional approach. The new proposed classification allows an aggregation of the volatile solids, ash and moisture of each fraction in order to calculate the classification of the overall waste. That can come from literature data or experimental data related to a specific case study.

In this Chapter it was demonstrated that is important to plan the optimisation of MSW valorisation adopting a model of characterisation more detailed than in the past. This effort would cost orders of magnitude less than the money that could be wasted in wrong designs of treatment plants.

3. CRITERIA FOR SELECTIVE COLLECTION OF MSW UNDER A CIRCULAR ECONOMY

This Chapter showed detailed aspects taken from the experience of the Municipality of Trento, Italy. There, we saw a top experience in the SC field, interesting to study its replicability. In the selected case, SC has recently reached 80% as shown in Fig.1

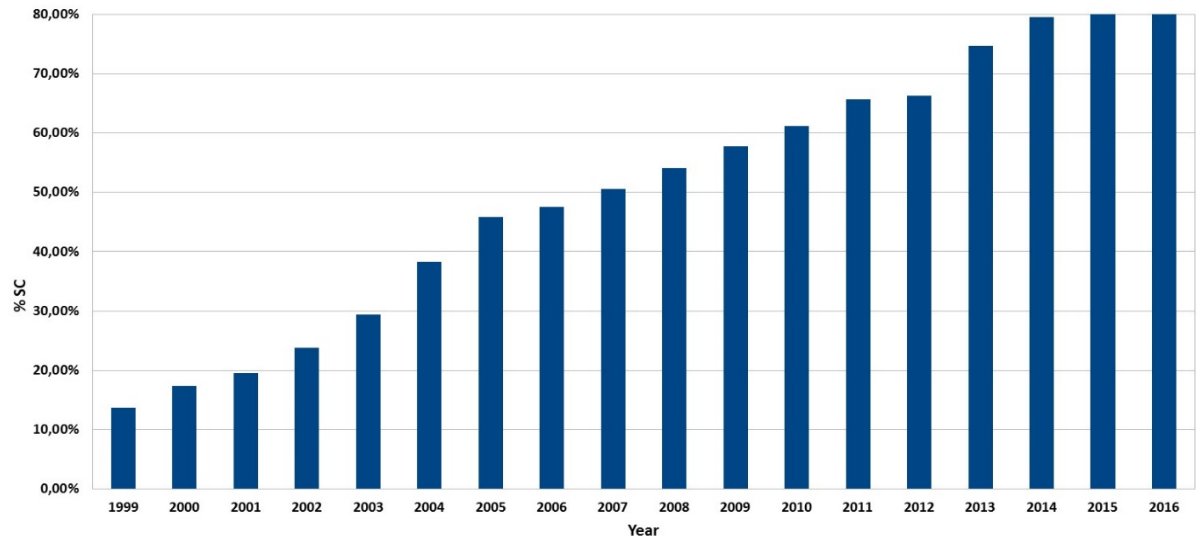

Figure 1. Dynamics of the SC rates in Trento

In Trento, the high medical textiles content in RMSW gave the opportunity to set a specific aim: to perform and valorize this fraction. This aspect was discussed giving today the chance to the construction of a pilot plant for anaerobic digestion after pre-treatment.

It is obvious that the presence of only 4% of organic material in RMSW is influencing the entire energetic value of the waste (by increasing), and on its tractability (not biologically). In extreme situations like the Trento one, SC acts as a pre-treatment of municipal waste, as recently reported in the literature.

In Fig. 2 the evolution of MSW and RMSW in the last years is presented. It is interesting to observe the declining trend of MSW generation even before the economic crisis. This trend could be related to a changed citizen behavior when buying a good. Another explanation could be that the reorganization of MSW collection avoids the inclusion of special waste in the stream of MSW.

Tab.1 reports the key aspects of the experience of waste collection in Trento.

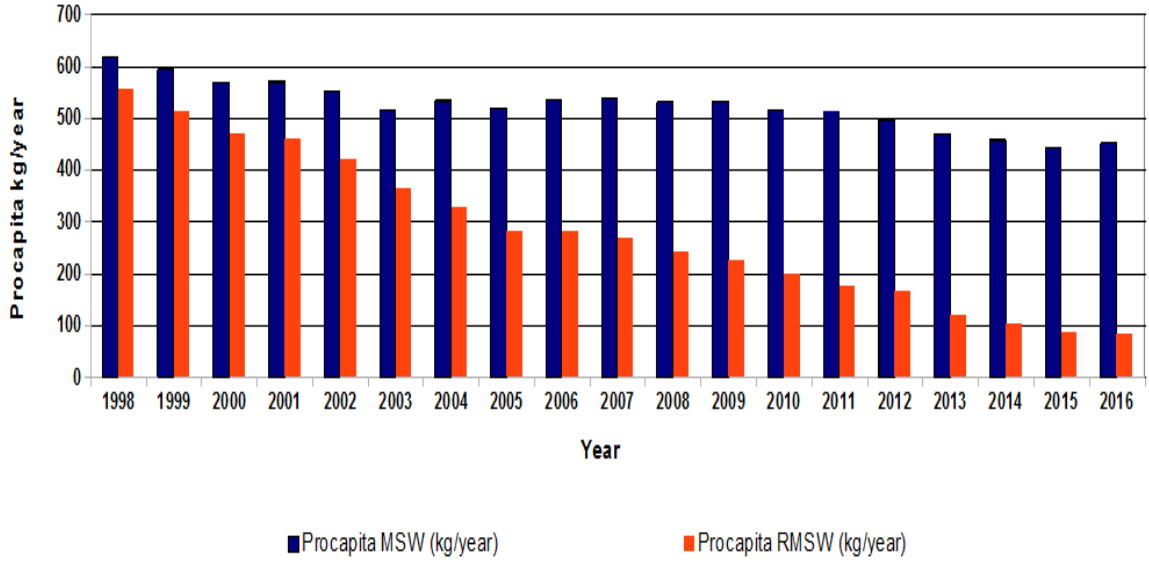

Figure 2. Dynamics of the specific amount of MSW and RMSW in Trento

Table 1. Key aspects of the experience of Trento in terms of collection criteria.

ASPECTS	NOTES
SC concept ***dissemination***	All media involved in an integrated project
Kerbside approach as basis	It allows direct responsibility of the citizen
Pre-paid bags for large buildings	It solves problems typical of large cities with vertical urbanization prevalent
Results ***reporting***	At yearly level
Tariff awarding best practices	Citizens see the advantages of their effort
Deep analysis of MSW composition	It allows detailed strategy calibration
Collected streams coupled with fate	Citizens must be sure the separated streams are valorized separately
Homogenization of criteria	Proximity areas must have the same collection strategies
Territory specificities preserved	Historical center managed taking into account the urban relevance
Street sweeping as visual comfort	Litter close to the street bins must be avoided
Tariff ***support*** (babies)	Supporting specific citizen categories gives the demonstration that the individual is not alone
Privacy	Supporting specific citizen categories gives the demonstration that the individual is not alone

4. MATERIAL RECOVERY FROM MUNICIPAL SOLID WASTE IN EU

Tab.2 shows the results of an original analysis where, for each proposed fraction for RMSW characterisation, SC criticalities/remarks and the status of valorisation technologies suitable for comply with the EU targets of CE are presented. Bold is used to point out aspects that deserve a specific analysis according to the CE principles.

Table 2. Proposed fractions for RMSW characterisation, SC criticalities, valorization aspects.

Fractions and sub-fractions	SC criticalities/remarks	Valorisation technologies status (for the treatment of the collected streams)
Organic	Street containers must be avoided. Kerbside collection must be at least 2 times per week to avoid odours	Anaerobic digestion is preferred to direct composting; kerbside collection is compulsory for quality reasons of food waste; **biomethane from biogas is the recent novelty: comparative criteria for choosing between biomethane and conventional co-generation based on biogas are not fully available.**
Green waste	-	Fully developed; added after anaerobic digestion (when present) in post-composting to avoid problems from lignin, not compatible for anaerobic process
Paper	Rainy days can affect moisture during collection operations. An alteration of moisture must be avoided.	Fully developed.
Cardboard	Rainy days can affect moisture during collection operations. An alteration of moisture must be avoided.	Fully developed.
Glass	It is usually collected in mixed colours	Fully developed; recycling plants can easily separate glass of colour by optic systems
Metals: Aluminium	This fraction has a high value thus dedicated machines at supermarkets can be placed to give discounts in change	Fully developed. When Aluminium must be separated from other fractions (co-collection) induction devices can easily separate it.
Metals: Ferrous materials	Avoid open street containers: they attract other waste	Fully developed. Magnetic separation can be adopted.
Metals: other	Other metals can be suitable as input in industrial processes (melting in steel making plants). They can be collected together other metals	Fully developed.
Light packaging: PET	This fraction has a high value on the market but co-collection should be	Fully developed. The principle of separation is by density

	preferable because they can be easily separated from a mixed stream	
Light packaging: HDPE	This fraction has a good value on the market but co-collection should be preferable because they can be easily separated from a mixed stream	Fully developed. The principle of separation is by density
Light packaging: PVC	-	Fully developed. X-ray devices can recognize it thanks to the presence of Chlorine (that characterises the PVC molecular structure)
Light packaging: other	Low density and low value are critical for transport and valorisation	Fully developed if energy recovery is adopted. In case of material recovery some interesting projects have reached the full scale. The mixed stream of plastics after specific selections is called Plasmix in Italy. The valorisation of Plasmix gives phonoabsorbing panels, garden furniture, plastic jars, brooms, etc.
Wood	-	Fully developed
Textiles: natural fibres	Keep separated from synthetic textiles	As material, not yet developed apart from reusable clothes. Non-reusable clothes can be sent to energy recovery (fully developed) considering their heterogeneity
Textiles: synthetic fibres	Keep separated from natural textiles	As material, not yet developed apart from reusable clothes. Non-reusable clothes can be sent to energy recovery (fully developed) considering their heterogeneity
Leather	The limited amount makes difficult a dedicated collection	Not specifically recovered today considering the limited amount. Energy recovery seems to be the preferable way
WEEE	It should be absent in the RMSW as a dedicated pathway of collection is activated in well organised systems	Fully developed for recovery various materials
Hazardous: exhausted batteries (used at domestic level, offices, etc.)	It should be absent in the RMSW as a dedicated pathway is activated in well organised systems	Technology exists but costs are not competitive
Hazardous: expired medicaments	It should be found absent in the RMSW as a dedicated pathway is activated in well organised systems	Combustion with energy recovery guarantees the correct management from the medical point of view
Hazardous: contaminated containers	It should be absent in the RMSW as a dedicated pathway is activated in well organised systems	Their valorization is difficult for obvious problems. Disposal after inertization is adopted.
Inert	At present it is not valorised, but it could become an input of an industrial process in the perspective of the circular economy. Inert could be separated from RMSW, slag (after combustion), etc.	Fully developed (to be valorised in the construction of roads; some limitations concern today the reuse from slag)

Mixed waste	Collected as RMSW	Energy recovery. They remain in the RMSW. They should be negligible is SC is well organised
Rubber	Not specifically collected	Energy recovery. They remain in the RMSW.
Diapers	Relevant in percentage in RMSW where SC is high for other materials. SC can create social problems for privacy reasons (adults)	**Technologies of material valorisation are at the level of pilot scale experience.**
Street sweeping (part of MSW)	Its collection is not yet optimised	**Technologies of material valorisation are developed but generally not implemented.**
Bulky waste (component of MSW)	-	Fully developed (recovery of metals, wood, plastics, etc.). Residues of their valorisation cannot be zero as products are not yet designed for a 100% recovery.

In March 2017 important modifications to the original CE package have been introduced during a discussion that seems to be more political than technical. What was critical for a correct interpretation of this target was the absence of a detailed explanation on how to calculate it. This Chapter put forward the most stringent interpretation of the landfill target based on direct and indirect actions concerning landfilling. As a consequence, also secondary streams in term of interest for material recovery must be taken into account for the future; to this concern street sweeping and diapers roles have been analysed. Technology for *street sweeping waste* treatment and valorization is ready for full scale adoption but decision makers have not yet developed a strategy for exploiting it. *Diapers* need pilot experiences (in progress) to confirm the expected values of material recovery. Another original analysis developed during the thesis concerned *food waste (OFMSW)* valorisation. The trend of the sector is towards anaerobic digestion as incentives today makes it preferable to direct composting. The future should confirm it even without incentives because of the technological evolution of the sector that gives higher specific production of biogas (referred to 1 ton of input). Apart from that, a question rising concerns the option of biomethane under a CE perspective. The developed analysis pointed out that biomethane can be preferable if the quality of the products to be generated must be high and the local impact of the OFMSW treatment plant must be minimized. Indeed, the amount of methane exploitable is around the same, if compared with biogas exploitation in an engine and the overall environmental impact can be better, but differences are not wide. Finally, we must point out that biomethane extraction from biogas can be coupled with the refinement of the remaining off-gas to produce CO_2 for industrial use. This is coherent with the material recovery principle, but limits are related to the sustainability of the cost of processing off gas.

5. ENERGY RECOVERY FROM MSW IN EU UNDER A CIRCULAR ECONOMY

If we consider the CE a priority in the EU waste management, the CE mentioned "package" points out the importance of reuse and recycling before the energy recovery. Indeed, the target is to close the loop of product lifecycles. This target is seen also in terms of positive balances for the environment and the economy. In this chapter, the effects of material recovery maximization were analyzed taking into account the strategies of energy recovery. Considering the present analysis in the CE context, the aims of the options alternative to combustion are to improve the environmental and energy balances and to have a valuable product as output (surely positive from the CE point of view).

The waste derived fuel is a MSW by-product when it meets a few classification standards. It must guarantee physical-chemical properties more stable than the initial raw material. It must be cheaper than primary fuels. Thus, it must be more attractive for the energy intensive industrial sectors. Examples of sectors interested are the cement industry, the pulp and paper industry and the thermal power plants. Recently, the sector of fuels generated from RMSW has been subject of continuous modifications. The related products have received various names. In the literature, the preferred one was Refuse Derived Fuel (RDF). More recently the name evolved towards Solid Recovered Fuel (SRF). The sustainability of RDF/SRF production is now based (in EU) on a regulated approach that takes into account some targets:

- guarantee a low content of pollutant in the product
- guarantee a clear and detailed classification of this product
- guarantee a viable storing of the product (by the adoption of the respirometric index)

The economic sustainability seems still critical. From the CE vision, the evolution of the SRF sector, when based on non-recyclable waste, can favour the "exploitation" of industrial plants. The case of cement factories is clear: ash from the input goes into a final product, without the need of constructing a new thermochemical plant. SRF should have only non-recyclable materials as RMSW should have only non-recyclable materials: From this point of view, SRF is coherent with the CE concept. The previous term RDF was not adequately normed.

Referring to MSW directly used (as RMSW) or indirectly used (in form of SRF) as input of thermochemical plants, an indicator suitable for assessing the performance of energy recovery management could be the percentage of thermochemically treated waste with LHV > 13MJ/kg (once taken as reference value to limit energetically valuable materials landfilling in

Italy). In a specific region, the MSW stream sent to thermochemical plants could be divided in sub-streams depending on the final destination and the adopted pre-treatment (if any). In both cases it is important to verify if the above mentioned threshold for addressing the energy strategies in the waste sector is considered or not. Administrations that send to a thermochemical treatment only fractions of waste with LHV > 13MJ/kg should obtain a 100% score in this evaluation.

Concerning MSW directly or indirectly used as input of thermochemical plants, another indicator could be the value in percentage of the waste having ash recovered. Bottom ash (slag) can be potentially used as a pozzolanic material in cement industry. Fly-ash could be potentially vitrified to be used as secondary product.

Referring to the fraction food waste (from SC), a third indicator could be the percentage of this stream anaerobically digested. As discussed above, the option of anaerobic digestion gives conventionally two products: biogas and compost. This configuration should be preferable to direct composting. Moreover, the biomethane obtained by extraction from the biogas should give a higher score. To this concern, the indicator could give a partial 100% score when biomethane is produced from 100% of the food waste available in the territory. Scenarios with conventional biogas could be differentiated considering a 60% coefficient to apply in order to reduce the value of the indicator (the value of 60% can be assumed as the rate of presence of methane in the biogas). For instance, if food waste had a rate of SC equal to 80% and if 50% of it were sent to anaerobic digestion where biogas (and not biomethane) were produced, the indicator would have the following value: $80\% \cdot 50\% \cdot 60\% = 0.24$

The sector of MSW management seems to be ready for complying with the criteria of CE. The economic sustainability seems to be still critical. From the CE point of view, the evolution of the SRF sector must be based on non-recyclable waste. That helps the decision makers to exploit correctly industrial plants, like the cement factories ones, where ash can be integrated into a final product, without the necessity of a new thermochemical plant. Unfortunately, often SRF is not yet considered as a real product (a real fuel) that deserves to be bought. On the contrary, often who generates SRF today has to pay a fee for its exploitation (in case a dedicated plant is not directly available for it). In spite of those criticalities, the perspective of CE towards RMSW management is oriented to options characterised by a double output: energy generation (from non-recyclable materials) and valorisation of the non-volatile solids.

6. PROPOSAL OF PERFORMANCE INDICATORS FOR THE MANAGEMENT OF MSW IN EU UNDER A PERSPECTIVE OF CIRCULAR ECONOMY

The sector of waste management is generally oriented to indicators, and indices based on indicators, working on a wide scale. Two specific needs emerged from the analysis of them:

- SC collection, strategic part of the approach oriented to CE, is generally taken into account without zooming on impurities. The recent targets of CE in the EU are oriented to consider the recyclable content of the source separated streams. Thus the present research put forward the proposal of an original quality index for SC.
- Source separated streams valorisation cannot reach 100%: a fraction of the collected material will be necessarily discarded during valorisation processes. An example is composting of source separated food waste: this process is characterised by a high process loss (e.g. water loss in form of humidity). An original indicator of CE coherence was put forward to this concern.

In order to adopt them, case studies had to be selected. In the EU, waste management is very different from country to country. However, a common approach in areas similar in habits and climate can be observed. For example, landfills are predominant especially in the southern countries. In Greece and in Romania, the stream landfilled is dominant. In Spain and in Italy, the landfilling role keeps significant. In the North of Europe, instead, incineration prevails, with the exception of Finland and England. A cold climate requires large quantities of thermal energy. Thus, cold climate orients towards a model of waste management that encourages recovery of its energy content. The fuel/biofuel production from MSW has become more and more important in the EU. In this context, there is an option always considered strategic: it is SC. Moving from this assumption, the Autonomous Province of Trento (Italy) implemented an integrated system for waste management looking at CE. Recovery material was put at the first place, but energy generation is not zero. Strategic policies aimed at the following targets:

1. a lower amount of MSW, considering the population growth too; this goal involves a reduction of the per capita generation;

2. the definition of specific SC targets for each waste fraction. These targets integrate the overall recycling percentage (%SC) widely used in the sector;

3. the definition of a RMSW threshold coming from a combination: the MSW production decrease and the SC evolution towards specific goals.

The system adopted in the Trentino Province demonstrated to be suitable for enhanced analyses. In order to focus on the improvable elements, a few indicators were proposed to be put together in a new index (selective collection quality index, SCQI).

$$SCQI = PI \times (1 + k_{\%SC}) \times (1 + k_{UNS}) \times (1 + k_{BW}) \times (1 + k_{AB})$$

Where PI is a purity index and the paranmeters k are correction factors that take into account the role of SC, unsorted waste UNS, bulky waste BW, tourism.

SCQI focuses on the quality of SC. Its role is central in the management of MSW but cannot be the unique tool to be adopted. Indeed, SC can be affected by the characteristics of the system put at disposal of the citizens for collect separated streams. In order integrate the approach based on the SCQI, an original indicator was put forward in this research, named "Circular Economy Coherence Indicator", CECI. The first assumption is that kerbside collection, integrated with eco-centers, is the best solution to reach high efficiency of source separated streams (in terms of quantity and quality). Apart from that, the idea at the base of the indicator was that the way of organizing the sector of MSW collection must be analysed by a new tool able to check if the activated streams of collection and the chosen options of RMSW treatment are coherent with the principles of CE. Strategies of reduction and reuse (of products near end of life) work before the generation of waste, thus are not considered part of this approach.

The construction of the indicator was based also on the analysis of the composition of MSW in an area. In particular, the following parameters were taken into account:

- Recyclable Streams (RS) in MSW (including bulky waste and street sweeping waste)
- Valorisable Rate of each RS (that is the highest percentage of material in each RS that can be valorized as material)
- Activation/inactivation of selective collection for each RS
- RMSW characteristics
- MSW ash content recycling

7. CASE STUDIES RESULTS

The main advantage of the methodology proposed is the data integration for quantifying many principles. Specifically, the involved principles are the ones of prevention, accountability, transparency, cooperation, techno- economic viability in MSW management. SCQI gives an aggregated information by the dynamics of its value. This is useful to check improvements in the managed area. Moreover the index is useful for comparison between areas. Tab.3 allows understanding the level of details reached in the analysis: the sum of the chatchment areas concerns a territory of around half a million people.

Table 3. Indexes values for distinguishing classes (brown = class 1; grey = class 2; blue = class 3) assessed for punctual tariff introduction year (Y), one before and one after.

	PI	PI	PI	$I_{\%SC}$	$I_{\%SC}$	$I_{\%SC}$	I_{UNS}	I_{UNS}	I_{UNS}	I_{BW}	I_{BW}	I_{BW}	I_{AB}	I_{AB}	I_{AB}	SCQI	SCQI	SCQI
Catchment areas	Y−1	Y	Y+1	Y−1	Y	Y+1	Y−1	Y	Y+1	Y−1	Y	Y+1	Y−1	Y	Y+1	Y − 1	Y	Y + 1
Val di Fiemme	12.4	6.6	7.1	14.8	78	8.3	17.9	8.5	9.4	14.5	7.6	7.8	19.8	10.5	11.3	39.7	18.7	19.3
Primiero	6.0	5.9	5.7	7.7	7.3	7.0	7.3	7.2	6.9	7.3	7.0	6.6	9.9	9.7	9.3	18.5	17.8	16.6
Bassa Valsugana	7.5	5.1	6.8	10.7	7.2	9.4	8.9	5.8	8.1	9.4	6.4	8.5	12.6	8.6	11.5	27.1	17.4	23.5
Alta Valsugana	6.6	3.1	4.4	8.9	4.1	5.6	7.7	3.4	5.0	7.5	3.5	4.9	10.4	5.0	6.9	18.8	7.9	11.4
PR-VDC-VDL-ADP	11.4	8.9	7.6	15.1	11.6	9.8	15.0	11.4	9.5	14.0	10.9	9.2	17.9	14.0	11.9	38.1	28.4	23.2
Val di Non	7.1	5.5	4.2	9.9	7.6	5.7	8.6	6.5	4.8	9.2	7.3	5.4	11.7	9.1	6.9	25.3	19.3	13.6
Val di Sole	5.3	5.5	3.9	10.7	10.4	7.0	5.6	5.8	4.1	5.8	6.0	4.3	8.1	8.3	5.8	18.6	18.3	12.4
Giudicarie	7.3	9.7	8.3	13.0	16.6	12.4	8.0	11.0	9.5	7.7	10.2	8.9	11.5	15.2	12.9	23.2	30.4	24.1
Alto Garda	8.3	7.4	9.0	14.3	13.2	15.5	9.2	8.2	10.0	9.2	8.1	9.6	13.0	11.6	14.0	27.8	24.5	28.7
Vallagarina	13.7	10.2	11.9	21.6	16.0	18.6	16.9	12.1	14.7	16.7	12.7	15.7	21.6	16.1	18.7	51.4	37.5	47.8
Val di Fassa	9.4	5.2	4.8	14.9	7.9	7.2	10.8	5.7	5.3	10.1	5.7	5.3	12.8	7.1	6.6	25.2	12.9	12.0
Rovereto	10.4	9.7	11.1	17.3	16.2	18.4	12.0	11.0	12.9	11.4	10.5	12.1	17.4	16.1	18.5	36.2	33.3	38.7
Trento	7.3	6.1	3.7	12.2	9.7	5.5	8.1	6.7	4.0	7.9	6.9	4.2	10.2	8.5	5.2	20.4	16.8	9.3
Province of Trento	8.8	7.0	6.6	13.6	10.5	9.6	10.2	7.9	7.6	9.9	7.9	7.6	8.8	7.0	6.5	17.7	13.6	12.6

This is information is not at zero cost. A detailed generation of data in time is compulsory. That must be done for each area where the responsibility in MSW collection is homogeneous. Having the same administrative responsibility does mean that the same effort is made in producing data for MSW characterization of collection and consequently for SCQI assessment. An example is done by the difference of the information seen when comparing alpine regions in the North of Italy or when comparing mountainous regions of various countries. The international tourism is an incentive for bettering the management of MSW collection. SCQI helps. However, its full exploitation needs adequate data.

The case study demonstrated that an enhanced collection systems adopted with a punctual tariff is a way to reach high levels of SC. Looking at the quantity collected separately, results are excellent. However, work remains on the quality. That means one of the priorities must be the lowering of the scrap. The proposed index helps in identifying how.

The evaluation of the SC efficiency as percent of the waste is controversial. The present work contributed to create a set of indicators and indices suitable to evaluate the factors affecting SC.

After defining SCQI, as seen in Tab.3, the index was adopted for each catchment area of the region selected. The used data refer to a historical period with areas starting first that reached a phase of consolidated system. It would be interesting to apply the model in cases where data belong to longer data series.

The proposed CECI has been applied to a case study, the one of the Municipality of Trento, whose information of SC activation was reported in Chapter 3. The items considered ($CECI_j$) concerns the way of managing each fraction in MSW ($CECI_1 = 1$ means that the fraction 1 is managed according to the CE principles). The result is the radar graph shown in Figure 7.3.

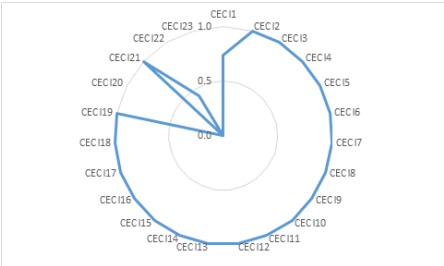

Figure 3. CECI radar for the case of Trento.

8. CONCLUSIONS, CONTRIBUTIONS AND FUTURE DEVELOPMENTS

The developed research was structured as a pathway towards the creation of new tools for MSW management under a CE perspective. Original outlooks have been drawn through a revision of each aspect concerning MSW management. The research demonstrated that the RMSW characterisation in an EU context needs more attention than the usual. The conventional approach risks generating inadequate information for an optimised design of the management system. The effort in improving MSW characterisation would cost much less than what would be wasted in wrong designed plants. This deeper analysis will allow the sector being more coherent with the CE principles. That analysis will have to be integrated also with tools CE specific as the ones proposed in this research. The indication of the EU on a stringent threshold limit for MSW landfilling makes compulsory a different generation of data. Those are necessary to implement a model of MSW characterisation like the one proposed in this research. Indeed, it takes into account the EU targets of the CE. In order to optimise the economic resources of the sector, the present research dealt with the proximate and ultimate analysis of waste and its fractions. The original proposed model zooms on waste preventing useless efforts for its characterisation. Thus, the model saves money.

Also SC of MSW is involved in the new vision of MSW management under a CE perspective. The Trento town case study was analysed as starting point of a model proposal. This model supports the organisation of a SC coherent with the CE principles, socially and economically sustainable. Trento was selected because its community reached one of the top results of SC and waste streams organisation in Italy (and in the EU). The kerbside option demonstrated to be the most reliable in quality and quantity of source separated streams. The adoption of a tariff in place of a tax helped a lot the public administration to reach the targets.

Concerning material recovery from MSW in EU, a proposal to assess the management performance under a CE perspective was developed during the present work. In March 2017 important modifications to the original CE package have been introduced. As discussed in the present document, a criticality is the absence of detailed criteria of interpretation of the EU targets. Taking into account this lack of details, the research presented the most stringent (original) interpretation of the landfill target. According to that, all the secondary streams in term of interest for material recovery must be taken into account for the future. It means, for example, that slag landfilling is not coherent with CE. The role of street sweeping and diapers

has been analysed too, showing potentialities and criticalities. They both can give a non-negligible percentage of material recovery. In spite of that, their adoption is not yet optimized. Another analysis concerned the food waste valorisation. The trend of the sector is towards biomethane production: extraction of methane from biogas. That gives the opportunity to generate a product of higher quality compared to biogas. This extraction can be coupled with the refinement of the remaining off-gas to produce CO_2 for industrial uses. This option is related to the concept of material recovery. Today, the limits are not technical. They concern the sustainability of the cost of off-gas processing. Off-gas is the gas remaining when biomethane is extracted from the biogas.

Energy recovery from MSW is depicted as a secondary topic in the frame of CE. Differently, the present work demonstrated that this option could fully integrate material recovery. RMSW cannot be reduced to zero. Few percentage points of MSW are not recyclable. Their energy content can open to a double step of valorisation. Of course, the recovery of energy is the first one. The recovery of incombustible materials can be a strategic second step. From this perspective, the evolution of the SRF sector, if based on non-recyclable waste exploitation, can help. The availability of industrial plants, like cement factories can support the inclusion of incombustible materials in CE approaches. Indeed, the process to produce cement integrates ash entering the plant into a final product, without the necessity of a dedicated plant. Efforts have been recently made by the EU to enhance the concept of SRF. Unluckily, in most of cases, SRF is not yet seen as a product deserving a market. Cement factories are not the unique way. Dedicated plants could send bottom ash to external plants for recycling. To this concern, a few real scale plants are operating in the sector. Additionally, enhanced solutions like indirect combustion with integrate vitrification of bottom ash can be coherent with the CE principles.

As final step, a few performance indicators and indices for MSW management (in the EU) under a CE perspective has been created.

SCQI allows summing up all the aspects that affect SC. It takes into account that the quality of the collected streams is crucial to comply with the EU principles. SCQI includes a few indicators that give additional information as they are. SCQI focuses on the quality of SC. Its role is central in the management of MSW. However, it cannot be the unique tool to adopt. Indeed, SC can be affected by the characteristics of the system made available to the citizens for collect separated streams.

In order integrate the potentiality of SCQI, a specific indicator was put forward in this research. It is the "Circular Economy Coherence Indicator". It considers the coherence of the organization of collection and treatment with the principles of CE.

Both of them have been adopted in two case studies. They are related to two realities that reached high levels of organization in the sector of MSW. The two realities are the Province of Trento and the Municipality of Trento.

In both cases the adoption of the proposed tools was viable. That demonstrates they are already suitable for a use in the sector. However, developments of the research should be related to the replication of the case studies. Indeed, it is important to find criteria to adapt the proposed tools to other situations. An interesting case could be the one related to the absence of a tradition in MSW data generation. Another interesting case could refer to a scenario with reduced amounts of data produced on MSW: a case with few data cannot fully exploit the potentiality of the indicators and indices in the present form.

The present thesis, having the title ***"The management of Municipal Solid Waste in EU under a circular economy perspective" – "Gestionarea Deșeurilor Municipale Solide în Uniunea Europeană în cadrul economiei circulare",*** focuses on a topic very important at national and international level. It concerns both the research field and the industrial application. Until now, the present research allowed the publication of **24** scientific papers, **14** of them indexed ***Thomson Reuters, ISI- Web of Science***. Thanks to these articles the international visibility of **Elena Cristina Rada** reached:

- In the Data base **Scopus**, **Elena Cristina RADA** has now 1,838 citations and Hirsch **H-index = 26**.
- In the Data base **ISI - Web of Science**, **Elena Cristina RADA** has now 997 citations and Hirsch **H-index = 18**.