POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in
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Energy Department

INTEGRATED MUNICIPAL SOLID WASTE MANAGEMENT SYSTEM: OPTIMISATION AND CASE STUDY FOR ITALY

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Extended summary

The world is nowadays characterised by a continuously raising attention to the issue of environmental and economic sustainability.
Every year, thousands of studies are published regarding energy efficiency, strategical use of resources and green-house gas emissions reduction.
This work of thesis perfectly inserts in such context, trying to relate the above mentioned aspects to the waste topic.
European Community established a common normative to discipline the waste management system of its member Nations in order to 'deliver the best overall environmental outcome'.
Italy accepted the EU Directive fixing *a priori* values of Separate Collection Levels to be respected by the entire territory without particular recommendations to what intercept and how, what to do with residual waste.
These are the questions that the model tries to answer by an engineering point of view.

In order to minimise the energetical, environmental and economic impacts of a municipal waste management system (Italian was chosen as a case study), an optimisation was performed.
A model representing a standard integrated waste management system was created with the purpose to describe all the processes that the waste flow can encounter from its origin, the household, to its final disposal.
When modelling the system, particular attention was paid to the following topics:

- Separate collection of the different fractions and composition of the intercepted flows.

- Selection and separation of the flows to be sent to the different Material Recovery Facilities.

- Environmental and energetic performances related to recycling.

- Environmental and energetic performances related to residual waste and residues treatment processes: Waste to Energy, Mechanical Biological Treatment, landfilling.

All the aspects above listed have been included in the model after some assumptions were made on the basis of literature, direct research, MatEr staff and personal knowledge of the subject.

Since the model is strictly related to these assumptions, its adaptability to contexts different from Italy, even if possible considering the model's implementation methodology, is difficult. The hypothesis sometimes do not even fit some specific Italian areas.

Anyway, the assumptions made are the most reliable as possible with the data so far available.

To give the model a broader perspective, some scenarios were implemented differing for separately collected flows purity, intercepted organic fraction treatment processes and power generation plants replaced.

In order to consider the whole system performances, a substitutive point of view was always (except from economic optimisation) assumed: the indicators inserted in the model were both deduced from LCA analysis and specifically built to simulate the current practices, to account for energy and emissions savings of the different waste treatment processes.

To deliver that, we considered what material and energy recovery outputs substitute: energy produced by the thermo-electric grid and primary materials which recycled fractions usually replace.

All the discussed considerations were included in the form of equations describing a model composed by the typical mathematical programming elements (Chapter 7 can be skipped by a reader which is confident with optimisation problems):

- Sets: the domains in which variables and parameters are defined, e.g. the merceological fractions and residual waste treatment processes sets.

- Variables: the values optimisation has to find, i.e. the different fractions' interception levels, the Unsorted Residual Waste destinations and the percentage of selection and recycling residues sent to incineration instead of landfilling.

- Objective function: sum of all the contributes of the different waste management treatments to the optimised issue.

- Constraints: bounds, mass and energy balances that variables must respect in order to find a feasible solution to the problem.

At first, a mono-objective optimisation was performed for all the three topics considered: energy, emissions and costs.
Then, because of the trade-off existing between the first two issues and the last one, a multi-objective optimisation was conducted considering together energy VS costs, emissions VS costs.
A Pareto plot was implemented to show the intermediate points found as well as the optima deriving from mono-objective optimisation.

The optimal waste management strategies were found for every scenario considered, answering the initial questions we posed.
Comparing the current Italian situation with the results we inferred that the energetic, environmental and economic performances of the Italian waste management system were always much worse than the optimal ones.
Even when optimising energy and emissions, the resulting costs were lower than Italian, meaning that we can attain optimal energy and environmental results saving money.
Pushing separate collection towards very high levels, as Italian Decree about waste imposes, does not represent the very best solution: much more attention must be paid to what intercept, as some fractions under certain assumptions are not to be separately collected, some others are always better left unsorted.
Special care should be given to residual waste management too: landfilling, the most diffused residual waste treatment process in Italy, must be avoided while considering energy and emissions.

WtE is the most recommended process relatively to URW treatment while MBT, under certain assumptions, is a valid alternative.
Important is the coordination between collection and residual waste disposal.

We can conclude by the model results that the rules the national regulatory framework imposed are not always efficient.
Though, more studies adopting the integrated perspective assumed by this work of thesis are required to reinforce the conclusions here achieved and contribute significantly to the waste management topic.

Riassunto esteso

In un contesto scientifico mondiale caratterizzato dalla crescente attenzione nei confronti delle tematiche di sostenibilità ambientale ed economica, il tema di gestione dei rifiuti si inserisce perfettamente potendo racchiudere al suo interno argomenti come l'efficienza energetica, l'uso strategico di risorse e la riduzione di gas serra.
Non a caso la Direttiva Europea che disciplina la gestione dei rifiuti degli Stati Membri cita espressamente che l'obiettivo da perseguire è: '[…] l'ottenimento del migliore risultato globale dal punto di vista ambientale.
L'Italia però, nel recepire i dettami della Direttiva, si è limitata a fissare dei valori soglia sulla percentuale di raccolta differenziata da conseguire entro differenti termini temporali, senza in maniera particolare accennare a cosa intercettare e a come gestire il flusso residuo di rifiuti.
A queste domande prova a rispondere da un punto di vista ingegneristico il modello qui presentato.

Allo scopo di minimizzare gli impatti energetici e ambientali del sistema di gestione dei rifiuti urbani italiano, senza tuttavia trascurare la tematica economica, è stato implementato e poi risolto un problema di ottimizzazione.
Per un sistema di gestione dei rifiuti standardizzato, è stato creato un modello che descrivesse i processi che il flusso di rifiuti incontra dalla sua produzione (generalmente l'abitazione) al suo smaltimento finale.
Per la creazione del modello particolare attenzione è stata posta sui seguenti aspetti:

- Raccolta differenziata delle diverse frazioni e composizione dei flussi intercettati.

- Selezione e separazione dei flussi che devono essere inviati alla filiera di recupero di materia.

- Valori relativi alle prestazioni ambientali ed energetiche associate al riciclo delle diverse frazioni.

- Valori inerenti alle prestazioni degli impianti di trattamento dei rifiuti residui e degli scarti da selezione e separazione: inceneritore, Trattamento Meccanico Biologico, discarica controllata.

Tutti gli aspetti sopra citati sono stati inclusi nel modello dopo aver effettuato alcune assunzioni sulla base dei dati trovati a letteratura, colloquio diretto con persone addette ed esperienza mia e del personale MatEr con cui ho avuto la possibilità di lavorare.
Siccome il modello è fortemente dipendente da tali assunzioni, anche se dal punto di vista dell'implementazione potrebbe adattarsi a contesti diversi da quello Italiano, difficilmente troverebbe dei valori affidabili. Infatti, alcune assunzioni considerate talvolta risultano strette anche a certe area dell'Italia stessa.
In ogni caso si tiene a precisare che si è cercato di effettuare le ipotesi più realistiche possibile con i dati ad oggi a disposizione.
Inoltre, per alleviare un po' il modello da tale dipendenza dalle assunzioni, sono stati implementati alcuni scenari che si differenziano tra di loro per purezza dei flussi separati, tipologia dei processi di trattamento delle frazioni organiche intercettate e parco di generazione elettrica considerato.

Per tenere conto delle prestazioni della totalità del sistema di gestione dei rifiuti, è stata adottata un'ottica sostitutiva (tranne che per l'ottimizzazione economica): sono stati inseriti nel modello sia valori dedotti tramite metodologia LCA sia indicatori costruiti allo scopo di considerare i risparmi di energia ed emissioni associati ai diversi processi.
Per fare ciò, si è andati a considerare cosa con maggiore probabilità gli output delle filiere di recupero di materia ed energia vanno a rimpiazzare, ovvero l'energia prodotta dal parco termo-elettrico e i materiali realizzati tramite produzione primaria che vengono normalmente sostituiti dalle frazioni riciclate.

Tutti gli elementi discussi sono stati inclusi dalle equazioni formanti il modello matematico, trascritto secondo le consuete norme della programmazione matematica (il Capitolo 7 può essere saltato da un lettore esperto riguardo i problemi di ottimizzazione); gli elementi che lo formano sono:

- Set: domini all'interno di cui vengono definite le variabili e i parametri, come ad esempio il dominio delle frazioni merceologiche.

- Variabili: sono i valori che devono essere ottimizzati. Le variabili considerate sono state: i livelli di intercettazione delle frazioni merceologiche, le percentuali di smaltimento del Rifiuto Urbano Residuo e le frazioni di scarti da selezione e riciclo inviata ad incenerimento anziché discarica.

- Funzione obiettivo: valore calcolato come la somma dei contributi dei diversi metodi di smaltimento dei rifiuti considerati rispetto l'argomento oggetto dell'ottimizzazione.

- Vincoli: valori limite, bilanci di massa ed energia che le variabili devono rispettare al fine di trovare una soluzione ammissibile.

In un primo momento è stata effettuata un'ottimizzazione mono-obiettivo per ciascuno dei tre aspetti considerati: energia, emissioni e costi.
In seguito, a causa della divergenza riscontrata (come atteso) tra le soluzioni proposte dalle ottimizzazioni ambientale ed energetica con quella dei costi, è stata condotta anche un'ottimizzazione multi-obiettivo che considerasse assieme energia e costi, ed emissioni e costi.
Si è costruita una frontiera di Pareto così da poter rappresentare i punti con valori intermedi insieme agli ottimi derivanti dai problemi mono-obiettivo.

Le strategie ottimali di gestione dei rifiuti sono state trovate per ogni scenario considerato in maniera tale da rispondere alle domande iniziali che ci siamo posti.
E' stato effettuato il paragone tra i risultati ottenuti e la situazione italiana corrente: per quanto riguarda le prestazioni energetiche, ambientali ed economiche, il sistema di gestione dei rifiuti italiano si è dimostrato ben peggiore rispetto quelli ottimali.

Anche quando sono state ottimizzate singolarmente energia ed emissioni, i costi risultanti erano sempre inferiori a quelli correnti: ottimizzando questi due aspetti si finisce anche col risparmiare denaro.

E' risultato evidente come spingere i livelli di raccolta differenziata a valori particolarmente alti come il Decreto Legislativo italiano impone non conduce a soluzioni ottimali: maggiore attenzione andrebbe conferita a quali frazioni intercettare, visto che alcune di esse sotto certe condizioni non conviene separarle proprio.

Particolare interesse andrebbe prestato al tema della gestione del rifiuto residuo; la discarica è ancora oggi il metodo di smaltimento più diffuso in Italia mentre invece andrebbe assolutamente evitata da un punto di vista energetico/ambientale.

Il termovalorizzatore in primis, ma anche l 'alternativa rappresentata dal Trattamento Meccanico Biologico, rappresentano le scelte ottimali per la gestione del rifiuto indifferenziato.

Possiamo concludere, a seguito dell'analisi dei risultati del modello, che i dettami della legislazione italiana riguardanti la tematica dei rifiuti non sono sempre efficaci.

Tuttavia, al fine di rafforzare ulteriormente le conclusioni a cui si è giunti con il qui presente elaborato e contribuire ulteriormente in modo significativo al tema della gestione dei rifiuti, sarebbero necessari ulteriori studi che adottino una visione d'insieme come quella qui assunta.

Summary

Abstract

The work of thesis here presented reports the results of an energetic, environmental and economic optimisation of the whole Italian municipal waste management system.

Adopting a substitutive perspective, all the processes related to waste disposal were considered in order to create a standard waste management model able to simulate Italian reality.

Reliable assumptions about intercepted flow purity, effectiveness of material recovery and national power production grid were made to analyse the subject in the most inclusive way.

Three mono-objective optimisations were singularly performed for the three topics of interest as well as two multi-objective optimisations aiming to consider together energy VS costs as well as emissions VS costs.

Optimisations results are quite in contrast with national regulatory framework who set Separate Collection Level up to 65% as a goal for the short-term future (such value was established for 2012 and recently remarked): the average value resulting from the optimisations is between 45-50%, proving that the best solution is not represented by intercepting everything as much as possible as Italian policies recommend.

A full integration between separate collection and residual waste management is instead required.

In order to demonstrate this achievement, optimal values of fractions interception, unsorted residual waste and selection and recycling residues management are reported.

Keywords: Separate Collection, waste management, Municipal Solid Waste, interception level, waste composition, Selection and Recycling Residues

Riassunto breve

Il lavoro di tesi qui presentato riporta i risultati di un'ottimizzazione condotta sull'intero sistema di gestione dei rifiuti urbani italiano dal punto di vista energetico, ambientale ed economico.

Adottando un'ottica sostitutiva, tutti i processi di trattamento in cui il rifiuto incorre durante il suo smaltimento vengono considerati al fine di creare un unico sistema di gestione standard a cui il modello possa fare riferimento in maniera da simulare nel modo più realistico possibile la situazione corrente del nostro Paese.

Per fare ciò sono state fatte delle assunzioni, le più realistiche possibili, al riguardo di: qualità della raccolta differenziata, benefici apportati dal recupero di materia e parco elettrico considerato. In tal modo si è affrontata la questione nella maniera più inclusiva possibile.

Sono state effettuate le tre ottimizzazioni mono-obiettivo, una per ciascuno dei tre aspetti sopracitati, e anche le due ottimizzazioni multi-obiettivo riguardanti energia e costi, emissioni e costi.

I risultati ottenuti sono in contrasto con la normativa vigente che prevede di raggiungere in un futuro prossimo (in realtà tale valore doveva essere raggiunto nel 2012 e recentemente è stato ribadito) la soglia del 65%: mediamente il valore che risulta dalle ottimizzazioni si aggira attorno al 45-50%.

Spingere al massimo l'intercettazione di tutte le frazioni come suggerisce la normativa italiana può risultare inefficiente; quello che invece è obbligatorio è una perfetta integrazione tra la raccolta differenziata e la gestione del rifiuto residuo.

Per dimostrare quanto appena detto vengono riportati i valori ottimali dei livelli di intercettazione così come quelli relativi alla gestione del rifiuto indifferenziato e degli scarti da selezione e riciclo.

Parole chiave: Raccolta Differenziata, gestione dei rifiuti, Rifiuto Urbano, livello di intercettazione, composizione del rifiuto, Scarti da Selezione e Riciclo

1 Introduction

1.1 The importance of waste management in modern society

With the increase of consumption of goods in modern society, and thus the production of residues, the issue of the waste management has become more and more of public domain. Words such as separated collection, incineration, landfilling are often pronounced by the media which continuously feeds public opinion with investigative reports. Just a few months ago the case of the city of Rome blew up [1], and few years ago the Campanian waste scandal happened [2].

Despite the recent popularity, the issue is very important by its own for a Developed Country's environmental and economic strategy because, as proved by the trends of total waste production, the quantity of waste produced by OECD (Organisation for Economic Co-operation and Development) Nations historically grew up in the last decades as showed by Figure 1.1.

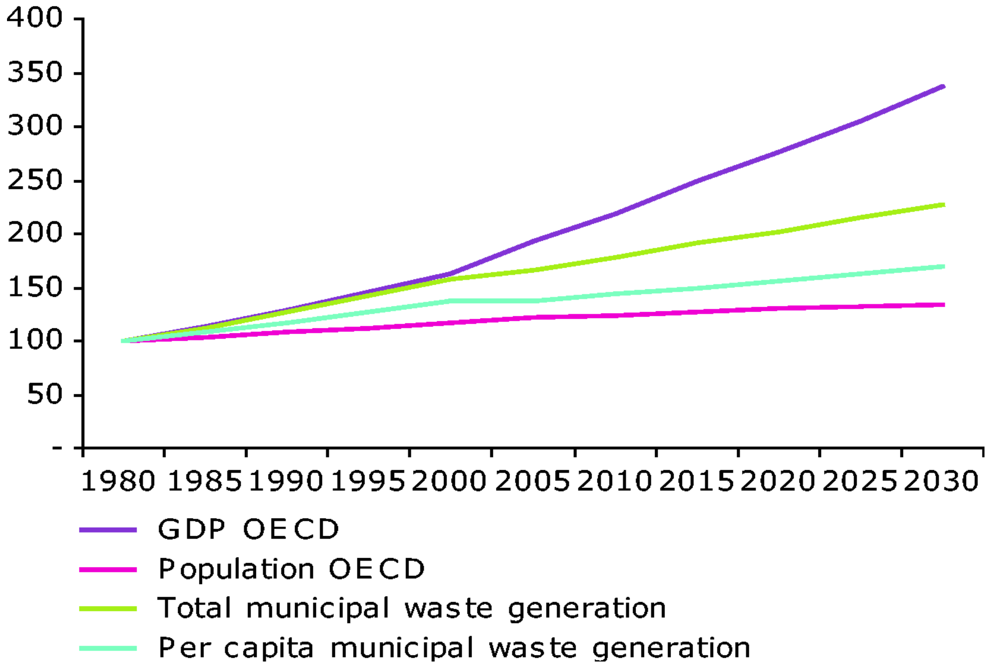


Figure 1.1 – OECD waste production – historical data and forecasts, years 1980 – 2030, [3]. *Values at 1980 fixed to 100*

Though recent studies highlight a smooth decoupling between the annual waste production of western countries and their Gross Domestic Product (GDP) for the very last years (Figure 3.1 referred to Italy) [4], [5] they confirm that it is hard to imagine a realistic scenario in which waste production decreases significantly [5], [6].

At most, it will probably remain stable. In fact, the weak decrease that has been noticed in the very last period can be reasonably accounted to the economic crisis rather than to a real assimilation by the population of the prevention and reduction policies [7], [5].

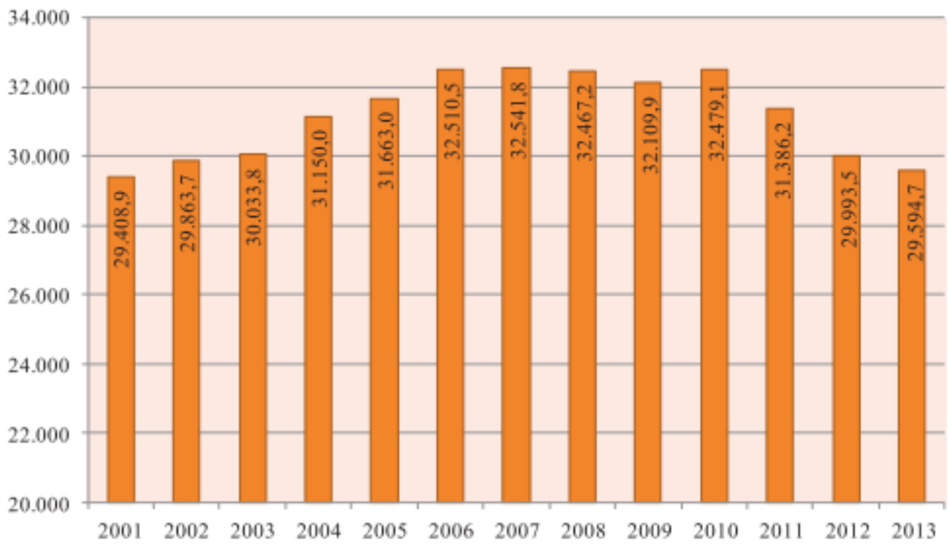


*Figure 1.2 - Urban waste production in Italy, [1000*tonne], years 2001-2013.)* [4]

For the specific case of Italy, a Nation which can realistically represent the European trend (Chapter 2), Figure 1.2 shows how the general tendency was a smooth increase in the last twelve years (29594 thousand tonnes since 29408) though the last period was characterised by a decrease that stopped in 2014, during which (paragraph 3.2) we assisted again to a little raise.

From the discussion of these data we can infer that, even in the less realistic case in which waste production is considered to be decreasing though GDP raising, the total quantity of waste that Developed Countries are expected to manage is not supposed to fall down to negligible values thus requiring a well-defined regulatory framework.

Otherwise, a superficial approach to this issue would lead to bad public health and urban decorum problems.

Anyway, as many studies have confirmed [5], [8], [9], [10] for waste management, what is often considered as a problem at first sight, could often become a resource if approached with long term planning and commitment.
In this sense, two data reported by Stefano Consonni, [7] Professor at the 'Politecnico di Milano' university, in "*Generalità sul recupero da rifiuti*" are very significant.
They concern with the Total Primary Energy Supply (TPES) of a Country: in industrialized nations the residual waste, if totally sent to Waste to Energy plants (with an average efficiency equal to 25%) would cover 2 to 3% of primary energy consumption of that Country; up to 10% if Special Waste (SW) is added. About Italy, it is shown that by incinerating with energy recovery the quantity of waste currently sent to landfilling, 4% of the national electricity demand would be covered.

Having so far discussed the importance of the issue with the help of some indicative data regarding waste production and possible recovery, let us now briefly describe this work of thesis.

1. It aims to give some guidelines for the planning of a waste management system intended to be sustainable from three perspectives: the environmental impact, the energy consumption and the economical aspects.

2. The results could be useful for the policy-maker as an instrument to evaluate from a scientific point of view the strategies ongoing and then choose the best goals to reach and the technologies to invest in.

3. The model has been tested on the Italian case study assuming a standard waste management system, as it is better described in the following chapters.

1.2 The background of this thesis: MatER research centre and previous thesis works on the subject

The work of thesis has been realized at the MatER (Materia ed Energia dai Rifiuti) centre, which is composed by professors and researchers of different departments of Polimi, some LEAP (Laboratorio Energia e Ambiente Piacenza) staff and the partnership of private companies (e.g. Federambiente, a2a, IREN).
Waste management is the main topic of research of the MatER which mission is 'identifying and analysing best available technologies for the recovery of material and energy from waste'.
Numerous studies and reports have been published by MatER staff [11], [12],[13] regarding different topics as urban waste composition and waste treatment systems.
The possibility to collaborate with experts of this topic showed a great benefit from different perspectives, particularly for data searching, model development and use of dedicated software.

Among MatEr projects, we must mention the work of thesis carried out by Matteo Delucchi [9], a former graduating student, who, anticipating this study, worked on the optimisation of the waste management system with a similar approach. With a particular focus on environmental and energetic topics, he came to the conclusion that pushing separate collection up to very high levels is useless or even counter-productive, in contrast with the modern tendency to talk about completely recycling and full circularity of products. Anyway Delucchi's work was quite rough and never tested on a real case study and its conclusions cannot be completely trusted.
The model here presented has been expanded and a more accurate cost optimisation was performed.
With respect to the work carried out by Delucchi, the model developed in this thesis is characterized by:

1. a wider consideration of the possible recovery technologies (e.g. the anaerobic digestion option for organic fractions)

2. the inclusion of the management of the residues produced by the material recovery processes

3. a detailed analysis and realistic use of the parameters inserted in the optimisation model (e.g. the energy savings indicators or the emission factors associated with the modelled processes)

4. a deeper study and modelling of the quality (i.e., the level of impurities) of the fractions of waste collected separately

Later, all these issues will be thoroughly discussed.

Though this work tries to be a step further with respect to what has been accomplished so far at MatER about waste management optimisation, it is yet conscious of its own limits and remaining open to forward actualisations and extensions.

1.3 The definition of waste

We need now to give some definitions in order to clarify what we are talking about.
Let us start from the definition of waste: Directive 2008/98 EC states that: " waste is any substance or object which the holder discards or intends or is required to discard" [14].
No word is said about the value that the object has or could have by reusing or recovering it.
European classification distinguishes the waste on the basis of the origin and risk for human health instead of its chemical composition or physical properties:

- Municipal Solid Waste (MSW): waste collected from private households or 'similar' activities

- Special Waste: waste from industrial, demolition, commercial and agricultural activities

- Hazardous Waste: every kind of waste expressly marked in the European Catalogue of Waste. This waste is hazardous from the origin

- Non Hazardous Waste

Municipal Solid Waste, though minor in quantity than Special Waste, is the only typology of waste here, and in the major part of literature studies, considered, because it can be sent to every destination without particular concerns about pre-treatment processes, hazardousness, special disposal.

Waste	**Non hazardous**	**Hazardous**
Municipal	- domestic waste - waste from public place - waste which can be assimilated to municipal	- batteries - TV, fridge - drugs
Special	- waste from agricultural activities - commercial and industrial packaging - residues from waste recovery or disposal plants	- sanitary waste - oil exhausted

Table 1.1 - Example of waste classification

In general the usual composition of MSW, according with *Giugliano* [8], is formed by the following fractions:

1. Paper
2. Wood
3. Plastic materials
4. Glass
5. Ferrous metals, i.e. steel
6. Non ferrous metals, i.e. aluminium
7. Food waste
8. Green waste
9. Inert fines

10. Other (WEEE, drugs, tyres…)

Because of the fact that the first eight fractions constitute almost 95% of MSW (see Chapter 4) and are the ones specified by the Italian regulatory framework to be subjected to separate collection [5], they represented the focus of the model. Their disposing was optimised by the model, while Other and Inert fines are considered to be managed by *a priori* fixed solutions.

2 Waste in Europe

2.1 European regulatory framework

The reference text talking about waste in Europe is the already mentioned Directive 2008/98 EC. It clearly describes the priority of the waste management system [14] from the first to the last item of the following list:

a) Prevention and reduction
b) Preparation for re-use
c) Recycling
d) Other recovery e.g. energy recovery
e) Disposal

The Directive adds that: “When applying the waste hierarchy, Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste.” It is obvious that applying strictly and locally the hierarchy, the so called ‘4 Rs’ (Reduce, Reuse, Recycle, Recover) rule, can be strongly inefficient from the economic and environmental points of view. That is why an optimisation model comprising the overall integrated management systems could provide useful indications regarding the most sustainable strategies for waste management.

2.2 Production

The 2015 Report elaborated by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale), reports European data (re-elaborated from Eurostat) regarding the production and management of waste until 2013 (see Table 2.1) while, as can be seen in Chapter 3, for Italy, the available data are up to 2014.

Paese/Raggruppamento	2011		2012		2013	
UNIONE EUROPEA (28 SM)	**250.898**		**246.148**		**243.240**	
UNIONE EUROPEA (15 SM)	**215.011**		**210.827**		**209.112**	
NUOVI STATI MEMBRI	**35.887**		**35.321**		**34.128**	
Belgio	5.035		5.004		4.905	
Bulgaria	3.732		3.364		3.135	
Repubblica Ceca	3.358		3.233		3.228	
Danimarca	4.393		4.242		4.192	
Germania	50.237		49.759		49.780	e
Estonia	399		371		386	
Irlanda	2.823		2.693		2.693	s
Grecia	5.586		5.585		5.585	s
Spagna	22.672		21.896		20.931	e
Francia	35.019		35.001	e	34.828	e
Croazia	1.645		1.670		1.721	
Italia	31.386		29.994		29.573	
Cipro	581		579		538	e
Lettonia	721		613		627	
Lituania	1.339		1.330		1.280	
Lussemburgo	345		346		355	e
Ungheria	3.809		3.988		3.738	
Malta	245		247		241	
Paesi Bassi	9.479		9.203		8.845	
Austria	4.807		4.883		4.905	
Polonia	12.129	e	12.084	e	11.295	e
Portogallo	5.178		4.766		4.598	
Romania	5.398	e	5.441	e	5.441	s
Slovenia	852		744		853	
Slovacchia	1.679		1.657		1.645	
Finlandia	2.719		2.738		2.682	
Svezia	4.266		4.304		4.350	
Regno Unito	31.066		30.413		30.890	

Note: (e) stima Stato membro; (s) stima Eurostat.

Table 2.1 –Production of urban waste in EU, [tonne / year], years 2011 – 2013 [5]. *s: value estimated by the Member Nation. e: value estimated by Eurostat*

As reported by (Table 2.1) during the last year a modest (1,2%) decrease was noticed, for EU 28 members, from a total waste production of 246,1 million tonnes to 243,3 million in accordance to what happened in 2012 (-1,9%).

This reduction, as just said, is probably caused more by economic recession rather than waste production and GDP decoupling.

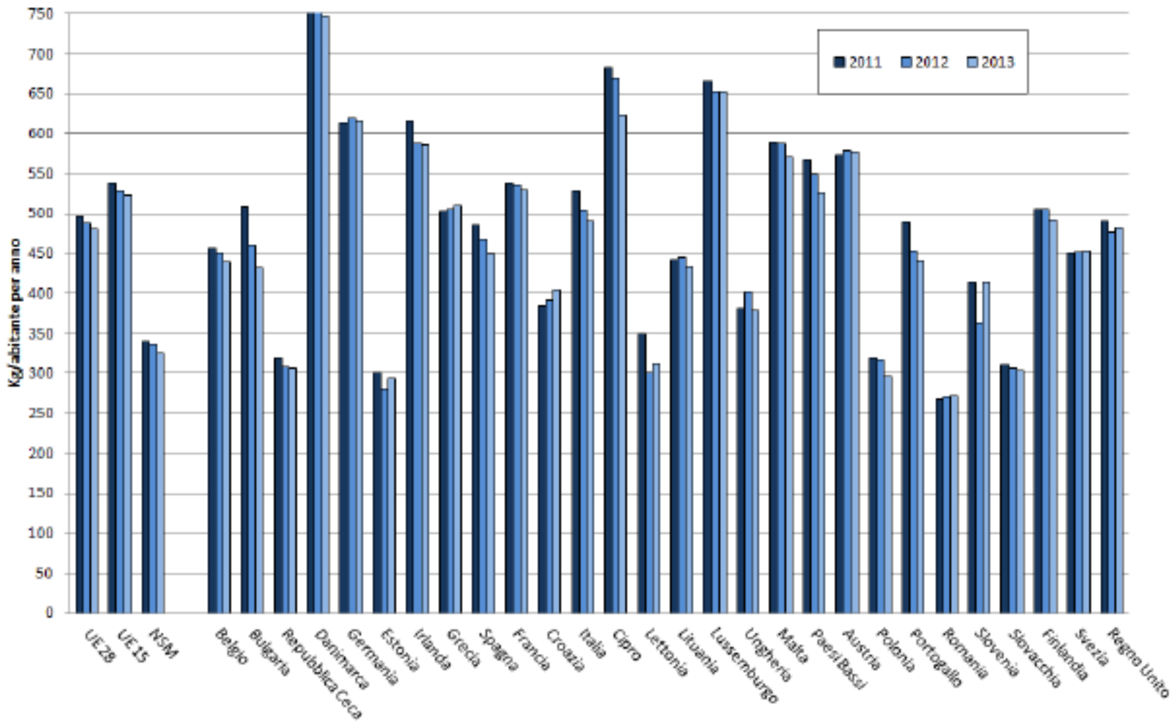


Figure 2.1 - Per capita production of MSW in EU [kg/inhabitant per year], years 2011 – 2013 [5]

Analysing the value of production per capita (Figure 2.1) we can better appreciate the great variability that characterizes the yearly waste production among the European countries: it spans from 272 kg/inhabitant in Romania to 747 kg/inhabitant in Denmark.

There is a remarkable difference between old and new Members: these last ones have lower values of per capita production, explainable considering their lower consumption due to their unfavourable economic conditions [5]. In fact, the value per capita is 521 for EU 15 (- 1,3% since 2012), while for New Member Countries the value is 325 kg/inhabitant every year (- 3,3% since 2012).

2.3 Municipal Solid Waste management in Europe

Waste management presents a great variability of approach among the European Union: common tendency, even if very smooth, is to adhere to the hierarchy described above.

Figure 2.2 gives the details of the management system for all the Members:

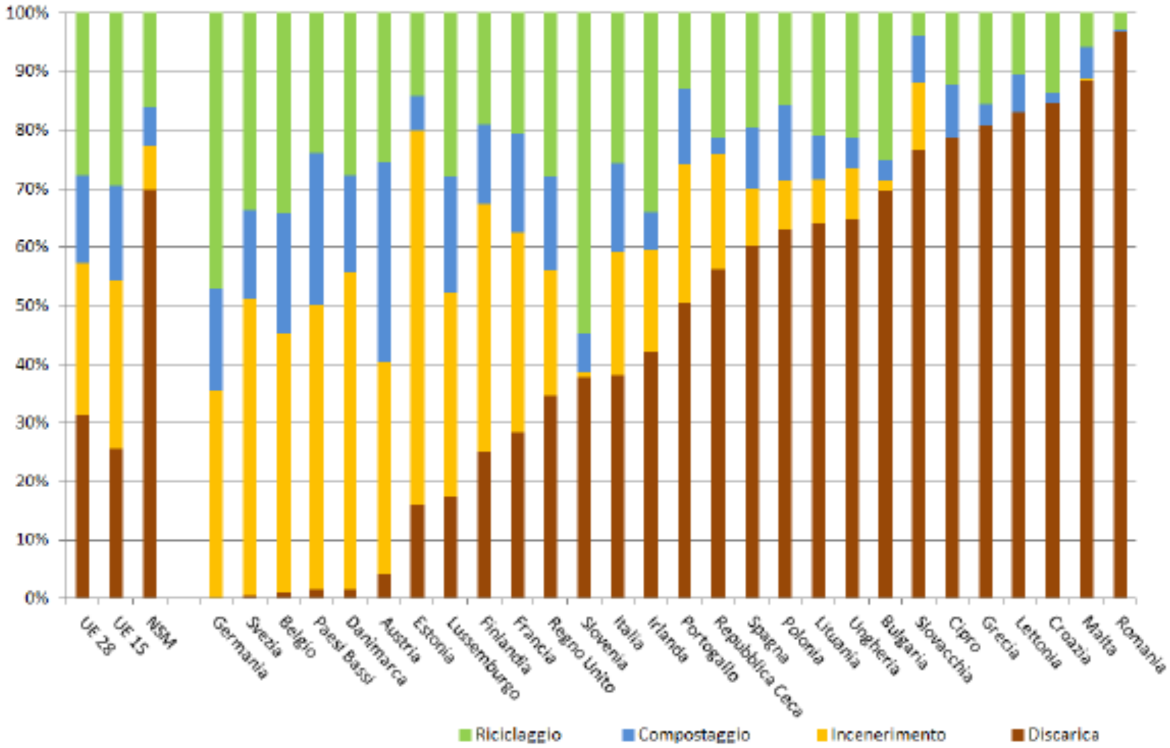


Figure 2.2 – Percentage of waste sent to a specific treatment in EU, [%], year 2013 [5]

The data show a great difference in waste management between New Member States, still relying on landfilling (probably due to its low cost) and Nations of EU 15 which have lower rate of landfilling and where sometimes such disposal is even completely avoided, e.g. Germany.

It is worth of notice, anyway, how Italy is a Country with higher landfilling values and lower incineration rates respect to the majority of other EU 15 Nations.

2.4 European research and the project Topwaste

Numerous studies are conducted internationally about waste and waste management particularly by academic world. Among them stands Topwaste, on which we focused for a better understanding of the subject and a comprehension of where international studies are aiming to.

2.4.1 Topwaste

Topwaste is a research project began in 2011 and partially supported by the private fund of investment ‘Innovation Fund of Denmark’. Its staff is mostly made of Professors and researchers of Danish universities DTU (Danish Technical University) and USD (University of Southern Denmark), but many other educational Institutions around the world collaborate to the project, e.g. Lunde University and Yale University.

Topwaste, as MatER centre, aims to contribute significantly to the waste issue studying the optimal policies to be adopted for energy and resource recovery, integrating economical aspects with environmental.
A lot of reports and studies have been published [15], [16], [17] as long as various software have been implemented as assessment or design tools:

- Optiwaste: an optimisation model of waste management system integrated with electric system
- Envirowaste: a modern LCA tool for environmental impact analysis
- FRIDA: an econometric model for future trends of waste production
- KISS: an Excel application for evaluating the CO_2 emissions from waste management

All these studies are based on Denmark and Northern Countries: this region is, in general, characterised by high incineration level and growing separate collection rates (anyway still minor than 50%) (paragraph 2.3).
The most significant goals claimed by Topwaste can be summarised as:

- Necessity of rigorous scientific instruments to study the issue [16]
- Integration of waste system with energy system [17]
- Separation of organic fraction needed in order to reach the separate collection levels specified by UE [18]
- Future scenario forecasts about waste and energy production [19]
- Definition of an international trade market for waste [20]

2.4.2 Optiwaste

A particular analysis has been conducted on the software Optiwaste, which resulted to be analogue to this work for purpose and implementation [21].
The model, as Balmorel, is written using the GAMS (Generic Algebraic Modelling System) language: GAMS in fact is a software designed exactly for optimisation problems.
Optiwaste consists in the union of the LCA methodology and the mathematical programming approach used for the optimisation of heat and electricity system. In other word, the optimisation, to model the processes, exploits the data found from LCA.
The long-term goal of the project is said to be the complete integration, in a unique model, of the waste management system with power generation and supply grid [21].

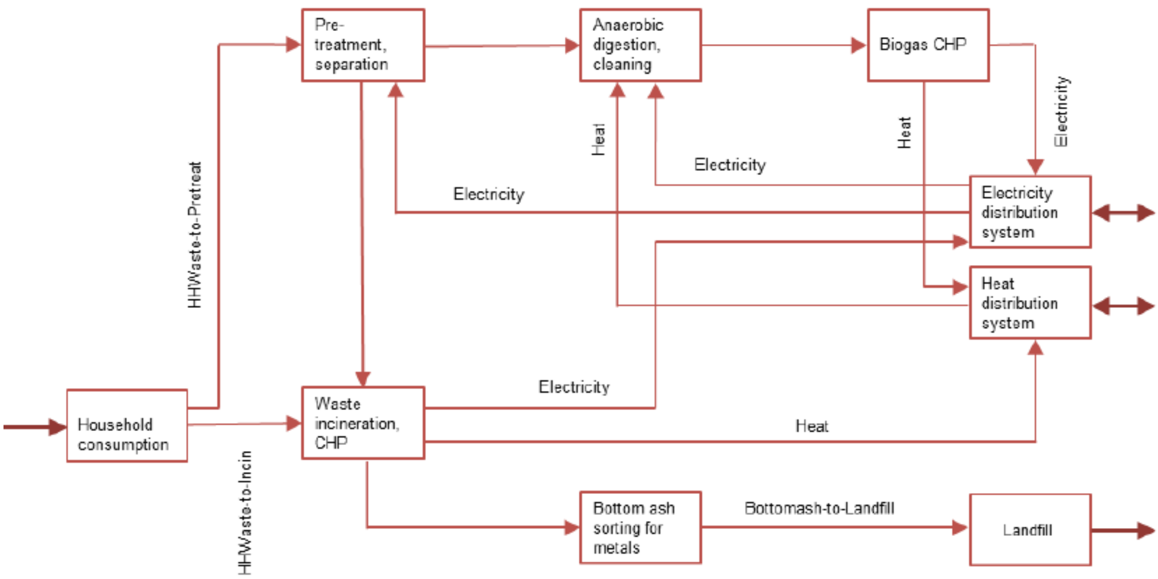


Figure 2.3 - Example of network in Optiwaste, Processes and Flows, [21]

The model is implemented through the typical mathematical programming language (variables, sets, constraints…) and is built as a network defined by Flows and Processes as pointed out by Figure 2.3. The nodes of the system represent all the possible treatments that waste can encounter from its origin (the household) to its final disposal (e.g. landfilling, incineration or the market of recycled fractions). Flows represent the quantities of waste, money or energy moving through the Processes.

Among the processes that can be included, there are also the energy conversion systems operating in the area considered by the model interacting with waste management plants: through these, the integration between the two systems (waste and energy) is reached.
The model presented in this thesis work is characterized by a lower level of detail with respect to the one developed in the Optiwaste project (e.g. in the present thesis project the energy conversion systems operating in the area considered by the model have been collectively, not singularly, represent) because of the preliminary starting point of the project and the available data.
The Optiwaste model is, in theory, able to consider many aspects of waste management such [21]:

- Integration with energy system
- Time resolution, even hourly
- Capacity and storage possibilities of treatment plants
- Geographical position
- Transport between the nodes

However, we must remark that concerning Optiwaste not even some applications to case studies has been published yet.
The model here presented instead, even though more simple, produced some reliable, and sometimes innovative, results (see Chapter 12 and 13) which can be used as a path to follow while aiming to a greater environmental and economic sustainability of the waste management system.

3 Waste in Italy

3.1 National regulatory framework

The Italian regulatory framework accepts the rules dictated by the European Directive described in paragraph 2.1.

The reference law is the 'Decreto Legislativo n° 152 del 2006' [22].

Great importance was given to "the promotion of high level of human health and environment quality […] through the recovery and disposal of waste in complete safety."

Priorities of a correct waste management system should be the " reduction and prevention of waste production and hazardousness" [22].

Once again, as established by the Directive, the first objective to pursue is reduction, followed by re-use, recycling and energy recovery. Landfilling is the very last process of the chain.

In order to increase the high separate collection rate suggested by EU the decree established the goals to reach:

- at least 35% within 31/12/2006;
- at least 45% within 31/12/2008;
- at least 65% within 31/12/2012.

These goals have been achieved partially and not by the whole territory, so they were remarked by the decree of 26th of May 2016: "*Linee guida per il calcolo della percentuale di raccolta differenziata dei rifiuti urbani*".

The reference law does not mention how such values should be achieved and how manage fractions not separately collected. It does not even mention how they have been settled and if they really respond to the environmental sustainability the EU Directive recommends.

3.2 Production

Paragraphs 3.2, 3.3 and 3.4 are fully devoted to analyse the waste production and management system in Italy.

Regione	2010	2011	2012	2013	2014
	(t)				
Piemonte	2.251.370	2.159.922	2.027.359	2.003.584	2.050.631
Valle d'Aosta	79.910	78.418	76.595	72.590	72.431
Lombardia	4.957.884	4.824.172	4.626.765	4.594.687	4.642.315
Trentino Alto Adige	508.787	521.503	505.325	495.427	495.425
Veneto	2.408.598	2.305.401	2.213.653	2.212.653	2.240.454
Friuli Venezia Giulia	610.287	575.467	550.749	546.119	553.433
Liguria	991.453	961.690	918.744	889.894	899.438
Emilia Romagna	2.999.959	2.918.957	2.800.597	2.780.295	2.829.543
Nord	**14.808.248**	**14.345.531**	**13.719.787**	**13.595.249**	**13.783.670**
Toscana	2.513.312	2.372.799	2.252.697	2.234.082	2.253.908
Umbria	540.958	507.006	488.092	469.773	476.375
Marche	838.196	822.237	801.053	764.139	796.142
Lazio	3.430.631	3.315.942	3.199.433	3.161.134	3.082.372
Centro	**7.323.097**	**7.017.984**	**6.741.275**	**6.629.128**	**6.608.797**
Abruzzo	681.021	661.820	626.639	600.016	593.080
Molise	132.153	132.754	126.513	124.075	121.123
Campania	2.786.097	2.639.586	2.554.383	2.545.445	2.560.486
Puglia	2.149.870	2.095.402	1.972.430	1.928.610	1.909.748
Basilicata	221.372	220.241	219.151	207.477	201.130
Calabria	941.825	898.196	852.435	829.792	809.974
Sicilia	2.610.304	2.579.754	2.426.019	2.380.046	2.342.219
Sardegna	825.126	794.953	754.896	732.668	725.024
Sud	**10.347.766**	**10.022.705**	**9.532.467**	**9.348.129**	**9.262.784**
Italia	**32.479.112**	**31.386.220**	**29.993.528**	**29.572.506**	**29.655.250**

Table 3.1 – Total urban waste production divided by region , [tonne / year], years 2010 – 2014 [5]

ISPRA Report 2015 [5] estimates (Table 3.1) that the urban waste production for the year 2014 has been almost 30 million tonnes, growing of 83 thousand tonnes since 2013 (+ 0,3%). Such an increase could signify that the tendency registered in the period 2010 – 2013, during which the production fell of about 2,9 million tonnes, is changing.

Even though, as said, for the very last years a smooth decoupling can be registered, waste production seems quite coherent to the data about socio-economic indicators reported by Figure 3.1.

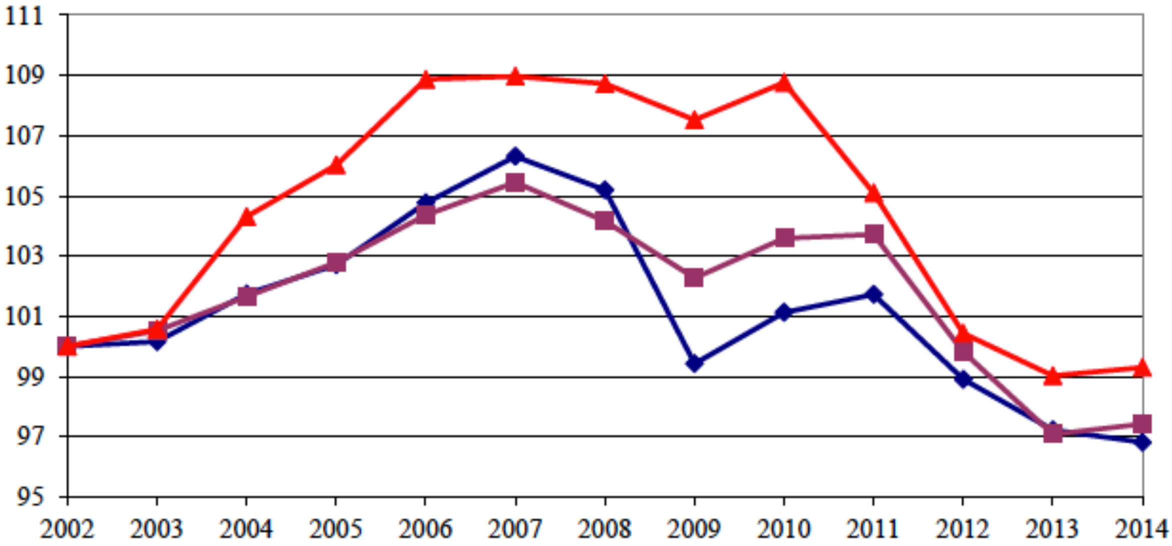
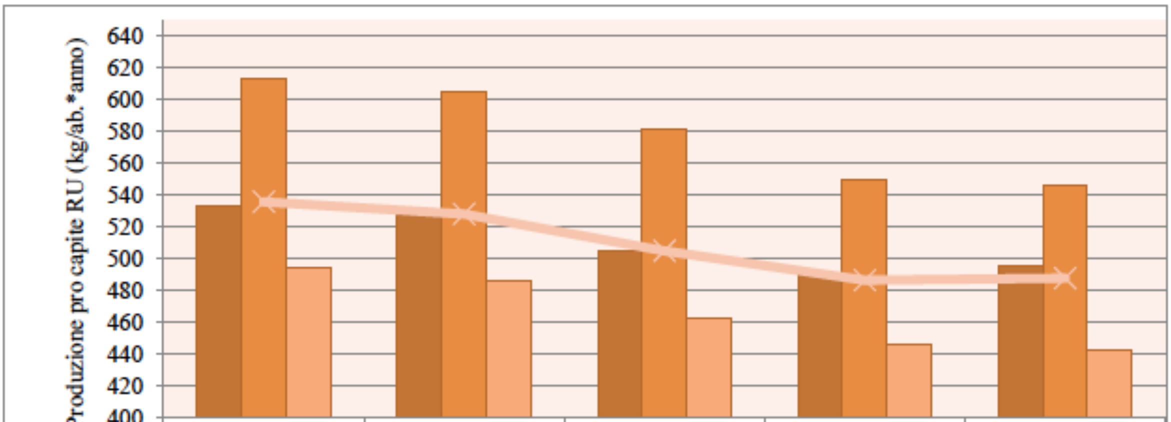


Figure 3.1 – Total MSW production related to socio-economic indicator, years 2002 – 2014 [5] *Note: Red line: MSW production. Purple line: family expenditure. Blue line: GDP. Chain indexes 2010. Value at 2002 was assumed to be 100*

As told before, a growing richness is usually accompanied by an increase in waste producing, implying that global waste production is not going to fall in the future even if reduction and re-use strategies will be completely assimilated by inhabitants.

Another interesting value is the per capita production (Figure 3.2) which in 2014 was 488 kg/inhabitant per year.



	2010	2011	2012	2013	2014
Nord	533	527	505	489	496
Centro	613	605	582	549	547
Sud	495	486	463	447	443
Italia	536	528	505	487	488

Figure 3.2 - MSW production divided by geographical area [kg / inhabitant per year], years 2010 - 2014 [5]

This value is interesting because testifies the differences in waste production occurring between the three macro-area forming Italy. Such diversity, alongside the differentiation between North and South in waste treatment plants reported by ISPRA (paragraph 3.4), confirm that a model implemented through many nodes spread in the whole territory would be more fitting Italian situation.

3.3 Separate collection

D.lgs. n. 152/2006 accepting the Directive 2008/98 EC established the yet seen goals for separate collection levels described in 3.1

The methodology used by ISPRA to calculate the value suggested, according to methodology 2 reported in the 'Commission decision of 25/11/2011' [23] is:

$$SCL = \frac{\sum_i SC_i}{MSW} \times 100$$

where

$$MSW = \sum_i SC_i + \sum_i URW_i + SRR$$

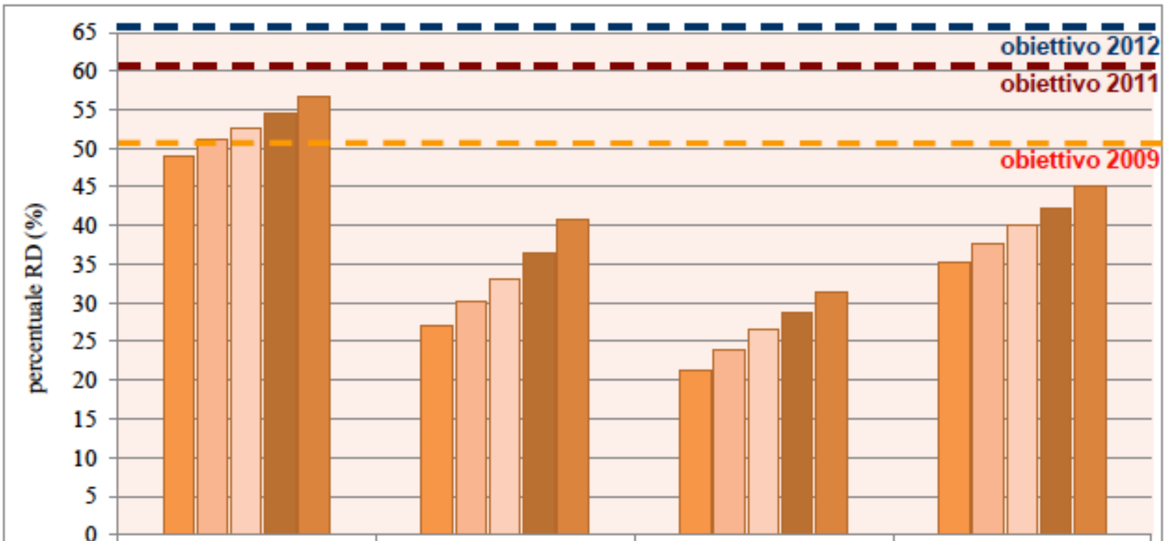
$$i \in I = \{paper, wood, plastics, glass, metals, organic, inert\ fines, WEEE, bulky\ materials\}$$

MSW: Municipal Solid Waste produced [tonnes]

SCL: Separate Collection Level [%]

SC_i: tonnes of i-th fraction intercepted by separate collection, net of SRR

SRR: tonnes of selection and recycling residues from Material Recovery Facilities of i-th fraction



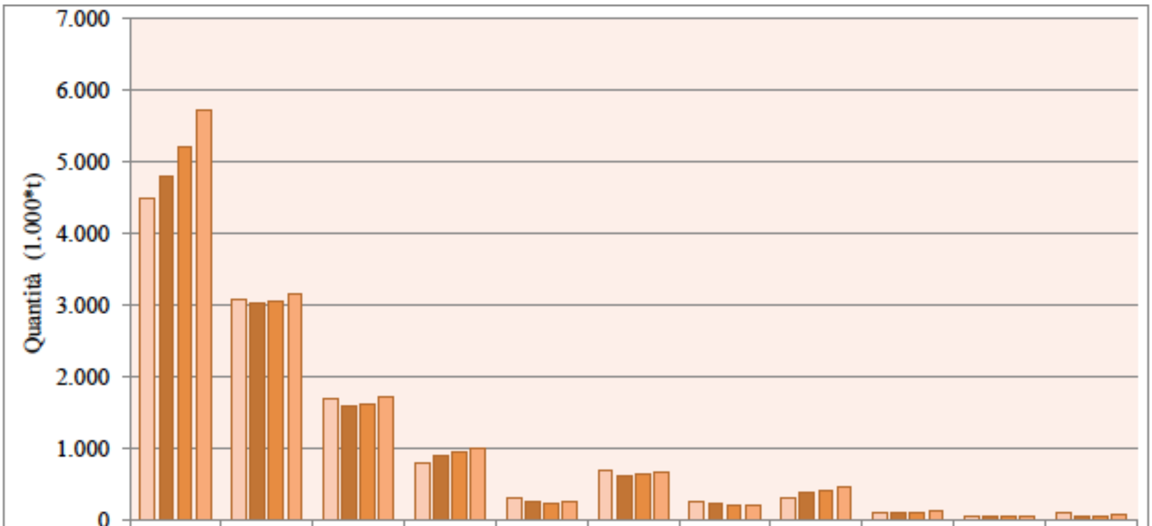
	Nord	Centro	Sud	Italia
2010	49,1	27,1	21,2	35,3
2011	51,1	30,2	23,9	37,7
2012	52,7	33,1	26,5	40,0
2013	54,4	36,4	28,8	42,3
2014	56,7	40,8	31,3	45,2

Figure 3.3 - Percentage of MSW separate collection rates (%), years 2010 - 2014 [5]

In 2014 the separate collection level in Italy was 45,2%, with a growth of near 3 points since 2013 (Figure 3.3). With a six year delay was achieved the goal the decree established for 2008 (45%).

In absolute value the quantity sent to recycling was 13,4 millions of tonnes, with an increase of 900 thousand tonnes since 2013 (+ 7,2%).

From a regional point of view, the percentages are: 56,7% in the North, 40,8% in the Centre and 31,3% in the South.



	Frazione organica	Carta	Vetro	Plastica	Metallo	Legno	RAEE	Ingomb. misti	tessili	selettiva	Altro
2011	4.500,8	3.068,9	1.700,0	787,9	303,0	693,3	249,3	304,3	96,7	39,9	103,9
2012	4.813,4	3.037,6	1.598,1	889,8	248,9	614,1	219,7	377,3	101,1	38,6	53,7
2013	5.216,9	3.051,4	1.608,1	945,2	241,0	635,2	209,2	398,5	110,9	39,9	52,2
2014	5.720,8	3.154,0	1.711,3	991,2	249,5	676,2	213,4	447,0	124,3	40,6	78,1

*Figure 3.4 - Separate collection divided in the different fraction, [1000*tonne / year], year 2011 - 2014* [5]

As showed by Figure 3.4, between 2013 and 2014, was reported a raise of about 500 thousand tonnes (+ 9,7%) of organic (food and green-waste) separate collection, aligned with the increase registered (+ 8,4%) between 2012 and 2013. The quantity of these fractions sent to biological treatment (mostly composting) is 3,2 millions of tonnes in the North (+ 7,8%), 1,1 million in the Centre (+ 18,8%) and 1,4 million in the South (+ 7,3%).

It is worth of notice that in 2014 42,7% of selected materials was composed by organic waste. Interception levels of packaging fractions is much lower, and not only because the quantities produced are minor.

Without organic waste Italian separate collection levels were far from being close to the fixed values, falling down to about 25% (elaboration from data reported by ISPRA).

The collection of packaging materials is still low.

One could raise the reasonable question if this is the right strategy relating to separate collection. The model here presented tries to give an answer reporting the optimal interception level of every fraction and proving that Italian strategy can be improved

3.4 MSW management

In this paragraph the current national quantities regarding waste management are defined. Unfortunately, as shown by Figure 3.5, landfilling was still the most diffused practice.

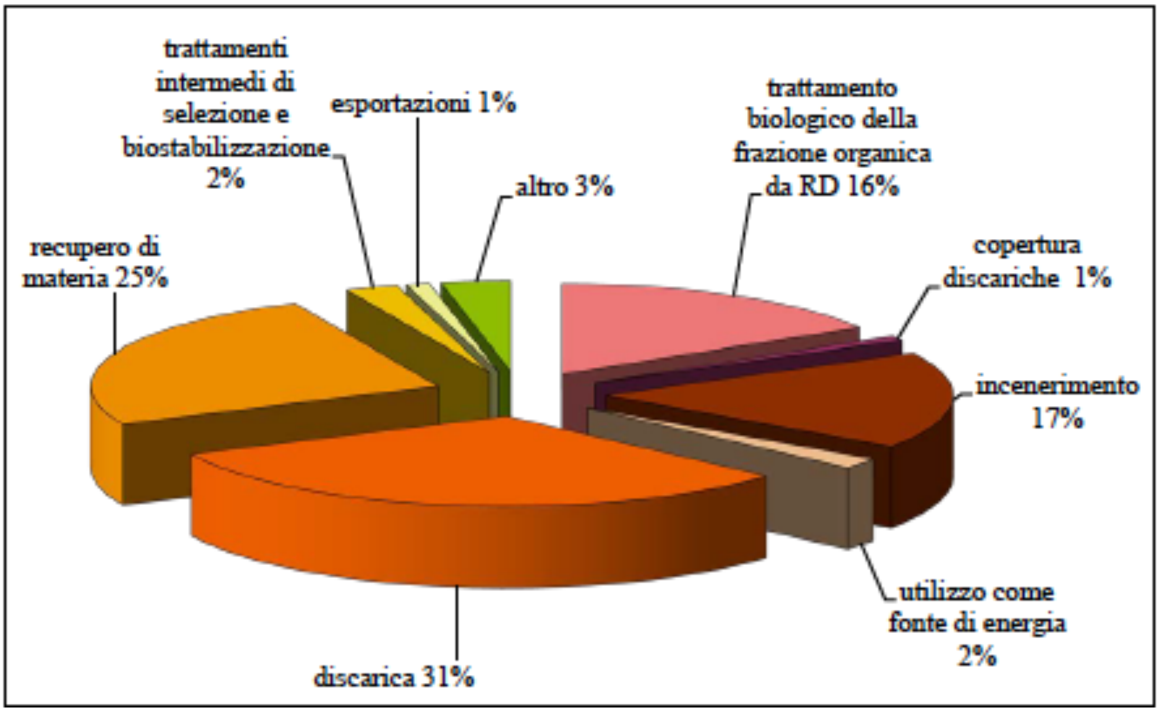
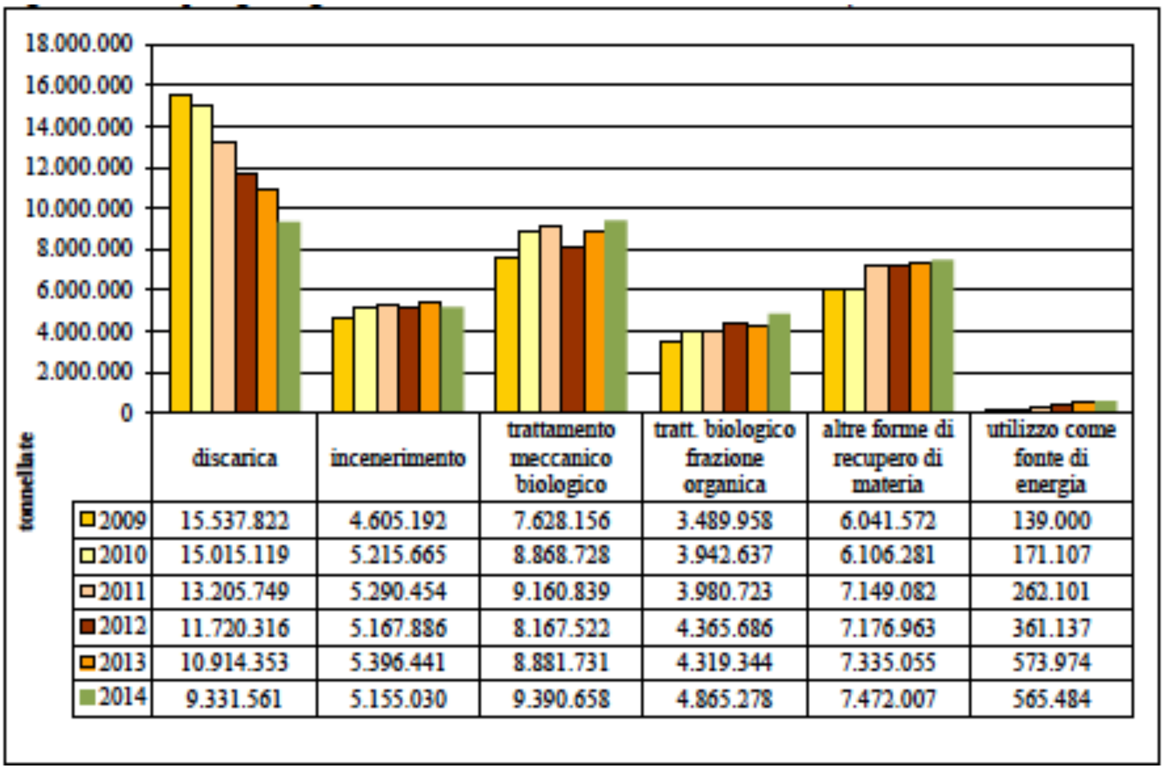


Figure 3.5 - Percentage distribution of treatment processes, 2014 [5]

It should anyway be said that the quantity of waste disposed in dumps, which was 9,3 million tonnes, decreased since 2013 of 14% of almost 1,6 million tonnes. Remarkable is the decrease registered in the centre regions that was equal to 27%. Furthermore, the share of waste landfilled after being pre-treated in MBT plants has increased during the last year, raising from 58% to 70%.

To compensate the reduction of waste landfilled, other form of processing as material recovery and biological treatment of organic fractions have increased.



	discarica	incenerimento	trattamento meccanico biologico	tratt. biologico frazione organica	altre forme di recupero di materia	utilizzo come fonte di energia
2009	15.537.822	4.605.192	7.628.156	3.489.958	6.041.572	139.000
2010	15.015.119	5.215.665	8.868.728	3.942.637	6.106.281	171.107
2011	13.205.749	5.290.454	9.160.839	3.980.723	7.149.082	262.101
2012	11.720.316	5.167.886	8.167.522	4.365.686	7.176.963	361.137
2013	10.914.353	5.396.441	8.881.731	4.319.344	7.335.055	573.974
2014	9.331.561	5.155.030	9.390.658	4.865.278	7.472.007	565.484

Figure 3.6 - National waste management strategies, [tonne / year], years 2009 – 2014 [5]

It is interesting to notice how:

- Values relative to landfilling decreased of about 40% in only five years, probably also because of the reduction in the total waste production and the very high initial value

- Incineration, after the growth registered during 2009 – 2011, stabilised

- Material recovery and biological treatment are increased respectively of 23% and 41%

Also Mechanical Biological Treatment became significant, disposing 26,3% of the whole MSW quantity, but being it a form of pre-treatment, we must analyse what happens next.

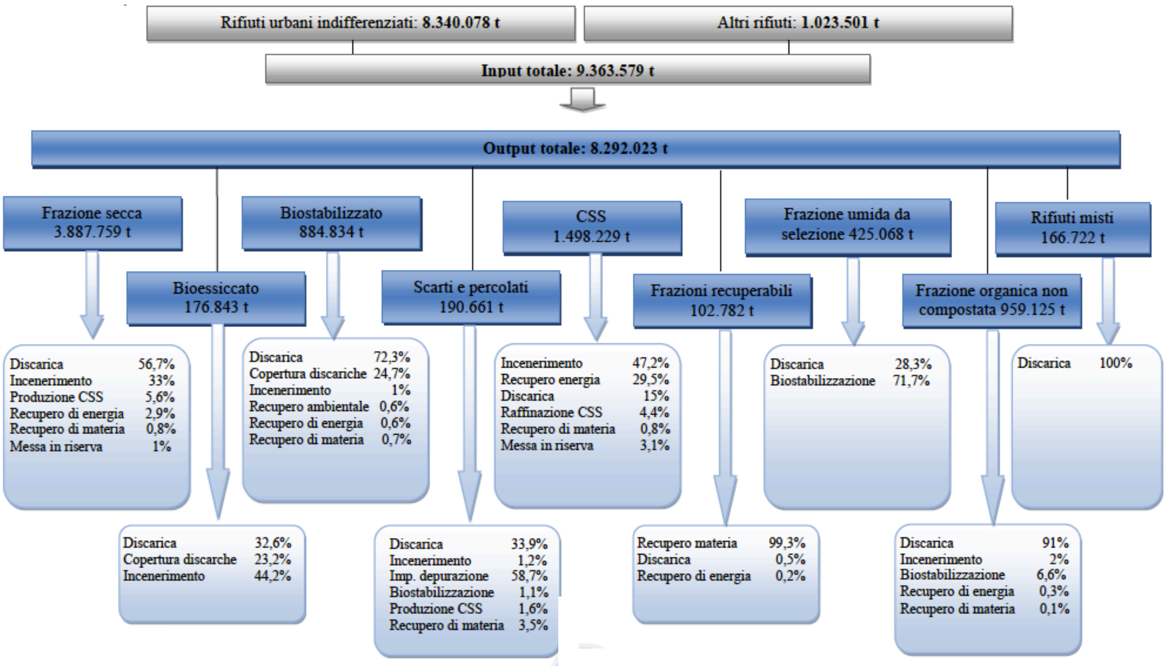


Figure 3.7 - Representation of the quantities and possible destination of the waste and materials exiting MBT, year 2014 [5]

As shown by Figure 3.7, of 8,3 million tonnes out from MBT, 4,3 million, more than the half, went to landfilling; very low is the quantity of Refuse Derived Fuel incinerated, and even lower is the part of recoverable fraction sent to recycling which is only 1,1% of the whole output: in many regions MNT works only as a bio-stabiliser.

In conclusion to the chapter we consider useful discussing about the situation of energy recovery in the Italy.

Probably due to new campaign against incineration at a regional and national level, Italy stopped investing in this technology and four plants were dismissed in the last year, seven since 2010.

MSW incineration decreased to 4,5 million tonnes (Figure 3.6) [5].

The major part of the incinerator, 29 out of 44, is located in Northern Italy, particularly in Lombardia, 13, and Emilia Romagna, 8.

It is worth of notice how these two regions recorded separate collection rates higher than 50% in 2014 proving how separate collection can be coupled efficiently with incineration; one solution does not exclude the other.

4 The waste treatment processes

In the following chapter we analyse more deeply the different ways to manage the waste flows that have been considered by the model. Both the operating principles of all the treatment systems considered and the hypothesis made to model them are discussed.
The two fundamental hypothesis on which the whole model is based are:

1. The waste management system configuration (Figure 4.1)
2. The composition of the municipal solid waste (Figure 4.2).

Regarding the first one, a standard waste management system as represented in Figure 4.1 was assumed for the model:

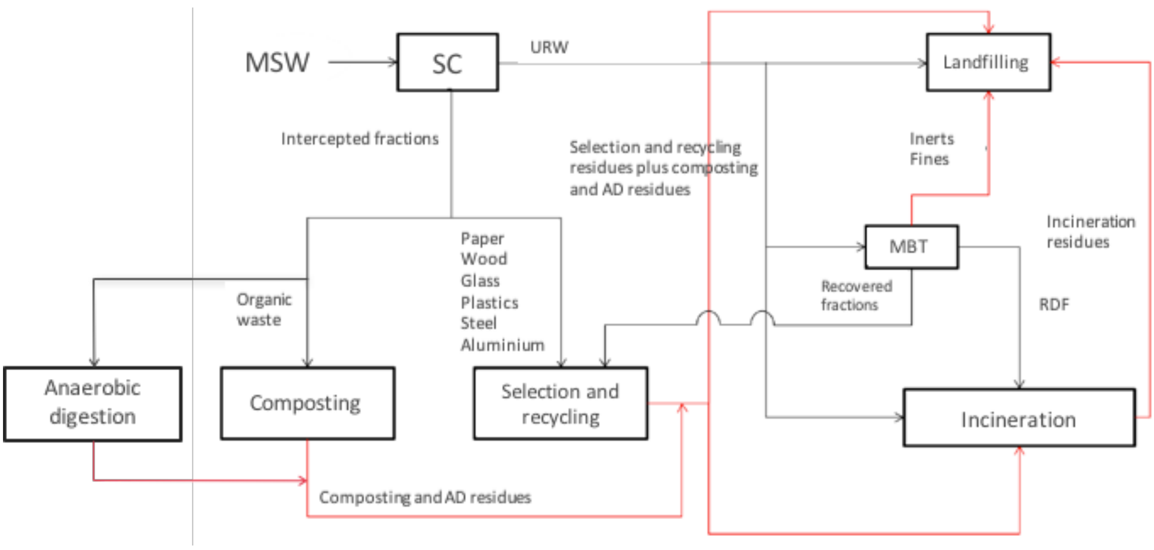


Figure 4.1 - Graphical representation of the standard waste management system considered. SC: Separate Collection, MBT: Mechanical Biological Treatment, MSW: Municipal Solid Waste, URW: Urban Residual Waste, RDF: Refuse Derived Fuel

It is a system comprehensive of all the possible disposing processes of a modern Country.

While we applied the model to a case study referred to Italy, the parameters to insert are the most representative as possible of Italian current situation.

Regarding the second one we assumed a MSW composition described by $f_i = \frac{kg\ fraction\ i\text{-}th\ in\ MSW}{kg\ MSW}$:

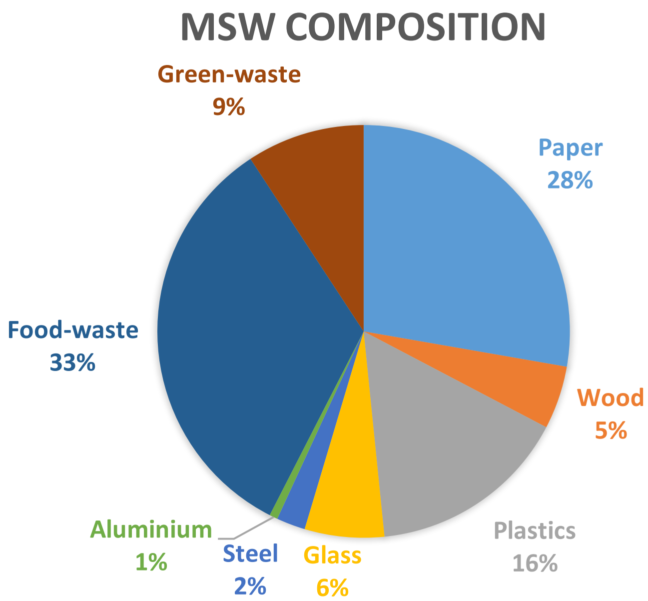


Figure 4.2 - Reference MSW composition used by the model, [%]. [8]

1. Paper (and cardboard): 25,8%
2. Wood: 4,6%
3. Plastic materials: 14,6%
4. Glass: 5,8%
5. Steel: 2,1%
6. Aluminium: 0,6%
7. Food waste (including organic fines): 30,9%
8. Green waste: 8,6%
9. Inert fines 3,9%
10. Other (WEEE, textile, drugs…): 3,1%

Such composition, assumed from *Giugliano* [8] is the result of a series of surveys around Italy and the analysis of bibliographical data

As the model concerns the whole country, the national average composition is assumed to be suitably representative.

The composition of the MSW is fundamental because the strategies identified by the model strongly depends on it, as it will be clarified in Chapters 6 and 7.
It must be said that the composition reported by *Giugliano* in [8] is very similar to the one estimated by ISPRA for 2014.
According with *Giugliano*, in the model fraction Inert fines is assumed to be never separately collected but entirely sent to URW.
Fraction Other instead is supposed to be completely collected and sent to specific treatment.

4.1 Separate collection

Separate collection means the sorting of waste into different flows with similar composition to facilitate the recovery.
The main strategies to carry out the separate are:

1. Kerbside collection: every household has its own bins in which divide the waste produced, the municipality provides the service to collect the waste for every household

2. Drop-off collection: a considerable quantity of containers is placed through the municipality and householders go there and throw their waste into the correct one

There are some fractions, commonly the bulky or particular ones, which are not collected by the municipality but the burden of bringing them to the ecological platform is left to the householders.
The model considered Wood and Green-waste among these fractions.
Another distinction among collection schemes is:

1. Mono-material collection: different fractions have their own specific container

2. Multi-material collection: some fractions are collected together in the same bin, e.g. aluminium and plastics

The four categories above described can mix together forming all the four solutions. Studies proved that kerbside collection is the scheme which provides the highest rate of intercepted materials while drop-off collection reaches the highest values of intercepted flow purity (the absence of extraneous fractions contamination) [8], [24].

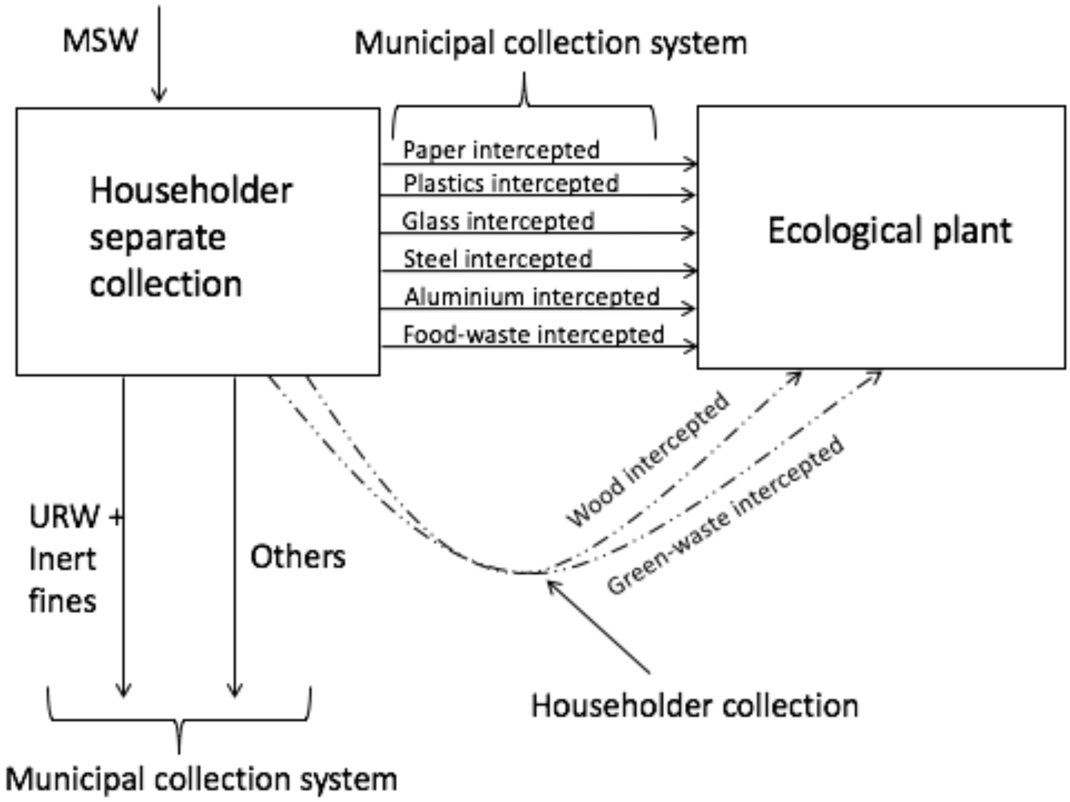


Figure 4.3 – Collection system considered by the model: kerbside mono-material collection. Wood and green-waste are brought to ecological plant by householders

The model assumes a kerbside mono-material collection for each fraction except from wood and green-waste which are supposed to be brought to the ecological platform by the householders in accordance with [8] (Figure 4.3).

As told, is assumed that Inert fines are completely destined to URW while the fraction other is entirely intercepted and sent to special treatment processes.

4.2 Material recovery

According to the EU Directive, " '*recycling*' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" [14].

Organic material reprocessing which the Directive refers to, is constituted by composting and anaerobic digestion: about that is discussed in the next chapter.

For sure, recycling represents a way to save resources [25] and is generally convenient for almost every fraction, but a more accurate analysis of this practice convenience is conducted in Chapter 5.

The material recovery process is composed by the following steps:

1. Separation: to separate multi-material flows collected together, e.g. LDPE, HDPE, LLDP composing plastics fraction

2. Selection: to remove the impurities from the intercepted fraction in order to send a pure stream to recycling

3. Secondary production: i.e. the recycling process itself

All these steps produce residues. We modelled this fact assuming that the steps can be described by the three material efficiencies:

- η_{sep}: separation efficiency (always assumed to be 1)
- η_{sel}: selection efficiency, variable with the interception level
- η_{rec}: recycling efficiency, fixed

	Recycling efficiencies
	[%]
Paper	89,00
Wood	95,00
Plastics	74,53
Glass	100,00
Steel	90,50
Aluminium	83,50
Food-waste	100,00
Green-waste	100,00

Table 4.1 - recycling efficiency values, [8]

Recycling efficiency values were taken from [8] and represented the Italian situation at 2011, reasonably not different in terms of material efficiencies from the current one.
Generally, the global efficiency of the entire material recovery process is given by the product of all the three terms and it is a value approximately around 80% [26]. For this reason, a not negligible quantity of residues to be managed is formed. Depending on their properties they can be sent to WtE or landfilling.

The model, considering mono-material collection, neglects the term η_{sep} and builds energy and CO_2 emission indicators for every fraction intercepted to evaluate the savings related to recycling: it is imagined that the quantity of secondary material obtained substitutes the same amount of material produced by primary production. This methodology, surely appropriate and accurate, revealed some weaknesses that in chapter 5 we discussed about.
As told, every stream of recovered fraction generates a flow of residues: it is left to the algorithm process deciding how much of the residues from every specific fraction recycling should be sent to incineration rather than landfilling.

4.3 Energy recovery

Energy recovery in Waste to Energy plants means the incineration of the waste flow with the production of electric energy alone or, as in the majority of the cases, cogeneration of heat and electricity. This could happen because some fractions, represented by plastics, paper, wood and organic, have a Lower Heating Value (LHV) good enough to be efficiently combusted in special power plants.

Furthermore, incineration has the quality that reduces the waste volume and sanitises it.

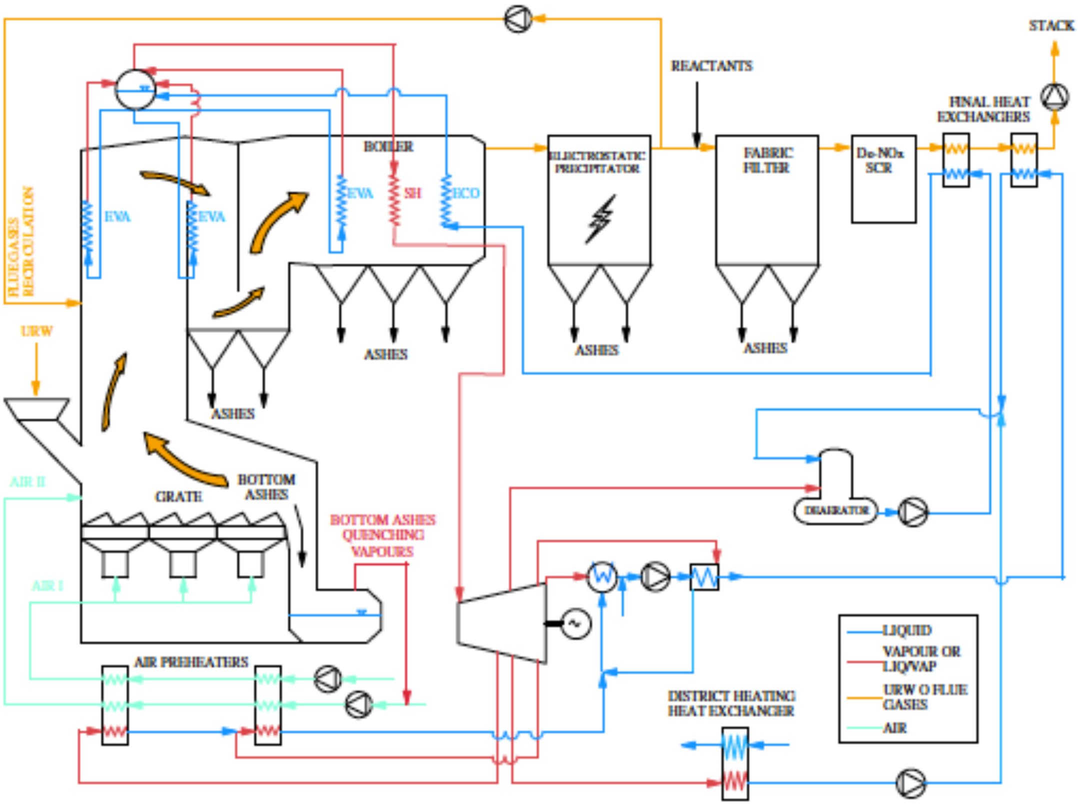


Figure 4.4 - Example of a WtE plant [27]

Energy recovery is made possible through a Rankine thermodynamic cycle that exploits the heat produced by waste combustion (external combustion) generating power (Figure 4.4).
While the components of the Rankine cycle are similar to the ones of a typical thermo-electric power plant (pumps, economisers, condenser and turbine, bleeding if heat power is needed), the boiler is slightly different.
The combustion chamber is often constituted by a grate where waste rotates while falling down in order to reach high mixing with air and being better oxidised. Sometimes, for the combustion of RDF, is preferred the fluidised bed.
To avoid chlorine components such as dioxin, the minimum temperature in the chamber should be in the range of 800° – 850° C [28].
The flue gas treatment is composed by particulate filters, electrostatic or fabric, Selective Catalytic Reduction (SCR) DeNOx reactors and a dry or wet (scrubber) acid compounds removal system.

It has been yet proved that environmental performances of a modern incinerator are similar to a modern power generation plant and that there is no risks for human health [7], [27]. While local pollutants production is controlled by the flue gas treatment discussed before, global pollutants, i.e. CO_2 emissions, depend on the properties of the fraction combusted. CO_2 emissions from the incinerator are calculated by the quantity of fossil carbon content in the different fraction estimated in [27] and reported in Table 4.2.

	LHV [MJ/kg]	Fossil carbon content [g/kg]
Paper	10,84	20,13
Wood	13,94	5,79
Plastics	25,63	603,07
Glass	-0,02	0
Steel	-0,02	0
Aluminium	-0,02	0
Food-waste	5,42	1,8
Green-waste	2,81	2,48
Inert fines	-0,83	0,53
Others	0	0

Table 4.2 - Properties of selected fractions [27].

The incinerating plant used to model WtE has little-medium size, typical of the major part of incinerator distributed in the territory (1200 tons/day): it is a cogenerative plant producing heat and electricity with an annual average thermal efficiency of 25% and electric efficiency of 20% [29].
A substitutive perspective is mantained by assuming that the energy produced by incineration substitutes the same amount of energy supplied by Italian thermoelectric grid. The same point of view is kept for environmental optimisation considering that the CO_2 emissions from the incinerator are compensated by the lack of the ones the thermoelectric grid would have emitted to produce the same amount of energy.
In order to account for possible changes in the Italian power generation system, a sensitivity analysis has been performed in which electricity produced by WtE plants substitutes the one by the whole electric grid, included renewables.

	Average electric efficiency (%)	Average thermal efficiency (%)	Electric emission factor (g_{CO_2}/kWh_{el})	Thermal emission factor (g_{CO_2}/kWh_{th})
Incinerator	0,2	0,25	Calculated by model	Calculated by model
Thermoelectric grid	0,46	0,9	554,7	229,6
Electric grid	Not considered	Not considered	337,4	229,6

Table 4.3 - Efficiencies and emission factors considered by the model, [29], [30], [31]

Efficiency and emission factors for electric and thermoelectric grid of Table 4.3 are taken from [29], [30] and [31].
The equations used to model these aspects are fully reported in Chapter 7.

4.4 Mechanical Biological Treatment

The main purposes of this form of waste pre-treatment are three:

1. Stabilisation of the organic fraction
2. Recovery of recyclable fractions, mostly metals and plastics
3. RDF production

To achieve these objectives, waste flow encounters a series of treatment apt to remove humidity by oxidation of great part of the Carbon present in the organic fractions, separation of inert and fine materials and the recovery of metals and plastics through magnetic, eddy current and NIR separators.

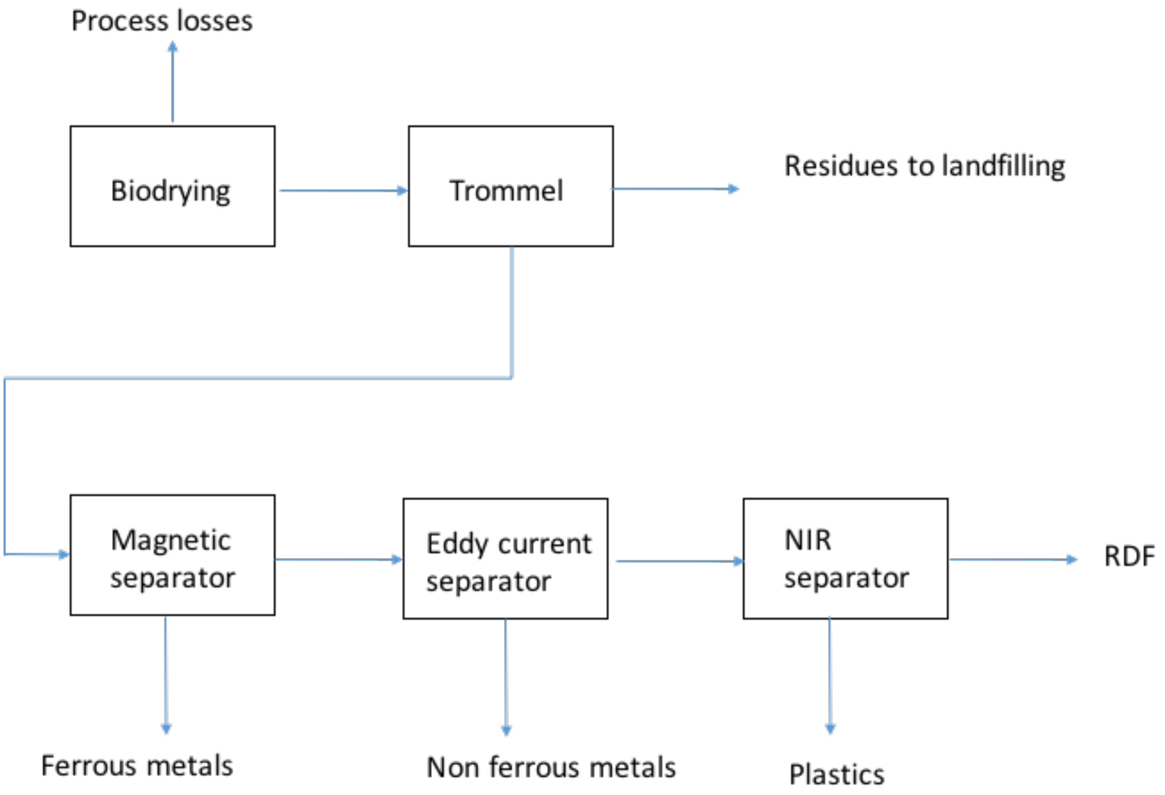


Figure 4.5 - MBT facility scheme

The configuration of the MBT represented in Figure 4.5 was the one assumed as reference for the model. It was estimated from MatEr bibliography referred to a case study representative of a modern MBT plant.

The full set of equations apt to model MBT can be found entirely in 8.12 and 9.12.

It is assumed that the fractions recovered are sent to recycle, the RDF produced to WtE plants and all the residues to landfilling.

4.5 Landfilling as a secure way of disposal

As deduced by the previous paragraphs, there is always going to be a not negligible flow to be disposed in dumps: at least the residues from the combustion of URW (sometimes recoverably) and SSR.

The EU Directive states: “ ‘disposal’ means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy” [14].

The general term disposing here means landfilling.

A modern disposal facility is formed by the following structures [7]:

- Impermeable covering to avoid hazardous fluid percolation at bottom and sides
- Fluid removal system
- Biogas capturing system
- Covering at the top

Biogas is a fluid formed by natural anaerobic digestion of the organic fraction. It is formed by CO_2 and CH_4, which, if released in atmosphere, has a high Global Warming Potential (GWP_{CH4} = 25 GWP_{CO2}). The percentage of methane in biogas is 0,6 [32]. A biogas production of 500 m^3/volatile fraction is assumed [33], [27].
The dump modelled is assumed to have a biogas capturing system with an efficiency of 40% [34]. Biogas slipped is released in atmosphere causing the noxious effect described; the fraction captured is supposed to be burnt in an internal combustion engine for electric power production with efficiency equal to 35% (average value from [35]).
Once again it is adopted the substitution perspective and all the electricity produced by the engine replaces the same quantity of energy from the thermoelectric grid avoiding anthropogenic CO_2 emissions.
It is worth of notice that landfilling is an environmental noxious way of disposal because of the fact that biogas slipped, which is more than a half of total biogas produced, has a very high GWP; the emission reduction due to biogas combustion do not balance the ones caused by biogas slip.

4.6 The collection and transport

It is obvious, looking the waste management diagram of Figure 4.1, that every flow of waste needs to be transported from a process to the following one. We considered two kinds of transfer:

1. Collection: the transportation from the household to the ecological platform

2. Transport: all the other form of transfer, i.e. transport from ecological plant to material recovery facility or WtE or dump, transport of SSR to WtE/dump and incineration residues transport to landfilling

	Collection distances [km/ton]	Transport distances [km/ton]
Paper	48,7	61
Wood	0	111,7
Plastics	55,4	79,5
Glass	37	81,4
Steel	25,4	96,4
Aluminium	25,4	86,6
Food-waste	65	100
Green-waste	0	100
URW	14,5	100 (every destination)
SSR	-	100 (every destination)
Incineration Residues	-	100

Table 4.4 - Collection and transport distances, [km / tonne] [8]

	Energy factor [MJ/km]	Emission factor [kg CO2/km]
Collection	17,44	1,244
Transport	2,66	0,165

Table 4.5 - Energy and emission factor relative to collection and transport, [MJ/km], [kg CO_2/km]. Values taken from Ecoinvent database

Energy consumption and emissions are calculated simply by multiplying quantities per distances per specific energy/emission factors (from the Ecoinvent database) reported in Table 4.4and Table 4.5.

As announced, wood and green-waste are assumed to be brought to the ecological platform directly by the householder. Therefore, energetic, environmental and economic expenses related to the collection of these fractions are excluded from the model. Actually the society bears these energetic and monetary costs but they are not easy to be modelled due to the lack knowledge of people habits.

5 Indicators for material recovery

This chapter is entirely devoted to the analysis of methodology adopted to model material recovery.
To evaluate energetic and environmental impact of material recovery, we needed to construct an indicator that took into account all the activities related to primary and secondary production of the merceological fractions.
In order to do that, we had to make use of the Life Cycle Assessment (LCA) methodology.
To better explain the followed procedures, we divided the explanation of the calculation of the indicators methodology in two paragraphs on the base of fractions composition.

5.1 The indicators for inorganic fractions

5.1.1 The indicators

Among inorganic fractions we included:

- Paper
- Wood
- Plastics
- Glass
- Steel
- Aluminium

For all of them the material recovery process brings to obtain a new product which can substitute primary material and has similar (in 5.1.3 we explain why similar and not equal) properties.

The indicator, which accounts for the reduction of energy consumption and emissions, was constructed for every single fraction:

$$E_{recycle} = \frac{MJ}{ton} = (CED_{\substack{primary\\production}} - CED_{\substack{secondary\\production}} \cdot S) \cdot \eta_{sel} \cdot \eta_{rec}$$

and

$$EM_{recycle} = \frac{kg_{CO2}}{ton} = (GWP_{\substack{primary\\production}} - GWP_{\substack{secondary\\production}} \cdot S) \cdot \eta_{sel} \cdot \eta_{rec}$$

where:

$E_{recycle}$: the indicator for energy

$EM_{recycle}$: the indicator for emissions

CED: Cumulative Energy Demand of the production process

GWP: Global Warming Potential of the production process

S: substituition ratio

η_{sel}, η_{rec}: selection and recycling efficiences

5.1.2 CED and GWP

CED and GWP is a particular terminology derived from LCA lexicon [36]:

- CED: the acronym stands for Cumulative Energy Demand and, as the name suggests, is a value that accounts for all the energy consumed by a specific material to be produced, considering its entire life cycle (from the cradle to the grave)[1]. It is calculated in terms of Primary Energy.

- GWP: Global Warming Potential, represents all the emissions caused by the entire life cycle of the product

[1] Sometimes, as the case of the model here presented, it is more useful to stop the analysis not to the grave, but to the gate of the production plant: *cradle to gate LCA*. Here, such approach is necessary to avoid double counting because the energy consumption and emissions related to disposal, being the object of the optimisation, are directly calculated by the model.

A graphical representation of some (all would have been impossible!) of the processes considered by LCA are reported in Figure 5.1 and Figure 5.2, both for primary and secondary production:

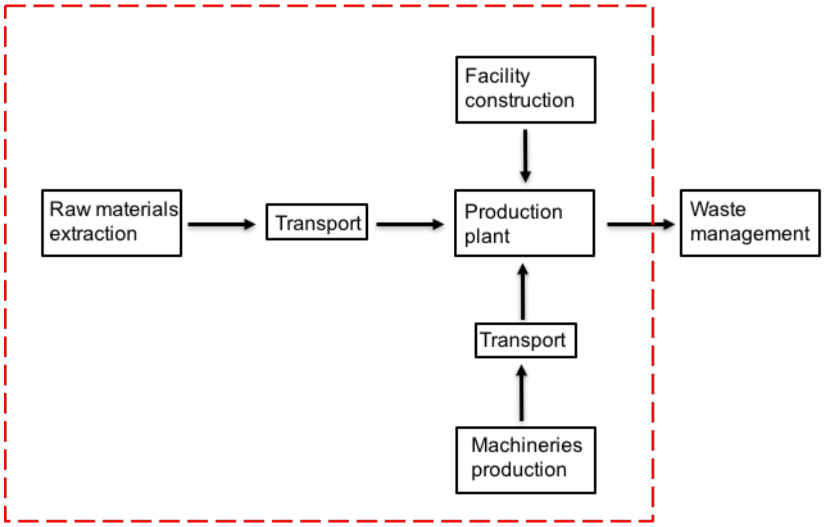


Figure 5.1 - Example of processes considered by LCA and the boundaries for the calculation of the values of CED and GWP for primary production

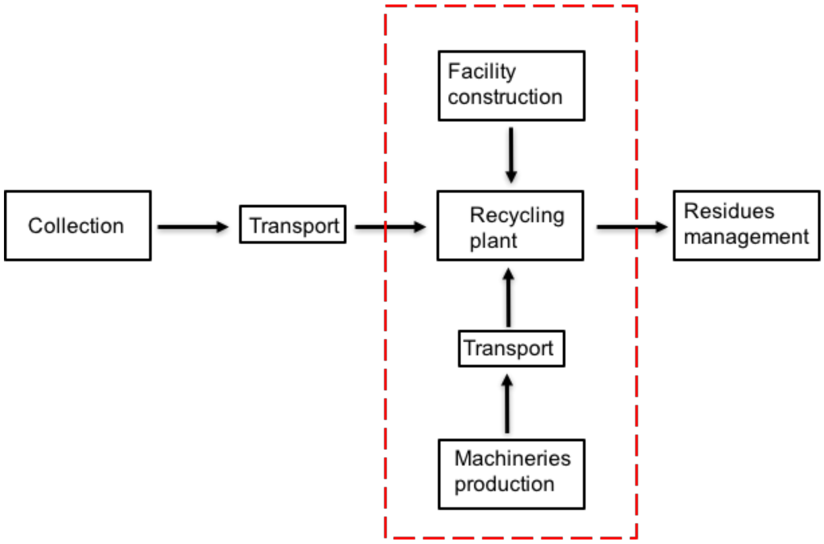


Figure 5.2 - Example of processes considered by LCA and the boundaries for the calculation of the values of CED and GWP for secondary production

Both values for primary and secondary production of CED and GWP where found by the use of the software Simapro made available by MatEr staff. The software collects automatically all the data from its database Ecoinvent 3.3 [37], and calculates the values of CED and GWP.

CED indicator is calculated through a specific methodology proposed by Ecoinvent (there is not a unique standardised methodology), while GWP through the characterisation methodology CML 2001 baseline, developed by Leiden University [38], [36].

Allocation, cut-off by classification was the chosen method among the proposed ones by Simapro: "this system model subdivides multi-product activities by allocation, based on physical properties, economic, mass or other properties. By-products of waste treatment processes are cut-off, as are all by-products classified as recyclable." [39].

In other words, it means that the positive effects due to material or energy recovery of a specific product, are not subtracted from primary production: this way a LCA *cradle to gate* was performed.

Two adjustments were made to better fit CED and GWP values found to the model:

- Primary production: for combustible fractions the *feedstock energy* [2] reported in the Ecoinvent module has been subtracted from their CED values.

- Secondary production: from the results found, energy consumption and emissions due to the collection and transport of waste have been subtracted. This to avoid double counting because, as we told, the model itself considers the collection and transport processes.

The values used by the model were found using software Ecoinvent and choosing representative data of European state of the art:

[2] Feedstock energy is the intrinsic energy of the fraction due to the fact that it is combustible (it often equals the LHV). It is added to the process energy for the calculation of the CED. It has been subtracted because it overestimates the energy consumption from primary production. Actually the fraction, as waste, can be incinerated if sent to WtE, so that amount of energy is not lost. Similarly, if recycled, energy is conserved!

	CED primary prod.	CED secondary prod.	GWP primary prod.	GWP secondary prod.
	[MJ/ton]	[MJ/ton]	[kg CO2/ton]	[kg CO2/ton]
Paper	25.120	2.427	1.190	145
Wood	13.848	10.558	363	273
Plastics	35.776	6.706	1.999	389
Glass	18.700	10.761	1.310	848
Steel	20.800	8.098	1.920	394
Aluminium	178.000	11.597	10.000	1.014

Table 5.1 - Values of CED and GWP found, [MJ/tonne], [kg CO_2/tonne]. Ecoinvent

Values relative to plastics and paper secondary production have been taken from [36] and are calculated on the basis of Italian plants real data.

5.1.3 Substitution ratio S

For the major part of the fraction is unrealistic to consider virgin and recovered material equal.

Recovered ones have often lower quality, performances or simply a lower economical value. Substitution ratio considers all these topics and is expressed as:

$$S = \frac{kg_{virgin\ material}}{kg_{recovered\ material}} \leq 1$$

The values of S used for the model were taken from [36], [40]:

	Substitution ratio [%]	
Paper	89	Technical considerations (max n° of recycling)
Wood	60	Technical considerations (physical properties)
Plastics	89	Economic considerations
Glass	100	Technical considerations
Steel	88,1	Technical considerations (presence of impurities)
Aluminium	83,5	Technical considerations (presence of impurities)

Table 5.2 - Substitution ratio values [36], [40]

5.2 The indicators for organic fractions

5.2.1 The indicators

Organic fractions are:

- Food-waste
- Green-waste

As established by the Directive, material recovery related to organic fractions can follow two different paths:

1. Anaerobic Digestion (AD)

2. Composting

Recycling of these fractions does not lead to a secondary material production with similar properties to primary, but it yields compost, a substance beneficial for soil, and in one case (AD), the production of biogas.
Therefore, it was impossible to use the equation reported in 5.1.1 but we had to adapt it:

$$E_{AD} = \frac{MJ}{ton} = CED_{AD} \cdot \eta_{sel}$$

and

$$EM_{AD} = \frac{kg_{CO2}}{ton} = GWP_{AD} \cdot \eta_{sel}$$

Where:

CED_{AD}: Cumulative Energy Demand required by the Anaerobic Digestion process (if negative energy is produced)
GWP_{AD}: Global Warming Potential associated to AD (if negative emissions are saved)

For composting, the indicator is calculated in the same way using CED_{comp} and GWP_{comp}.

5.2.2 Composting

Composting is an aerobic digestion process which produces fertilizers and soil amendments from waste.
In particular compost can be divided into [41]:

- Green compost: entirely produced by green-waste, it is often used as amendment able to increase physical and biological properties of soil

- Mixed compost: produced by organic fraction in general, but with a minimum presence of ligneous material. This type of compost functions as both amendment and fertilizer

The values of CED and GWP for composting are taken from [25]:

	CED comp	GWP comp
	[MJ/ton]	[kg CO2/ton]
Food-waste	15	-55,5
Green-waste	15	-55,5

Table 5.3 - Values of CED and GWP for composting, , [MJ/tonne], [kg CO_2/tonne]. [25]

Since generally food-waste and organic-waste are mixed together when sent to composting, the values are equals and refer to a mixture of both of them.
We consider this fact not to be particularly limiting because, even if one of them is not intercepted at all, there will always be a certain quantity of the other coming from processes different from MSW management (e.g. agricultural waste)
The main hypothesis assumed by *Grosso* and *Rigamonti* to find such values of CED and GWP are [25]:

- Yields in compost between 30% and 50%

- Electricity consumption between 50 and 60 kWh per tonne to be treated
- A content of nutrients of 6,2 to 7,5 kg for N, 2 to 5 kg for P, and 4,5 to 6 kg for K

5.2.3 Anaerobic digestion

Anaerobic digestion is a set of processes by which microorganisms break down biodegradable fractions in the absence of oxygen; it can be wet or dry.
The process begins with bacterial hydrolysis of input material and ends with the methanogens of acetic acid formed [32].
The outputs are digestate and biogas.

	CED AD	GWP AD
	[MJ/ton]	[kg CO2/ton]
Food-waste	-2312,5	-151
Green-waste	-2312,5	-151

Table 5.4 - Values of CED and GWP for anaerobic digestion, [MJ/tonne]. [25]

The hypothesis assumed are [25]:

- Digestate: it undergoes a process of aerobic digestion producing compost with similar properties to the one produced by conventional composting processes.

- Biogas: it is used to produce thermal and electric power or electricity alone in internal combustion engines. Energy produced replaces the one supplied by conventional fossil fuel plants.

Is worth to be remarked that the substitution of energy produced by AD with the one by thermoelectric grid is the same assumption considered for incineration.

5.3 Considerations about the use of LCA indicators

CED and GWP values have a great impact on the developed model affecting the material recovery results.
Therefore, we are very conscious that the right choice of this values is mandatory.
While CED and GWP for composting and Anaerobic Digestion have been objects of many studies referred to the Italian situation [25], [41], inorganic fraction data referred specifically to the Italian production system are harder to find.

5.3.1 LCA values from bibliography

In order to evaluate the reliability of the values used for inorganic fractions found by Ecoinvent, a bibliographic research was performed for all them.

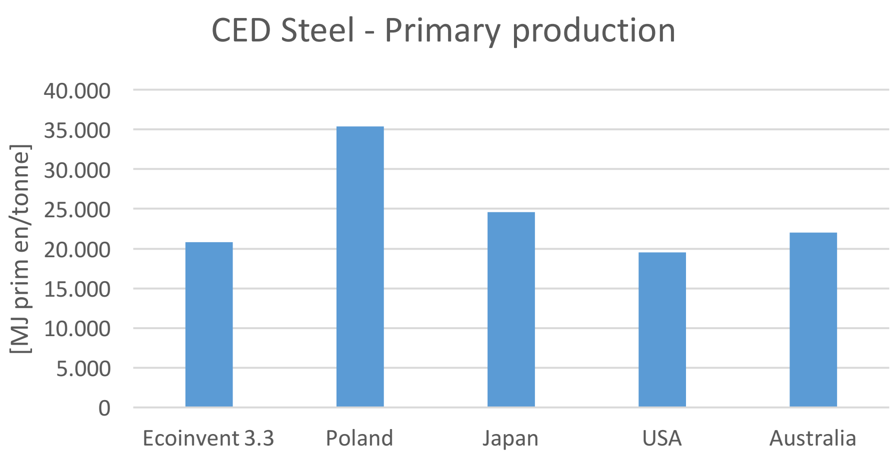


Figure 5.3 - Values of CED found for steel [42]–[45]

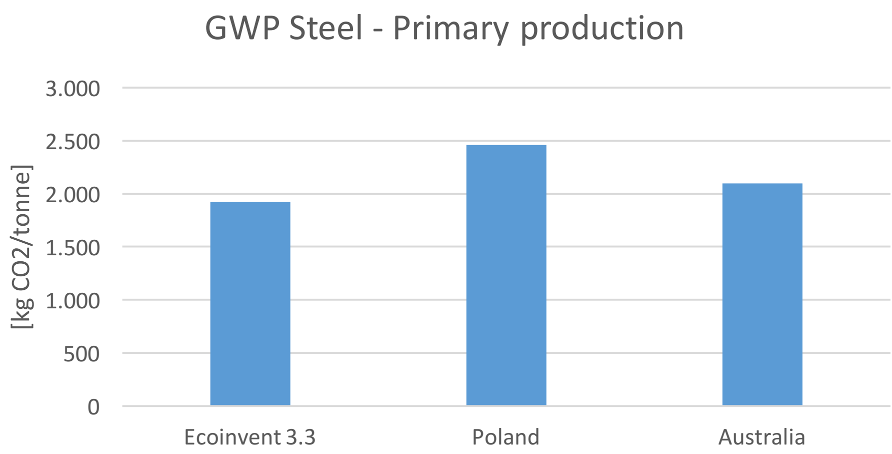


Figure 5.4 - GWP values for steel, (MJ/kg) [42], [45]

Figure 5.3 and Figure 5.4 provides the values related to energy consumption and emissions produced by steel primary production in different geographical areas.

Looking at all the values found concerning CED and GWP (reported in Appendix 1), for primary and secondary production, we were able to infer that:

- Steel, glass and aluminium have LCA results, apart from some outliers, coherent both in terms of CED and GWP

- Plastics suffers scarcity of data, but the few found are similar

- Paper and wood have LCA results quite different

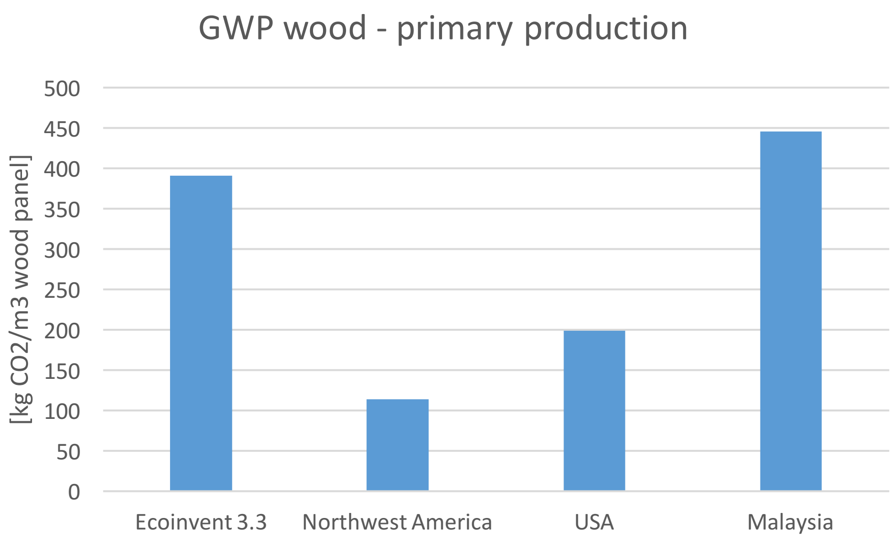


Figure 5.5 - GWP values for wood, (kg CO2/m3) ,[46], [47], [48]

LCA methodology has a strong geographical dependency because transport, extraction processes, and particularly final-to-primary energy conversion factors (more or less represented by national grid thermal and electric efficiencies) are quite different among Countries (as the case of Poland in Figure 5.3).

The correct LCA values to be inserted in the model would be the ones referred to specific Italian situation, but Ecoinvent lacks this data.

In order to examine the reliability of the data found, the analysis has been extended to the final energy consumption of the production plants which should less depend on spatial boundaries.

5.3.2 The production plants values

In this paragraph we show the evaluation of production plants final energy consumption, which, theoretically, should be very similar among different Nations apart from slightly variation due to technology level.

The phase of the entire production process now considered is:

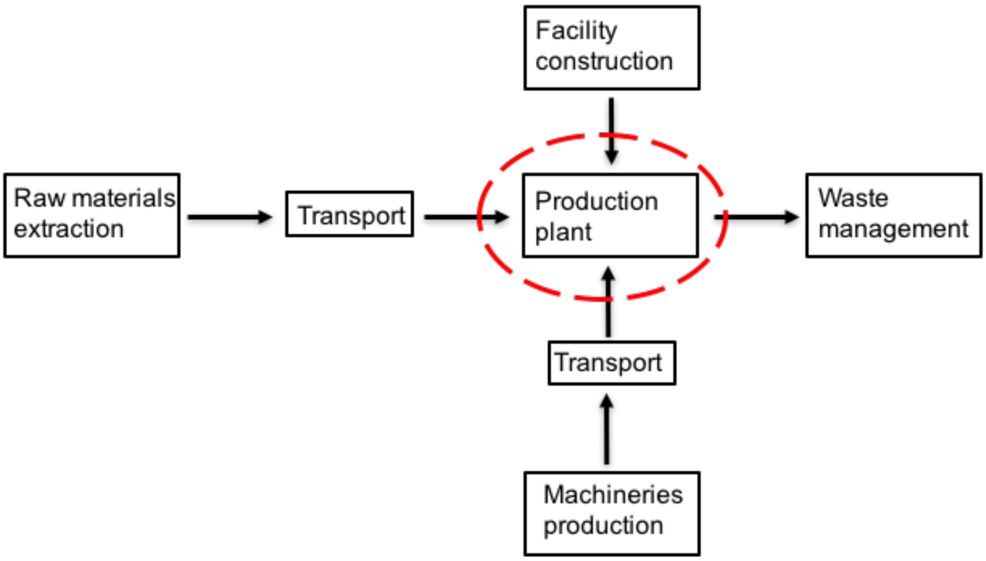


Figure 5.6 - The phase analysed for final energy consumption

Once again we searched in bibliography the values and, where possible, looking also for the sub-processes.

Data taken by Ecoinvent often refers to the reports published together with the software [49]–[53], [54].

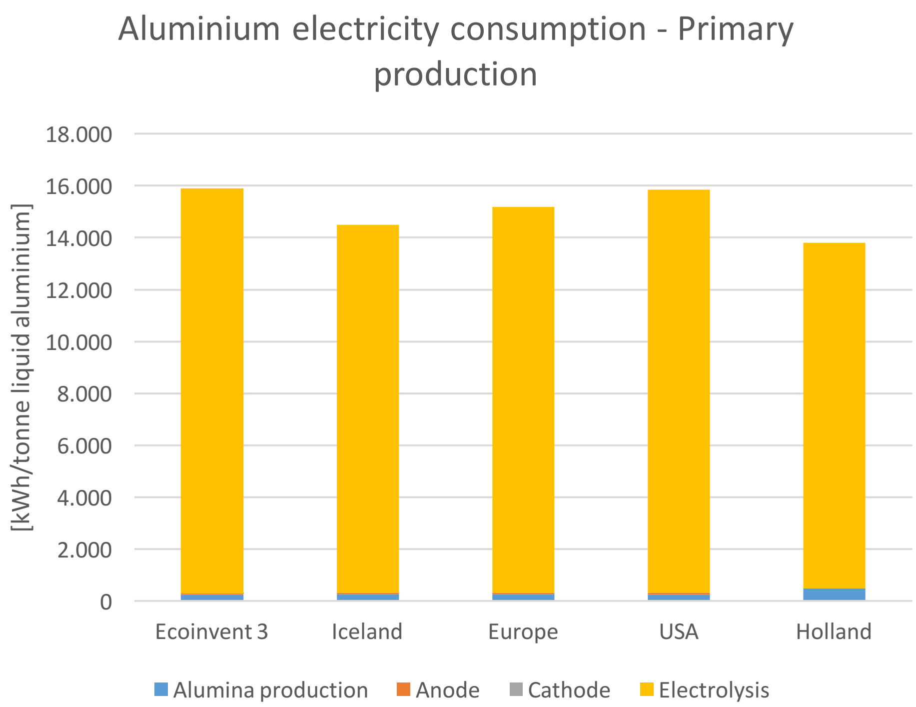


Figure 5.7 - Electricity consumption for primary aluminium production (kWh/tonne),[55] , [39], [57], [58]

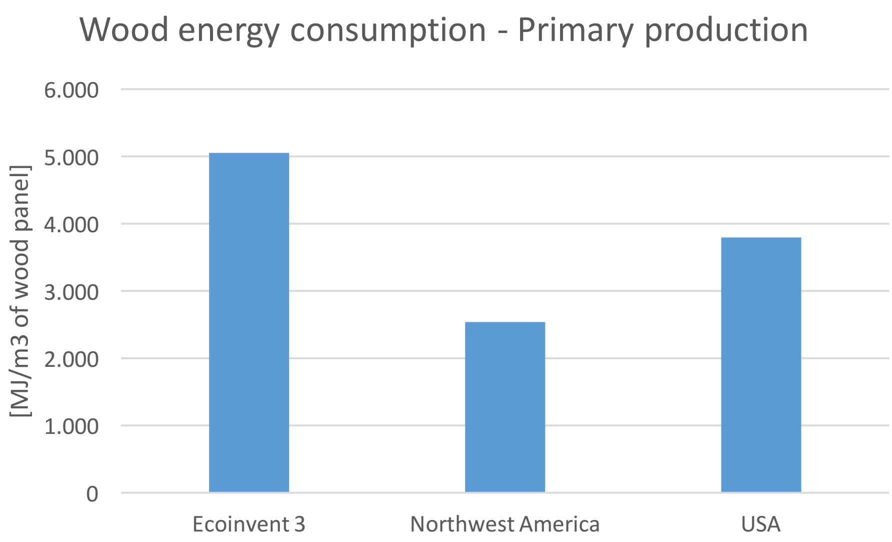


Figure 5.8 - Electricity consumption for primary wood production (MJ/m3), [47], [48]

The results for every fractions are reported only in Appendix 1 to avoid weighing down the paper.
Anyway, from the bibliographical research can be inferred that:

- Steel, glass, aluminium and paper have final energy consumption results, apart from some outliers, coherent

- Plastics suffers scarcity of data, but the few found are similar, as happened for LCA

- Wood have results quite different

5.3.3 Conclusions about using LCA data in the model

As reported, a deep analysis was conducted to better understand LCA results.
Ecoinvent outputs are coherent with the ones found bibliographically for the major part of the fractions. Final energy values related to production plants supports this statement giving to the Ecoinvent software a good reliability.

The fraction paper needs further analysis in term of LCA but production plant values are similar.
Ecoinvent LCA results for wood are quite incoherent and with others and is not even supported by similar production plant consumptions.
Anyway its values of CED and GWP are low compared to the others and this incoherence do not affect the model results[3].

Finally, we can conclude that LCA is a very powerful methodology able to capture all the aspects of a product entire life; however, due to its accuracy it results very complicate and its outputs can be affected too much by the authors' hypothesis and boundaries, not always clear, considered.
For a global perspective of the whole waste management system, the model necessarily needs to be fed by found-by-LCA-data.
In any case, we are fully conscious that model results are strongly dependant on them.
LCA data for the Italian situation properly fitting the model would be preferred to the European Ecoinvent data found, but, as shown in 5.3.2, the values of CED and GWP that most affect the model results (steel, aluminium, paper and plastics) are quite certain and will hardly change in the short future!

[3] Furthermore, the fact that wood has a high LHV and a quite low presence of fossil carbon content, makes incineration always preferable even though its CED and GWP values double or triple!

6 Interception and selection phases

In this chapter we intend to explain how the phases of interception and selection have been modelled.

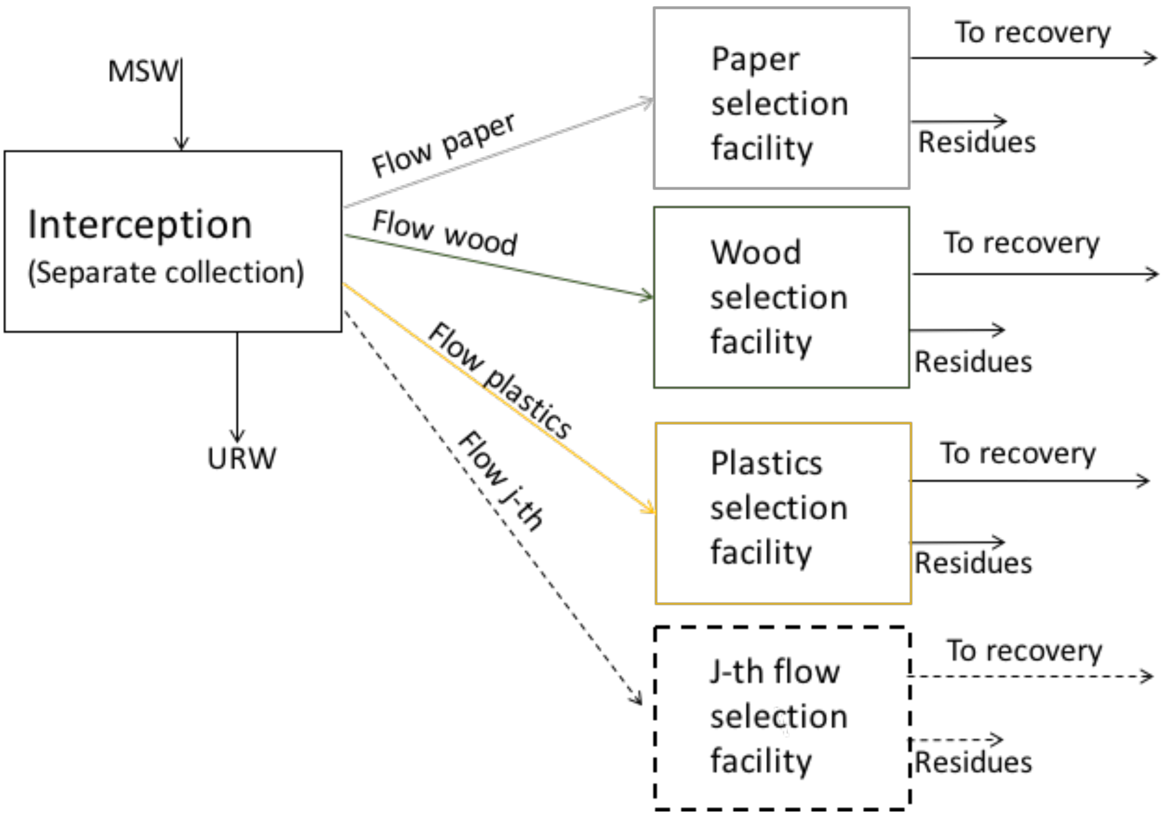


Figure 6.1 - Example of interception and selection phases

As represented by the figure, every flow intercepted by separate collection is sent to the selection facility to be purified from contamination in order to be recycled. This is done due to the fact that recycling plants require a very low presence, almost null, of extraneous fractions.

Though, what comes out from the recycle bin (both from drop-off and kerbside collection), is something that is never pure: in the majority of the cases intercepted flows contain a not negligible presence of other fractions.

To account that, the first ten variables in the model, representing the interception levels, are defined as:

$$x_j = \frac{kg\ of\ j\text{-}th\ intercepted\ dirty\ flow}{kg\ of\ i\text{-}th\ fraction\ in\ MSW}$$

with *j* always equal to *i*.

As it is defined, x_j can assume a value greater than one, especially when the purity of intercepted flow is low.
The only constraint is represented by the mass balance on URW described in 6.1.
The index *i* and *j* are defined by the sets:

- Merceological fractions set:
  $i \in I$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*
  These are the merceological fractions composing MSW and consequently intercepted flows and URW.
- Intercepted flow set:
  $j \in J$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*
  Dirty flow intercepted by separate collection.

The two sets conceptually represent something different, fractions and flows, actually they are formed by the same elements. This is due to the fact that the model considers a mono-material collection for every fraction composing MSW.
Another issue descends from the consideration that intercepted flows are contaminated: how varies their purity with the variation of the interception level?
As later discussed, it is a reasonable hypothesis to consider contaminations directly proportional to the interception level.
To include the all two aspects, the model introduces an analytic relation defining the composition of the intercepted flow, varying with the interception level.

6.1 The interception phase

Interception is the phase in which fractions are divided into different flows and sent to MRF (Material Recovery Facilities).

The numbers reported by Figure 6.2 are just an example.

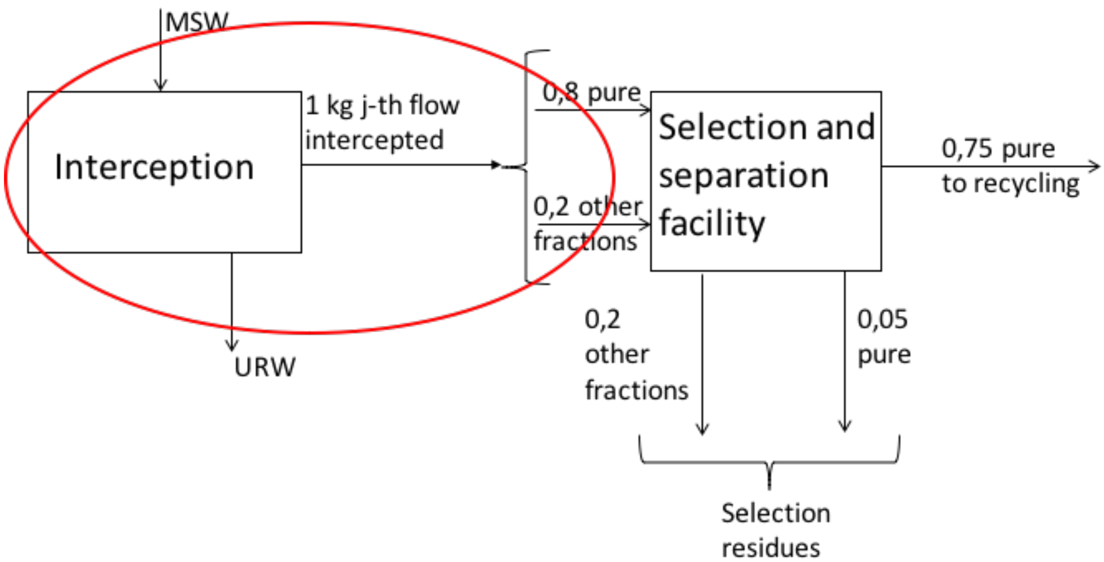


Figure 6.2 - Schematic representation of interception and selection of specific j-th flow. Focus on interception.

As told, we need the composition of all the flows to model what happens after separate collection.

The composition of the intercepted flows is given by the matrix A: it is a $m{\times}n$ matrix.

m is the number of merceological fractions, determined by index i, n the intercepted flows, index j.

The generic element a_{ij}, for a specific interception level, represents:

$$\frac{kg\ fraction\ i-th}{kg\ dirty\ flow\ intercepted\ j-th}$$

For example, considering only three fractions:

Intercepted flows j-th

Fractions i-th

	Plastics	Wood	Glass
Plastics	0,8	0,04	0,08
Wood	0,1	0,9	0,07
Glass	0,1	0,06	0,85

Table 6.1 - Example of matrix A for a three fraction waste system, [kg i-th fraction / kg dirty j-th flow]

The composition of the plastics intercepted flow is simply defined by:

$kg\ pure\ plastics\ intercepted\ in\ flow\ plastics = MSW \cdot f_i \cdot x_j \cdot a_{ij}$ i = j = plastics

$kg\ total\ pure\ plastics\ intercepted = MSW \cdot \sum_{j=1}^{|I|} f_j \cdot x_j \cdot a_{ij}$ i=plastics

where:

$$f_i = \frac{kg\ fraction\ i\text{-}th\ in\ MSW}{kg\ MSW}$$

The composition of URW is determined by the mass balance applied to the whole interception phase:

$$URW_i = \left[\frac{kg\ fraction\ i - th\ to\ URW}{kg\ MSW}\right] = MSW \cdot f_i - MSW \cdot \sum_{j=1}^{|I|} f_j \cdot x_j \cdot a_{ij} \geq 0$$

with *i* fixed at the merceological fraction considered.

This mass balance, not only is the set of equations to evaluate URW_i, it represents also the vector of non linear constraints to the variables:

$$f_i - \sum_{j=1}^{|I|} f_j \cdot x_j \cdot a_{ij} \geq 0$$

Such constraints are very important and limiting even because they point out that is impossible to push until values similar to the unity two fractions contaminating each other; otherwise the value of URW for these fractions would be negative.

6.2 The selection phase

As explained before, selection is the treatment by which dirty intercepted flows are purified by separation of extraneous fractions.

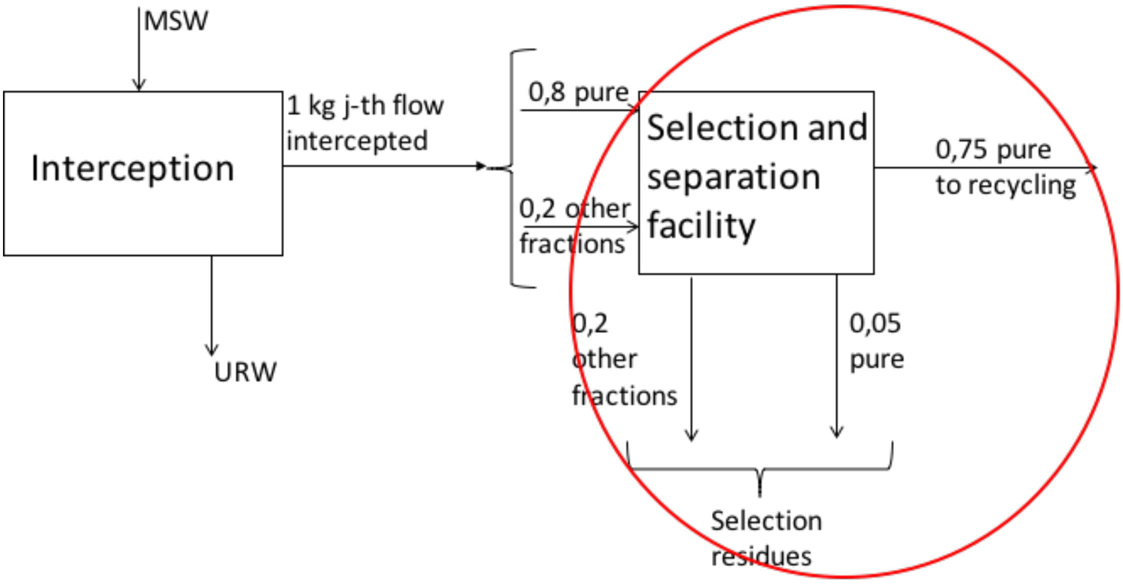


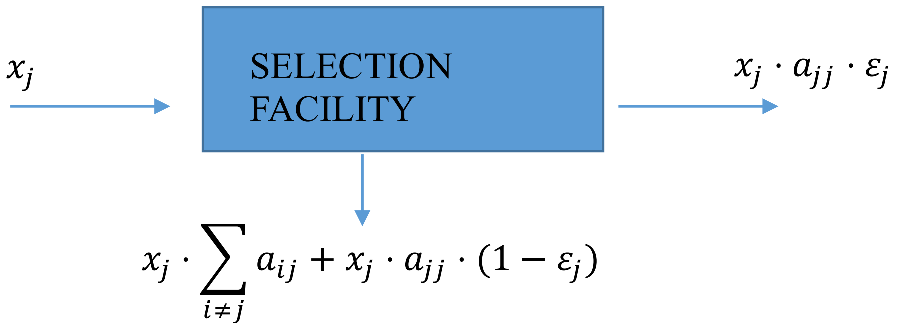
Figure 6.3 - Schematic representation of interception and selection of specific j-th flow. Focus on selection.

Two realistic assumptions of the model can be inferred by Figure 6.3:

1. The flow sent to recycling is completely pure
2. A little percentage of the fraction intercepted is discharged as a residue

Selection residues are formed by all the extraneous fractions present in the flow, plus a little of the fraction intercepted [59], [60].
A new parameter can be identified, representing the quantity of the flow j-th intercepted that is effectively sent to the recycling plant:

$$\varepsilon_j = \left[\frac{kg\ of\ pure\ fraction\ \mathrm{i}-th\ in\ flow\ j-th\ \mathrm{to}\ recycling}{kg\ of\ pure\ fraction\ \mathrm{i}-th\ in\ flow\ j-th\ \mathrm{intercepted}}\right]$$



Assuming, for a specific value of $x_j = \overline{x_j}$ to know $\bar{\eta}_{j,sel}$ and $\bar{a}_{ij}$, ε_j could be calculated from the mass balance of the residues applied to selection phase:

$$residues\ from\ j - th\ flow = \left[\frac{kg\ residues\ from\ j - th\ flow}{kg\ fraction\ i - th\ in\ MSW}\right]$$
$$= x_j \cdot (1 - \eta_{j,sel}) = x_j \cdot \sum_{i \neq j} a_{ij} + x_j \cdot a_{ii} \cdot (1 - \varepsilon_j)$$

The model assumes that the value of ε_j remains constant with the j-th interception level variation. This in accordance with the opinion of some supervisors of selection plants and our experience.

For different values of intercepted flows, η_{sel} can be calculated using the mass balance just seen, with the value of ε_j found now, and the ones of a_{ij} as evaluated in the next paragraph.

This way we defined all the flows sent to material recovery. Anyway, we still have to describe how matrix A was built up.

6.3 The matrix A

By now, we did not mention anything about how the matrix A was filled up: its calculation is the issue of this paragraph.

As we said, it is a $m{\times}n$ matrix with m representing the number of merceological fractions, determined by index i, and n the intercepted flows, with index j.

The generic element $a_{i,j}$, for a specific interception level, stands for:

$$\frac{kg\ fraction\ i-th}{kg\ dirty\ flow\ intercepted\ j-th}$$

The model assumes that the purity decreases with the interception level increasing: so $a_{ij} = f(x_j)$.

Firstly the values of a_{ij} have been found for a specific x_j and then, using simple relations, a_{ij} values for different interception levels were calculated.

For a specific $x_j = \overline{x_j}$, the values of $a_{ij} = \overline{a_{ij}}$ were found by bibliography (for some fractions, when there were no bibliographical data available, the values were assumed by a realistic consideration of people behaviour and materials composition).

	Paper	Wood	Plastics	Glass	Steel	Aluminium	Food-waste	Green-waste
Paper	0,974	0,000	0,044	0,020	0,000	0,000	0,016	0,000
Wood	0,000	0,970	0,013	0,000	0,000	0,000	0,000	0,000
Plastics	0,0192	0,000	0,825	0,025	0,050	0,035	0,032	0,030
Glass	0,000	0,000	0,079	0,945	0,000	0,000	0,000	0,000
Steel	0,000	0,000	0,020	0,000	0,950	0,000	0,000	0,000
Aluminium	0,000	0,000	0,005	0,000	0,000	0,965	0,000	0,000
Food-waste	0,006	0,000	0,015	0,010	0,000	0,000	0,952	0,000
Green-waste	0,000	0,030	0,000	0,000	0,000	0,000	0,000	0,970
Selection efficiency: $\overline{\eta_{sel}}$	0,970	0,865	0,569	0,922	0,900	0,950	0,800	0,800
Interception level: $\overline{x_j}$	0,36	0,65	0,24	0,77	0,40	0,74	0,41	0,750
Source	Comieco [61]	Corepla [59]	CoReVe [62]	CiAl [63]	CIC [60]	Giugliano et al. [8]	Author hypothesis	

Table 6.2 - Matrix A and selection efficiencies values for specific interception levels (last row), [kg i-th fraction in dirty j-th flow / kg j-th fraction in MSW]

Selection efficiencies values, where not reported by the consortium, are assumed using the ones proposed by *Giugliano et al* for that specific value of j-th flow interception, or a similar one.

Thus, A matrix for $x_j = \overline{x_j}$ was created.

When interception levels increase, it has been assumed that the purity, i.e. a_{ij} with $i = j$, linearly decreases, and vice versa.

The linearity assumption, considered the fairest one after having read a great quantity of papers issuing separate collection, should be confirmed by specific studies now completely missing.
Anyway, describing by mathematical equations the not-always-rational human behaviour is often very difficult and sometimes even involves awkward hypothesis.
The values used by the model for the linear interpolation are:

	$x_{j,min}$	$a_{ii,max}$	$\bar{x_j}$	$\bar{a}_{ii}$	$x_{j,1}$	$a_{ii,1}$
Paper	0,00	0,99	0,36	0,97	1,00	0,93
Wood	0,00	1,00	0,65	0,97	1,00	0,97
Plastics	0,00	0,95	0,24	0,83	1,00	0,45
Glass	0,00	0,98	0,77	0,95	1,00	0,90
Steel	0,00	1,00	0,40	0,95	1,00	0,95
Aluminium	0,00	1,00	0,74	0,97	1,00	0,97
Food-waste	0,00	1,00	0,41	0,95	1,00	0,90
Green-waste	0,00	1,00	0,75	0,97	1,00	0,97

Table 6.3 - Extremities of interpolation

It is worth of notice to remember that $x_j = 1$ is not the maximum value for the interception level (see 6.1), it was only a convenient point used for the interpolation.
Such values, apart from $\bar{a}_{ii}$ and $\bar{x_j}$, for which the references are reported above, have been estimated by reasonable and realistic assumptions made together with MatEr researchers and Polimi lecturers combining different bibliographical information on this topic with personal experience.
This way we obtained three points that can be used by the linear interpolation.
Must be noticed that:

- Paper, plastics, glass and food-waste, which together form the major part of the MSW composition, have defined bibliographically values of $\bar{a}_{ii}$; furthermore $a_{ii,1} \neq \bar{a}_{ii}$, meaning that the purity was assumed even to decrease below $\bar{a}_{ii}$

- Wood, steel, aluminium and green-waste are assumed only to increase their purity from $\bar{a}_{ii}$ if their interception decreases

For every values of the different interception levels, $a_{i,j}$ with $i = j$, i.e. the purity level, is known only by using the simple equations:

- if $x_j < \overline{x_j}$ $$\frac{x_j - x_{\mathrm{j,min}}}{\overline{x_j} - x_{\mathrm{j,min}}} = \frac{a_{ij} - a_{ij,max}}{\bar{a}_{ij} - a_{ij,max}} \quad \forall\, i = j$$

- if $x_j > \overline{x_j}$ $$\frac{x_j - x_{\mathrm{j,1}}}{\overline{x_j} - x_{\mathrm{j,1}}} = \frac{a_{ij} - a_{ij,1}}{\bar{a}_{ij} - a_{ij,1}} \quad \forall\, i = j$$

As an example the values of $a_{i,j}$ (with $i = j$) are graphically reported:

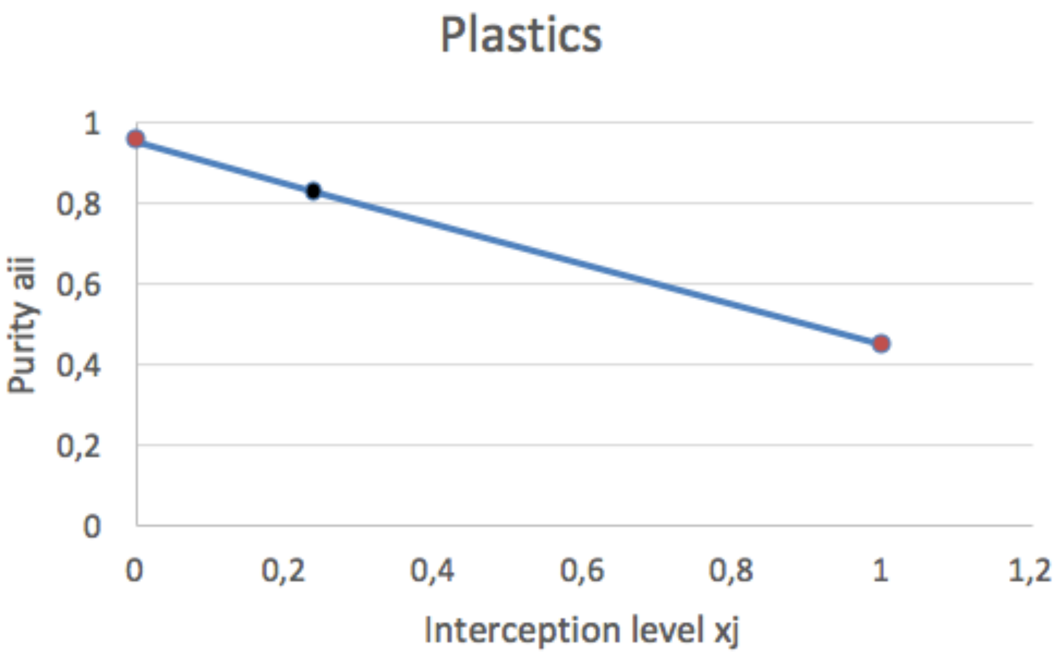


Figure 6.4 - Purity variation with interception level for paper. [kg i-th fraction in dirty i-th flow / kg i-th fraction in MSW]. Black point: value from literature. Red points: values estimated.

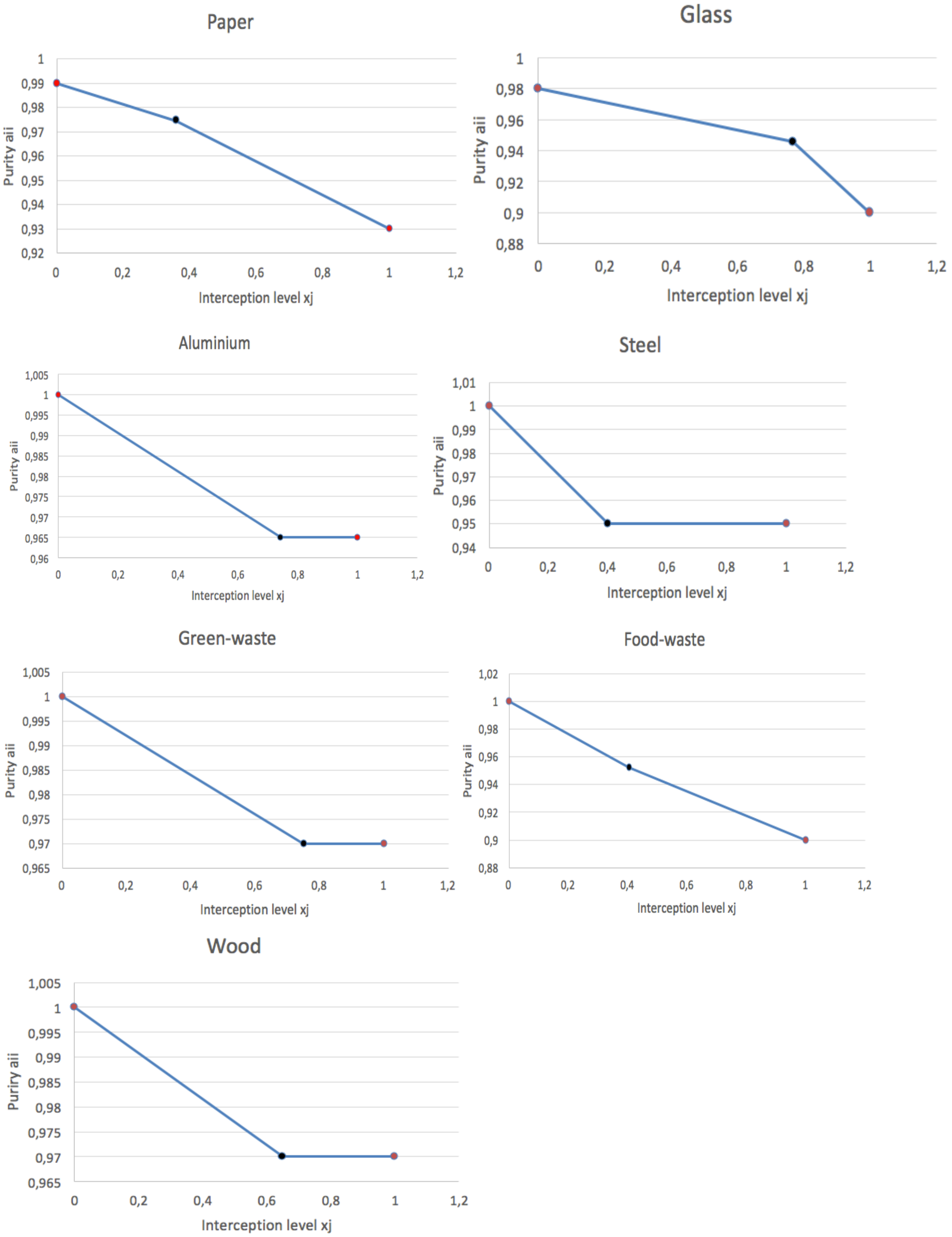


Figure 6.5, A, B, C, D, E, F, G - Purity variation with interception level for the different intercepted flows. [kg i-th fraction in dirty i-th flow / kg i-th fraction in MSW]. Black points: value from literature. Red points: values estimated

Relatively to the values of $a_{i,j}$ when $i \neq j$, it was simply assumed that the increase/diminution of i-th contaminant is proportional to its mass fraction in the base case $\overline{a_{ij}}$:

$$a_{ij} - \overline{a_{ij}} = -\frac{\overline{a_{ij}}}{1 - \overline{a_{ii}}} \cdot (a_{ii} - \overline{a_{ii}}) \ \forall \ i \neq j$$

The final result is a matrix A dependant to the *n* values of the interception levels.
For example, considering the plastics intercepted:

$x_{plastics} = 0{,}3$	Plastics
Paper	0,05
Wood	0,02
Plastics	0,80
Glass	0,09
Steel	0,02
Aluminium	0,01
Food-waste	0,02
Green-waste	0,00

$x_{plastics} = 0{,}7$	Plastics
Paper	0,10
Wood	0,03
Plastics	0,60
Glass	0,18
Steel	0,05
Aluminium	0,01
Food-waste	0,03
Green-waste	0,00

Table 6.4 – Left: Plastics intercepted flow composition when x=0,3, base Scenario, [kg i-th fraction in dirty plastics flow / kg plastics fraction in MSW]; Right: Plastics intercepted flow composition when x=0,7, base Scenario, [kg i-th fraction in dirty plastics flow / kg plastics fraction in MSW]

Finally, for defined interception levels, the matrix A is:

	Paper	Wood	Plastics	Glass	Steel	Aluminium	Food-waste	Green-waste
Paper	0,944	0,000	0,100	0,031	0,000	0,000	0,019	0,000
Wood	0,000	0,991	0,030	0,000	0,000	0,000	0,000	0,000
Plastics	0,033	0,000	0,598	0,040	0,050	0,034	0,038	0,030
Glass	0,000	0,000	0,181	0,914	0,000	0,000	0,000	0,000
Steel	0,000	0,000	0,045	0,000	0,950	0,000	0,000	0,000
Aluminium	0,000	0,000	0,011	0,000	0,000	0,966	0,000	0,000
Food-waste	0,023	0,000	0,034	0,016	0,000	0,000	0,944	0,000
Green-waste	0,000	0,009	0,000	0,000	0,000	0,000	0,000	0,970
Interception level x_j	0,800	0,200	0,700	0,930	0,800	0,729	0,500	1,000

Table 6.5 - Matrix A for specific values of interception levels (last row), base Scenario, [kg i-th fraction in dirty j-th flow / kg j-th fraction in MSW]

Once the matrix A is defined for every value of x_j, all the flows to material recovery are known. Figure 6.6 gives a representation of the flows composition for interception levels equal to Table 6.5

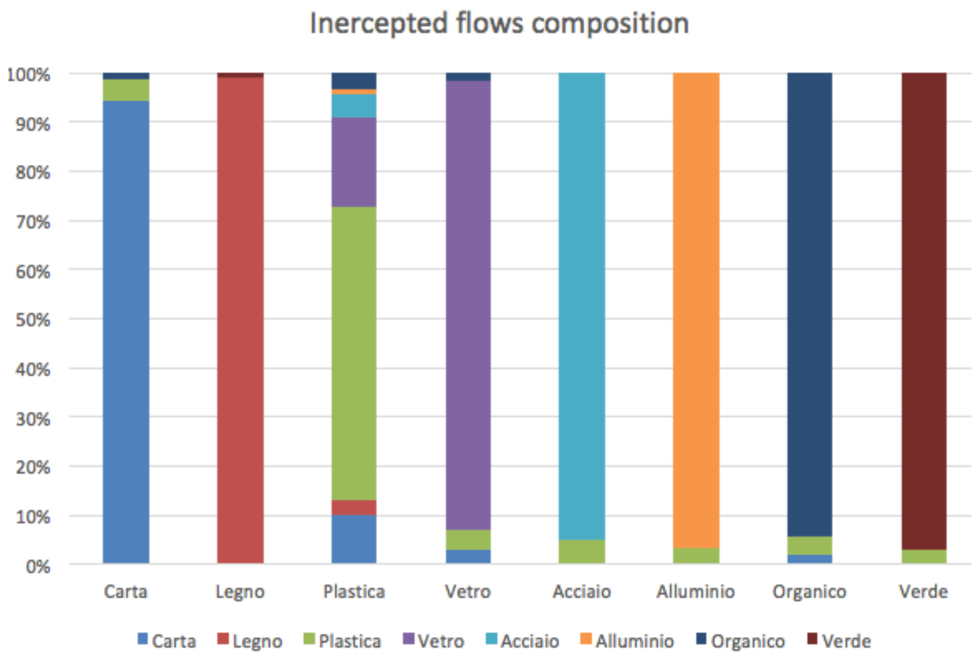


Figure 6.6 - Intercepted flow composition for specified interception level, base Scenario,[kg i-th fraction in dirty j-th flow / kg j-th fraction in MSW]

6.4 The 'high civic awareness' case

In order to give to the model a better adaptability to the different scenarios that could come true in the next years, a new case was implemented too. It considers an upgrade of the social awareness about the waste issue and a consequent increase in the separate collection in terms of quality.

This fact, for what concerns the model parameters just seen (matrix A, selection efficiencies), was built simply through the following hypothesis:

1. a_{ii} for every flow was multiplied by 1,01 except for plastics which was multiplied by a 1,05 factor

2. Metals presence, both steel and aluminium, were removed from plastics intercepted flow

3. $\bar{\eta}_{sel}$ for every flow was multiplied by 1,01 except for plastics which was multiplied by 1,05.

4. $a_{ii,1}$ for every flow was multiplied by 1,01 except for plastics about which it was supposed to be 0,65 (instead of 0,45).

Table 6.6 graphically summarises what just told.

	Paper	Wood	Plastics	Glass	Steel	Aluminium	Food-waste	Green-waste
Paper	0,984	0,000	0,066	0,018	0,000	0,000	0,013	0,000
Wood	0,000	0,980	0,000	0,000	0,000	0,000	0,000	0,000
Plastics	0,0119	0,000	0,867	0,025	0,041	0,025	0,026	0,020
Glass	0,000	0,000	0,039	0,955	0,000	0,000	0,000	0,000
Steel	0,000	0,000	0,000	0,000	0,960	0,000	0,000	0,000
Aluminium	0,000	0,000	0,000	0,000	0,000	0,975	0,000	0,000
Food-waste	0,004	0,000	0,029	0,003	0,000	0,000	0,962	0,000
Green-waste	0,000	0,020	0,000	0,000	0,000	0,000	0,000	0,980
Selection efficiency: $\bar{\eta}_{sel}$	0,980	0,874	0,597	0,931	0,909	0,960	0,808	0,808
Interception level: $\bar{x_j}$	0,358	0,650	0,240	0,768	0,400	0,743	0,405	0,750
Values multiplied by 1,01		Values multiplied by 1,05		Values set to 0			

Table 6.6 - Matrix A and selection efficiencies values for specific interception levels, case 'high civic awareness', [kg i-th fraction in dirty j-th flow / kg j-th fraction in MSW]

It is worth of notice how the increase of intercepted flows purities was modelled with special assumptions for plastics!

It is the fraction which was considered to improve better because it starts from much lower values of purity than the others.

We also estimated that bringing the minimum purity level up to 0,65 should not represent a painful effort for householders.

On the contrary, the slightly increase registered in purity level of the other fractions does not involve any variation in the results in terms of waste management.

The equations made for the entire material recovery phase remain equal to the base case.

The new values discussed led to purer intercepted flows as represented in Table 6.7:

	Paper	Wood	Plastics	Glass	Steel	Aluminium	Food-waste	Green-waste
Paper	0,953	0,000	0,130	0,030	0,000	0,000	0,016	0,000
Wood	0,000	0,994	0,000	0,000	0,000	0,000	0,000	0,000
Plastics	0,035	0,000	0,736	0,043	0,041	0,025	0,031	0,020
Glass	0,000	0,000	0,078	0,923	0,000	0,000	0,000	0,000
Steel	0,000	0,000	0,000	0,000	0,960	0,000	0,000	0,000
Aluminium	0,000	0,000	0,000	0,000	0,000	0,975	0,000	0,000
Food-waste	0,012	0,000	0,057	0,004	0,000	0,000	0,953	0,000
Green-waste	0,000	0,006	0,000	0,000	0,000	0,000	0,000	0,980
Interception level x_j	0,800	0,200	0,700	0,930	0,800	0,729	0,500	1,000

Table 6.7 - Matrix A for the intercepted flows composition values at fixed interception levels, case 'high civic awareness', [kg i-th fraction in dirty j-th flow / kg j-th fraction in MSW]

Model simulations for both scenarios were carried out, with some differences in the outcomes, as accurately explained in the chapter devoted to results.

	Paper		Wood		Plastics		Glass		Steel		Aluminium		Food-waste		Green-waste	
	Base	High awareness	Base	High awareness	Base	High awareness	Base	High awareness	Base	High awareness	Base	High awareness	Base	High awareness	Base	High awareness
Paper	0,974	0,984	0,000	0,000	0,044	0,066	0,020	0,018	0,000	0,000	0,000	0,000	0,016	0,013	0,000	0,000
Wood	0,000	0,000	0,970	0,980	0,013	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Plastics	0,015	0,012	0,000	0,000	0,825	0,867	0,025	0,025	0,050	0,041	0,035	0,025	0,032	0,026	0,030	0,020
Glass	0,000	0,000	0,000	0,000	0,079	0,039	0,945	0,955	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Steel	0,000	0,000	0,000	0,000	0,020	0,000	0,000	0,000	0,950	0,960	0,000	0,000	0,000	0,000	0,000	0,000
Aluminium	0,000	0,000	0,000	0,000	0,005	0,000	0,000	0,000	0,000	0,000	0,965	0,975	0,000	0,000	0,000	0,000
Food-waste	0,011	0,004	0,000	0,000	0,015	0,029	0,010	0,003	0,000	0,000	0,000	0,000	0,952	0,962	0,000	0,000
Green-waste	0,000	0,000	0,030	0,020	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,970	0,980
Selection efficiency: $\bar{\eta}_{sel}$	0,970	0,980	0,865	0,874	0,569	0,597	0,922	0,931	0,900	0,909	0,950	0,960	0,800	0,808	0,800	0,808
Interception level: $\bar{x}_j$	0,358	0,358	0,650	0,650	0,240	0,240	0,768	0,768	0,400	0,400	0,743	0,743	0,405	0,405	0,750	0,750

Table 6.8 - Composition of collected flows for specified interception levels: the matrix A

	$a_{ii,1}$	
	Base	High awareness
Paper	0,930	0,939
Wood	0,970	0,980
Plastics	0,450	0,650
Glass	0,900	0,909
Steel	0,950	0,960
Aluminium	0,965	0,975
Food-waste	0,900	0,909
Green-waste	0,970	0,980
$x_{j,1}$	1	1

Table 6.9 - Purity level assumed when interception level was set to 1

6.5 Considerations about the methodology

The section just discussed explained in detail all the assumptions made to model the interception and recycling phases.

Some of them, particularly the ones about the purity variation with the interception level are formulated without bibliographical sources because studies specifically regarding this issue are missing.

In literature the topic is considered [24], [8], but a real case study reporting some useful values for the interception phase modelling do not exist.

Being aware of the fact that such hypothesis influence the model outputs we implemented two realistic scenarios, beginning with the available data found by bibliography.

Anyway, the model here presented would require a more rigorous approach which would request an additional work of thesis or maybe more.

7 The mathematical optimisation

The work of thesis here present consists in an optimisation of the standard waste management system discussed above and represented by Figure 7.1.

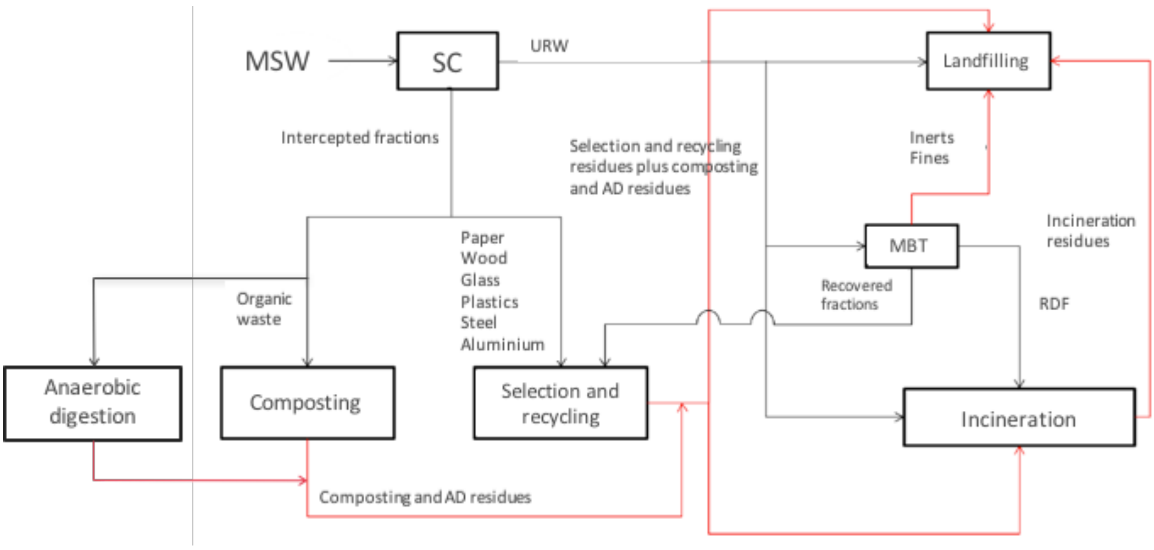


Figure 7.1 - Graphical representation of the standard waste management system considered

7.1 Mono-objective optimisation

Mathematical optimisation, also named mathematical programming, is the selection of the best element from a set of alternatives.

Analytically the optimisation problem can be formulated as follows [64]:

find

$$x = \{x_1, x_2, \dots, x_n\}$$

which minimizes

$$f(x)$$

subject to the constraints:

$lb_i \leq x \leq ub_i$: upper and lower bounds for the variable x

$A_j \cdot x \leq b_j$: linear inequality constraints

$Aeq_k \cdot x = beq_k$: linear equality constraints

$c_l(x) \leq 0$: non linear inequalities

$ceq_m(x) = 0$: non linear equalities

x: design vector containing the n variables

$f(x)$: objective function

The model here discussed provides for the minimisation (maximisation of the absolute value) of three different objective functions (energy, emissions and cost).
The three topics are at first considered separately, in a so called mono-objective optimisation:

- Energetic: part of the model optimising the waste management system in order to maximise Italian energy savings [MJ]

- Environmental: part of the model optimising the waste management system in order to maximise Italian CO_2 emissions savings [kg $CO_{2,eq}$]

- Economic: brief part of the model devoted to minimise variable costs of the waste management system

7.2 Multi-objective optimisation

Multi-objective optimisation is the analytical method apt to find the best solution of a mathematical optimisation problem composed by two contrasting objectives together considered. For a nontrivial multi-objective optimisation problem, a single solution that simultaneously optimises each objective does not exist, so the solution found represents the best compromise between them.

The definition of what we mean by optimal solution of a multi-purpose problem was firstly given by Edgeworth and then reformulated by Pareto in 1896 [65].
The multi-objective optimisation problem can be analytically defined [66], [67]:

find

$$x = \{x_1, x_2, \dots, x_n\}$$

which minimizes

$$F(x) = \{f_1(x), f_2(x), \dots, f_m(x)\}$$

x: design vector containing the n variables
$F(x)$: vector composed by the m mono-objective functions $f(x)$

subject to the constraints:

$lb_i \leq x \leq ub_i$: upper and lower bounds for the variable x
$A_j \cdot x \leq b_j$: linear inequality constraints
$Aeq_k \cdot x = beq_k$: linear equality constraints
$c_l(x) \leq 0$: non linear inequalities
$ceq_m(x) = 0$: non linear equalities

Definition 1: given the two vectors F^1 and $F^2 \in R^m$, we say that F^1 dominates F^2 if:

$F_o^1 \leq F_o^2$ for every $o = 1, 2, \dots, m$

and

$F_p^1 \leq F_p^2$ for at least an index $p \in= \{1,2, \dots, m\}$

Definition 2: a design vector x^* represents a Pareto optimal solution if:
$f_0(x^*) \leq f_0(x)$ for every $o = 1, 2, \dots, m$

and

$f_p(x^*) < f_p(x)$ for at least an index $p \in= \{1,2, \dots, m\}$

In general, a solution is considered optimal if there is no another solution (Pareto) dominating it.
The maximisation problem is defined in an analogous way:

$f_o(x^*) \geq f_o(x)$ for every $o = 1, 2, \dots, m$

and

$f_p(x^*) \geq f_p(x)$ for at least an index $p \in= \{1,2, \dots, m\}$

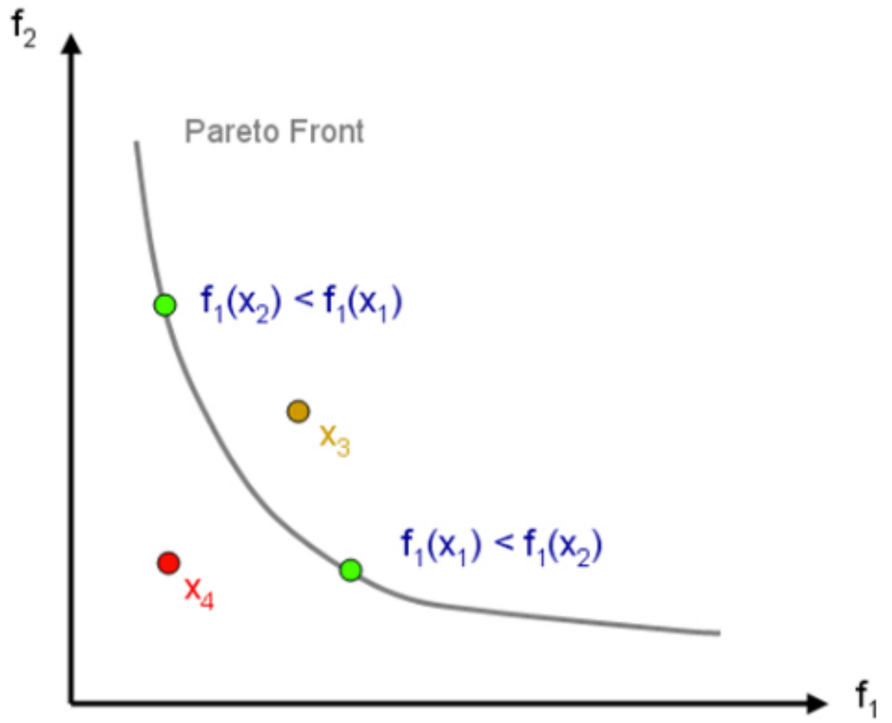


Figure 7.2 - Example of two-dimensional Pareto front for a minimisation two-objective problem. Yellow point: feasible but not optimal solution. Green points: Pareto optimal points. Red point: point outside the feasible region

The set of the (Pareto) optimal points forms the so-called Pareto front.
The choice of the right point among the ones lying along the Pareto front cannot be carried out by the optimisation algorithm and is up to an external decision maker.

The multi-objective optimisation completed were:

- Energy VS costs
- Emissions VS costs

The methodology used to perform the two-objective optimisations is described in 11.2.

8 Energy mathematical model

Below follows the entire description of the mathematical model concerning energy optimisation, with all the equations used and assumptions made.

8.1 Sets

The sets defining variable domains are**:**

- Merceological fractions set:
  $i \in I$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Intercepted flow set:
  $j \in J$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Possible URW destinations set:
  $k \in K$ = *{WtE, landfilling, MBT + WtE}*

- MBT merceological fractions considered set:
  $m \in M$ = *{paper, wood, glass, steel, aluminium, food-waste, green-waste, organic fines, PET, LDPE, HDPE}*

- MBT waste treatment set:
  $n \in N$ = *{sack-opener, bio-drying, trommel, magnetic separator, eddy current separator, ballistic separator, PET NIR separator, LDPE NIR separator, HDPE NIR separator, grinder, pelletizing}*

8.2 Variables

- Vector **x** ∈ ℝ representing, as said, interception levels of the ten merceological fractions : $\left[\frac{\text{kg dirty j−th flow intercepted}}{\text{kg MSW}}\right]$

- matrix A_{ij} and its general element α_{ij}: $\left[\frac{kg\ fraction\ i{-}th}{kg\ dirty\ flow\ intercepted\ j{-}th}\right]$

- vector **y** ∈ ℝ representing the fraction of URW sent to the specific treatment: $\left[\frac{\text{kg URW to k−th treatment}}{\text{kg MSW}}\right]$

- vector **z** ∈ ℕ representing the fraction of SRR of a specific intercepted flow to WtE instead of landfilling $\left[\frac{\text{kg SRR j−th to WtE}}{\text{kg SRR}}\right]$

$$z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ WtE$$
$$1 - z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ landfilling$$

8.3 Objective function

The objective function is the summation of different terms referring to the different waste flow considered:

$$\min \{E_{total} = \mathrm{E_{REC}} + E_{URW} + E_{SSR} + E_{COLL,TRANSP}\}$$

the terms are:

- Energy saving/consumption by material recovery:

$$\mathrm{E_{REC}} = \sum_j INTERCEPTED_j \cdot E_{RECYCLING\ j}$$

- Energy saving/consumption due to URW management:

$$E_{URW} = URW_{WtE} \cdot E_{WtE,URW} + URW_{landfilling} \cdot E_{landfilling,URW} + URW_{TMB} \cdot E_{TMB+WtE,URW})$$

- Energy saving/consumption due to SRR management:

$$E_{\mathrm{SRR}} = \mathrm{SRR}_{WtE} \cdot E_{WtE,\mathrm{SRR}} + \mathrm{SRR}_{landfilling} \cdot E_{landfilling,\mathrm{SRR}})$$

- Energy consumption due to collection and transport of the different waste flows:

$$\begin{aligned} E_{COLL,TRANSP} = & \sum_j INTERCEPTED_j \cdot d_{COLL,j} \cdot E_{spec,COLL} + URW \cdot d_{COLL,URW} \\ & \cdot E_{spec,COLL,URW} + \sum_j INTERCEPTED_j \cdot d_{transp,j} \cdot E_{spec,transp,j} \\ & + URW \cdot d_{transp,URW} \cdot E_{spec,transp,URW} \\ & + \sum_j \mathrm{SRR}_{WtE,j} \cdot d_{transp,\mathrm{SRR},j} \cdot E_{spec,transp,\mathrm{SRR}} \\ & + \sum_j \mathrm{SRR}_{landfilling,j} \cdot d_{transp,\mathrm{SRR},j} \cdot E_{spec,transp,\mathrm{SRR}} \\ & + (WtE\ residues_{URW} + WtE\ residues_{\mathrm{SRR}} + residues_{MBT}) \\ & \cdot d_{transp,WtE\ residues} \cdot E_{spec,transp,WtE\ residues} \end{aligned}$$

8.4 Lower and upper bounds

- $lb_j \leq x_j \leq ub_j$: lower e upper bounds for x
- $lb_k \leq y_k \leq ub_k$: lower e upper bounds for y
- $lb_i \leq z_i \leq ub_i$: lower e upper bounds for z

Lower bounds were all set to 0, values less than 0 are meaningless because the variables represent percentage of material flow.
The upper bounds related to **y** and **z** are one as they are percentages.
x, being the ratio between two conceptually different things as explained in 6.1, can be greater than one and its upper bound was set to infinite. A strong constraint on **x** is given by the mass balance expressed by the non linear constraint (8.6).
Even though a source [8] reported the values of some maximum interception level reachable, we preferred to leave the model free to identify the feasible (i.e. respecting the assumptions and the mass balances) best management strategy. It's up to the policy maker pursue it and to the householders respect it.

8.5 Linear constraints

- $x_{other} = \bar{x}_{other} = 1$: fraction other interception constraint

- $x_{inert\ fines} = \bar{x}_{inert\ fines} = 0$: fraction inert fines interception constraint

- $\sum_k y_k = 1$: URW mass balance

8.6 Non-linear constraints

- $f_i - \sum_{j=1}^{|I|} f_j \cdot x_j \cdot \alpha_{ij} \geq 0$ interception phase mass balance
- $\sum_j INTERCEPTED_j \cdot \eta_{sel,j} = \overline{SCL}$: possible constraint on separate collection level

8.7 Parameters

When the value of the parameter was not yet discussed, the source is reported:

- MSW: annual quantity of Municipal Solid Waste [kg]
- f: MSW composition [kg fraction i-th/kg MSW]
- $\bar{a}_{ij}$: values of matrix A when $x_j = \bar{x}_j$

- $x_{\mathrm{j,min}}$: minimum interception value
- $x_{\mathrm{j,1}}$: unity value used for the interpolation
- $\alpha_{ii,max}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,min}}$
- $\alpha_{ii,1}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,1}}$
- $d_{COLL,j}$ e $d_{COLL,URW}$: collection distance [km/kg j-th flow] e [km/kg URW]
- $d_{transp,SSR,j}$ e $d_{transp,WtE\ residues}$: distance for transport from MRF or WtE to dump site [km/kg j-th flow] and [km/kg $WtE\ residues$]
- $d_{transp,j}$ e $d_{transp,URW}$: distance for transport to specific treatment plant [km/kg di j-th flow] and [km/kg URW]
- $E_{spec,COLL}$ e $E_{spec,COLL,\mathrm{URW}}$: specific consumption due to collection [MJ/km]
- $E_{spec,transp}$ e $E_{spec,transp,\mathrm{URW}}$: specific consumption due to transport [MJ/km]
- $E_{spec,transp,SRR}$ e $E_{spec,transp,WtE\ residues}$: specific consumption due to transport [MJ/km]
- $\bar{x}_{inert\ fines}$: fixed inert fines interception level (to 0)
- $\bar{x}_{other}$: fixed ther interception level (to 1)
- $\eta_{rec,j}$: recycling efficiencies
- $\bar{\eta}_{sel,j}$: selection efficiencies when $x_j = \bar{x_J}$
- ε_{j}: $\frac{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{to}\ recycling}{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{intercepted}}$
- $CED_{primary\ production,i}$: energy consumption for primary production of fraction i-th [MJ/kg fraction i-th]
- $CED_{secondary\ production,i}$: energy consumption for secondary production of fraction i-th [MJ/kg fraction i-th]
- $CED_{AD,i}$: energy saving/consumption due to anaerobic digestion of food-waste and green-waste
- $CED_{comp,i}$: energy saving/consumption due to composting of food-waste and green-waste
- S_i: substitution ratio [$\frac{kg_{primary\ material\ substituted}}{kg_{secondary\ material}}$]
- $\eta_{el,WtE}$: incinerator electric efficiency
- $\eta_{th,WtE}$: incinerator thermic efficiency

- $\eta_{el,ref}$: national thermoelectric grid electric efficiency
- $\eta_{th,ref}$: national thermoelectric grid thermic efficiency
- C_m: fraction m-th carbon content [kg C/kg fraction m-th]
- C_{ox}: percentage of oxidised carbon in food-waste and green-waste by biodrying
- $\varphi_{th,loss}$: useful heat percentage released by biodrying
- $\Delta H_{ox,C}$: thermal energy released by carbon oxidation [MJ/kg C]
- $\Delta H_{vap,H2O}$: heat required by water to vaporise [MJ/kg H_2O]
- $MOIST_m$: water percentage in m-th fraction [27]
- $\varepsilon_{n,m}$: percentage of m-th fraction remaining in the main flow after n-th
- $cons_{el,spec\ MBT,n}$: electric consumption of MBT specific n-th treatment for one tonne of flow
- $y_{CH_4,biogas}$: methane mass fraction in biogas
- $\eta_{el,ICE}$: electric efficiency of the internal combustion engine by which methane is burnt
- ϱ_{biogas}: biogas density at 20° C and 1 atm.
- $\eta_{capt,biogas}$: digester's biogas capturing efficiency
- ε_{vol}: conversion efficiency of volatile matter to biogas
- $x_{vol,org}$: volatile organic matter percentage in food-waste and green-waste
- $\varepsilon_{conv,VM}$: volatile organic matter conversion yield

8.8 Mass balance related constraints

- Matrix $INTERCEPTED_{i,j}$: kg of i-th fraction in j-th flow intercepted by separate collection

1. $INTERCEPTED_{i,j} = MSW \cdot f_j \cdot x_j \cdot \alpha_{ij}$
2. $INTERCEPTED_j = MSW \cdot \sum_i f_j \cdot x_j \cdot \alpha_{ij} = MSW \cdot f_j \cdot x_j$

- Vector URW_i: it represents: $\frac{kg\ i\text{−}th\ fraction\ to\ URW}{kg\ MSW}$

1. $URW_i = MSW \cdot f_i - MSW \cdot \sum_j f_j \cdot x_j \cdot \alpha_{ij} \geq 0$
2. $URW = \sum_i MSW_i$
3. $URW_{k,i} = \left[\frac{kg\ i-th\ fraction\ in\ URW\ to\ k-th\ treatment}{kg\ MSW}\right] = URW_i \cdot y_k$

- Matrix $SRR_{i,j}$:

1. $SRR_{i,j} = RSU \cdot f_j \cdot x_j \cdot \alpha_{ij}\ \ \forall\ i \neq j$
2. $SRR_{i,j} = RSU \cdot \left[f_i \cdot x_i \cdot \alpha_{ij} \cdot (1-\varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot \left(1-\eta_{i,ric}\right)\right]\ \forall\ i = j$
3. $SRR_i = [total\ SRR\ \ kg\ of\ i-th\ fraction\ generated] = MSW \cdot [\sum_{j \neq i} f_j \cdot x_j \cdot \alpha_{ij} + f_i \cdot x_i \cdot \alpha_{ii} \cdot (1-\varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot \left(1-\eta_{i,rec}\right)]$
4. $SRR = \sum_i SRR_i$
5. $SRR_{WtE,ij} = \left[\frac{kg\ \ SRR\ of\ i-th\ fraction\ from\ j-th\ flow\ to\ WtE}{kg\ MSW}\right] = SRR_{i,j} \cdot z_j$
6. $SRR_{WtE,i} = \sum_j SRR_{i,j} \cdot z_j$
7. $SRR_{landfilling,ij} = \left[\frac{kg\ \ SRR\ of\ i-th\ fraction\ from\ j-th\ flow\ to\ landfilling}{kg\ MSW}\right] = SRR_{i,j} \cdot \left(1-z_j\right)$
8. $SRR_{landfilling,i} = \sum_j SRR_{i,j} \cdot (1-z_j)$

8.9 Matrix A elements and selection efficiencies calculation

Diagonal elements: $\alpha_{ij}\ \ \ i = j$

- if $x_j < \overline{x_j}$ $\qquad \alpha_{jj} = \alpha_{jj,max} + (\overline{\alpha}_{jj} - \alpha_{jj,max}) \cdot \frac{x_j - x_{\mathrm{j,min}}}{\overline{x_j} - x_{\mathrm{j,min}}}$
- if $x_j > \overline{x_j}$ $\qquad \alpha = \alpha_{jj,1} + (\overline{\alpha}_{jj} - \alpha_{jj,1}) \cdot \frac{x_j - x_{\mathrm{j,1}}}{\overline{x_j} - x_{\mathrm{j,1}}}$

Non diagonal elements: $\alpha_{ij}\ \ \ i \neq j$

$$\alpha_{ij} = \bar{a}_{\mathrm{ij}} - \frac{\bar{a}_{\mathrm{ij}}}{1-\bar{a}_{jj}} \cdot (\alpha_{jj} - \bar{a}_{jj})$$

Selection efficiency:

$$\eta_{sel,j}=1-\sum_{i\neq j}\alpha_{ij}-\alpha_{jj}\cdot\left(1-\varepsilon_j\right)=\varepsilon_j\cdot\alpha_{jj}$$

8.10 Separate Collection Level

It was calculated following the ISPRA definition reported in paragraph 3.3:

$$SCL=\sum_j INTERCEPTED_j\cdot\eta_{sel,j}$$

8.11 Energy from intercepted fractions

$$E_{RECYCLE,j}=[\frac{MJ}{kg}]=\frac{CED_{\substack{primary\\production,i}}-CED_{\substack{secondary\\production,i}}\cdot S_i}{1000}\cdot\eta_{sel,j}\cdot\eta_{rec,j}\quad\forall\, i=j,\quad j\neq food-waste,green-waste$$

$$E_{EECYCLE,j}=[\frac{MJ}{kg}]=\frac{CED_{AD,j}}{1000}\cdot\eta_{sel,j}\ \forall\, j=food-waste,green-waste$$

8.12 Energy from URW

- Primary energy saving/consumption[4] due to incineration: $E_{\mathrm{WtE,URW}}$

URW LHV:

$$LHV_{\mathrm{URW}}=\frac{\sum_i(\mathrm{URW}_{WtE,i}\cdot LHV_i)}{\mathrm{URW}_{WtE}}$$

Primary energy required by Italian thermoelectric grid substituted by URW incineration energy:

- [4] The indicator is built by accounting the substitutive perspective discussed in Chapter 4

$$E_{WtE,\mathrm{URW}} = \left[\frac{\mathrm{MJ}}{\mathrm{kg\ URW\ to\ }WtE}\right] = -\frac{LHV_{\mathrm{URW}} \cdot \eta_{el,WtE}}{\eta_{el,ref}} - \frac{LHV_{\mathrm{URW}} \cdot \eta_{th,WtE}}{\eta_{th,ref}}$$

$$WtE\ residues_{\mathrm{URW}} = \sum_i \left(\mathrm{URW}_{WtE,i} \cdot WtE\ residues_i\right)$$

- Primary energy from landfilling $E_{\mathrm{landfilling,URW}}$:

$$LHV_{biogas} = LHV_{CH_4} \cdot y_{CH_4,biogas}$$

$$EE = \frac{LHV_{biogas} \cdot \eta_{el,ICE}}{\eta_{el,ref}}$$

$$E_{landfilling,\mathrm{URW}} = \left[\frac{\mathrm{MJ}}{\mathrm{kg\ URW\ to\ landfilling}}\right] = -EE \cdot \varrho_{biogas} \cdot \eta_{capt,biogas} \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot \frac{\mathrm{URW}_{landfilling,food-waste} + \mathrm{URW}_{landfilling,green-waste}}{\mathrm{URW}_{landfilling}}$$

- Primary energy saved/consumed by MBT + WtE $E_{\mathrm{MBT+WtE,URW}}$:

The configuration of the modelled MBT is represented and was estimated from MatEr bibliography related to a modern Italian MBT plant.

Fractions are re-distributed among *n* set to respect MBT flows considered. Food-waste was divided in traditional food-waste and organic fines, according with *Giugliano* [8].
The composition of plastics was estimated by *Rigamonti* [24].

$$\mathrm{URW}'_{paper} = \mathrm{URW}_{MBT,paper}$$
$$\mathrm{URW}'_{wood} = \mathrm{URW}_{MBT,wood}$$
$$\mathrm{URW}'_{glass} = \mathrm{URW}_{MBT,glass}$$
$$\mathrm{URW}'_{steel} = \mathrm{URW}_{MBT,steel}$$

$$\text{URW}'_{aluminium} = \text{URW}_{MBT,aluminium}$$

$$\text{URW}'_{food-waste} = \text{URW}_{MBT,food-waste} \cdot 0{,}71$$

$$\text{URW}'_{green-waste} = \text{URW}_{MBT,green-waste}$$

$$\text{URW}'_{organic\ fines} = \text{URW}_{MBT,food-waste} \cdot 0{,}29$$

$$\text{URW}'_{PET} = \text{URW}_{MBT,plastics} \cdot 0{,}55$$

$$\text{URW}'_{HDPE} = \text{URW}_{MBT,plastics} \cdot 0{,}20$$

$$\text{URW}'_{LDPE} = \text{URW}_{MBT,plastics} \cdot 0{,}25$$

Moisture of different fraction decreases proportionally to energy released by oxidation occurring during biodrying:

$$H_2O_{vap} = \frac{\left(\text{URW}'_{food-waste} \cdot C_{food-waste} + \text{URW}'_{green-waste} \cdot C_{green-waste} + \text{URW}'_{organic\ fines} \cdot C_{organic\ fines}\right)}{\Delta H_{eva,H2O}} \cdot C_{ox} \cdot \varphi_{th,loss} \cdot \Delta H_{ox,C}$$

$$\text{URW}''_{m} = \text{URW}'_{m} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) \quad \forall\, m \neq food-waste, green-waste, organic\ fines$$

$$\text{URW}''_{food-waste} = \text{URW}'_{food-waste} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{food-waste} \cdot C_{food-waste} \cdot C_{ox}$$

$$RUR''_{green-waste} = RUR'_{green-waste} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{green-waste} \cdot C_{green-waste} \cdot C_{ox}$$

$$\text{URW}''_{organic\ fines} = \text{URW}'_{organic\ fines} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{organic\ fines} \cdot C_{organic\ fines} \cdot C_{ox}$$

rdf is composed by the m-th fractions not intercepted by separators remaining in the main flow:

$$rdf_m = [\frac{kg\ rdf}{kg\ \text{URW}}] = \frac{\text{URW}''_m \cdot \prod_n \varepsilon_{n,m}}{\sum_m \text{URW}'_m}$$

m-th fraction recovered by MBT is composed by what is intercepted by the separators [kg rec/kg URW]:

$$rec_m = \left[\frac{kg\ recovered\ material}{kg\ \text{URW}}\right] = \frac{\text{URW}''_m \cdot \prod_n \left(1 - \varepsilon_{n,m}\right)}{\sum_m \text{URW}'_m}\ \forall\, m \neq trommel, ballistic\ separator$$

Residues are formed by the flows separated by trommel and ballistic separator:

$$MBT\ residues_m = \text{URW}''_m \cdot \prod_n \left(1 - \varepsilon_{n,m}\right)\ \forall\, m = trommel, ballistic\ separator$$

$$LHV_{rdf} = \frac{\sum_m (rdf_m \cdot LHV_m)}{\sum_m rdf_m}$$

Electricity consumption of MBT n-th treatment process must be considered too:

$$Q_n = \sum_m \text{URW}''_m \cdot \prod_{o=\,ballistic\ separator}^{\text{n}-1} \varepsilon_{o,m}\ \ \forall\, n > 2$$

$$Q_{sack-opener} = \text{URW}_{MBT} = \sum_m \text{URW}'_m$$

$$Q_{biodrying} = \text{URW}_{MBT}$$

$$cons_{el,MBT} = \sum\nolimits_n cons_{el,spec\ MBT,n} \cdot Q_n$$

Energy saved/consumed without considering recycling of recovered fractions:

$$EP = \left[\frac{\text{MJ}}{\text{kg rdf}}\right] = -\frac{LHV_{\text{rdf}} \cdot \eta_{el,WtE}}{\eta_{el,ref}} - \frac{LHV_{\text{rdf}} \cdot \eta_{th,WtE}}{\eta_{th,ref}} + \frac{cons_{el,MBT}}{\eta_{el,ref} \cdot (\sum_m \text{URW}'_m \cdot rdf_m)}$$

Total energy saved/required by MBT:

$$E_{MBT+WtE,URW} = \left[\frac{\text{MJ}}{\text{kg URW to MBT}}\right] = EP \cdot \sum_m rdf_m + \sum_m rec_m \cdot$$
$$\left(E_{secondary\ production,m} - S_m \cdot E_{primary\ production,m}\right) \cdot \eta_{rec,m}$$

$$residues_{MBT} = \sum_m (rdf_m \cdot MBT\ residues_m)$$

8.13 Energy from SRR

- Primary energy through WtE $E_{\text{WtE,SRR}}$:

$$LHV_{\text{SRR}} = \frac{\sum_i \left(\text{SRR}_{\text{WtE},i} \cdot LHV_i\right)}{\text{SRR}_{\text{WtE}}}$$

$$E_{\text{WtE,SRR}} = \left[\frac{\text{MJ}}{\text{kg SRR to WtE}}\right] = -\frac{LHV_{\text{SRR}} \cdot \eta_{el,\text{WtE}}}{\eta_{el,ref}} - \frac{LHV_{\text{SRR}} \cdot \eta_{th,\text{WtE}}}{\eta_{th,ref}}$$

$$WtE\ residues_{\text{SRR}} = \sum_i \left(\text{SRR}_{\text{WtE},i} \cdot ash_i\right)$$

- Primary energy through landfilling $E_{\text{landfilling,SRR}}$:

Residues from MBT disposed in the dump must be added:

$$\text{SRR}'_{paper} = MBT\ residues_{paper}$$

$$\text{SRR}'_{wood} = MBT\ residues_{wood}$$

$$\mathrm{SRR'}_{plastics} = MBT\ residues_{PET} + MBT\ residues_{LDPE} + MBT\ residues_{HDPE}$$

$$\mathrm{SRR'}_{glass} = MBT\ residues_{glass}$$

$$\mathrm{SRR'}_{steel} = MBT\ residues_{steel}$$

$$\mathrm{SRR'}_{aluminium} = MBT\ residues_{aluminium}$$

$$\mathrm{SRR'}_{food-waste} = MBT\ residues_{food-waste} + MBT\ residues_{organic\ fines}$$

$$\mathrm{SRR'}_{green-waste} = MBT\ residues_{green-waste}$$

$$\mathrm{SRR'}_{\mathrm{landfilling},i} = \mathrm{SRR'}_{i} + \mathrm{SRR}_{\mathrm{landfilling},i}$$

$$LHV_{biogas} = LHV_{CH_4} \cdot y_{CH_4,biogas}$$

$$EE = \frac{LHV_{biogas} \cdot \eta_{el,ICE}}{\eta_{el,ref}}$$

$$E_{\mathrm{landfilling},SRR} = \left[\frac{\mathrm{MJ}}{\mathrm{kg\ SRR\ to\ landfilling}}\right] = -EE \cdot \varrho_{biogas} \cdot \eta_{capt,biogas} \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot \frac{\mathrm{SRR'}_{\mathrm{landfilling},food-waste} + \mathrm{SRR'}_{\mathrm{landfilling},green-waste}}{\mathrm{SRR}_{\mathrm{landfilling}}}$$

9 Environmental mathematical model

Below follows the entire description of the mathematical model concerning environmental optimisation, with all the equations used and assumptions made.

9.1 Sets

The sets defining variable domains are**:**

- Merceological fractions set:

  $i \in I$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Intercepted flow set:

  $j \in J$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Possible URW destinations set:

  $k \in K$ = *{WtE, landfilling, MBT + WtE}*

- MBT merceological fractions considered set:

  $m \in M$ = *{paper, wood, glass, steel, aluminium, food-waste, green-waste, organic fines, PET, LDPE, HDPE}*

- MBT waste treatment set:

  $n \in N$ = *{sack-opener, bio-drying, trommel, magnetic separator, eddy current separator, ballistic separator, PET NIR separator, LDPE NIR separator, HDPE NIR separator, grinder, pelletizing}*

9.2 Variables

- vector **x** ∈ ℝ representing, as said, interception levels of the ten merceological fractions : $\left[\frac{\text{kg dirty j−th flow intercepted}}{\text{kg MSW}}\right]$

- matrix A_{ij} and its general element α_{ij}: $\left[\frac{kg\ fraction\ i{-}th}{kg\ dirty\ flow\ intercepted\ j{-}th}\right]$

- vector **y** ∈ ℝ representing the fraction of URW sent to the specific treatment: $\left[\frac{\text{kg URW to k−th treatment}}{\text{kg MSW}}\right]$

- vector **z** ∈ ℕ representing the fraction of SRR of a specific intercepted flow to WtE instead of landfilling: $\left[\frac{\text{kg SRR j−th to WtE}}{\text{kg SRR}}\right]$

$$z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ WtE$$
$$1 - z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ landfilling$$

9.3 Objective function

The objective function is the summation of different terms referring to the different waste flow considered:

$$\min\left\{EM_{total} = \mathrm{EM_{REC}} + EM_{URW} + EM_{SSR} + EM_{COLL,TRANSP}\right\}$$

the terms are:

- Emissions saved/produced by intercepted flow recycling:

$$\mathrm{EM_{REC}} = \sum_j INTERCEPTED_j \cdot EM_{RECYCLING,j}$$

- Emissions saved/produced by URW management:

$$EM_{URW} = URW_{WtE} \cdot EM_{WtE,URW} + URW_{landfilling} \cdot EM_{landfilling,URW} + URW_{TMB} \cdot EM_{TMB+WtE,URW})$$

- Emissions saved/produced by SRR management:

$$EM_{\mathrm{SRR}} = \mathrm{SRR}_{WtE} \cdot EM_{WtE,\mathrm{SRR}} + \mathrm{SRR}_{landfilling} \cdot EM_{landfilling,\mathrm{SRR}})$$

- Emissions due to collection and transport of the different waste flows:

$$\begin{aligned} EM_{COLL,TRANSP} &= \sum_j INTERCEPTED_j \cdot d_{COLL,j} \cdot EM_{spec,COLL} + URW \cdot d_{COLL,URW} \\ &\cdot E_{spec,COLL,URW} \\ &+ \sum_j INTERCEPTED_j \cdot d_{transp,j} \cdot EM_{spec,transp,j} \quad + URW \\ &\cdot d_{transp,URW} \cdot EM_{spec,transp,URW} \\ &+ \sum_j \mathrm{SRR}_{WtE,j} \cdot d_{transp,\mathrm{SRR},j} \cdot EM_{spec,transp,\mathrm{SRR}} \\ &+ \sum_j \mathrm{SRR}_{landfilling,j} \cdot d_{transp,\mathrm{SRR},j} \cdot EM_{spec,transp,\mathrm{SRR}} \\ &+ (WtE\ residues_{URW} + WtE\ residues_{\mathrm{SRR}} + residues_{MBT}) \\ &\cdot d_{transp,WtE\ residues} \cdot EM_{spec,transp,WtE\ residues} \end{aligned}$$

9.4 Lower and upper bounds

- $lb_j \leq x_j \leq ub_j$: lower e upper bounds for x

- $lb_k \leq y_k \leq ub_k$: lower e upper bounds for y

- $lb_i \leq z_i \leq ub_i$: lower e upper bounds for z

The upper bounds related to **y** and **z** are one as they are percentages.
x, being the ratio between two conceptually different things as explained in 6.1, can be greater than one and its upper bound was set to infinite. A strong constraint on **x** is given by the mass balance expressed by the non linear constraint (8.6).
Even though a source [8] reported the values of some maximum interception level reachable, we preferred to leave the model free to identify the feasible (i.e. respecting the assumptions and the mass balances) best management strategy. It's up to the policy maker pursue it and to the householders respect it.

9.5 Linear constraints

- $x_{other} = \bar{x}_{other} = 1$: fraction other interception constraint

- $x_{inert\ fines} = \bar{x}_{inert\ fines} = 0$: fraction inert fines interception constraint

- $\sum_k y_k = 1$: URW mass balance

9.6 Non-linear constraints

- $f_i - \sum_{j=1}^{|I|} f_j \cdot x_j \cdot \alpha_{ij} \geq 0$ interception phase mass balance
- $\sum_j INTERCEPTED_j \cdot \eta_{sel,j} = \overline{SCL}$: possible constraint on separate collection level

9.7 Parameters

When the value of the parameter was not yet discussed, the source is reported:

- MSW: annual quantity of Municipal Solid Waste [kg]
- f: MSW composition [kg fraction i-th/kg MSW]
- $\bar{a}_{ij}$: values of matrix A when $x_j = \bar{x_j}$
- $x_{\mathrm{j,min}}$: minimum interception value
- $x_{\mathrm{j,1}}$: unity value used for the interpolation
- $\alpha_{ii,max}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,min}}$
- $\alpha_{ii,1}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,1}}$
- $d_{COLL,j}$ e $d_{COLL,URW}$: collection distance [km/kg j-th flow] e [km/kg URW]
- $d_{transp,SSR,j}$ e $d_{transp,WtE\ residues}$: distance for transport from MRF or WtE to dump site [km/kg j-th flow] and [km/kg $WtE\ residues$]
- $d_{transp,j}$ e $d_{transp,URW}$: distance for transport to specific treatment plant [km/kg di j-th flow] and [km/kg URW]
- $EM_{spec,COLL}$ e $EM_{spec,COLL,\mathrm{URW}}$: specific consumption due to collection [MJ/km]
- $EM_{spec,transp}$ e $EM_{spec,transp,\mathrm{URW}}$: specific consumption due to transport [MJ/km]
- $EM_{spec,transp,SRR}$ e $EM_{spec,transp,WtE\ residues}$: specific consumption due to transport [MJ/km]
- $\bar{x}_{inert\ fines}$: fixed inert fines interception level (to 0)
- $\bar{x}_{other}$: fixed other interception level (to 1)
- $\eta_{rec,j}$: recycling efficiencies
- $\bar{\eta}_{sel,j}$: selection efficiencies when $x_j = \bar{x_j}$
- ε_{j}: $\frac{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{to}\ recycling}{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{intercepted}}$
- $GWP_{primary\ production,i}$: emissions attributable to primary production of fraction i-th [MJ/kg fraction i-th]
- $GWP_{secondary\ production,i}$: emissions attributable to secondary production of fraction i-th [MJ/kg fraction i-th]
- $GWP_{AD,i}$: emissions attributable to anaerobic digestion of food-waste and green-waste
- $GWP_{comp,i}$: emissions attributable to composting of food-waste and green-waste

- S_i: substitution ratio $[\frac{kg_{primary\ material\ substituted}}{kg_{secondary\ material}}]$
- $\eta_{el,WtE}$: incinerator electric efficiency
- $\eta_{th,WtE}$: incinerator thermic efficiency
- $\eta_{el,ref}$: national thermoelectric grid electric efficiency
- $\eta_{th,ref}$: national thermoelectric grid thermic efficiency
- $em_{el,grid}$: Italian thermoelectric grid emission factor for electricity production [kg CO_2/MJ_{el}].
- $em_{th,parco}$: Italian thermoelectric grid emission factor for thermal energy production [kg CO_2/MJ_{th}].
- $C_{fossil,i}$: fossil carbon content in i-th fraction [kg C/kg i-th fraction]
- $C_{fossil,m}$: fossil carbon content in m-th fraction treated by MBT [kg C/kg m-th fraction]
- C_m: fraction m-th carbon content [kg C/kg fraction m-th]
- C_{ox}: percentage of oxidised carbon in food-waste and green-waste by biodrying
- $\varphi_{th,loss}$: useful heat percentage released by biodrying
- $\Delta H_{ox,C}$: thermal energy released by carbon oxidation [MJ/kg C]
- $\Delta H_{vap,H2O}$: heat required by water to vaporise [MJ/kg H_2O]
- $MOIST_m$: water percentage in m-th fraction [27]
- $\varepsilon_{n,m}$: percentage of m-th fraction remaining in the main flow after n-th
- $cons_{el,spec\ MBT,n}$: electric consumption of MBT specific n-th treatment for one tonne of flow
- $y_{CH_4,biogas}$: methane mass fraction in biogas
- $\eta_{el,ICE}$: electric efficiency of the internal combustion engine by which methane is burnt
- ϱ_{biogas}: biogas density at 20° C and 1 atm.
- $\eta_{capt,biogas}$: digester's biogas capturing efficiency
- ε_{vol}: conversion efficiency of volatile matter to biogas
- $x_{vol,org}$: volatile organic matter percentage in food-waste and green-waste
- $\varepsilon_{conv,VM}$: volatile organic matter removing yield

9.8 Mass balance related constraints

- Matrix $INTERCEPTED_{i,j}$: kg of i-th fraction in j-th flow intercepted by separate collection

3. $INTERCEPTED_{i,j} = MSW \cdot f_j \cdot x_j \cdot \alpha_{ij}$
4. $INTERCEPTED_j = MSW \cdot \sum_i f_j \cdot x_j \cdot \alpha_{ij} = MSW \cdot f_j \cdot x_j$

- Vector URW_i: it represents: $\frac{kg\ i-th\ fraction\ to\ URW}{kg\ MSW}$

4. $URW_i = MSW \cdot f_i - MSW \cdot \sum_j f_j \cdot x_j \cdot \alpha_{ij} \geq 0$
5. $URW = \sum_i MSW_i$
6. $URW_{k,i} = \left[\frac{kg\ i-th\ fraction\ in\ URW\ to\ k-th\ treatment}{kg\ MSW}\right] = URW_i \cdot y_k$

- Matrix $SRR_{i,j}$:

9. $SRR_{i,j} = RSU \cdot f_j \cdot x_j \cdot \alpha_{ij}\ \ \forall\ i \neq j$
10. $SRR_{i,j} = RSU \cdot [f_i \cdot x_i \cdot \alpha_{ij} \cdot (1 - \varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot (1 - \eta_{i,ric})]\ \ \forall\ i = j$
11. $SRR_i = [total\ SRR\ \ kg\ of\ i - th\ fraction\ generated] = MSW \cdot [\sum_{j \neq i} f_j \cdot x_j \cdot \alpha_{ij} + f_i \cdot x_i \cdot \alpha_{ii} \cdot (1 - \varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot (1 - \eta_{i,ric})]$
12. $SRR = \sum_i SRR_i$
13. $SRR_{WtE,ij} = \left[\frac{kg\ \ SRR\ of\ i-th\ fraction\ from\ j-th\ flow\ to\ WtE}{kg\ MSW}\right] = SRR_{i,j} \cdot z_j$
14. $SRR_{WtE,i} = \sum_j SRR_{i,j} \cdot z_j$
15. $SRR_{landfilling,ij} = \left[\frac{kg\ \ SRR\ of\ i-th\ fraction\ from\ j-th\ flow\ to\ landfilling}{kg\ MSW}\right] = SRR_{i,j} \cdot (1 - z_j)$
16. $SRR_{landfilling,i} = \sum_j SRR_{i,j} \cdot (1 - z_j)$

9.9 Matrix A elements and selection efficiencies calculation

Diagonal elements: $\alpha_{ij} \quad i = j$

- if $x_j < \overline{x_j}$ $\qquad \alpha_{jj} = \alpha_{jj,max} + (\overline{\alpha}_{jj} - \alpha_{jj,max}) \cdot \frac{x_j - x_{j,\min}}{\overline{x_j} - x_{j,\min}}$
- if $x_j > \overline{x_j}$ $\qquad \alpha = \alpha_{jj,1} + (\overline{\alpha}_{jj} - \alpha_{jj,1}) \cdot \frac{x_j - x_{j,1}}{\overline{x_j} - x_{j,1}}$

Non diagonal elements: $\alpha_{ij} \quad i \neq j$

$$\alpha_{ij} = \bar{a}_{\mathrm{ij}} - \frac{\bar{a}_{\mathrm{ij}}}{1 - \bar{a}_{jj}} \cdot (\alpha_{jj} - \bar{a}_{jj})$$

Selection efficiency:

$$\eta_{sel,j} = 1 - \sum_{i \neq j} \alpha_{ij} - \alpha_{jj} \cdot \left(1 - \varepsilon_j\right) = \varepsilon_j \cdot \alpha_{jj}$$

9.10 Separate Collection Level

It was calculated following the ISPRA definition reported in paragraph 3.3:

$$SCL = \sum_j INTERCEPTED_j \cdot \eta_{sel,j}$$

9.11 Emissions from intercepted fractions

$$EM_{RECYCLE,j} = [\frac{MJ}{kg}] = \frac{GWP_{\substack{primary \\ production,i}} - GWP_{\substack{secondary \\ production,i}} \cdot S_i}{1000} \cdot \eta_{sel,j} \cdot \eta_{rec,j} \quad \forall\, i = j, \quad j \neq food - waste, green - waste$$

$$EM_{RECYCLE,j} = [\frac{MJ}{kg}] = \frac{GWP_{AD,j}}{1000} \cdot \eta_{sel,j} \quad \forall\, j = food - waste, green - waste$$

9.12 Emissions from URW

- Emissions saving/production[5] due to incineration: $\mathrm{EM}_{\mathrm{WtE,URW}}$

URW LHV:

$$LHV_{\mathrm{URW}} = \frac{\sum_i (\mathrm{URW}_{WtE,i} \cdot LHV_i)}{\mathrm{URW}_{WtE}}$$

Gross emissions due to the incineration of one kg of URW:

$$EM = \left[\frac{\mathrm{kg\ CO_2}}{\mathrm{kg\ URW\ to\ WtE}}\right] = \frac{\sum_i \frac{C_{fossil,i} \cdot \mathrm{URW}_{WtE,i}}{\mathrm{URW}_{WtE}} \cdot \frac{MM_{CO_2}}{MM_C}}{LHV_{WtE}}$$

Net emissions saved/produced by URW incineration:

$$EM_{WtE,\mathrm{URW}} = \left[\frac{\mathrm{kg\ CO_2}}{\mathrm{kg\ URW\ to\ WtE}}\right]$$
$$= LHV_{\mathrm{URW}} \cdot \left(EM - \eta_{el,WtE} \cdot em_{el,grid} - \eta_{th,WtE} \cdot em_{th,grid}\right)$$

$$WtE\ residues_{\mathrm{URW}} = \sum_i \left(\mathrm{URW}_{WtE,i} \cdot WtE\ residues_i\right)$$

- Emissions due to landfilling $\mathrm{E}_{\mathrm{landfilling,URW}}$:

$$LHV_{biogas} = LHV_{CH_4} \cdot y_{CH_4,biogas}$$

Electric energy produced by biogas

$$EE_{landfilling,URW} = -LHV_{biogas} \cdot \eta_{el,ICE} \cdot \varrho_{biogas} \cdot \eta_{capt,biogas} \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot \frac{\mathrm{URW}_{landfilling,food-waste} + \mathrm{URW}_{landfilling,green-waste}}{\mathrm{URW}_{landfilling}}$$

- [5] The indicator is built by accounting the substitutive perspective discussed in Chapter 4

Emissions due to slipped biogas:

$$EM_{biogas} = \varrho_{biogas} \cdot (1 - \eta_{capt,biogas}) \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot \frac{\text{URW}_{\,landfilling,food-waste} + \text{URW}_{\,landfilling,green-waste}}{\text{URW}_{\,landfilling}} \cdot y_{CH_4,biogas}$$

Net emissions due to landfilling:

$$EM_{landfilling,URW} = \left[\frac{\text{kg CO}_2}{\text{kg URW to landfilling}}\right] = EM_{biogas} - EE_{landfilling,URW} \cdot em_{el,grid}$$

- Emissions from the system MBT + WtE $EM_{MBT+WtE,URW}$:

The configuration of the modelled MBT is represented and was estimated from MatEr bibliography related to a modern Italian MBT plant.

Fractions are re-distributed among *n* set to respect MBT flows considered. Food-waste was divided in traditional food-waste and organic fines, according with *Giugliano* [8].
The composition of plastics was estimated by *Rigamonti* [24].

$$\text{URW}'_{paper} = \text{URW}_{\,MBT,paper}$$
$$\text{URW}'_{wood} = \text{URW}_{\,MBT,wood}$$
$$\text{URW}'_{glass} = \text{URW}_{\,MBT,glass}$$
$$\text{URW}'_{steel} = \text{URW}_{\,MBT,steel}$$
$$\text{URW}'_{aluminium} = \text{URW}_{\,MBT,aluminium}$$
$$\text{URW}'_{food-waste} = \text{URW}_{\,MBT,food-waste} \cdot 0{,}71$$
$$\text{URW}'_{green-waste} = \text{URW}_{\,MBT,green-waste}$$
$$\text{URW}'_{organic\,fines} = \text{URW}_{\,MBT,food-waste} \cdot 0{,}29$$

$$\text{URW}'_{PET} = \text{URW}_{MBT,plastics} \cdot 0{,}55$$
$$\text{URW}'_{HDPE} = \text{URW}_{MBT,plastics} \cdot 0{,}20$$
$$\text{URW}'_{LDPE} = \text{URW}_{MBT,plastics} \cdot 0{,}25$$

Moisture of different fraction decreases proportionally to energy released by oxidation occurring during biodrying:

$$H_2O_{vap} = \frac{\left(\text{URW}'_{food-waste} \cdot C_{food-waste} + \text{URW}'_{green-waste} \cdot C_{green-waste} + \text{URW}'_{organic\ fines} \cdot C_{organic\ fines}\right)}{\Delta H_{eva,H2O}} \cdot C_{ox} \cdot \varphi_{th,loss} \cdot \Delta H_{ox,C}$$

$$\text{URW}''_{m} = \text{URW}'_{m} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) \quad \forall\, m \neq food-waste, green-waste, organic\ fines$$

$$\text{URW}''_{food-waste} = \text{URW}'_{food-waste} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{food-waste} \cdot C_{food-waste} \cdot C_{ox}$$

$$URW''_{green-waste} = URW'_{green-waste} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{green-waste} \cdot C_{green-waste} \cdot C_{ox}$$

$$\text{URW}''_{organic\ fines} = \text{URW}'_{organic\ fines} \cdot \left(1 - \frac{MOIST_m \cdot H_2O_{vap}}{\sum_m \text{URW}_{m} \cdot MOIST_m}\right) - \text{URW}'_{organic\ fines} \cdot C_{organic\ fines} \cdot C_{ox}$$

rdf is composed by the m-th fractions not intercepted by separators remaining in the main flow:

$$rdf_m = [\frac{kg\ rdf}{kg\ \text{URW}}] = \frac{\text{URW}''_{m} \cdot \prod_n \varepsilon_{n,m}}{\sum_m \text{URW}'_{m}}$$

m-th fraction recovered by MBT is composed by what is intercepted by the separators [kg rec/kg URW]:

$$rec_m = \left[\frac{kg\ recovered\ material}{kg\ \mathrm{URW}}\right] = \frac{\mathrm{URW}''_m \cdot \prod_n \left(1-\varepsilon_{n,m}\right)}{\sum_m \mathrm{URW}'_m}\ \forall\, m \neq trommel, ballistic\ separator$$

Residues are formed by the flows separated by trommel and ballistic separator:

$$MBT\ residues_m = \mathrm{URW}''_m \cdot \prod_n \left(1-\varepsilon_{n,m}\right)\ \forall\, m = trommel, ballistic\ separator$$

$$LHV_{rdf} = \frac{\sum_m (rdf_m \cdot LHV_m)}{\sum_m rdf_m}$$

$$EM_{WtE,cdr} = LHV_{cdr} \cdot \left(\frac{\sum_m \frac{c_{fossil,m} \cdot rdf_m}{rdf} \cdot \frac{MM_{CO_2}}{MM_C}}{LHV_{rdf}} - \eta_{el,tu} \cdot em_{el,grid} - \eta_{th,WtE} \cdot em_{th,grid}\right)$$

Emissions related to electricity required by MBT n-th treatment process must be included:

$$Q_n = \sum_m \mathrm{URW}''_m \cdot \prod_{o=\,ballistic\ separator}^{\mathrm{n}-1} \varepsilon_{o,m}\ \ \forall\, n > 2$$

$$Q_{sack-opener} = \mathrm{URW}_{MBT} = \sum_m \mathrm{URW}'_m$$

$$Q_{biodrying} = \mathrm{URW}_{MBT}$$

$$cons_{el,MBT} = \sum_n cons_{el,spec\ MBT,n} \cdot Q_n$$

$$EM_{cons\ el,MBT} = \frac{cons_{el,MBT} \cdot em_{el,grid}}{\sum_m URW'_m \cdot rdf_m}$$

Net emissions related to MBT:

$$EM = EM_{WtE,rdf} + EM_{cons\,el,MBT}$$

$$EM_{MBT+WtE,URW} = \left[\frac{\text{kg CO}_2}{\text{kg URW to MBT}}\right] = EM \cdot \sum_m rdf_m + \sum_m rec_m \cdot \left(EM_{secondary\ production,m} - S_j \cdot EM_{primary\ production,m}\right) \cdot \eta_{rec,m}$$

$$ash_{rdf} = \sum_m (rdf_m \cdot ash_m)$$

9.13 Emissions from SRR

- Emissions reduction/increase due to WtE: $\text{EM}_{\text{WtE,SRR}}$

$$LHV_{\text{SRR}} = \frac{\sum_i \left(\text{SRR}_{\text{WtE},i} \cdot LHV_i\right)}{\text{SRR}_{\text{WtE}}}$$

Gross emissions produced by incineration of 1 kg of SRR:

$$EM = \frac{\sum_i \frac{C_{fossil,i} \cdot \text{SRR}_{\text{WtE},i}}{\text{SRR}_{\text{WtE}}} \cdot \frac{MM_{CO_2}}{MM_C}}{LHV_{\text{SRR}}}$$

Net emissions due to SRR incineration:

$$EM_{WtE,SRR} = \left[\frac{\text{kg CO}_2}{\text{kg URW to WtE}}\right] = LHV_{\text{SRR}} \cdot \left(EM - \eta_{el,\text{WtE}} \cdot em_{el,grid} - \eta_{th,\text{WtE}} \cdot em_{th,grid}\right)$$

- Emissions due to SRR landfilling $\text{EM}_{\text{landfiling,SRR}}$:

Residues from MBT disposed in the dump must be added:

$$\mathrm{SRR'}_{paper} = MBT\ residues_{paper}$$

$$\mathrm{SRR'}_{wood} = MBT\ residues_{wood}$$

$$\mathrm{SRR'}_{plastics} = MBT\ residues_{PET} + MBT\ residues_{LDPE} + MBT\ residues_{HDPE}$$

$$\mathrm{SRR'}_{glass} = MBT\ residues_{glass}$$

$$\mathrm{SRR'}_{steel} = MBT\ residues_{steel}$$

$$\mathrm{SRR'}_{aluminium} = MBT\ residues_{aluminium}$$

$$\mathrm{SRR'}_{food-waste} = MBT\ residues_{food-waste} + MBT\ residues_{organic\ fines}$$

$$\mathrm{SRR'}_{green-waste} = MBT\ residues_{green-waste}$$

$$\mathrm{SRR'}_{\mathrm{landfilling},i} = \mathrm{SRR'}_{i} + \mathrm{SRR}_{\mathrm{landfilling},i}$$

$$LHV_{biogas} = LHV_{CH_4} \cdot y_{CH_4,biogas}$$

Electric energy produced through landfilling:

$$EE_{landfilling,SRR} = -LHV_{biogas} \cdot \eta_{el,ICE} \cdot \varrho_{biogas} \cdot \eta_{capt,biogas} \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot \frac{\mathrm{SRR'}_{\mathrm{landfilling},food-waste} + \mathrm{SRR'}_{\mathrm{landfilling},green-waste}}{\mathrm{SRR}_{\mathrm{landfilling}}}$$

Emissions due to slipped biogas:

$$EM_{biogas} = \varrho_{biogas} \cdot (1 - \eta_{capt,biogas}) \cdot \varepsilon_{vol} \cdot x_{vol,org} \cdot \varepsilon_{conv,VM} \cdot$$

$$\frac{\text{SRR}'_{\text{landfilling},food-waste}+\text{SRR}'_{\text{landfilling},green-waste}}{\text{SRR}_{\text{landfilling}}} \cdot y_{CH_4,biogas}$$

Net emissions related to landfilling:

$$EM_{\text{landfilling,SRR}} = \left[\frac{\text{kg CO2}}{\text{kg SRR to landfilling}}\right] = EM_{biogas} - EE_{\text{landfilling,SRR}} \cdot em_{el,grid}$$

10 Economic mathematical model

Below follows the entire description of the mathematical model concerning economic optimisation, with all the equations used and assumptions made.

Only the variable costs relating to waste management are considered.
Such methodology does not assume the substitutive perspective used for the other two optimisations but it was the only one feasible with reliability due to the scarcity of bibliographical data.
A deeper cost analysis, realised similarly to energy and emissions would have been surely more appropriate for the model, but the awkwardness of the issue requires a similar effort study.
In this case the objective function was linear and easy to be optimised because it was convex.

10.1 Sets

The sets defining variable domains are**:**

- Merceological fractions set:
  $i \in I$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Intercepted flow set:
  $j \in J$ = *{paper, wood, plastics, glass, steel, aluminium, food-waste, green-waste, inert fines, other}*

- Possible URW destinations set:
  $k \in K$ = *{WtE, landfilling, MBT + WtE}*

- MBT merceological fractions considered set:
  m ∈ M = {paper, wood, glass, steel, aluminium, food-waste, green-waste, organic fines, PET, LDPE, HDPE}

- MBT waste treatment set:
  n ∈ N = {sack-opener, bio-drying, trommel, magnetic separator, eddy current separator, ballistic separator, PET NIR separator, LDPE NIR separator, HDPE NIR separator, grinder, pelletizing}

10.2 Variables

- vector **x** ∈ ℝ representing, as said, interception levels of the ten merceological fractions : $\left[\frac{\text{kg dirty j−th flow intercepted}}{\text{kg MSW}}\right]$

- matrix A_{ij} and its general element α_{ij}: $\left[\frac{kg\ fraction\ i{-}th}{kg\ dirty\ flow\ intercepted\ j{-}th}\right]$

- vector **y** ∈ ℝ representing the fraction of URW sent to the specific treatment: $\left[\frac{\text{kg URW to k−th treatment}}{\text{kg MSW}}\right]$

- vector **z** ∈ ℕ representing the fraction of SRR of a specific intercepted flow to WtE instead of landfilling $\left[\frac{\text{kg SRR j−th to WtE}}{\text{kg SRR}}\right]$

$$z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ WtE$$

$$1 - z_{paper} = SRR\ percentage\ from\ paper\ intercepted\ flow\ to\ landfilling$$

10.3 Objective function

The objective function is the summation of different terms referring to the different waste flow considered:

$$\min\{C_{total} = \mathrm{C_{SC}} + C_{URW}\}$$

the terms are:

- Cost related to collection and recovery of intercepted waste flows:

$$\mathrm{C_{SC}} = \sum_j INTERCEPTED_j \cdot (C_{collection\ and\ transport,j} + C_{recovery,j})$$

- Cost related to collection and disposal of URW:

$$C_{URW} = URW_{WtE} \cdot (C_{collection\ and\ transport,URW} + C_{WtE,URW}) + URW_{MBT} \cdot (C_{collection\ and\ transport\ ,URW} + C_{MBT,URW}) + URW_{landfilling} \cdot (C_{collection\ and\ transport,URW} + C_{landfilling,URW})$$

10.4 Lower and upper bounds

- $lb_j \leq x_j \leq ub_j$: lower e upper bounds for x
- $lb_k \leq y_k \leq ub_k$: lower e upper bounds for y
- $lb_i \leq z_i \leq ub_i$: lower e upper bounds for z

The upper bounds related to **y** and **z** are one as they are percentages.
x, being the ratio between two conceptually different things as explained in 6.1, can be greater than one and its upper bound was set to infinite. A strong constraint on **x** is given by the mass balance expressed by the non linear constraint (10.6).
Even though a source [8] reported the values of some maximum interception level reachable, we preferred to leave the model free to identify the feasible (i.e. respecting the assumptions

and the mass balances) best management strategy. It's up to the policy maker pursue it and to the householders respect it.

10.5 Linear constraints

- $x_{other} = \bar{x}_{other} = 1$: fraction other interception constraint
- $x_{inert\ fines} = \bar{x}_{inert\ fines} = 0$: fraction inert fines interception constraint
- $\sum_k y_k = 1$: URW mass balance

10.6 Non-linear constraints

- $f_i - \sum_{j=1}^{|I|} f_j \cdot x_j \cdot \alpha_{ij} \geq 0$ interception phase mass balance
- $\sum_j INTERCEPTED_j \cdot \eta_{sel,j} = \overline{SCL}$: possible constraint on separate collection level

10.7 Parameters

- MSW: annual quantity of Municipal Solid Waste [kg]
- f: MSW composition [kg fraction i-th/kg MSW]
- $\bar{a}_{ij}$: values of matrix A when $x_j = \bar{x}_j$
- $x_{\mathrm{j,min}}$: minimum interception value
- $x_{\mathrm{j,1}}$: unity value for interpolation
- $\alpha_{ii,max}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,min}}$
- $\alpha_{ii,1}$: percentage of i-th fraction in flow i-th when $x_j = x_{\mathrm{j,1}}$
- $\bar{x}_{inert\ fines}$: fixed inert fines interception level (to 0)
- $\bar{x}_{other}$: fixed other interception level (to 1)
- $\eta_{rec,j}$: recycling efficiencies
- $\bar{\eta}_{sel,j}$: selection efficiencies when $x_j = \bar{x}_j$
- ε_{j}: $\frac{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{to}\ recycling}{kg\ of\ pure\ fraction\ \mathrm{i}{-}th\ in\ flow\ i{-}th\ \mathrm{intercepted}}$

- $C_{collection\ and\ transport,j}$: cost related to collection and transport of j-th intercepted flows [€/kg]
- $C_{recovery,j}$: cost related to recovery of j-th intercepted flows [€/kg]
- $C_{collection\ and\ transport,URW}$: collection and transport to every destination cost of URW
- $C_{WtE,URW}$: WtE tariff
- $C_{landfilling,URW}$: landfilling tariff
- $C_{MBT,URW}$: MBT tariff

	Collection and transport [€/tonne]	Disposal tariff [€/tonne]	Total cost [€/tonne]
Paper	149,08	16,56	165,63
Wood	65,02	24,33	89,35
Plastics	185,20	39,08	224,28
Glass	100,35	11,16	111,51
Steel	115,06	36,02	151,08
Aluminium	115,06	36,02	151,08
Food-waste	150,63	84,04	234,68
Green-waste	60,98	33,69	94,68
URW to WtE	89,00	105,94	194,94
URW to landfilling	89,00	89,38	178,38
URW to MBT	89,00	100,71	189,71

Table 10.1 - Costs assumed by the model, [€/tonne]

Collection and transport cost, and recovery costs are taken by ISPRA [5], while URW disposal tariffs by Novambiente [68], which reported Italian regional values for the three treatment processes; in this last case the results found were averaged on the base of input quantities to obtain an unique national value.

We must highlight that there is no distinction of cost between AD and composting of organic fractions: ISPRA, the source of the data, does not divide the two different contribution to cost. For the model we assumed equal disposal tariffs for both AD and composting. While the values reported by ISPRA concerning organic recycling are confirmed by [69], [70], our assumption is validated by [71], a report studying European plants (one of the in Monza,

Italy), and [72]. The last two papers state that AD and composting disposing costs differ of 5 euro on average.
After all this considerations, and due to the lack of some reliable data for the current Italian situation, we preferred to keep the two values identical.

10.8 Mass balance related constraints

- Matrix $INTERCEPTED_{i,j}$: kg of i-th fraction in j-th flow intercepted by separate collection

5. $INTERCEPTED_{i,j} = MSW \cdot f_j \cdot x_j \cdot \alpha_{ij}$
6. $INTERCEPTED_j = MSW \cdot \sum_i f_j \cdot x_j \cdot \alpha_{ij} = MSW \cdot f_j \cdot x_j$

- Vector URW_i: it represents: $\frac{kg\ i\!-\!th\ fraction\ to\ URW}{kg\ MSW}$

7. $URW_i = MSW \cdot f_i - MSW \cdot \sum_j f_j \cdot x_j \cdot \alpha_{ij} \geq 0$
8. $URW = \sum_i MSW_i$
9. $URW_{k,i} = \left[\frac{kg\ i\!-\!th\ fraction\ in\ URW\ to\ k\!-\!th\ treatment}{kg\ MSW}\right] = URW_i \cdot y_k$

- Matrix $SRR_{i,j}$:

17. $SRR_{i,j} = RSU \cdot f_j \cdot x_j \cdot \alpha_{ij}\ \ \forall\ i \neq j$
18. $SRR_{i,j} = RSU \cdot \left[f_i \cdot x_i \cdot \alpha_{ij} \cdot (1 - \varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot \left(1 - \eta_{i,ric}\right)\right]\ \forall\ i = j$
19. $SRR_i = [total\ kg\ i - th\ SRR\ generated] = MSW \cdot [\sum_{j \neq i} f_j \cdot x_j \cdot \alpha_{ij} + f_i \cdot x_i \cdot \alpha_{ii} \cdot (1 - \varepsilon_i) + f_i \cdot x_i \cdot \alpha_{ii} \cdot \varepsilon_i \cdot \left(1 - \eta_{i,ric}\right)]$
20. $SRR = \sum_i SRR_i$
21. $SRR_{WtE,ij} = [\ kg\ \ SRR\ of\ i - th\ fraction\ from\ j - th\ flow\ to\ WtE] = SRR_{i,j} \cdot z_j$
22. $SRR_{WtE,i} = \sum_j SRR_{i,j} \cdot z_j$

23. $SRR_{landfilling,ij} = [kg\ \ SRR\ of\ i-th\ fraction\ from\ j-th\ flow\ to\ landfilling] = SRR_{i,j} \cdot (1 - z_j)$

24. $SRR_{landfilling,i} = \sum_j SRR_{i,j} \cdot (1 - z_j)$

10.9 Matrix A elements and selection efficiencies calculation

Diagonal elements: $\alpha_{ij}\quad i = j$

- if $x_j < \overline{x_j}$ $\qquad \alpha_{jj} = \alpha_{jj,max} + (\overline{\alpha}_{jj} - \alpha_{jj,max}) \cdot \frac{x_j - x_{j,\min}}{\overline{x_j} - x_{j,\min}}$
- if $x_j > \overline{x_j}$ $\qquad \alpha = \alpha_{jj,1} + (\overline{\alpha}_{jj} - \alpha_{jj,1}) \cdot \frac{x_j - x_{j,1}}{\overline{x_j} - x_{j,1}}$

Non diagonal elements: $\alpha_{ij}\quad i \neq j$

$$\alpha_{ij} = \bar{a}_{ij} - \frac{\bar{a}_{ij}}{1 - \bar{a}_{jj}} \cdot (\alpha_{jj} - \bar{a}_{jj})$$

Selection efficiency:

$$\eta_{sel,j} = 1 - \sum_{i \neq j} \alpha_{ij} - \alpha_{jj} \cdot (1 - \varepsilon_j) = \varepsilon_j \cdot \alpha_{jj}$$

10.10 Separate Collection Level

It was calculated following the ISPRA definition reported in paragraph 3.3:

$$SCL = \sum_j INTERCEPTED_j \cdot \eta_{sel,j}$$

11 Optimisation computational approach

The whole mathematical model was described.
A mono-objective optimisation was conducted for all the three aspects analysed: energetic, environmental and economic.
While energetic and environmental optimisations gave similar outputs, the economic one achieved different results making clear the trade-off between energy/emissions and cost.
Given that, on a second time a multi-objective optimisation was performed in order to find the solution best fitting reality, where the resources and environment best are aimed in parallel with cost.
The software used to perform the optimisations was Matlab, the multi-paradigm numerical computing environment by Mathworks [73]. The optimisation algorithms were chosen among the ones proposed by Matlab Optimization Toolbox.
Objective function, constraint and variables tolerance was set to 10^{-6} (the default Matlab value used by its Global Optimisation Toolbox).
For this reason, every value below such limit is considered a full 0 in results chapters.

11.1 Mono-objective optimisation

The mono-objective optimisation methods followed were two: one for cost and one for emission and energy optimisations.
Different scenarios were considered (as better explained in the 'results' section) on the base of the input parameters given to the model: composting/AD, constraint on separate collection level / no constraint, base case / 'high civic awareness'.

11.1.1 Cost optimisation

The cost optimisation problem resulted to be non mixed integer, with non linear constraints and an O.F. dependent on the design vector by a second power law.

The O.F. was regular and smooth in all the domain considered.
For these reasons, the cost optimisation was easy to perform, and the Matlab function *fmincon* was used.
The algorithm suggested by Matlab, and used by the model, was the *Interior Point* method. Interior Point methods are classes of algorithm that find the optimum moving through the feasible region, not along the front, and use a logarithmic barrier function to account for the non linear constraints [74].
Due to the convexity of the cost objective function, the global minimum was always found even changing the first attempt values vector.

11.1.2 Energy and emissions optimisation

Differently from cost, energy and emissions optimisation problems were non mixed integer with both O.F. and constraints non linear. There was up to a sixth power dependence between O.F. and the variables.
In this case, the O.F. was non smooth and surely non convex.
Such optimisation problems are the most difficult to solve because local method algorithms (moving along the gradient direction), representing the major part of algorithms, can fail finding the global minimum, stopping at local ones.
The optimisation algorithms suggested by Matlab, able to release from local method problems, are the Genetic Algorithm and the Pattern-Search algorithm, with their respectively Matlab functions *ga* and *patternsearch*.
The Genetic Algorithm is a heuristic belonging to the class of evolutionary algorithm. Contrary to deterministic ones, it will never supply always the same solution and do not guarantee that the global minimum will be found. It ensures anyway that the solution found is sufficiently good and has the advantage that often requires much less time to be performed. Shortly, GA operates by creating an initial population, with each person (chromosome) representing the variables (genes) vector, evaluating the O.F. (fitness function) and making the population evolve through new generations bred only by fit, i.e. with a high value of the fitness function, individuals [75].
Pattern Search instead is a deterministic method particularly adapt to non smooth O.F. problems because it is derivative free. In order to avoid to be stuck into local minimums, it both operates with local and larger movements.

The main idea is to find some improving direction (not necessarily the most improving, which would be the gradient) by perturbing the current point (initially the first attempt point) by small amounts in each of the variable directions and observing whether the objective function value improves or worsens. The movement then is increased into a pattern move multiplying the perturbation by the *acceleration factor* [76].

By default, Matlab routine uses the *mesh adaptive search* method and the model exploits it; *generalised pattern search* and *generating set search* are implemented too.

For mono-objective optimisation we chose the Pattern-Search algorithm because it is deterministic.

In order to be sure to avoid local minimums a lot of different attempts were tried varying the initial values vector.

The ones later proposed are the best solutions found.

11.2 Multi-objective optimisation

This work of thesis considered two multi-objective optimisations:

1. Energy VS Cost
2. Emission VS Cost

It's easy to understand looking the mono-objective optimisation results, that both Energy – Cost and Emission – Cost represent multi-objective non-trivial problems.

In order to find the Pareto front for both these problems the algorithm used has been the Genetic Algorithm described in the previous paragraph, adapted to the multi-objective optimisation.

The Matlab function used to solve such problems has been *gamultiobj* which found the (Pareto) optimal objective functions values for the sets energy-cost and emission-cost.

The mathematical model remained the same as yet shown for the mono-objective optimisation

12 Energy optimisation results

In this Chapter waste management strategies as well as the data concerning energy and emissions saved (-), or required (+), and cost sustained, are reported. In order to give the magnitude of the results achieved, some important quantities are reported too.
To compare the results found with the current situation, the data related to Italian system up to 2014 have been estimated on the basis of what reported by ISPRA report 2015 [5].

		2014
Emissions	[Mtonne CO2]	-2,32
Energy	[Mtoe]	-3,12
Cost	[G€]	5,76
SCL	[%]	45,20
URW management		Landfilling/MBT/WtE

Table 12.1 - Waste management system data and strategy, Italy, 2014

Data shown in Table 12.1 were calculated (not optimised!) by the model after the variables were fixed at the values reported by ISPRA [5].
The values here reported are useful alas for Chapter 13.

12.1 Considered scenarios

In order to make the model fit to the different possible future conditions, three scenarios (Table 12.2) have been implemented, and later optimised, differing for intercepted quality and separately collected organic fractions process considered.

Scenario	Intercepted flows purity	Organic fraction management
1	lower	AD
2	lower	composting
3	higher	AD

Table 12.2 - Scenarios considered by energy mono-objective optimisation

We included composting because, even though AD results more convenient both in terms of energy and emissions savings, in Italy its diffusion is yet limited compared to AD and in the very last year even decreased [5].

12.2 Some preliminary values to understand results

Energy saved (minus sign), costs and management strategy are reported and discussed in this section.

To better understand whether a fraction has better performance if incinerated than recycled Table 12.3 summarizes energy savings/demand associated to the treatment of 1 kg of fraction.

		Energy from WtE including collection and transport	Energy from recycling including collection and transport
		[MJ /kg pure fraction]	[MJ /kg pure fraction]
	paper	-7,21	-16,73
	wood	-9,41	2,43
	plastics	-16,74	-17,55
	glass	0,52	-7,08
	steel	0,52	-8,56
	aluminium	0,52	-113,75
AD	food waste	-3,34	-0,54
	green waste	-1,48	-1,58
Comp	food waste	-3,34	1,41
	green waste	-1,48	0,28

Table 12.3 - Energy savings/demand associated to material and energy recovery, [MJ / kg pure i-th fraction].

Table 12.3 was calculated on the basis of what explained in Chapter 4 and 5 using equations of paragraph 8.11 and 8.12.

Incineration of every fraction but inert ones is energetically convenient; recycling has positive (energy required instead of saved) values only for wood and organic composting.

The energy related to the management of SRR generating from intercepted flow is neglected by Table 12.3 but is an important driver for the optimisation.

12.3 Results summary

		Scenario 1	Scenario 2	Scenario 3
Energy	[Mtoe]	-6,61	-6,59	-6,68
Cost	[G€]	5,01	5,27	5,04
SCL	[%]	47,50	40,20	49,34
URW management		WtE	WtE	WtE
SRR management		WtE	WtE	WtE
Δ cost (compared to 2014)	[G€]	-0,75	-0,49	-0,72
GDP variation	[%]	-0,04	-0,02	-0,04
Δ energy (compared to 2014)	[Mtoe]	-3,50	-3,47	-3,56
Energy variation (compared to 2014)	[%]	-112,17	-111,43	-114,34
Energy produced cost (compared to cost optimum)	[€/toe]	108,49	187,29	114,29

Table 12.4 - Waste management system data and strategy, energy optimisation, scenarios reported in Table 12.1

As shown by Table 12.4, there are no significant differences in terms of objective function values. Increasing the purity of the intercepted fractions with particular attention for plastics (Scenario 4 and Scenario 5) we can only notice the soft increase of SCL and the better O.F. value due to the better exploitation of the recycling process as explained in 12.4.

The smaller costs reported by Table 12.4 for the scenarios considering AD instead of composting are related to the pronounced SCL variation due the differences of Green-waste separate collection strategies discussed in 12.4.

URW and SRR were always disposed by WtE plants (Figure 12.6 and Figure 12.7).

In Figure 12.1 are shown in a diagram the main flows referred to Scenario 1.

Scenario 2 is very similar to the first one apart that there is no organic flow separately collected: green-waste is left in URW to incineration (Appendix 2).

Scenario 3 is equal to Scenario 1 with a little more intercepted quantity due to the higher purity levels (Appendix 2).

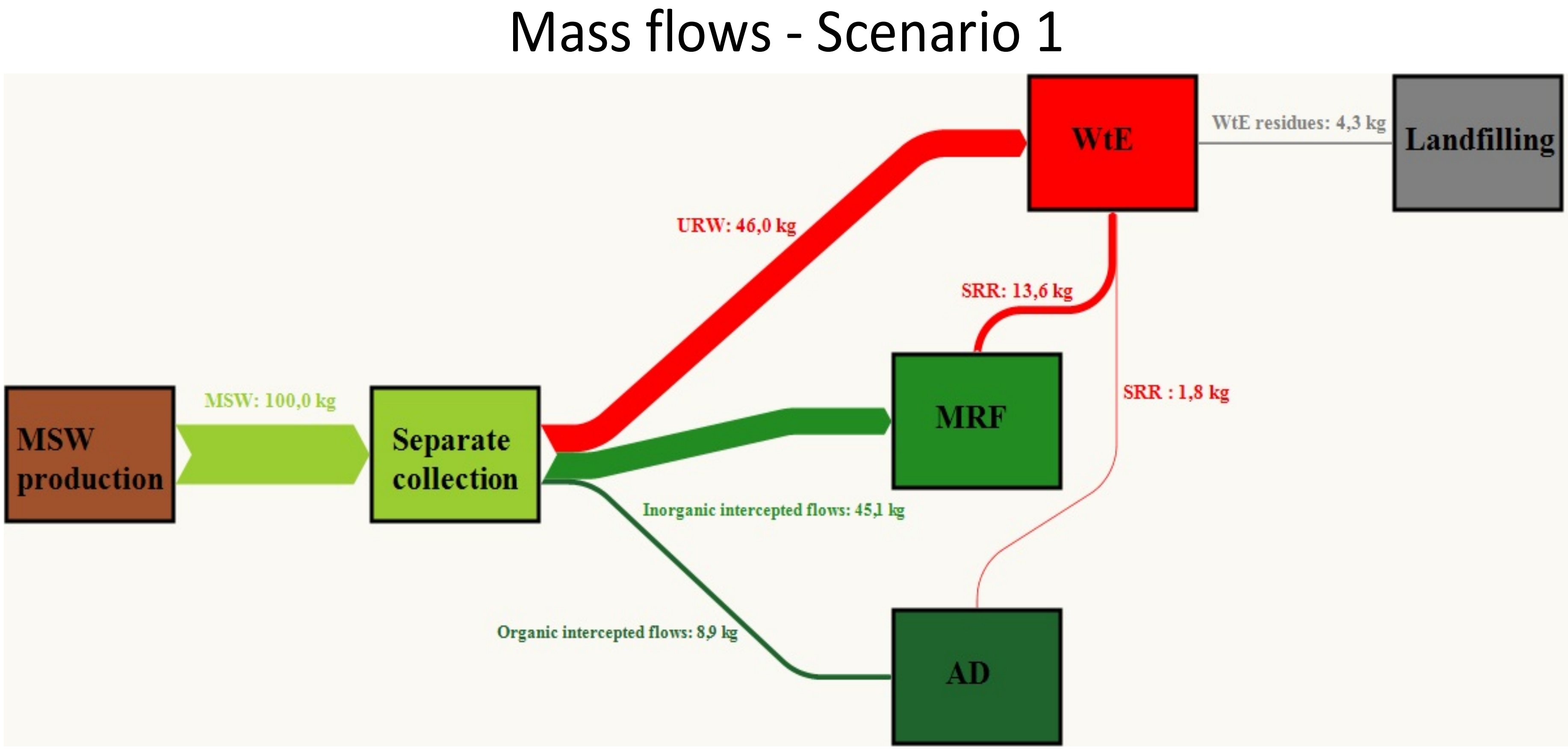


Figure 12.1 – Mass flows Sankey diagram, Scenario 1, energy optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy.

12.4 Interception levels

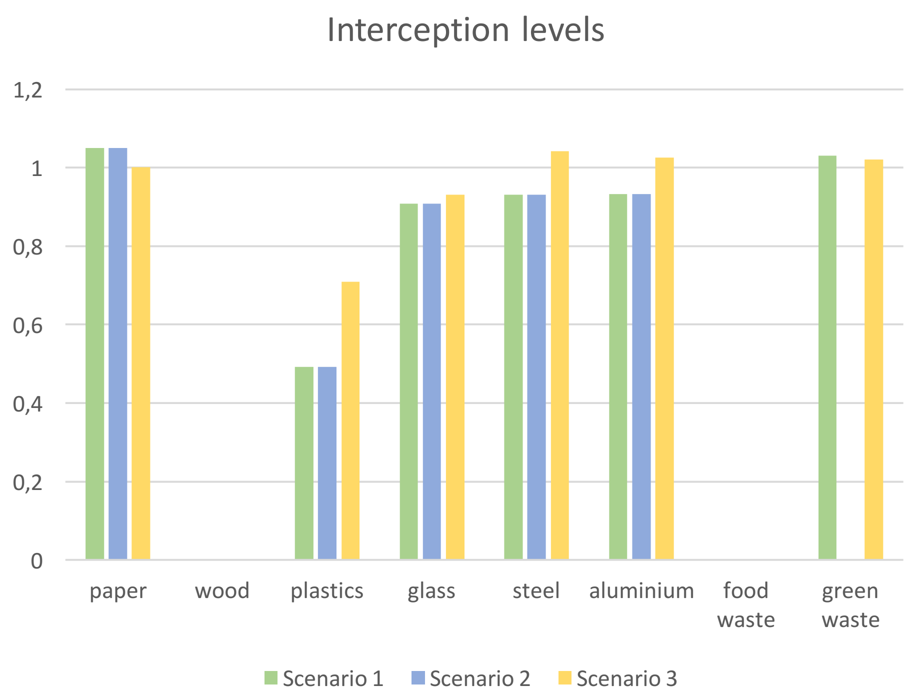


Figure 12.2 – Interception levels, all scenarios, energy optimisation [kg dirty j-th flow intercepted / kg of j-th fraction in MSW], scenarios reported in Table 12.1

Figure 12.2 reports the interception levels of all the scenarios which in this paragraph we analysed.

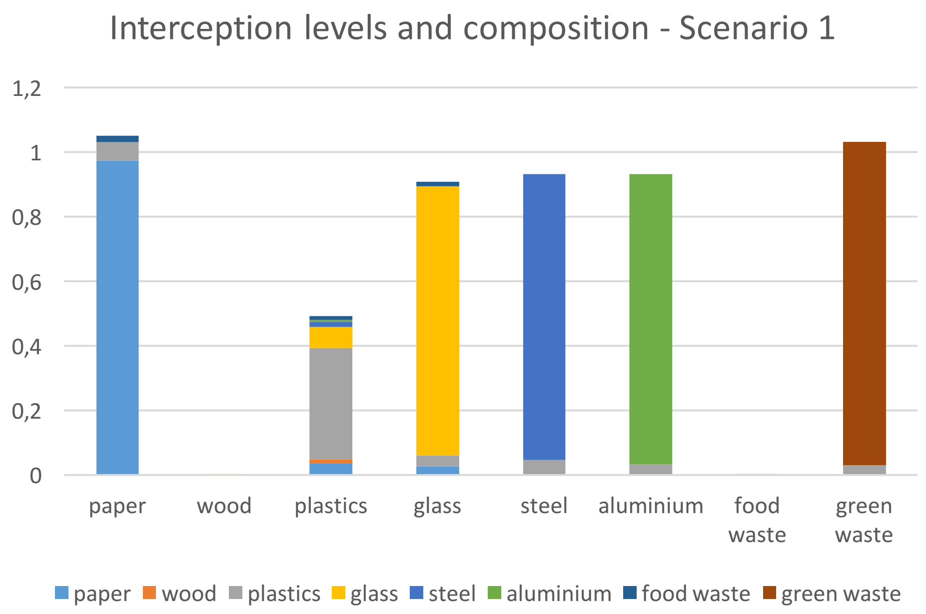


Figure 12.3 - Interception levels and composition of intercepted flows, Scenario 1, energy optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW] , scenarios reported in Table 12.1

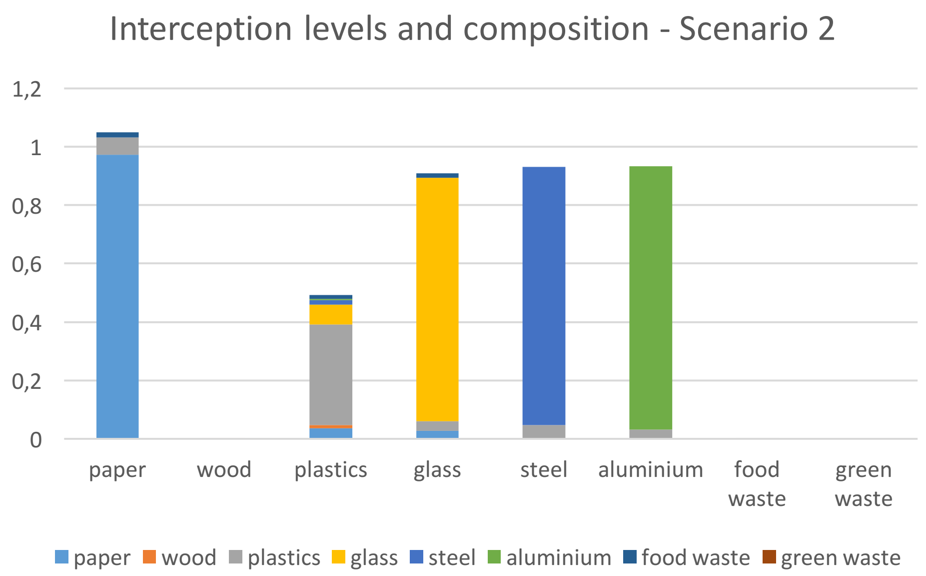


Figure 12.4 - Interception levels and composition of intercepted flows, Scenario 2, energy optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW] , scenarios reported in Table 12.1

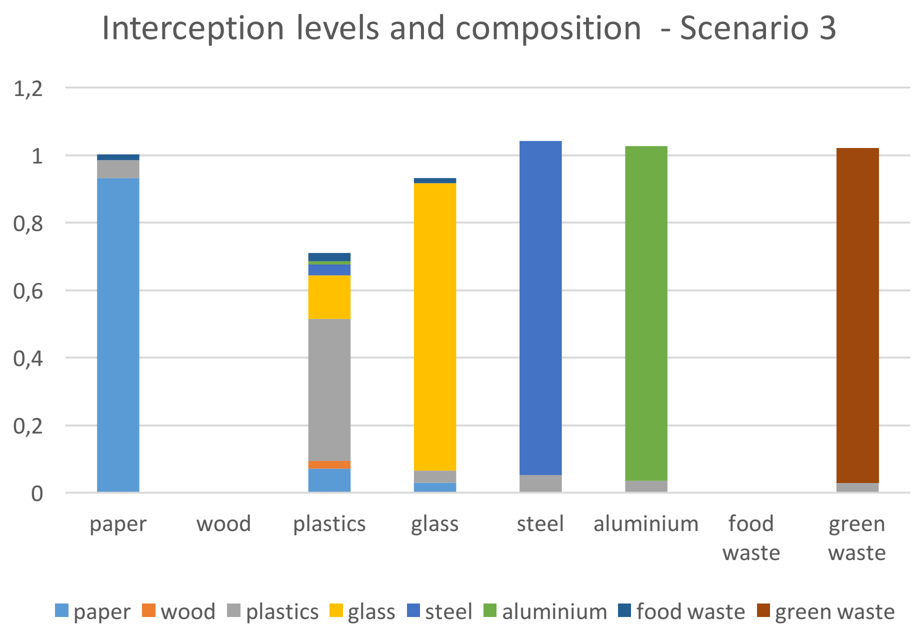


Figure 12.5 - Interception levels and composition of intercepted flows, Scenario 3, energy optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW], scenarios reported in Table 12.1

Figure 12.3, Figure 12.4 and Figure 12.5 report the optimal interception levels of every fraction; as explained in Chapter 6, it can be greater than one, its purity level instead must be strictly less than the unity because some quantity is intercepted by the flows it contaminates (see paper for example).

Let us analyse singularly the interception values:

1. Paper: paper recycling is more convenient than incineration as showed by Table 12.3. The interception of paper reaches in every Scenario the maximum value possible by mass balance: if I would have the paper entirely intercepted by paper flow, I could no more separately collect plastics and glass.

2. Wood: it is entirely sent to WtE because of its high LHV and bad (positive) values of energy associated to recycling.

3. Plastics: it does not reach a high value to respect the mass balance of the fraction which is contaminated of. Increasing plastics interception would cause a decrease in: only glass for Scenario 3, both glass and metals for the other two scenarios. In

Scenario 3, metals were assumed not to contaminate plastics so they are 'free' to be intercepted by their respective flows, as shown by Figure 12.5; only glass constrained plastics interception. In Scenario 1 and 2 the optimisation function found the best compromise between recycling metals and glass the most as possible and intercepting anyway some plastics[6].

4. Glass: its separate collection in every scenario limits plastics interception because it strongly contaminates plastics flow.

5. Metals (steel and aluminium): having higher (in absolute value) energy savings through material recovery than plastics (and a null LHV), they are preferred to be separately collected the most as possible sacrificing the interception of some plastics.

6. Food-waste is completely sent to energy recovery because such destination has better values than AD and much more than composting (Table 12.3).

7. Green-waste is separately collected only when AD is considered (Scenarios 1 and 3, Figure 12.3 and Figure 12.5) because composting, as discussed in paragraph 5.2, has bad values of CED and GWP. Anyway a LHV of Green-waste of approximately 3,15 MJ/kg instead of 2,81 MJ/kg would lead to incineration as more convenient than AD.

12.5 URW and SRR management

While optimising energy, every flow not intercepted is sent to WtE (Figure 12.6) because, MBT is efficient only in separating plastics and metals (η_{sel}~60%) while other fractions are discarded while only few remains in the RDF flow.
Landfilling instead produces a very small amount of energy only by anaerobic digestion of organic fractions.

[6] It should be remembered that we assumed for plastics that at maximum interception level the purity is 0,45 (Scenario 1 and 2), or 0,65 (Scenario 3). Such values are low if compared to other fractions', If is also considered that plastics is much more present in MSW than glass and metals it is easy to understand why optimal interception level is so low.

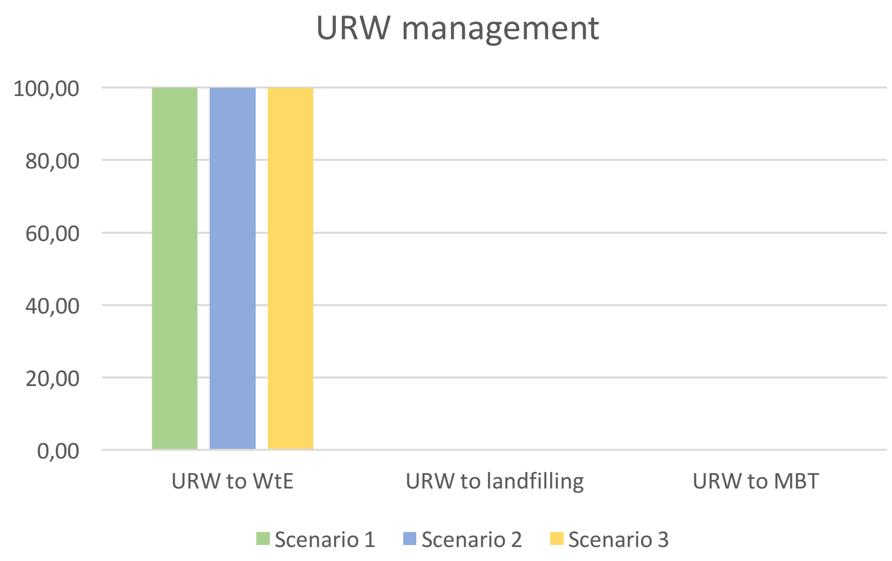


Figure 12.6 - URW management, energy optimisation [%], scenarios reported in Table 12.1

SRR are entirely sent to incineration too as shown by Figure 12.7.

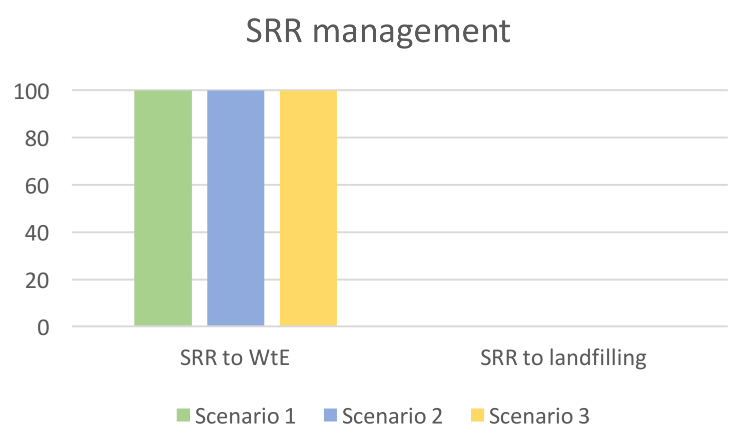


Figure 12.7 - SRR management, energy optimisation [%], scenarios reported in Table 12.1

SRR from inert flows contain some combustible fractions (often plastics) which make incineration convenient even though the burden of residues transport must be paid (Figure 12.8), also when intercepted flows are purer (Scenario 3).

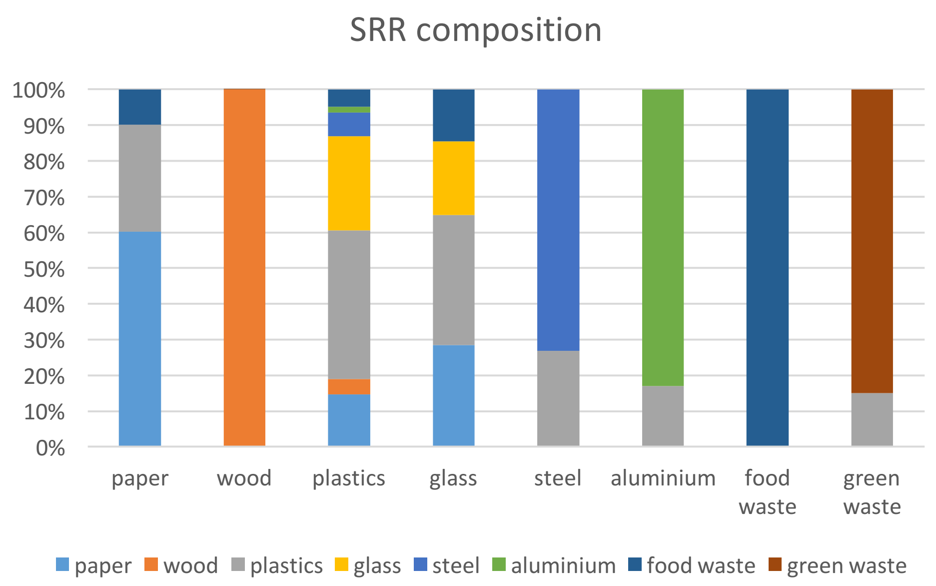


*Figure 12.8 - SRR composition, Scenario 3, energy optimisation, [kg i-th fraction / 100*kg of j-th SRR], scenarios reported in Table 12.1*

12.6 The comparison with current Italian situation

In this paragraph with the help of some graphs, we want to briefly compare Italian situation with the model results.

The comparison was conducted between 2014 Italian situation reported by ISPRA and Scenario 2 which is the most similar to our Country's current condition (see Table 12.1).

		Scenario 2	Italy 2014
Energy	[Mtoe]	-6,63	-3,12
Cost	[G€]	5,26	5,76
SCL	[%]	40,75	45,20

Table 12.5 – General data, Scenario 2 VS Italy 2014, energy optimisation. Italy 2014 data from ISPRA [5]

Table 12.5 shows the different values between the two waste management systems. Energy performance of Scenario 2 more than doubles the Italian ones and costs are minor (-8,6%). In 2014 Italy registered a higher SCL than the optimal value but saved less energy: this was due to the interception of the wrong fractions, as proved by Figure 12.9.

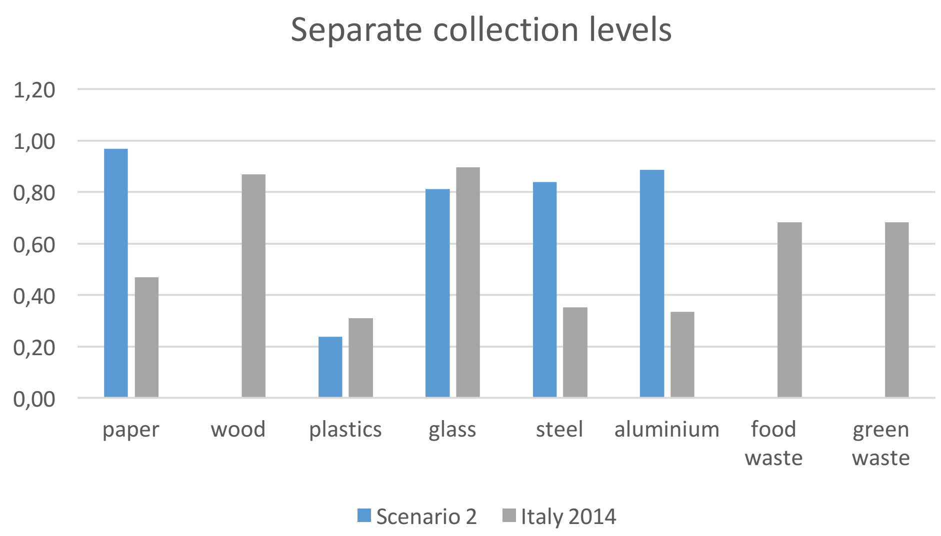


Figure 12.9 - Separate collection levels, Scenario 2 VS Italy 2014, energy optimisation, [kg i-th fraction sent to recycling / kg i-th flow intercepted]. Italy 2014 data from ISPRA [5]*, Scenario 2 values calculated on the basis of methodology reported in 3.3*

Figure 12.9 shows the different separate collection levels, i.e. interception minus selection residues, as explained in 4.1.

To increase the separate collection level as required by the decree (3.1), Italy pushed the interception of wood and organic fractions which, from an energetic point of view, is more convenient to incinerate, particularly if composting is the recycling process. Paper and metals interception, the fractions which are most useful recycling (Table 12.3), is instead too low.

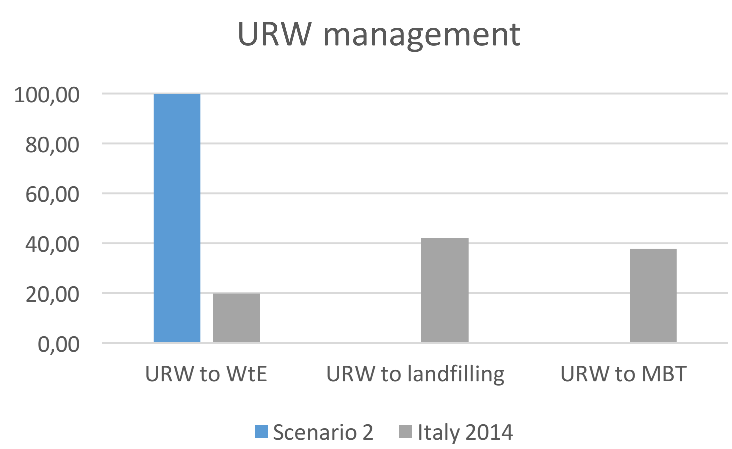


Figure 12.10 – URW management, Scenario 2 VS Italy 2014, energy optimisation,[%] Italy 2014 data from ISPRA [5].

As just discussed in 3.4, landfilling is still too diffused as URW disposal process while incineration would be the best practice (Figure 12.10).
It is worth of notice how, even though landfilling is cheapest than WtE, the costs of Scenario 2 are inferior than Italian: this is due to the inefficient interception strategy of Italy, specially concerning food-waste.
A perfect integration is required between separate collection and URW management as proved by this comparison (and the optimisation results in general).
For sure, increasing the separate collection does not automatically mean improving the waste management system performances.

13 Emissions optimisation results

13.1 Considered scenarios

The same scenarios as energy optimisation were implemented and considered as reported by Table 13.1.

Scenario	Intercepted flows purity	Organic fraction management
1	lower	AD
2	lower	composting
3	higher	AD

Table 13.1 - Scenarios considered by emissions mono-objective optimisation

13.2 Some preliminary values to understand results

Environmental and energetic optimisations are similar with the great difference that, when trying to minimise emissions, plastics incineration must be avoided because of the high fossil Carbon content of this fraction, as shown by Table 13.2.

		WtE emissions including transport	Recycling emissions including transport
		[g CO2/kg]	[g CO2/kg]
	paper	-398,54	-742,90
	wood	-596,08	70,87
	plastics	1047,31	-953,68
	glass	34,54	-402,79
	steel	34,54	-1126,96
	aluminium	34,54	-6080,06
AD	food waste	-212,31	-53,64
	green waste	-87,78	-134,50
Comp	food waste	-212,31	41,86
	green waste	-87,78	-39,00

Table 13.2 - Emission savings/production associated to material and energy recovery, [g CO2 / kg pure i-th fraction]

This is the reason why URW incineration is environmentally sustainable only if its plastics content is low.

13.3 Results summary

		Scenario 1	Scenario 2	Scenario 3
Emissions	[M tonne CO2]	-9,08	-7,96	-9,30
Cost	[[G€]	5,18	5,27	5,07
SCL	[%]	74,28	40,54	50,67
URW management		MBT	WtE	WtE
SRR management		WtE	WtE/Landfilling	WtE/Landfilling
Δ cost (compared to 2014)	[G€]	-0,58	-0,49	-0,69
GDP variation	[%]	-0,03	-0,02	-0,03
Δ emissions (compared to 2014)	[M tonne CO2]	-6,76	-5,64	-6,98
Emissions variation (compared to 2014)	[%]	-291,63	-243,15	-301,26
Emissions avoided cost (compared to cost optimum)	[€/tonne CO2]	16,77	20,25	13,16

Table 13.3 - Waste management system data and strategy, emissions optimisation, scenarios reported in Table 13.1

Environmental optimisation revealed a greater variability than the energy one among the different scenarios, both in terms of interception strategy and URW management, in order to avoid as much as possible incinerating plastic materials as explained in the following paragraphs Figure 13.1 reports the flow diagram referred to Scenario 1 in order to summarise the principal quantities.

We reported even the flow diagram referred to Scenario 3 (Figure 13.2), because, as explained in 13.4, the mass flows are different.

Scenario 2 is similar to Scenario 3 with the difference that green waste is left in URW and total intercepted quantity is lower due to the assumptions on purity level (Appendix 2).

It is worth of notice how, even though all the URW is sent to MBT, 5,7 million tonnes every year are incinerated to dispose SRR flow

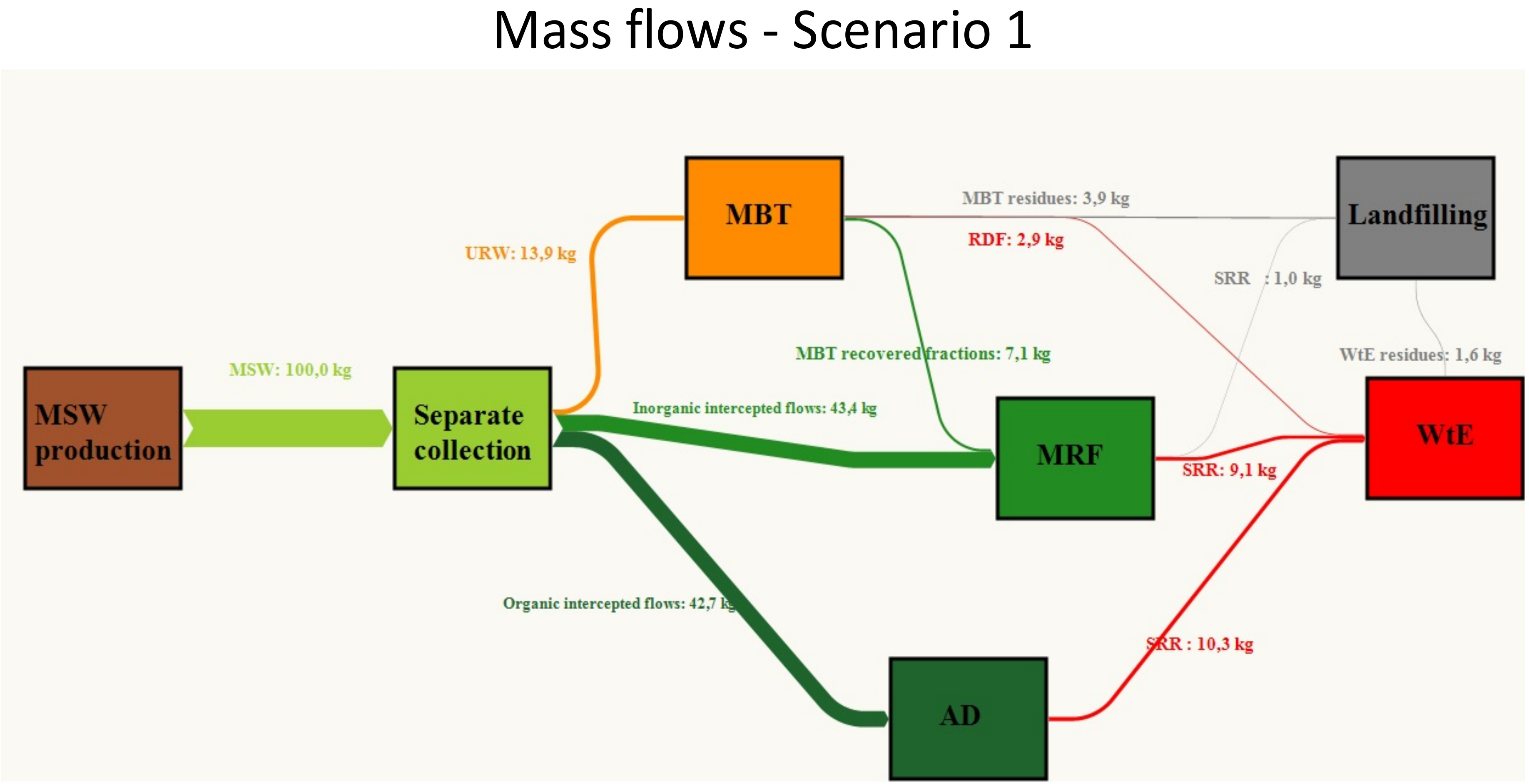


Figure 13.1 - Mass flows Sankey diagram, Scenario 1, emissions optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy; MBT: Mechanical Biological Treatment

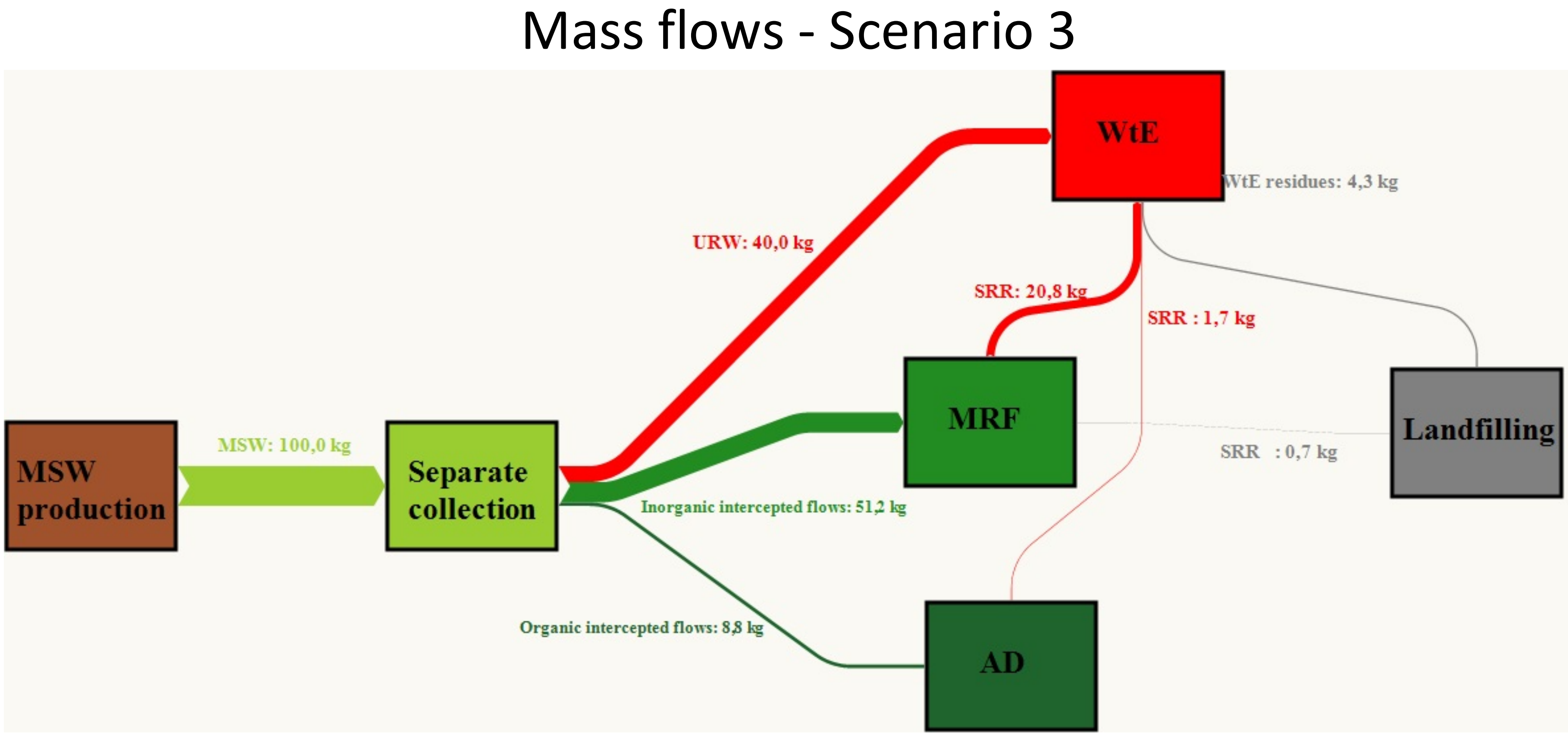


Figure 13.2 - Mass flows Sankey diagram, Scenario 3, emissions optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy

13.4 Interception levels

The two main drivers of the interception strategy when minimising emissions are:

- Incineration of plastic fraction to be avoided
- Organic fractions composting very low performances; the high weight of food-waste on total MSW strongly affects the waste management strategy

Figure 13.3 shows the optimal interception levels of every fraction which will be again singularly analysed.

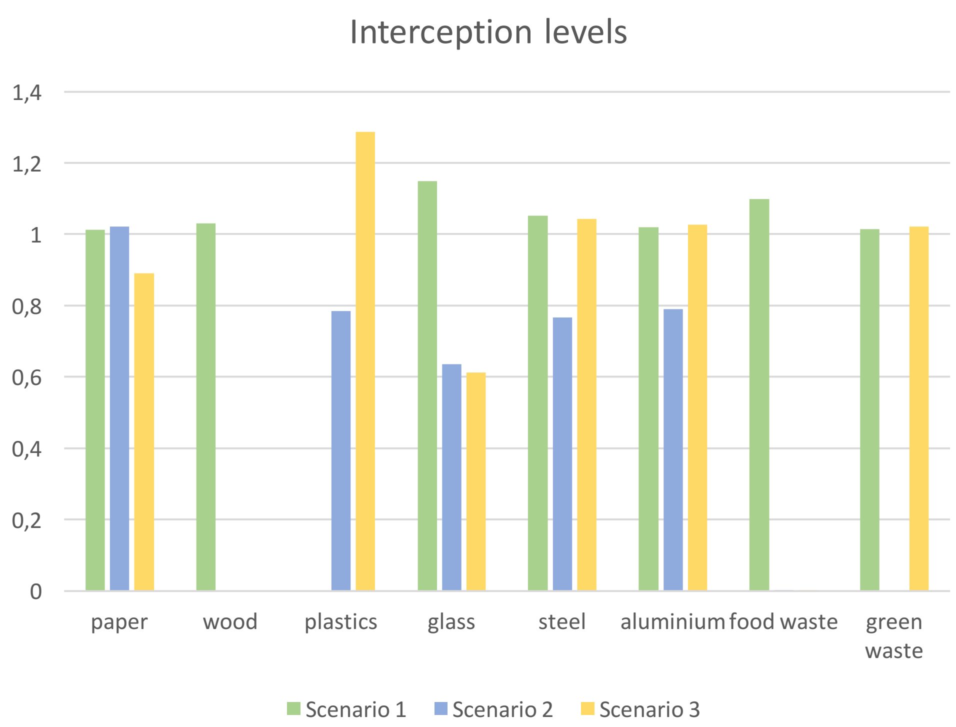


Figure 13.3 - Interception levels, all scenarios, emissions optimisation, [kg dirty j-th flow intercepted / kg of j-th fraction in MSW] , scenarios reported in Table 13.1

Once again, to fully understand the results, the histograms with the intercepted composition are reported.

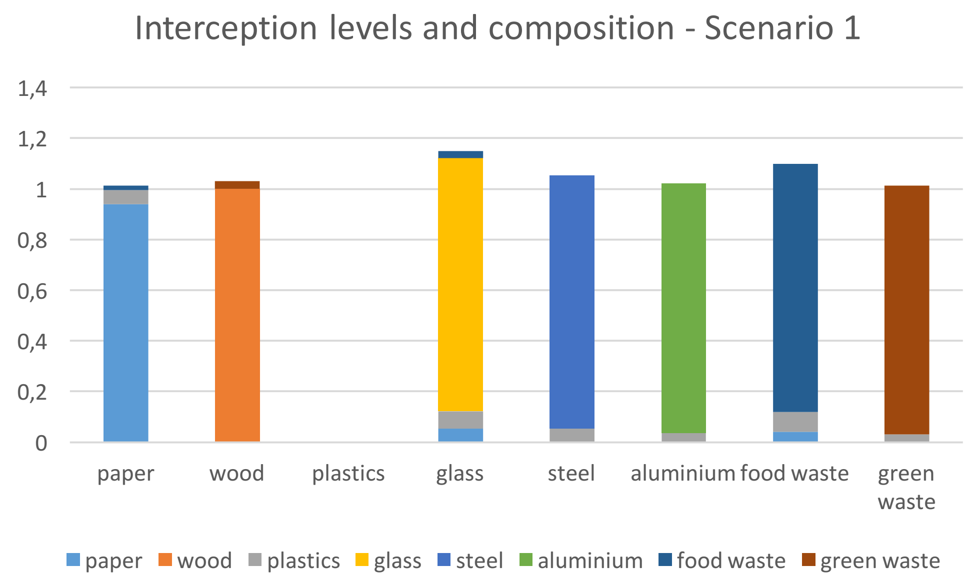


Figure 13.4 - Interception levels and composition of intercepted flows, Scenario 1, emissions optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW], scenarios reported in Table 13.1

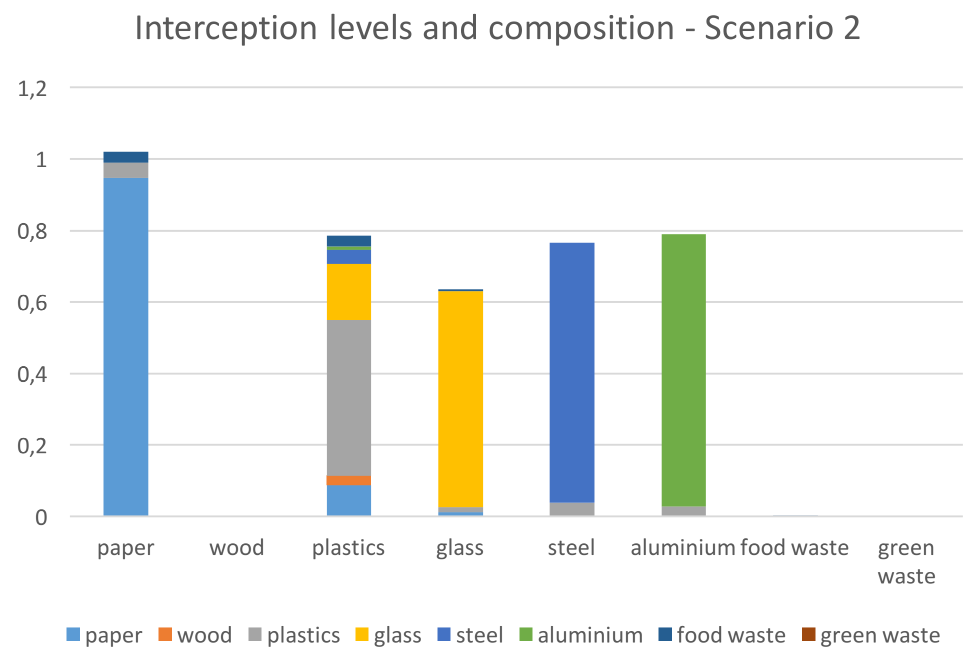


Figure 13.5 - Interception levels and composition of intercepted flows, Scenario 2, emissions optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW], scenarios reported in Table 13.1

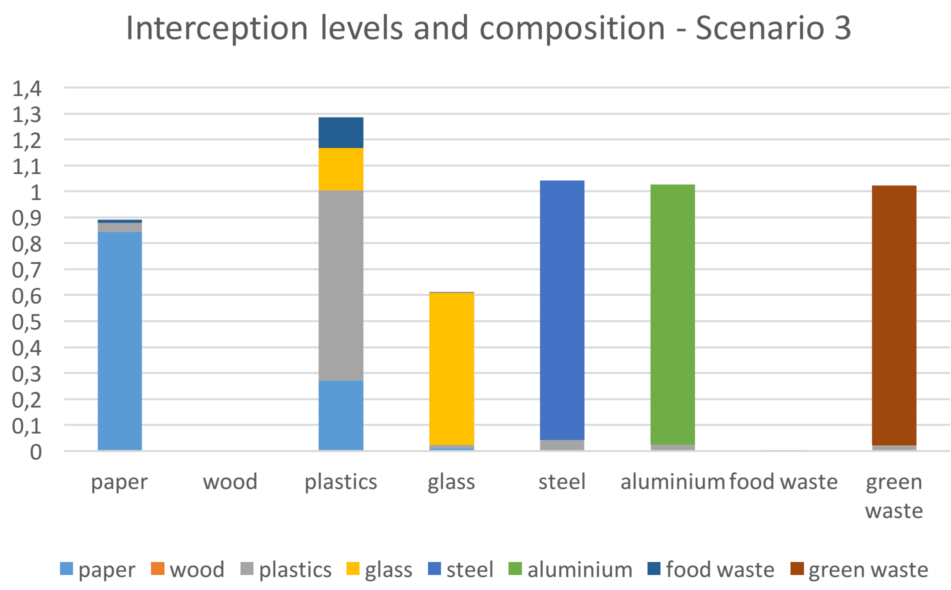


Figure 13.6 - Interception levels and composition of intercepted flows, Scenario 3, emissions optimisation [kg i-th fraction in dirty j-th flow intercepted / kg of j-th fraction in MSW] , scenarios reported in Table 13.1

1. Paper: paper recycling is more convenient than incineration as showed by Table 13.2, so the interception of paper reaches almost in every Scenario the maximum allowed by mass balance. In Scenario 3 the value is less than 90% in order to let plastics reach the value of 1,28.

2. Wood: it is separately collected only in Scenario 1. It is the only scenario in which URW is sent to MBT where it is almost entirely discarded (~85%). If collected, even though recycling produces, instead of saving, emissions, its SRR (~20% of intercepted flow and only composed by wood and food-waste) can be sent to incineration. Furthermore, the environmental burden of wood collection are set equal to zero in the model (it is up to the householder, paragraph 4.6). If WtE is selected as URW treatment wood interception always is 0 (Scenario 2 and 3).

3. Plastics: the interception of paper is, with food-waste responsible of URW management.

- Scenario 1: in this scenario people are modelled (on the basis of real current data) to collect the plastics flow quite inefficiently causing that the intercepted flow contains little plastics at high interception levels as showed by Figure 13.7 (at the maximum interception level purity is 0,45). MBT revealed itself to be more efficient in plastics separation than householder (~60% is separated) so it is chosen as URW management system and there all the plastics present in MSW is sent causing the interception rate of plastics to be equal to 0 (Figure 13.4).
- Scenario 2: because of the positive values of composting for organic fractions, the model finds the optimal solution incinerating URW and intercepting plastics as much as possible (even if purity is low as shown by Figure 13.7). It should be remembered that food-waste represents a great fraction of MSW composition: an inefficient management of it rapidly decrease objective function.
- Scenario 3: minimum intercepted flow purity is 0,65: plastics flow is more efficiently collected than Scenario 1 and 2 and the model pushes its interception up to 1. In this case URW can be incinerated because its plastics content is low.

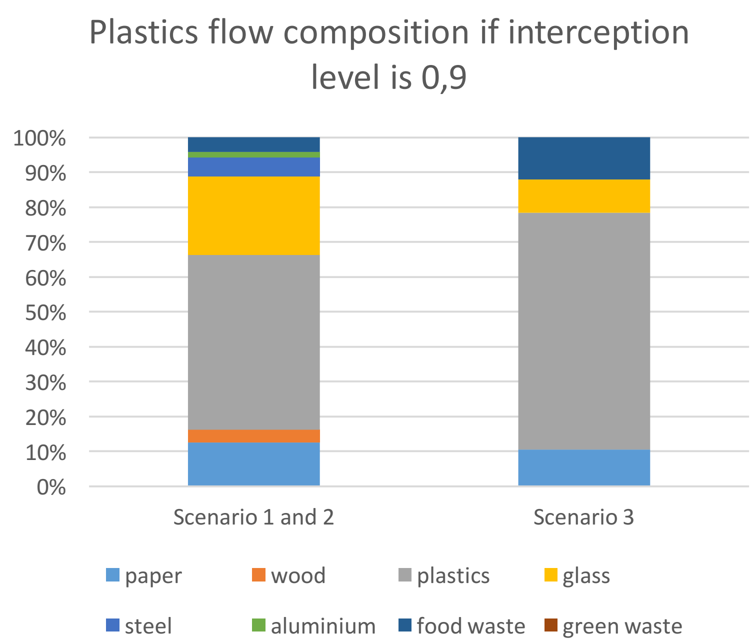


*Figure 13.7 - Intercepted plastics flow composition for a specific interception level, Scenario 1, 2 and 3, [kg i-th fraction in dirty plastics flow intercepted / 100*kg of plastics fraction in MSW] , scenarios reported in Table 13.1*

4. Glass: it is intercepted as much as possible because recycling is convenient (Table 13.2) and its purity level is always quite high (at least 90%). In Scenario 2 and 3 its separate collection represents the optimal compromise between intercepting glass and plastics (which as shown by Figure 13.7 contains always a not negligible quantity of glass).

5. Metals: as glass, their interception, being recycling environmentally advantageous, is limited only by plastics mass balance (Figure 13.5).

6. Food-waste: such fraction is never separately collected unless URW is sent to MBT. In this last case, because of the fact that food-waste fraction recovered by MBT to produce RDF is only 0,05% (organic fraction material recovery of MBT is null), AD results more convenient. If composting is the treatment considered, food-waste is responsible of the waste management overturning (Scenario 1 VS Scenario 2).

7. Green-waste: it is always intercepted except when composting.

13.5 URW and SRR management

URW management and separate collection are strictly related and influences each other as clarified in section 13.4.
Residual waste optimal treatment process strictly depends on URW composition (reported by Figure 13.8).

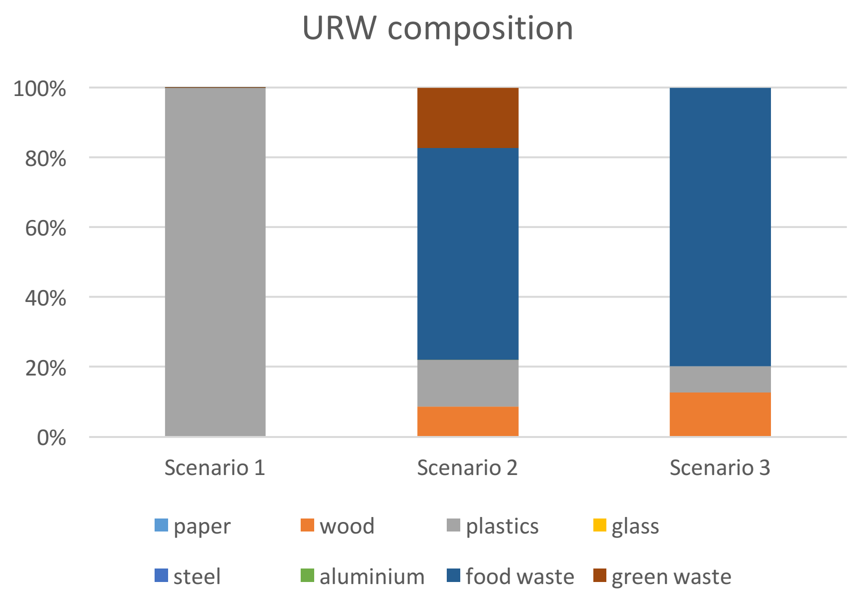


Figure 13.8 - URW composition for the three scenarios analysed [%], scenarios reported in Table 13.1

Low plastics residual waste can be sent to WtE; differently it must be sent to MBT (Figure 13.9).

Landfilling must be avoided specially for organic fractions that are responsible of methane slips.

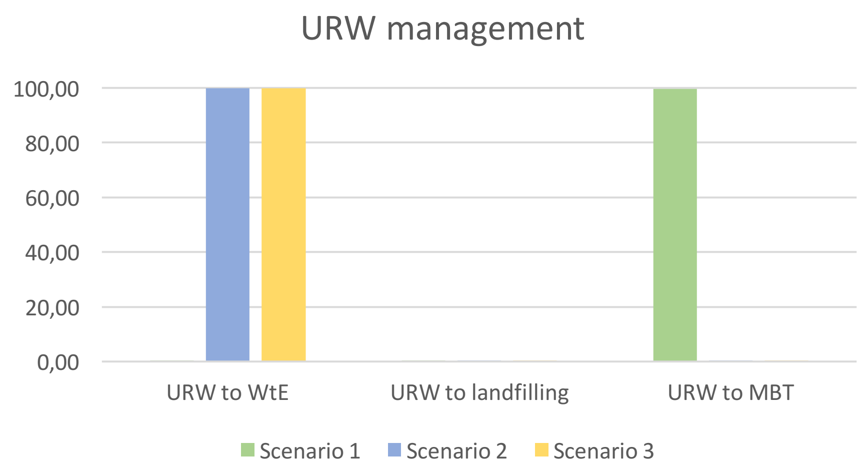


Figure 13.9 - URW management, emission optimisation, [%], scenarios reported in Table 13.1

SRR are always sent to energy recovery except from the flows with high plastics content as Plastics, Steel and Aluminium of which the composition is reported in Figure 13.10:

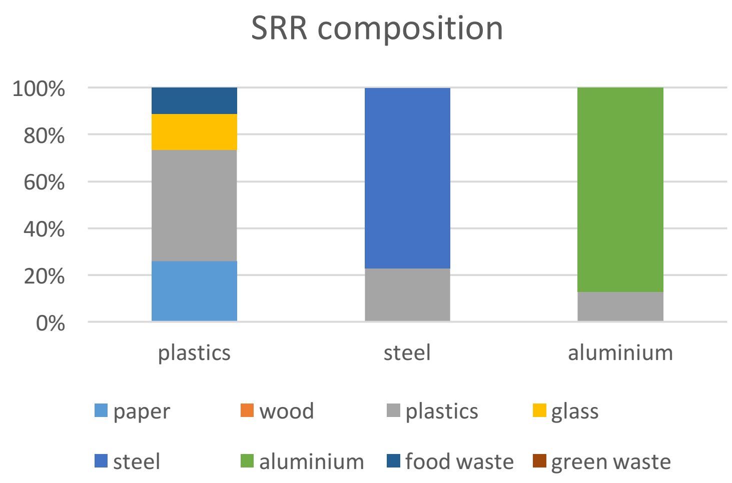


*Figure 13.10 - SRR composition of plastics, steel and aluminium, Scenario 3, [kg i-th fraction / 100*kg of j-th SRR] , scenarios reported in Table 13.1*

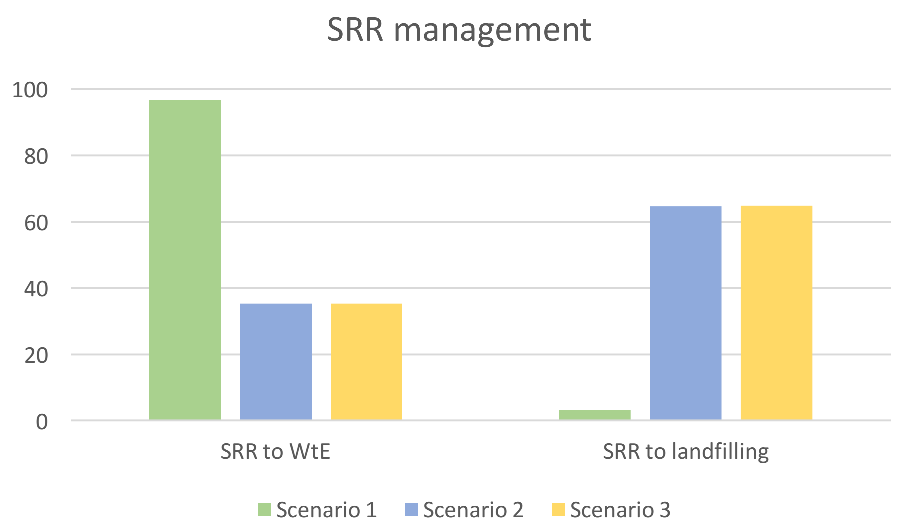


Figure 13.11 - SRR management, emissions optimisation, [%],scenarios reported in Table 13.1

SRR of Scenario 1 are almost totally sent to incineration because plastics is not intercepted and does not generates a selection and recycling residues stream as in the other scenarios (Figure 13.11), though steel and aluminium SRR are small in quantity.

13.6 The comparison with current Italian situation

Once again, a comparison with Italian situation was carried out.

		Scenario 2	Italy 2014
Emissions	[Mtoe]	-7,96	-2,32
Costs	[G€]	5,27	5,76
SCL	[%]	40,54	45,20

Table 13.4 – General data, Scenario 2 VS Italy 2014, emissions optimisation. Italy 2014 data from ISPRA [5]

Table 13.4 shows how, also when considering the environmental issue, Italian waste management system is inefficient: even though Italian SCL is greater, it performs less than a third of optimal emission savings and greater costs (+ 8 %).

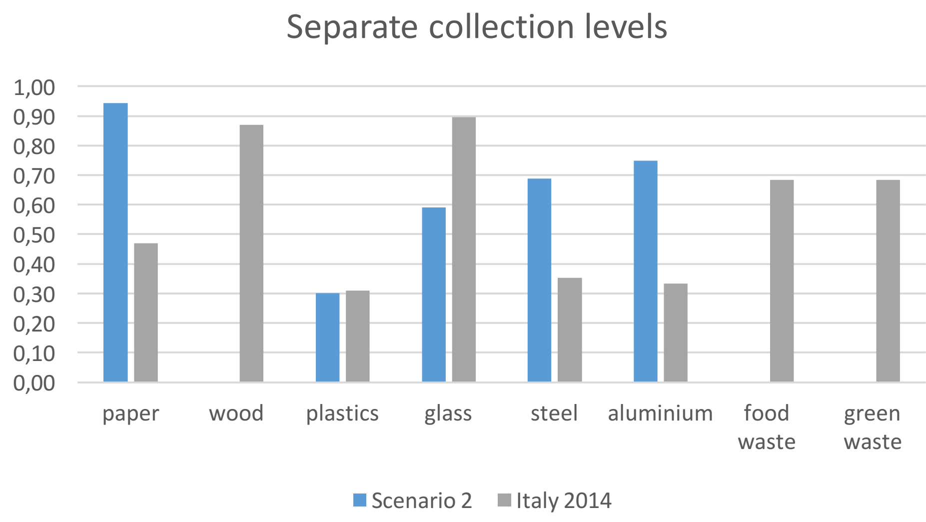


Figure 13.12 - Separate collection levels, Scenario 2 VS Italy 2014, emissions optimisation, [kg i-th fraction sent to recycling / kg i-th flow intercepted]. Italy 2014 data from ISPRA [5], *Scenario 2 values calculated on the basis of methodology reported in 3.3*

As we just told (12.6), current Italian separate collection is focused on the fractions with the lowest recycling values (Figure 13.12). Apart from plastics, the other fractions interception is far from being optimal.

URW management is far from being optimal too because landfilling of organic fractions must be avoided when considering emissions while in Italy is still done.

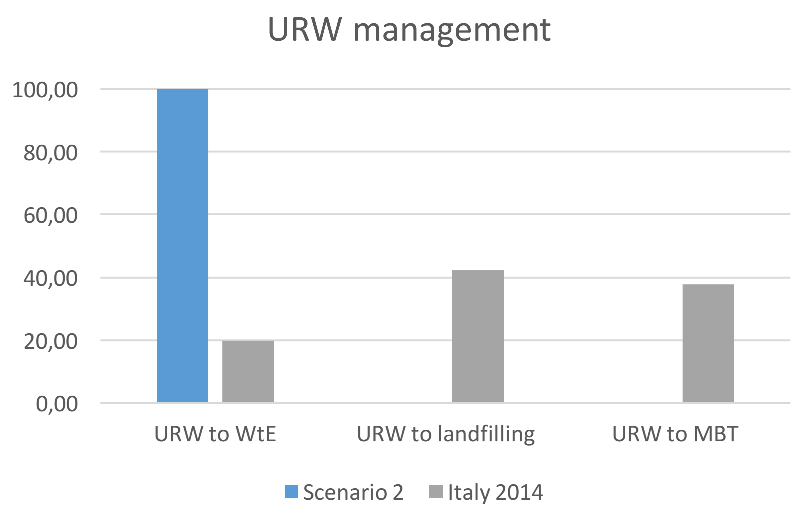


Figure 13.13 - URW management, Scenario 2 VS Italy 2014, Italy 2014 data from ISPRA [5]

As discussed in section 13.5, MBT could represent an effective way to dispose URW but only accompanied by some specific interception levels. Its diffusion in Italy is anyway too low to guarantee good environmental performances (Figure 13.13).

13.7 An example of sensitivity analysis

While Scenario 3 can represent a hypothetical future condition where awareness policies revealed to be effective, we decided to examine it more deeply with a very simple sensitivity analysis.

We compared it with a new scenario in which incinerator is modelled to replace energy produced by the entire electric grid, including renewables, instead of thermo-electric.

This assumption was simply realised by considering the new emission factor reported in 4.3. Incineration emissions of the different fractions are reported in Table 13.5 Material recovery values remain equal to the ones in Table 13.2.

		WtE emissions including transport (electric grid substituted)
		[g CO2/kg]
	paper	-267,68
	wood	-427,80
	plastics	1356,72
	glass	34,54
	steel	34,54
	aluminium	34,54
AD	food waste	-146,88
	green waste	-53,86
Comp	food waste	-146,88
	green waste	-53,86

Table 13.5 - Emission savings/production associated to energy recovery, electric grid considered, [g CO2 / kg pure i-th fraction]

Plastics incineration turns to be more noxious than in the other scenarios and to avoid its combustion MBT is once again the optimal choice. In fact, the plastics contained by RDF flow exiting the MBT is less then 20% of plastics entering.

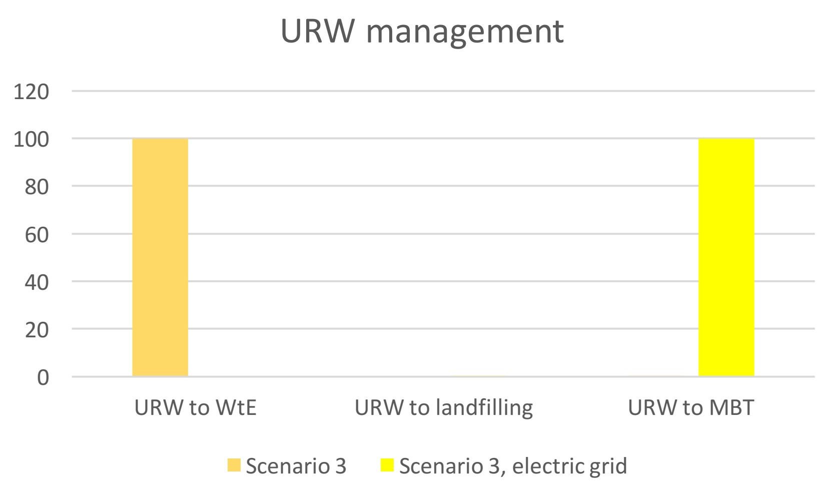


Figure 13.14 –URW management, emissions optimisations, Scenario 3 and 3 electric grid, [%], scenario 3 as reported in Table 12.1, Scenario 3 electric grid as reported in 13.7

Figure 13.14 shows how URW is sent entirely to MBT.

Such treatment process revealed itself to be the most efficient way to recover plastics because by householder interception some percentage is discarded during the selection process and some other is not intercepted at all (due to the extraneous fraction presence).
SCL (74%) and interception levels are identical to Scenario 1 (Figure 13.15).

Figure 13.15 – Interception levels, emissions optimisations, Scenario 3 and 3 electric grid, [%], scenario 3 as reported in Table 12.1, Scenario 3 electric grid as reported in 13.7

14 Cost optimisation results

Due to the assumption considered to model this topic, cost optimisation represented the computationally easiest optimisation performed.

14.1 Results summary

		Scenario 1	Scenario 3
Cost	[G€]	4,60	4,59
Energy	[Mtoe]	-4,46	-4,45
Emissions	[Mtonne CO2]	20,09	20,10
SCL	[%]	49,12	49,23
URW management		Landfilling	Landfilling
Δ cost (compared to 2014)	[G€]	-1,16	-1,17
GDP variation	[%]	-0,06	-0,06
Δ emissions (compared to 2014)	[Mtonne CO2]	22,40	22,42
Δ energy (compared to 2014)	[Mtoe]	-1,34	-1,33

Table 14.1 - Waste management system data and strategy, cost optimisation, scenarios reported in Table 13.1n

As highlighted by Table 14.1 there is no particular differences among the two scenarios reported: values of costs, emissions and energy varies only because of the slightly differences concerning interception values. When the flows are more contaminated and plastics is left in URW (the flow which more capture other fractions if separately collected), a greater quantity can be intercepted before the mass balance constraint activates causing a very small increase in the total intercepted quantity and a corresponding decrease of total URW.

Scenarios referring to composting are not reported because they performed identical results due to the assumptions about cost modelling explained in 10.7.

A value that must be highlighted is represented by emission: if all the URW (more than a half formed by Food-waste, Figure 14.2) is sent to landfilling (Figure 14.3) the

environmental objective function turns to be really high, i.e. much $CO_{2,eq}$ is released in the atmosphere due to biogas slip. Energy objective function instead remains negative.
Figure 14.1 reports the flow diagram related to Scenario 1 (Scenario 3 is equal, see Appendix 2)

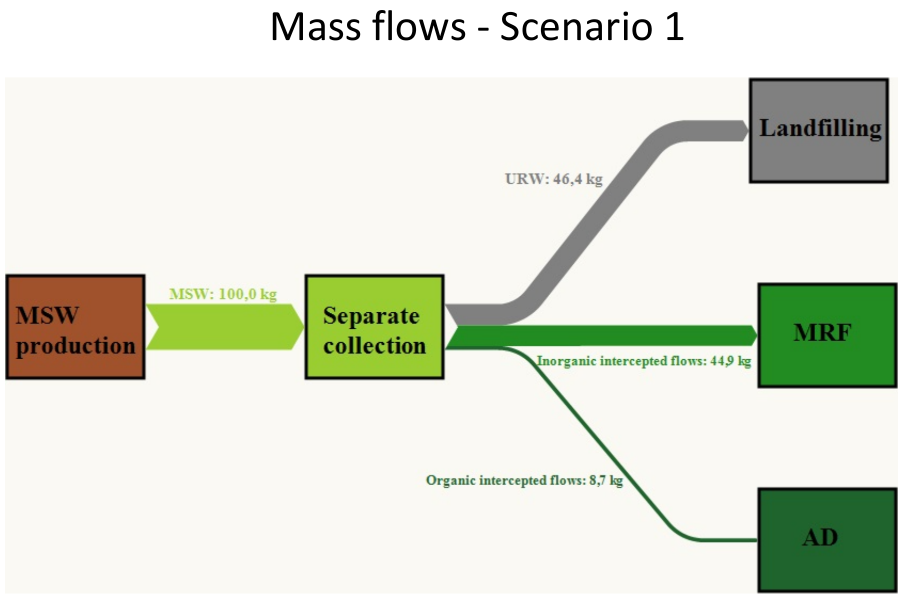


Figure 14.1 – Mass flows Sankey diagram, Scenario 1, cost optimisation, (kg / year). MRF: Material Recovery Facility;AD: Anaerobic Digestion; MSW: Municipal Solid Waste; URW: Urban Residual Waste

14.2 Interception levels

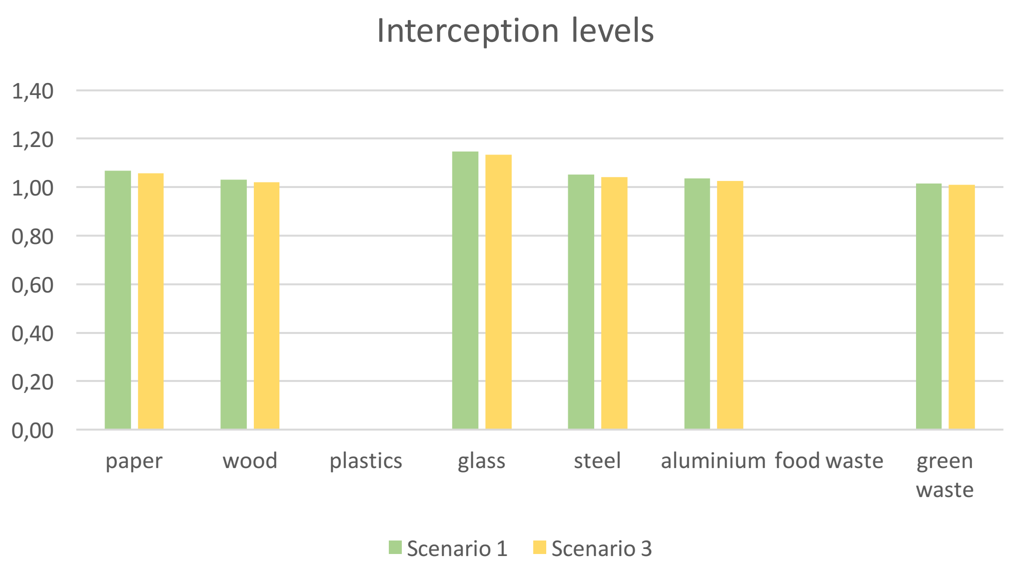


Figure 14.2 - Interception levels, cost optimisation, [kg dirty j-th flow intercepted / kg of j-th fraction in MSW], scenarios reported in Table 13.1

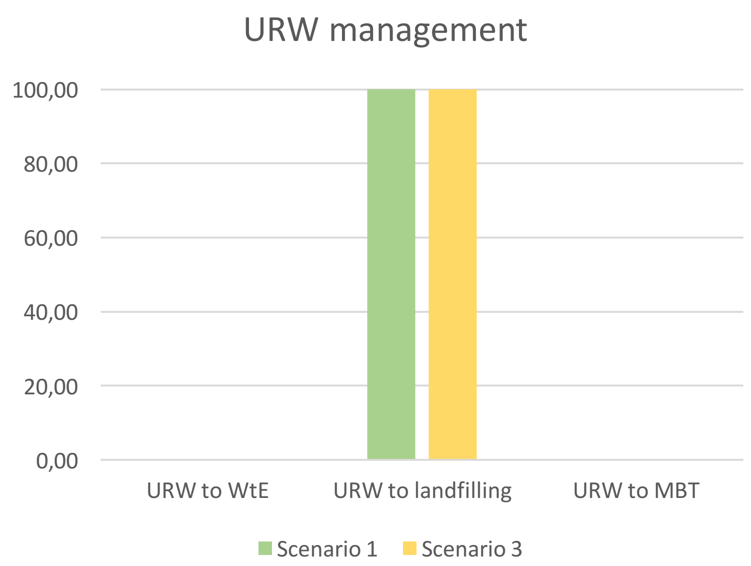


Figure 14.3 - URW management, cost optimisation, [%],scenarios reported in Table 13.1

Figure 14.2 and Figure 14.3 show the optimal management strategy in order to minimise cost.

The fractions economically convenient to separately collect are intercepted up to the limits, while the remaining are entirely sent to landfilling.
Such results are anyway easy to understand simply looking at Table 10.1 and are completely consistent with previous studies [7], [77].

15 Multi-objective optimisation results

15.1 Scenarios considered

Table 15.1 summarises the scenarios considered by two-objective optimisation.

Scenario	Intercepted flows purity	Organic fraction management
1	lower	AD
3	higher	AD

Table 15.1 - Scenarios considered by the two-objective optimisation

Two-objective optimisation was performed only for Scenario 1 and Scenario 3 which the mono-objective optimisation proved to be the ones with lower values of the objective functions.

As told, mono-objective optimisation considered separately energy, emissions and cost while multi-objective evaluated together energy/emissions and cost.

About the methodology used to perform the two multi-objective optimisations we have already discussed in section 11.2.

At first, as said, the Matlab function *gamultiobj* was set and the classical shape of the Pareto front was found (see Figure 15.1)

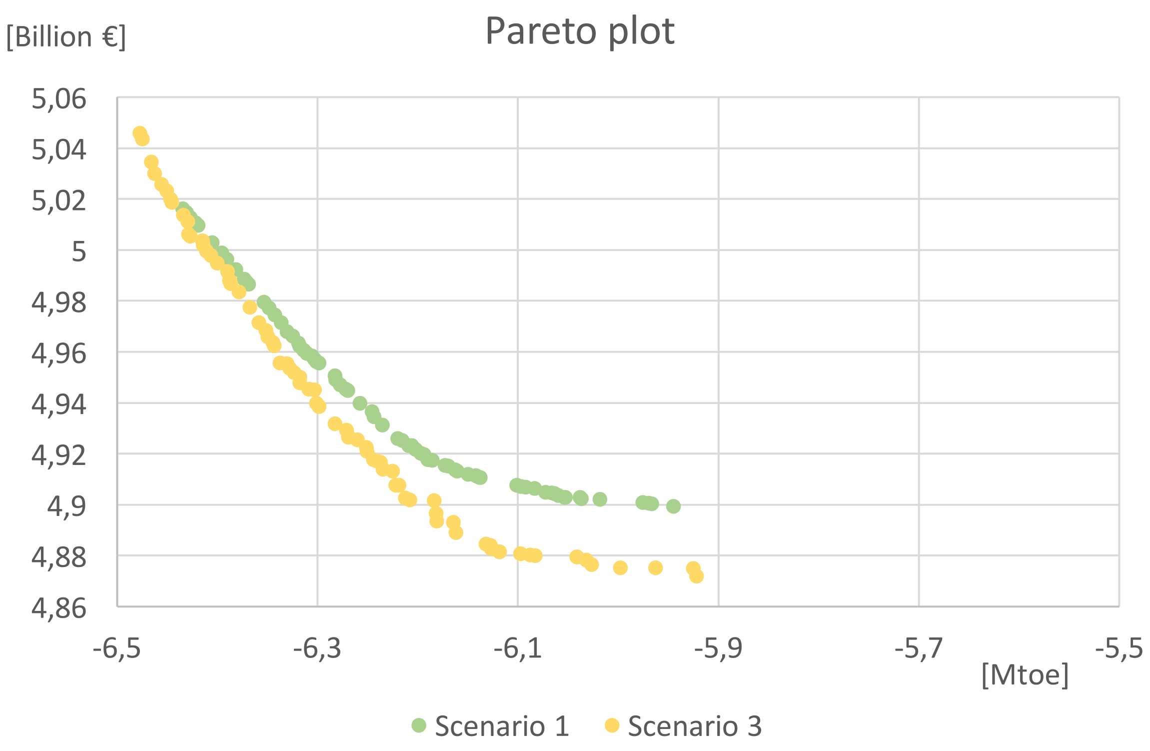


Figure 15.1 - Example of energy Pareto plot, gamultiobj, scenarios reported in Table 15.1

By the knowledge of the model, and after iterated tests, it was discovered that the solutions found by the genetic algorithm was not the very optimal.

As sometimes happens when trying to solve non linear problems with non-convex objective functions, only local minima were found.

In order to exceed such difficulty and attempt to find a Pareto front closer to the optimal one, it was decided to perform a mono-objective optimisation on costs, adding a non linear constrain on energy/emissions.

Proceeding this way, we found the very optimal energy and emissions points relatively to some fixed values of costs.

This methodology has been in a second time tested conducting the energetic/environmental optimisation, constraining costs. The results found were perfectly coherent with the first ones.

15.2 Energy VS Costs optimisation

Figure 15.2 shows the Pareto front relative to energy-cost optimisation.

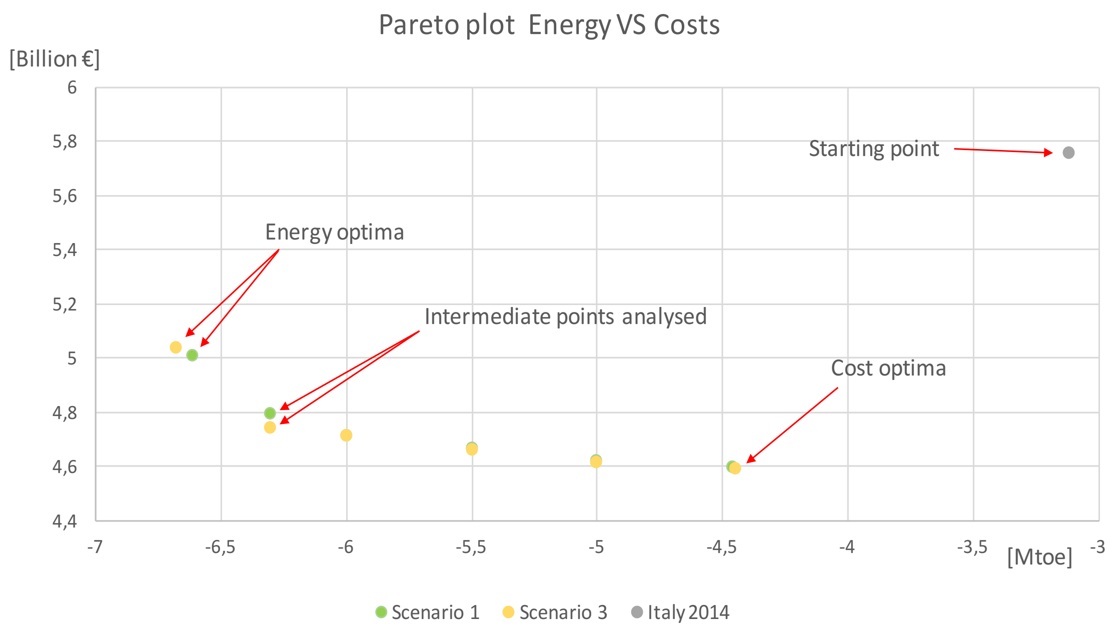


Figure 15.2 – Energy VS Costs Pareto front. Green dots: Scenario 1. Yellow dots: Scenario 3 (increased purity levels). Grey dot: Scenario 3. Scenarios reported in Table 15.1. For lower cost green and yellow dots are very close.

Points of Figure 15.2 lie below the ones in Figure 15.1 meaning that, if not the optimal, at least a better solution was found.

As expected, Scenario 3 recorded costs slightly lower than Scenario 1 for every fixed value of energy because increasing the purity levels entails a better working of recycling processes. The extremity points of the plot are energy and cost optima found by mono-objective optimisation, their waste management strategies have been already discussed in paragraphs 12.3.

The front is not characterised by a very stiff gradient region, anyway we decided to analyse the points just before the change in slope: their strategies are shown by Figure 15.3 and Figure 15.4.

As shown in Figure 15.2, such value of energy savings does not entail a much greater economic effort than economic optimum, and can give a rough estimate of the costs that can be sustained to sensitise the community on the waste issue (the cost difference between green and yellow points).

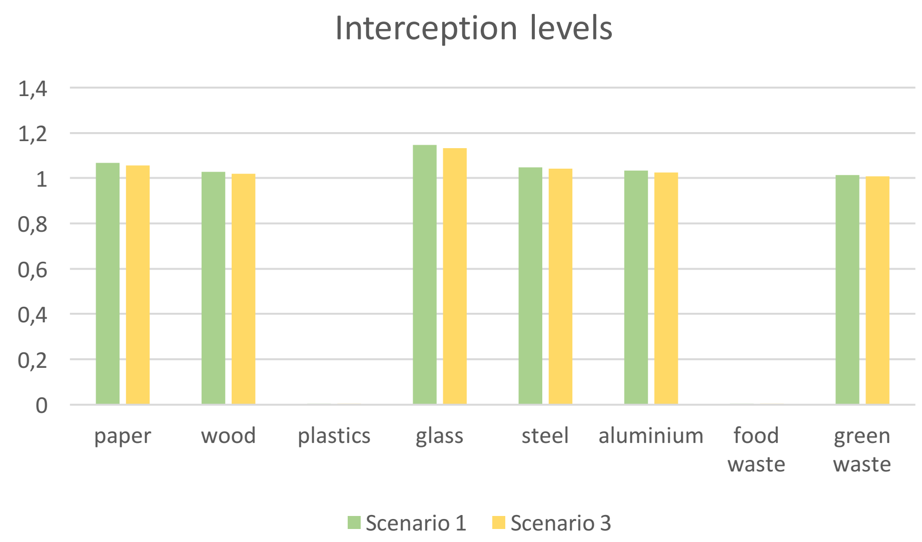


Figure 15.3 - Interception levels, intermediate point, energy VS cost optimisation, [kg dirty j-th flow intercepted / kg of j-th fraction in MSW] , scenarios reported in Table 15.1

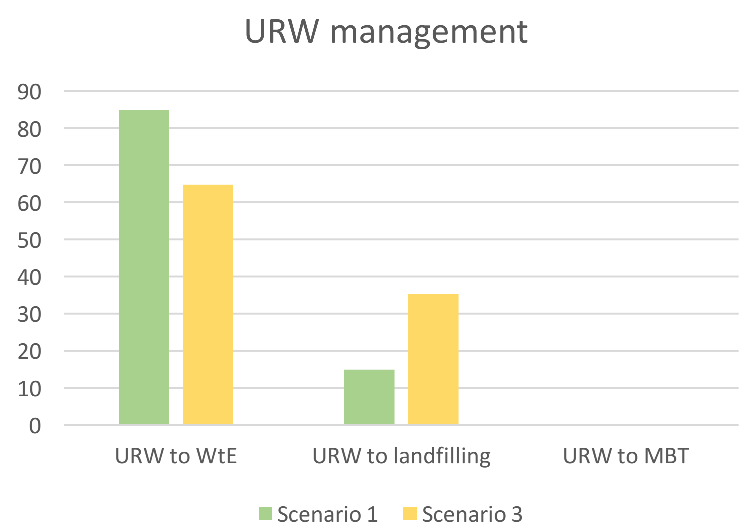


Figure 15.4 – URW management, intermediate point, energy-cost optimisation, [%], scenarios reported in Table 15.1

Because of the fact that in Scenario 3, as explained in Chapter 14, the total intercepted quantity is lower than Scenario 1 but the global recycling performances are higher, more URW can be landfilled entailing a cost reduction.

All the SRR, the not negligible quantity of 2,54 million tonnes every year, are sent to incineration.

An interesting result emerges from energy-cost objective optimisation: when considering the energy topic, MBT choice is never considered as optimal by the model, not even when costs are included.

15.3 Emissions VS Costs optimisation

Once again the trade-off between the two topics is evident, according with the shape of the Pareto front described by the points reported in Figure 15.5.

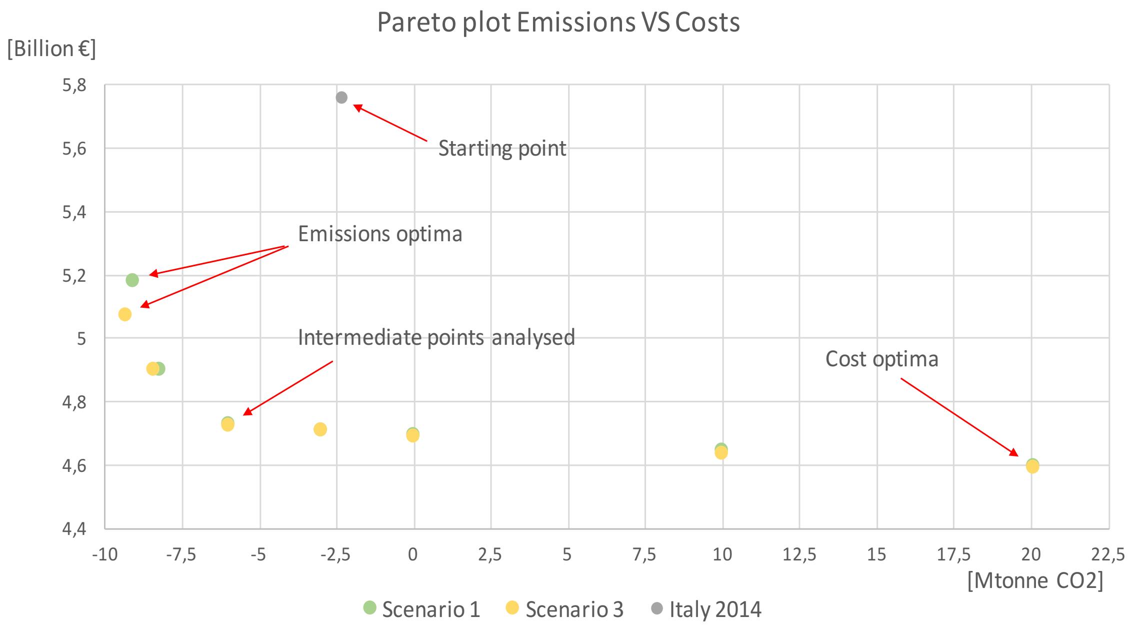


Figure 15.5 – Emissions VS Costs Pareto front. Green dots: Scenario 1. Yellow dots: Scenario 3 (increased purity levels). Grey dot: Scenario 3. Scenarios reported in Table 15.1. For lower cost green and yellow dots are very close.

In Figure 15.6 and Figure 15.7 the waste management strategies of the intermediate point lying just before the beginning of the stiff gradient are shown.

This intermediate point is very important because it could represent the aim that a modern Country as Italy, as well as many other EU 15 Nation, could set as a medium-term goal in order to accept EU Directive, because it implicates a cost of CO_2 avoided of only 4,9 €/tonne; aspiring to higher values of emission savings can result to be economically expensive (Scenario 1) unless civic awareness on the waste issue does not increase, as assumed by Scenario 3 (13,2 €/tonn versus 16,6 €/tonn).

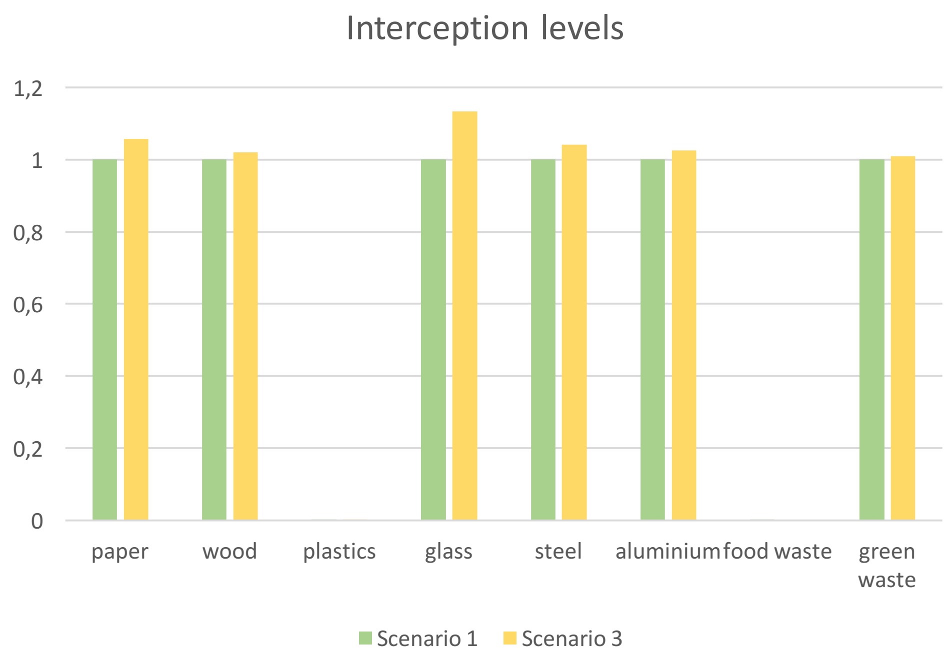


Figure 15.6 - Interception levels, intermediate points, emission-cost optimisation, [kg dirty j-th flow intercepted / kg of j-th fraction in MSW]

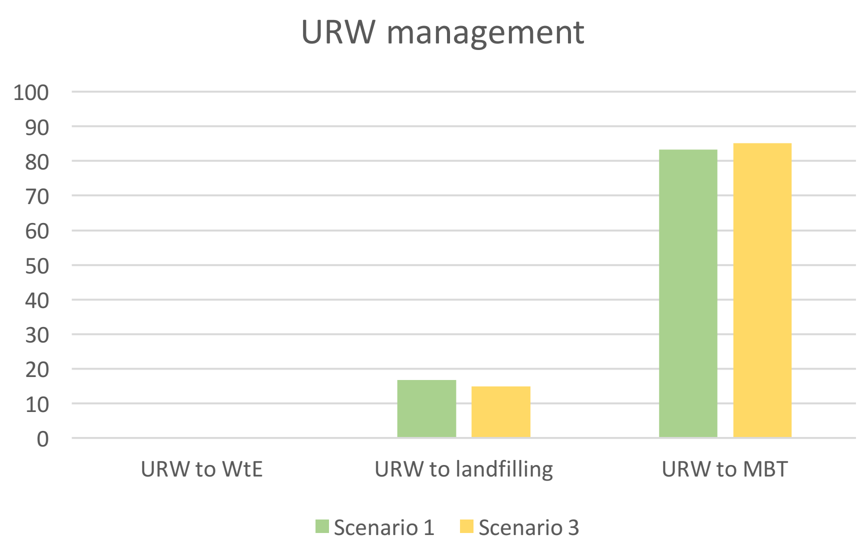


Figure 15.7 – URW management, intermediate points, emission-cost optimisation, [%]

To keep costs low, food-waste fraction and plastics are not intercepted (Figure 15.6).

As discussed in 13.4 and 13.5, the only strategy allowing good URW environmental performances when plastics fraction is not intercepted is MBT and in fact residual waste is entirely (Figure 15.7) sent to such process, apart from a small percentage disposed through landfilling to lower costs.

Interception levels difference have been yet explained in Chapter 14; in Scenario 3 URW is composed by a greater organic fraction, so a slightly minor quantity can be landfilled.

The other intermediate points strategies consist only in an increase of landfilling until it reaches 100% (cost optimum).

It must be said that incineration still plays an important role as SRR disposal treatment (2,53 million tonnes every year, i.e. almost the entire flow of SRR).

16 Conclusions

The model was set to optimise the entire Italian waste management system considering the three aspects of sustainability nowadays more debated: energy efficiency, emission savings and economic affordability.

Considering the implementation methodology, it can be referred with some adjustments to the major part of the EU 15 Countries to which the Directive was aimed.

16.1 Possible improvements

We are conscious that the results achieved strictly rely on the assumptions made: to lighten such dependence some different Scenarios have been implemented in order to make the model more reliable.

Some critical points affecting the model anyway still remain, the most important can be summarised as:

1. Geographical dependence

2. Quality of separate collection

3. Cost optimisation

All the three topics reported require an explanation.

Assuming a standard waste management system for the entire Italian territory is a strong, and for some specific regions maybe unrealistic, hypothesis, because input parameters vary across Nation. The data about waste production and management of our Country reported in 3.2, 3.3 and 3.4 can only confirm this theory.

For these reasons, a step forward to this thesis could be done by the rearrangement of the implementation towards a regional, or even local, optimisation, achieved by modelling the system through nodes, as the case of Optiwaste (paragraph 2.4.2). This would also open the possibility to adopt a marginal substitution perspective.
A simpler solution to solve this geographical dependence could be represented by the insertion of parameters specific to the aggregation of similar (about waste management and production) regions or even smaller areas.
When talking about the parameters to insert, first of all we refer to the CED and GWP indicator used to model the recycling process. As explained in Chapter 5, LCA depends on the considered area: for this reason specific LCA studies, maybe based on the analysis of Italian plants, are required.

Another critical point is the quality of separate collection. As already widely discussed in Chapter 6, assuming that intercepted flows are pure, is unrealistic for the major part of the fractions (at least the most important) composing MSW. Neglecting that purity is inversely proportional to the interception level is unrealistic too.
To account for that, the model implemented a complicated methodology based partially on bibliographical data (always done when possible) and some reasonable assumptions, derived by MatEr staff experience on the subject and mine.
To reinforce this methodology, more specific reports on the composition of collected fractions, as well as its variation with the interception level, completely missing so far, are required.

The last awkward point we want to discuss about is represented by the cost analysis.
Because of the lack of data and the extension of the subject, we preferred to limit optimisation only to variable costs, for which we had certain data (9.7). In order to adopt, coherently with energy and emissions optimisation, a substitutive perspective, fixed cost should be considered too.

16.2 Towards a more sustainable waste management system

Considering the results of the model as indicative of the strategies to follow, and not as compulsory limit to reach, the work of thesis here presented attained useful achievements.
In every Scenario considered, optimisation does not push separate collection beyond 70% (only in one specific case), while the average value is between 45% and 50%; intercepting everything as much as possible is never an optimal strategy; talking about complete recycling is even false because of the residues that every process, particularly recycling (e.g. selection residues), produces.
Policies aimed to exclusively increase the separate collection level can result to be inefficient by their own even when assuming an increased quality of flows intercepted (Table 16.1), due to a greater civic awareness about waste issue.

		Italy 2014	Scenario 65%	Scenario 3
Emissions	[Mtonne CO2]	-2,32	-7,50	-9,30
Costs	[G€]	5,76	5,26	5,07
SCL	[%]	0,45	65,00	50,67

Table 16.1 - Comparison between different future scenarios and current Italian situation, emissions optimisation. Scenario 65% was optimised in the same way as Scenario 3 but constraining SCL to 65%.

The focus must be diverted from how much intercept, to what intercept: paper, glass and metals, differently from current Italian situation, should always be separately collected; some other fractions instead, specially wood, food-waste and plastics, are convenient to be intercepted only under certain assumptions on URW management.
About that, Figure 16.1 shows how imposing SCL entails a different interception management than the optimal one.

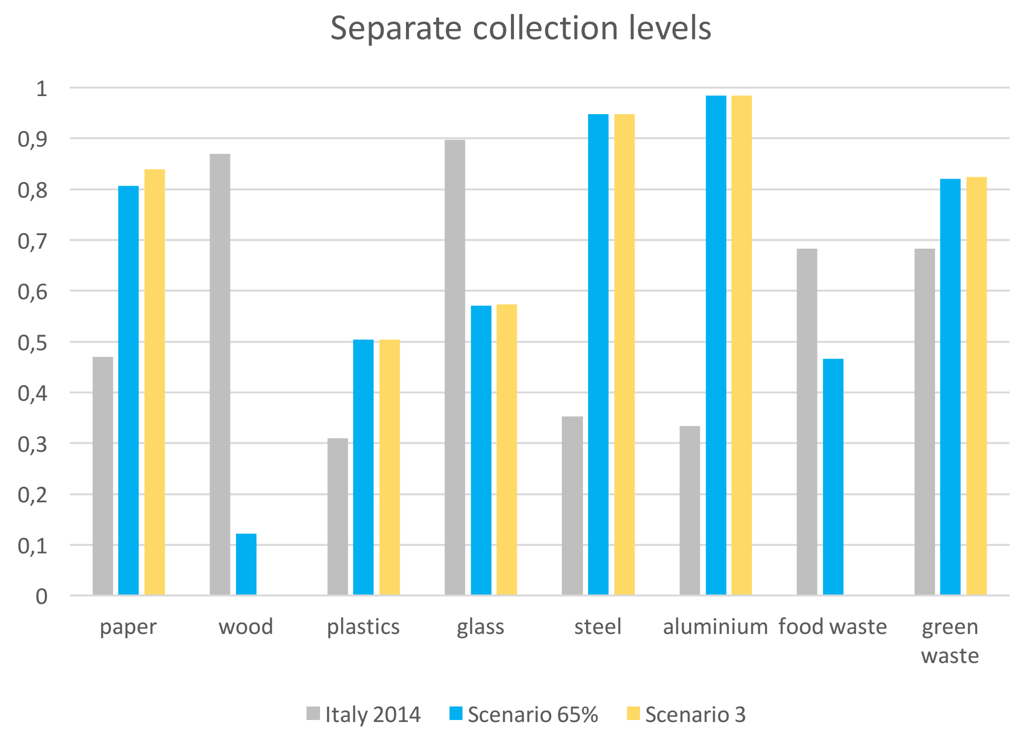


Figure 16.1 – Separate collection levels of different future scenarios and 2014 Italian situation, emissions optimisation. Scenario 65% was optimised in the same way as Scenario 3 but constraining SCL to 65%.

The cost increase and worse emissions value reported in Table 16.1 by the SCL=65% optimisation is simply explained by Figure 16.1: to reach the separate collection level of 65%, food-waste interception is mandatory.

Separately collecting food-waste is not only environmental inefficient, but also very expensive.

More in general, constraining separate collection up to high levels leads to intercept fractions that would be better to leave unsorted with energetic and environmental lower performances as well as cost increases.

The same conclusions can be inferred considering the energy optimisation.

What emerges to be really necessary is a perfect integration between separate collection and URW management: they should always be considered together.

MBT and WtE, with their peculiarities, are both sustainable processes when optimising energy (MBT less) and emissions.

Optimisation proved that incinerating is not opposite to separate collection but the two solutions complete each other: even regions with quite high separate collection rates, e.g. Lombardia and Emilia-Romagna, can still rely on WtE in an environmentally friendly way. WtE plants at least have to dispose the not negligible quantity of SRR, which, when Scenario 1 was environmentally optimised (the only case without URW incineration), were 5,7 million tonnes every year (Figure 13.1).

Landfilling has in cheapness its only reason to exist (apart from WtE and MBT residuals disposing) but as proved by multi-objective analysis, (paragraph 15.3) with just a little economic effort, less than 0,01% of Italian GDP, we can achieve much better solutions than the economically optimal ones.

We anyway consider important to remark that every energetic and environmental optimum found had lower management costs than the ones Italy borne in 2014 (Table 12.1, Table 12.4 and Table 13.3).

This fact means that aiming exclusively to energetic/environmental goals, differently from what usually happens, when referring to waste management can lead to economic improvements too.

Appendix 1

LCA data found for the different fractions:

Steel primary production		Total
Ecoinvent 3.3	MJ eq	20.800
Poland	MJ eq	35.413
Japan	MJ eq	24.600
US	MJ eq	19.500
Australia	MJ eq	22.000

Steel secondary production		Total
Ecoinvent 3.3	MJ eq	8.098
Poland	MJ eq	8.066
Japan	MJ eq	9.400
Australia	MJ eq	5.800

Steel primary production		Total
Ecoinvent 3.3	kg CO2 eq	1.920
Poland	kg CO2 eq	2.458
Australia	kg CO2 eq	2.100

Steel secondary production		Total
Ecoinvent 3.3	kg CO2 eq	-32
EASETECH (DTU)	kg CO2 eq	529
Poland	kg CO2 eq	0
Australia	kg CO2 eq	700

Figure 0.1- Steel LCA values, [44], [42], [43], [45], [78]–[81]

Aluminium primary production		Alumina production	Anode	Cathode	Total
Ecoinvent 3.3	MJ eq				178.000
US	MJ eq				155.000
Holland	MJ eq	143.000		26.500	169.500
World	MJ eq				175.000
Iceland	MJ eq				166.060
Europe	MJ eq				157.000
Aluminium Association	MJ eq	104.000		34.100	138.100

Aluminium secondary production		Total
Ecoinvent 3.3	MJ eq	11.597
Holland	MJ eq	13.100
Europe	MJ eq	8.540

Aluminium primary production		Alumina production	Anode	Cathode	Others	Total
Ecoinvent 3.3	kg CO2 eq					10.000
ETSAP	kg CO2 eq	2.500		1.500	5.500	9.500
US	kg CO2 eq					9.700
Europe	kg CO2 eq					8.540
Allluminium Association	kg CO2 eq	5.670		2.010	215	7.875

Aluminium secondary production		Total
Ecoinvent 3.3	kg CO2 eq	1.014
EASETECH (DTU)	kg CO2 eq	1.113
Europa	kg CO2 eq	507
Allluminium Association	kg CO2 eq	1.130

Figure 0.2 – Aluminium LCA values [55]–[58], [82]

Glass primary production		Total
Ecoinvent 3.3	MJ eq	18.700
North America	MJ eq	16.600
World	MJ eq	17.000
US	MJ eq	17.935
Europe	MJ eq	15.620

Glass secondary production		Total
Ecoinvent 3.3	MJ eq	10.761
Energy implications	MJ eq	14.800
USA	MJ eq	15.614

Glass primary production		Total
Ecoinvent 3.3	kg CO2 eq	1.310
North America	kg CO2 eq	1.250
Europa	kg CO2 eq	1.230

Glass Secondary production		Total
Ecoinvent 3.3	kg CO2 eq	848
EASETECH (DTU)	kg CO2 eq	395

Figure 0.3 - Glass LCA values [83]–[85],[86]

Wood primary production		Total
Ecoinvent 3.3	MJ eq	13.848
Northwest America	MJ eq	4.634
US	MJ eq	7.156
World	MJ eq	5.344

Wood secondary production		Total
Ecoinvent 3.3	MJ eq	10.558
Northwest America	MJ eq	9.517

Wood primary production		Total
Ecoinvent 3.3	kg CO2 eq	363
Northwest America	kg CO2 eq	106
USA	kg CO2 eq	185
Malaysia	kg CO2 eq	414

Wood secondary production		Total
Ecoinvent 3.3	kg CO2 eq	273
EASETECH (DTU)	kg CO2 eq	410
Northwest America	kg CO2 eq	349

Figure 0.4- Wood LCA values, [47], [48], [87], [88]

Paper primary production		Total
Ecoinvent 3.3	MJ eq	25.120
World best	MJ eq	22.600

Paper secondary production		Total
Grosso	MJ eq	2.427
Industrial	MJ eq	1.850
World best	MJ eq	3.900

Paper primary production		Total
Ecoinvent 3.3	kg CO2 eq	1.190
EASETECH (DTU)	kg CO2 eq	679
Italia	kg CO2 eq	550

Figure 0.5 – Paper Lca values, [83], [89], [36], [90]

Plastics primary production		1 tonne PET	1 tonne HDPE
PlasticsEurope	MJ eq	44.400	34.000
Ecoinvent 3.3	MJ eq	51.100	36.000

Plastics secondary production		1 tonne PET
Grosso	MJ eq	7.443
World 2010	MJ eq	2500-6000
World 2012	MJ eq	9.500

Plastics primary production		1 tonne PET	1 tonne HDPE
World	kg CO2 eq	2000-3000	2000-3000
World 2	kg CO2 eq	2.468	1.891
PlasticsEurope	kg CO2 eq	2.150	1.800
Ecoinvent 3.3	kg CO2 eq	2.850	2.010

Plastics secondary production		1 tonne PET
Grosso	kg CO2 eq	426
EASETECH (DTU)	kg CO2 eq	155
World 2010	kg CO2 eq	310-720

Figure 0.6 – Plastics LCA values, [90]–[95]

Production process related energy consumption:

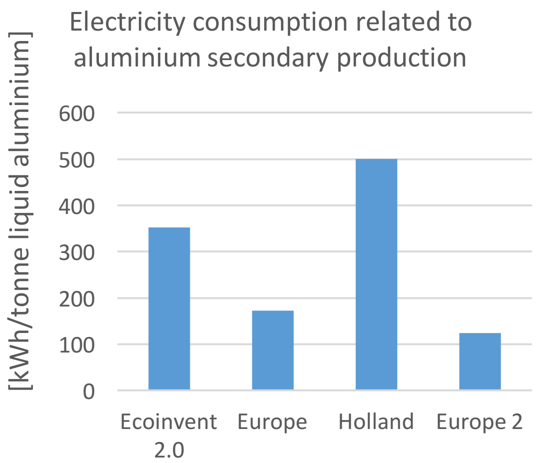


Figure 0.7- Electricity consumption related to aluminium secondary production, [51], [56], [58], [96], [97]

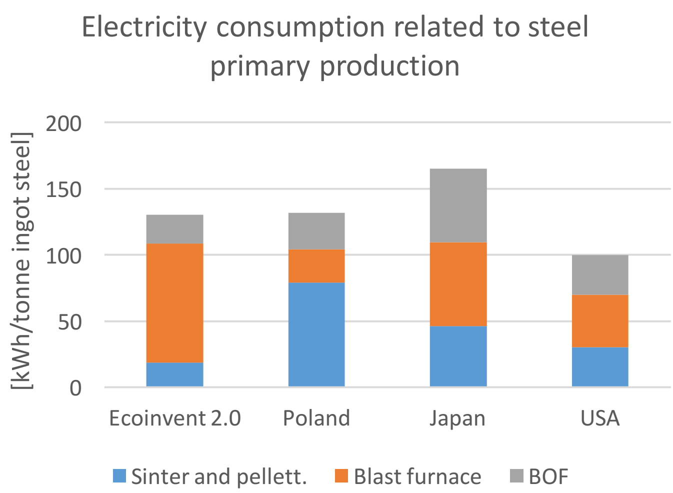


Figure 0.8 - Electricity consumption related to steel primary production,[41], [51], [79], [97]

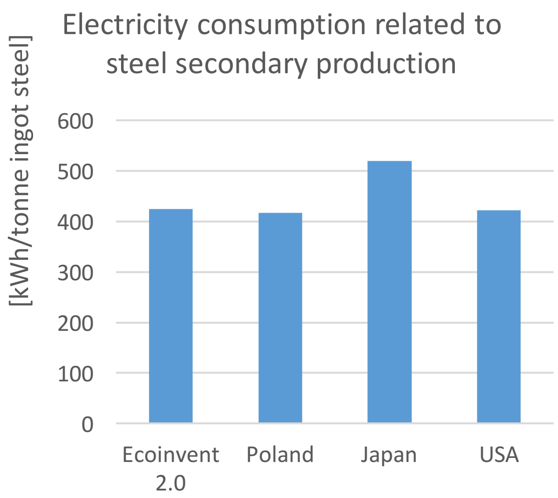


Figure 0.9 - Electricity consumption related to steel secondary production, [42], [80], [98], [51]

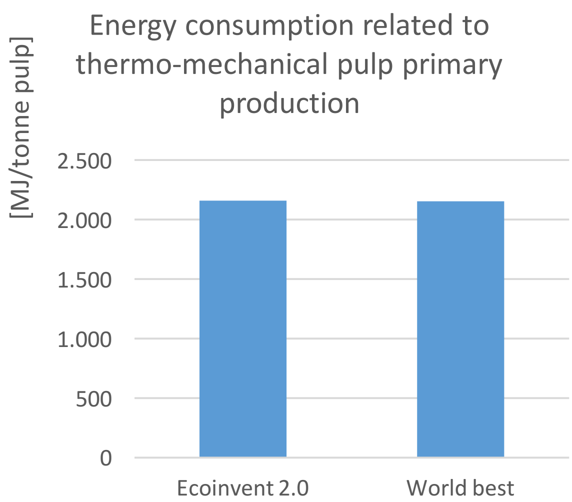


Figure 0.10 – Energy consumption related to thermo-mechanical process plant[52], [83]

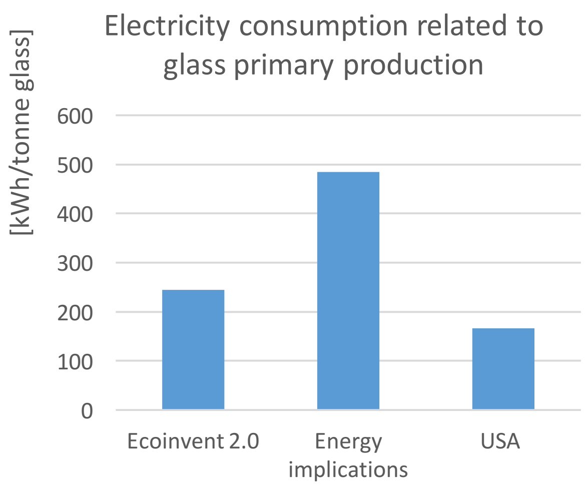


Figure 0.11- Electricity consumption related to the glass production plant, [83], [85], [53]

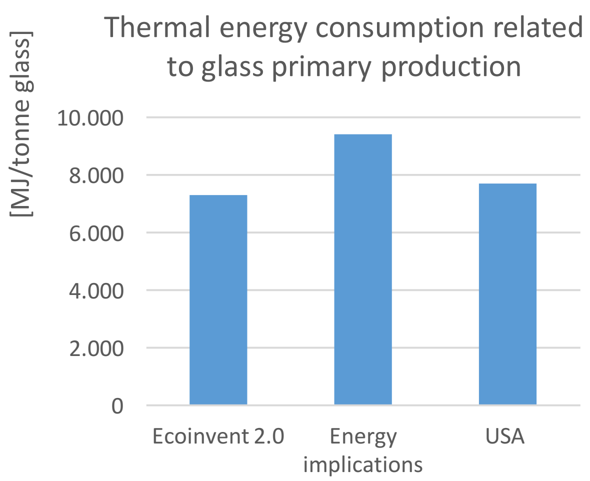


Figure 0.12 – Thermal energy consumption related to the glass production plant, [83], [85], [53]

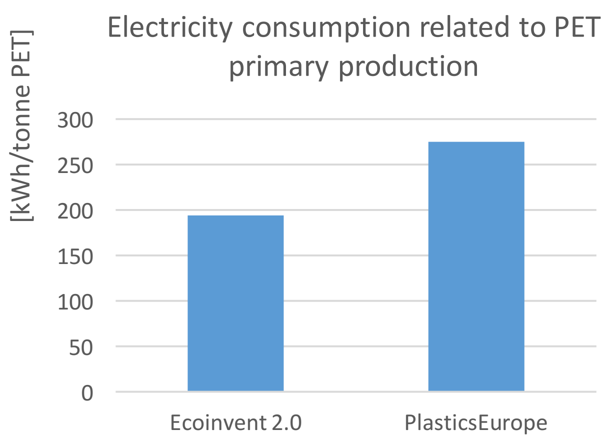


Figure 0.13 - Electricity consumption related to the PET production plant, [54], [99]

Appendix 2

Sankey diagrams of scenarios not reported in results section:

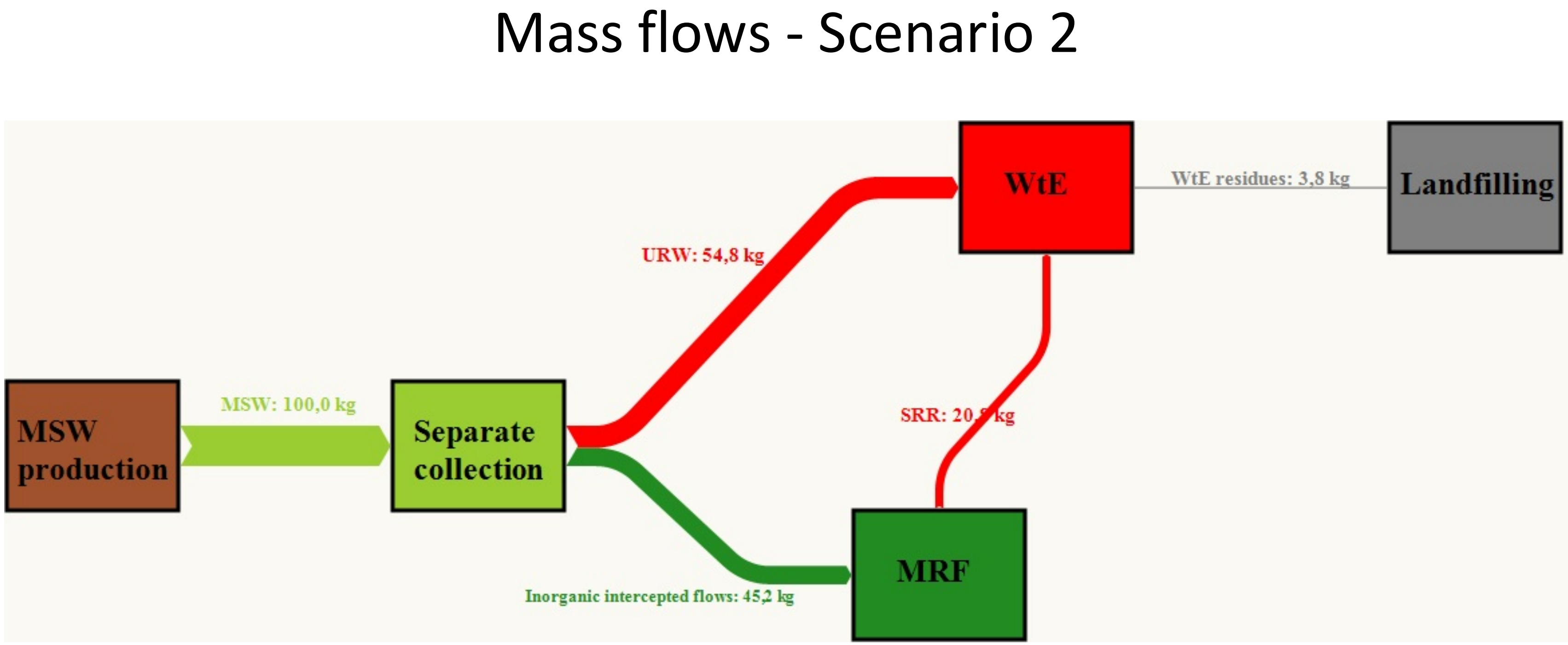


Figure 02.1 – Mass flows Sankey diagram, Scenario 2, energy optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy.

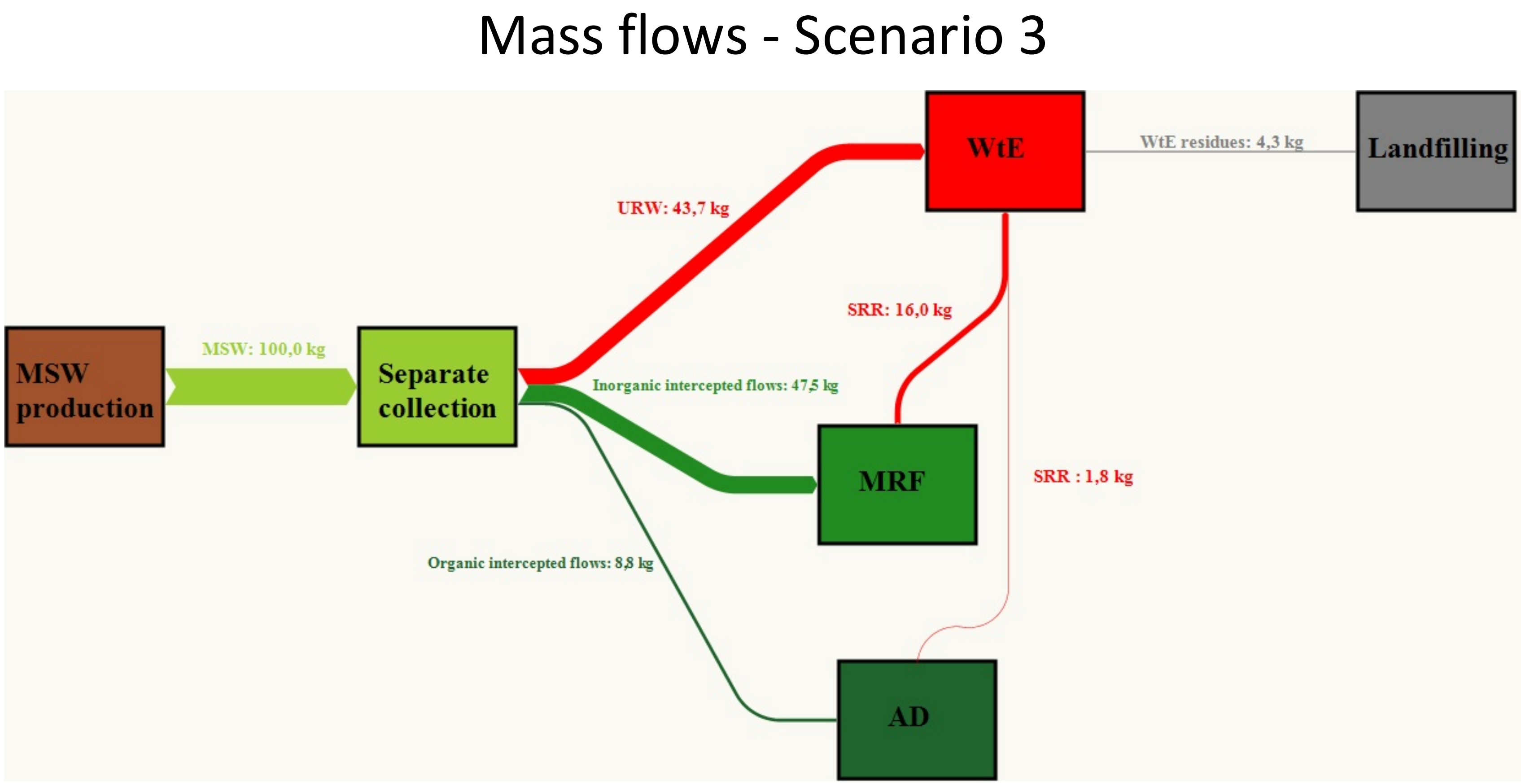


Figure 02.2 – Mass flows Sankey diagram, Scenario 3, energy optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy.

Mass flows - Scenario 2

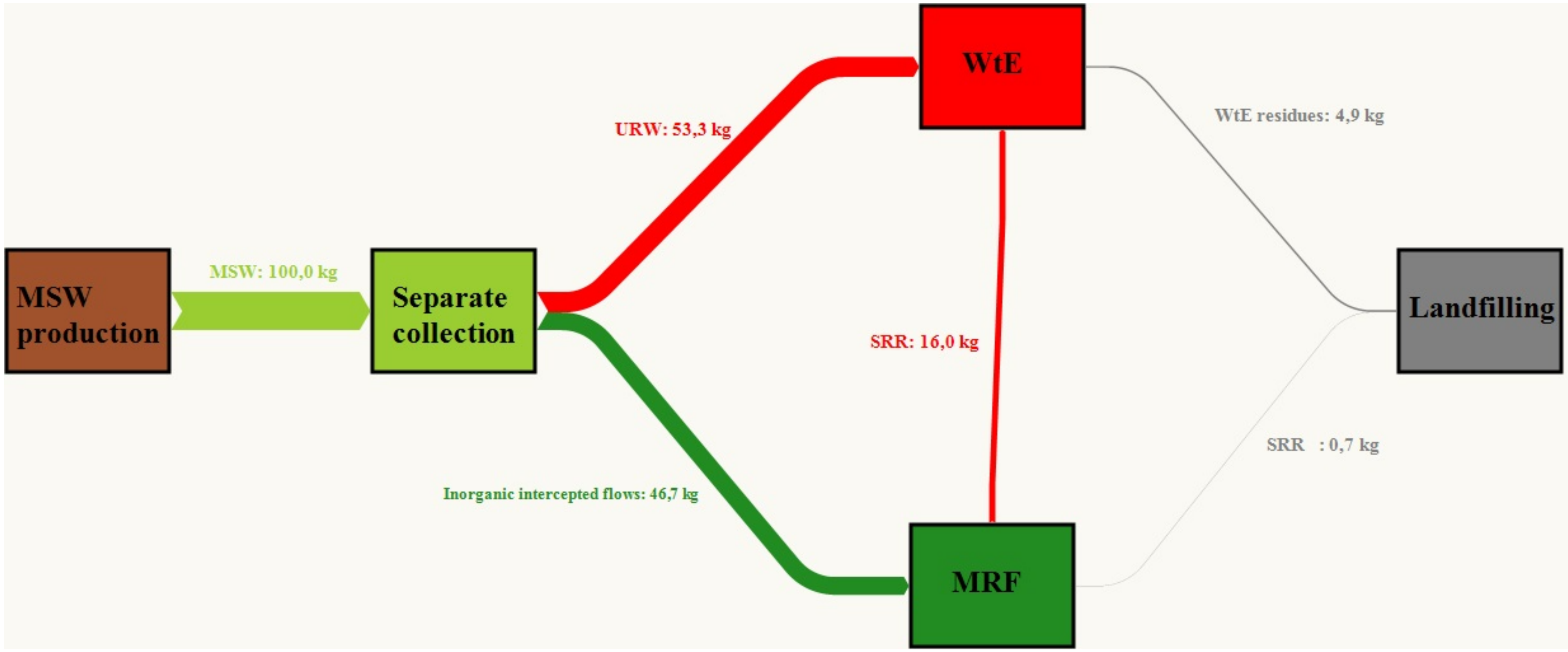


Figure 02.3 - Mass flows Sankey diagram, Scenario 2, emissions optimisation, (kg / year). MSW: Municipal Solid Waste; URW: Urban Residual Waste; SRR: Selection Recycling Residues; MRF: Material Recovery Facility; AD: Anaerobic Digestion; WtE: Waste to Energy

Mass flows - Scenario 3

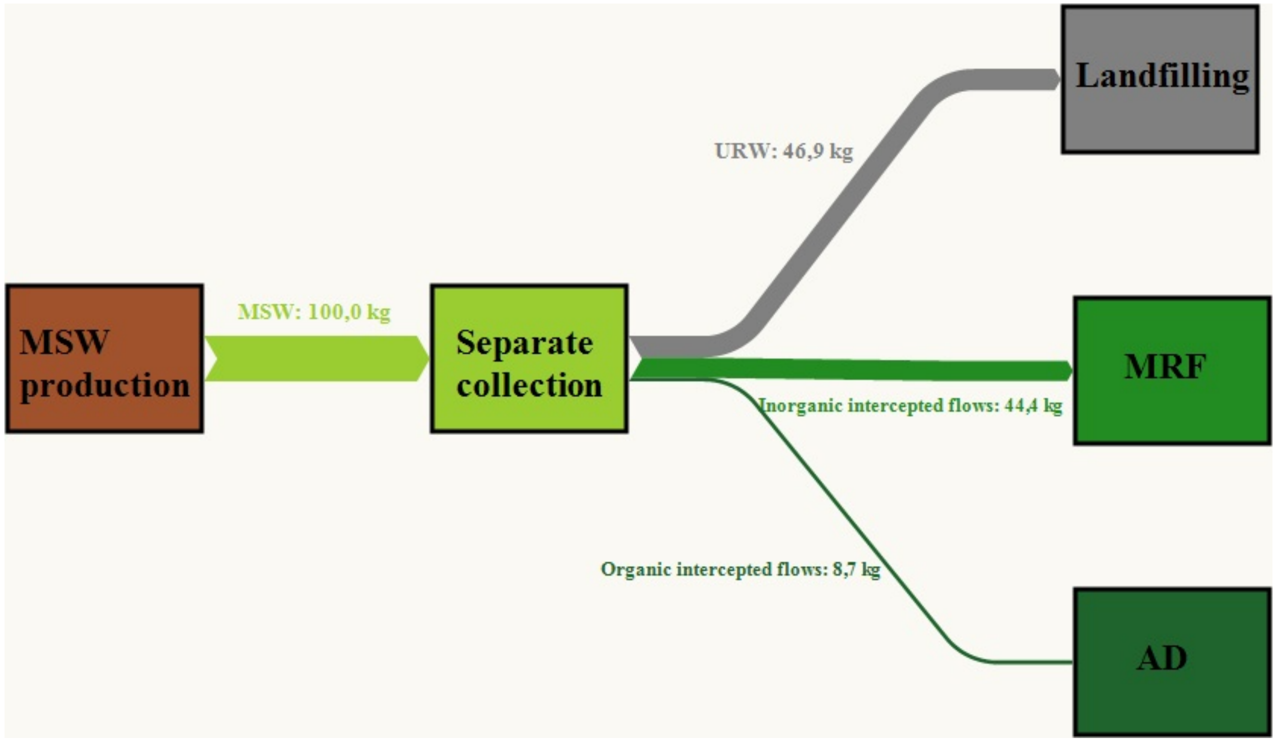


Figure 02.4 - Mass flows Sankey diagram, Scenario 3, cost optimisation, (kg / year). MRF: Material Recovery Facility;AD: Anaerobic Digestion; MSW: Municipal Solid Waste; URW: Urban Residual Waste

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