Waste Management 78 (2018) 717–729

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Modelling solid waste management solutions: The case of Campania, Italy

Maria Federica Di Nola [a,*], Marta Escapa [a,c], John P. Ansah [b]

[a] University of the Basque Country (UPV/EHU), Avenida Lehendakari Aguirre 81, Bilbao 48015, Spain
[b] Duke-NUS Graduate Medical School, Singapore
[c] Basque Centre for Climate Change (BC3), Leioa 48940, Spain

ARTICLE INFO

Article history:
Received 29 December 2017
Revised 27 April 2018
Accepted 4 June 2018

Keywords:
Municipal solid waste management
Waste modelling
System dynamics modelling
Waste policy
Policy analysis
Decision support tool

ABSTRACT

The waste crisis in Campania has inspired a huge body of literature that has described its complex nature. Quantitative analysis in this regard provides useful insight into single aspects of the problem but from a static perspective. In this work, a dynamic model has been developed to analyse the interactions between the main elements of the waste system in Campania and their evolution over the critical time horizon. The model considers the process of capacity construction that has been developed to deal with the crisis and the flow of waste through the treatment options available, showing how the waste system behaves if such infrastructures are not able to cope with the amounts expected. The model also provides the analytical framework to explore the effects of alternative waste policies.

1. Introduction

The solid waste management process is complex as it involves multiple actors and dimensions that dynamically affect each other and cannot be described from an isolated and static perspective. Waste management systems require adequate analysis tools and systemic approaches have proven useful in supporting policy decisions by providing a comprehensive representation of those systems, considering the interactions between their main elements and their evolution over time.

The waste crisis in Campania is a clear example of this complexity. Since 1994, the region has experienced several periods of crisis that have revealed the weaknesses of its waste management system and, as some recent studies show, the problem is still the object of academic debate (Chifari et al., 2017; Ripa et al., 2017; Hornsby et al., 2017). The region was recently fined by the EU Court of Justice for failing to fulfil its obligation to create “an integrated network of installations to ensure waste disposal in the area” and there is still divergence at different institutional levels on the most adequate solution to the problem.

The public perception of the crisis, as the press and the policy-makers termed it, relates to a problem of capacity, the development of which has been impeded by local criminality and the community, the former making profits by disposing of waste illegally, the latter opposing the expansion of capacity because of its “not in my backyard” attitude. However, academic analysis provides alternative theories, where a more complex picture emerges that contradicts the “oversimplified” understanding of the problem and moves the focus away from the criminal elements and community to the political inability to deal with the complexity of the problem and define an effective exit strategy to the crisis (D’Alisa and Armiero, 2013; D’Alisa et al., 2010; Rabitti, 2008).

The waste crisis in Campania has inspired a huge body of literature (for a detailed review see D’Alisa et al., 2010, 2012) and different decision-making support tools have been proposed to deal with it: Chifari et al. (2017) analyse the municipal solid waste problem in Naples in 2012, based on a multi-scale integrated assessment combined with participatory process; Ripa et al. (2017) use life cycle analysis to identify critical points and driving factors on which to base waste management decisions; D’Alisa and Di Nola (2013) discuss the need to adapt waste management targets to the biophysical characteristics of the individual areas; D’Alisa et al. (2012) propose a novel set of indicators for the analysis of waste patterns; and Mastellone et al. (2009) assess different waste management scenarios by means of a material flow analysis.

These analyses provide useful insights into the diverse aspects of the problem, although they rely on a static perspective, without offering a comprehensive dynamic representation of it. The failure

---

* Corresponding author.
E-mail address: mariafederica.dinola@gmail.com (M.F. Di Nola).

https://doi.org/10.1016/j.wasman.2018.06.006

to implement the waste management plans approved to deal with the crisis (2008, 2012) demonstrates the need for dynamic decision-making support tools that take into account the interactions between the main variables involved and their evolution over time. This is also recognised in the latest regional waste plan, updated in 2016, where a scenario analysis is conducted to calculate the regional need for different infrastructures over the period 2016–2020. Therefore, in this work, a dynamic analysis is proposed by means of a system dynamics model developed to represent the waste crisis in Campania over the critical time horizon and explore the effects of different waste management policy scenarios over a 30-year time horizon.

System dynamics methodology has proven effective in handling specific waste management issues, including the management of electrical and electronic equipment waste (Ardi and Leisten, 2016; Ghisolfi et al., 2017), hospital waste (Chaerul et al., 2008), and solid waste in developing countries (Kum et al., 2005; Sufian and Bala, 2007; Sudhir et al., 1997). Karavezyris et al. (2002) propose an integrated framework for waste management in the city of Berlin, where the system dynamics approach is completed by the use of fuzzy logic to deal with qualitative variables. Dyson and Chang (2005) use system dynamics modelling to forecast solid waste generation in a fast-growing region based on a limited data sample. Inghels and Dullaert (2011) develop a system dynamics model to evaluate the effects of prevention initiatives in Flemish waste management.

Moreover, waste management models that focus on public policies have been developed to demonstrate how system dynamics is particularly suited to helping understand complex waste management systems, discovering their frequently counter-intuitive behaviour and exploring the effects of different policies and management options. For example, system dynamics models have been developed to analyse eco-design policies in Latvia (Dace et al., 2014), the long-term effects of local policies in Switzerland (Ulli-Beer et al., 2007), the impact of different policies on the overall cost of the transition from a landfill-dominated system to alternatives such as incineration and recycling (Mashayekhi, 1993), the dynamic effects of waste recycling market development (Chung, 1992) and the impacts of different policies to transform a wasteful society into a recycling society (Randers and Meadows, 1973).

The paper is organised as follows. Section 2 presents the background story of the waste crisis in Campania. Section 3 synthesises the system dynamics methodology. Section 4 illustrates the model and Section 5 describes the model validation. Section 6 illustrates the policy scenario results and, finally, Section 7 draws some general conclusions.

2. Background of waste management in Campania

Campania is located in south-west Italy. It is one of the most populated regions with almost 6 million people, and the one with the largest population density, with 430 inhabitants per km^2 in 2017. The capital is the city of Naples.

For more than two decades, Campania has suffered a waste crisis and the region has been an example of bad waste management. The crisis officially started in 1994, when the decreasing landfill capacity and failure to develop and implement a regional waste plan led the national government to declare a "state of emergency". A special commissioner was appointed with full power to rapidly prepare a waste management plan. By that time, landfilling had been the only treatment option and the limited legal landfill capacity had been reducing dramatically as a result of all the waste generated in the region, as well as the illegal waste coming from the rest of the country (D'Alisa et al., 2010; Greyl et al., 2010).

The plan approved in 1997 introduced the concept of integrated waste management. The main guidelines were: promoting separate collection; treating the mixed waste; recovering energy from the burnable fraction and stabilising the humid fractions; landfilling the residual waste.

To meet these goals, the separate collection (SC) target was set at 35% and seven mechanical biological treatment (MBT) plants and two incinerators (INC) were planned to be built by 2000. The MBT plants were designed to handle the waste remaining after separation and their main outputs were meant to be a stabilised organic fraction (SOF) to be used for land restoration and a refuse derived fuel (RDF) product. In the meantime, in accordance with the plan, the RDF would be treated outside the region until the incinerators began operating, in order to avoid its accumulation.

The construction of the planned infrastructures took longer than expected and, due to the lack of alternative waste treatment options, the regional landfill capacity was exhausted and waste started to accumulate in the streets. To address the crisis, temporary disposal sites were opened to cope with the waste generated (ARPAC, 2008). Waste was removed from the streets to external regions or foreign countries (ISPRA, 2008) or to unspecified treatment or disposal sites, as a result of which they did not appear in the official statistics, as pointed out by D'Alisa and Armiero (2013). From then on, emergency[1] solutions, such as opening temporary disposal sites or exporting waste to other regions in Italy or abroad, became a common management practice to free Campania's streets from waste.

As MBT plants started operating, RDF began to accumulate at disposal sites waiting for the incinerator, despite the planned solutions. However, the construction of one of the two incinerators planned, with a capacity of about 600,000 tons per year, took longer than expected and by 2008 it was still not in operation. In the meantime, about 6 million tons of RDF was stored throughout the region. This enormous stock pile was supposed to be burned in the incinerator, but its content was unsuitable for energy recovery use (Mastellone et al., 2009). In 2016, these amounts were still in storage, waiting to be incinerated, sent to landfill, exported or treated in an alternative manner. At the same time, the SOF produced was not used for land restoration as planned but disposed of into landfill.

The waste management system in Campania is currently organised as follows. Separate collection has increased up to 52% in 2016, due mainly to the improvement of door to door collection, half of which is organic fraction that is sent outside the region to produce compost due to the lack of adequate plants. Seven MBT plants treat the mixed waste, which is lower than their total capacity. The incinerator burns up to 700,000 tons per year and the remaining LF capacity is estimated at 560,000 tons. RDF is still stored throughout the region and measures have been proposed to deal with it, among them the use of underused MBT capacity.

Due to the lack of adequate landfill capacity, the region still exports waste to the rest of the country and, for this reason, in 2015 the European Court of Justice fined Italy and ordered it to pay a lump sum and a daily penalty as a result of Campania failing to implement an adequate waste management plan. More specifically, the Commission pointed out the lack of necessary waste infrastructures, among them landfills and incinerators, to fulfil the principle of regional self-sufficiency, which is a binding principle imposed to treat mixed waste within the region.[2] However, divergences have emerged with the regional government, which

---

[1] In this work, the term "emergency" is used to mean beyond ordinary practices. We have adopted this term as it has already been used by Mastellone et al. (2009) and D'Alisa et al. (2010).

[2] Self-sufficiency is not binding for separate collection, the treatment of which is subject to free market rules.

maintains that the improvements in separate collection in recent years have made it possible to minimise the use of landfill and avoid the construction of incinerators.

3. Methodology

System dynamics is a modelling method that aims to gain insight into the interactions and feedback mechanisms that determine the dynamics of complex systems. It helps understand the causes of resistance to certain policies and design more effective ones. First developed to address industrial issues (Forrester, 1961), it then proved to be effective in the socioeconomic field (Meadows et al., 2004, 1972; Forrester, 1971a,b).

The starting point of a system dynamics model is a problematic behaviour that evolves over time. The underlying assumption is that such behaviour is determined by a certain structure deriving from the interactions of feedbacks, accumulation processes, time delays and nonlinearities.

Therefore, the first step in the modelling process consists of identifying the problem. Once the problem has been defined over an appropriate time horizon, the next step is to formulate the theory that explains the problematic behaviour identified. In system dynamics, this theory is called the dynamic hypothesis; dynamic because it explains the problem behaviour over time in terms of its feedback structure and stock and flows; hypothesis because it is provisional, being an iterative modelling process in itself. The main tools used to elicit the dynamic hypothesis are the causal loop diagram and the stock and flow diagram.

Causal loop diagrams explain the feedback structure of a system. They consist of variables linked by arrows that represent the causal relation between them. Fig. 1. illustrates the typical example of causal loop notation represented by the population dynamics. Each relation has a polarity that can be positive (e.g. birth rate and population) or negative (e.g. death rate and population). It is positive if an increase (decrease) in the independent variable produces an increase (decrease) "above (below) what it would otherwise have been". It is negative if an increase (decrease) in the independent variable produces a decrease (increase) "below (above) what it would otherwise have been" (Sterman, 2000).

The overall diagram in Fig. 1. comprises two feedback loops. The left hand side illustrates a positive feedback, also called reinforcing feedback, as it tends to amplify what is happening in the system: the bigger the population, the higher the birth rate, leading the population to increase still more. The right hand side shows a negative feedback, also called balancing loop, as it tends to counteract the change: the bigger the population, the higher the death rate, resulting in a population decrease. The loop identifier, together with the sign, also indicates the direction in which the loop circulates.

Causal loop diagrams are useful tools for simplifying the relevant information and drawing preliminary sketches of causal hypotheses along the modelling process. However, by reading a causal loop diagram it is not possible to distinguish stock and flow elements. For this purpose, system dynamics makes use of stock and flow diagrams.

Stock and flow diagrams represent the physical structure of the system and track the accumulations that move through it. Stocks are state variables that represent the accumulations in the system. They are key elements of a system dynamics model, as they provide systems with inertia and memory, generate delays, decouple rates of flow and create disequilibrium dynamics (Mass, 1980). Flows are rates of change and represent those activities that fill in or drain the stocks. The translation of the population causal loop diagram into a stock and flow diagram is shown in Fig. 2. The stock is represented by the box variable that is filled in by the inflow of births and drained by the outflow of deaths, whereas the rest are auxiliary variables, which are assumed to be exogenous in this example for simplicity purposes.

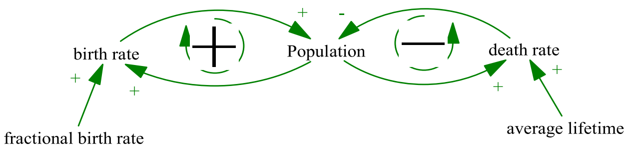


Fig. 1. Causal loop diagram notation.

In mathematical terms, the stock integrates the difference between the inflow and the outflow and can be represented by means of an integral equation. Moreover, the flows are functions of the stock and auxiliary variables. Finally, auxiliary variables may be exogenous inputs, as in the example above, or functions of the stocks and exogenous inputs. Their inclusion makes it possible to define the feedback polarity.

Once the dynamic hypothesis has been defined, the next step consists of formulating a simulation model. This means shifting from a conceptual model to a formal model with equations, parameters and initial conditions. Different software packages are used in system dynamics modelling. In this work, the Vensim[3] package is used in the construction and testing of the model.

4. The model

The waste management model presented herein has three linked sectors: (1) waste generation and separation sector; (2) management of mixed waste sector and (3) waste treatment by-product sector. Full equations for the model are provided in the Appendix.

4.1. Waste generation and separation sector

The waste generation and separation sector is represented in Fig. 3. Total waste generated, as represented in the model, is determined by GDP per capita. Here, it is assumed that as GDP per capita increases, waste generated per person is assumed to increase as well. Hence, total waste generated is estimated as:

$$\begin{aligned} \textit{total waste generated}(t) &= \textit{initial total waste generated}(t) \\ &\quad * \textit{elasticity of GDP per capita on waste generated}(t) \end{aligned}$$

$$\begin{aligned} &\textit{elasticity of GDP per capita on waste generated}(t) \\ &\quad = f(\textit{trend GDP per capita}(t)) \end{aligned}$$

GDP per capita, the estimated resources available to each individual, is a function of GDP and total population. GDP is assumed to change by an estimated GDP growth rate.

Total waste generated is categorised into two broad groups: separated and mixed waste. The proportion of total waste separated is determined by a target separation rate, which is a policy variable. However, the enforcement of the separation rate target is assumed to increase as demand for landfill capacity increases. The equations for separation rate and change in separation rate are:

$$\begin{aligned} \textit{separated waste rate}(t) = &\int_{t_0}^{t} [\textit{net change in separation rate}(t)]dt \\ &+ \textit{separated waste rate}(t_0) \end{aligned}$$

---

[3] Vensim is an icon-based program designed to provide a user-friendly icon-based interface to modelling based on the principles first published by Forrester (1961). The Vensim package is a registered trademark of Ventana System, Inc. 60 Jacob Gates Road, Harvard, MA 01451, US (see http://www.vensim.com/software.html).

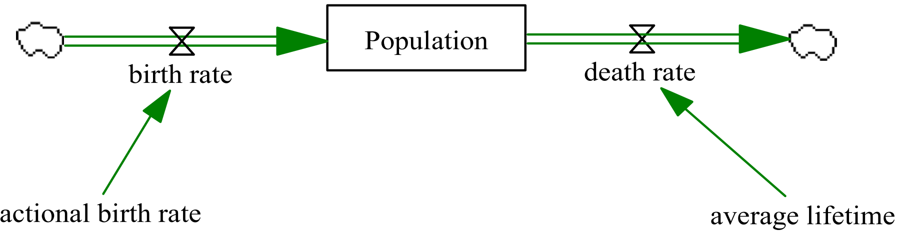


Fig. 2. Stock and flow diagram.

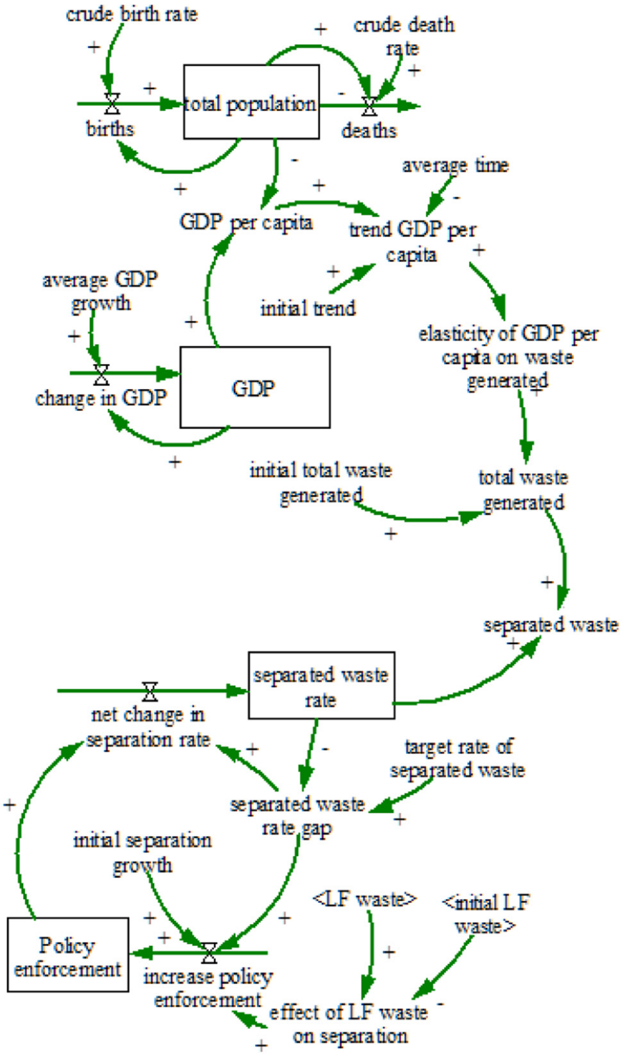


Fig. 3. Waste generation and separation sector.

$$\textit{change in separtion rate}(t) = \left(\frac{\textit{separated waste rate gap}}{\textit{adjustment time}}\right) * \textit{policy enforcement}$$

$$\textit{policy enforcement}\ (t) = \int_{t_0}^{t} [\textit{increase policy enforcemnt}\ (t)]\ dt + \textit{policy enforcement}\ (t_0)$$

4.2. Management of mixed waste sector

Fig. 4 represents the mixed waste sector. Total waste generated, as indicated above, is divided into separated and mixed waste.

Separated waste is treated using the available regional capacity for organic, paper, plastic and other materials or is exported. However, mixed waste is collected and either sent to MBT for treatment, incineration for burning, landfill for disposal or exported. Mixed waste which has been collected, but not sent to any of the available options for treatment or disposal, is referred to herein as untreated waste. The stock of untreated waste increases as mixed waste is collected and decreases as waste is treated by MBT, incineration or disposed of in a landfill or exported.

The quantity of untreated waste allocated to MBT, incineration and landfill depends on the available capacity. The capacity of MBT, incineration and landfill is modelled with a similar structure. Desired capacity of MBT, incineration or landfill is determined by policy-makers. This variable may change over time. The desired capacity is then compared to actual capacity, and an effort is made to close the gap by initiating the development of new capacity. For illustration purposes, only the equations for MBT capacity will be shown here. The equations for MBT capacity development are:

$$\textit{MBT Capacity}(t) = \int_{t_0}^{t} [\textit{new MBT capacity}(t)]dt + \textit{MBT capacity}(t_0)$$

$$\textit{new MBT capacity}(t) = \textit{initiation of MBT development}(t)(\textit{time} - \textit{time to complete capacity})$$

$$\textit{MBT capacity under development}(t) = \int_{t_0}^{t} [\textit{initiation of MBT development}(t) - \textit{new MBT capacity}(t)]dt + \textit{MBT capacity under development}(t_0)$$

$$\textit{MBT capacity gap}(t) = (\textit{desired MBT capacity}(t) - (\textit{MBT capacity} + \textit{MBT capacity under development}))/\textit{adjustment time})$$

4.3. Waste treatment by-product sector

The waste treatment by-product sector is illustrated in Fig. 5 and focuses on the management of MBT and incineration outputs. The stock of MBT waste increases as untreated waste is allocated to MBT for treatment and produces the following outputs: SOF waste, RDF and losses such as metals and leachates. Likewise INC waste increases as untreated waste and RDF waste is allocated to incineration for treatment and produces bottom and fly ash, that requires further management as well as flue gas. The RDF produced by MBT is immediately stored, referred to herein as RDF split. Following storage, a portion of RDF is incinerated, depending on INC capacity, and the remainder is put into storage. Thus, the stock of RDF split increases by RDF from MBT to RDF split and decreases as RDF is either incinerated or put into storage. Likewise, RDF stock increases as RDF split that is not incinerated is moved to storage and decreases as RDF that is stored is sent for incineration.

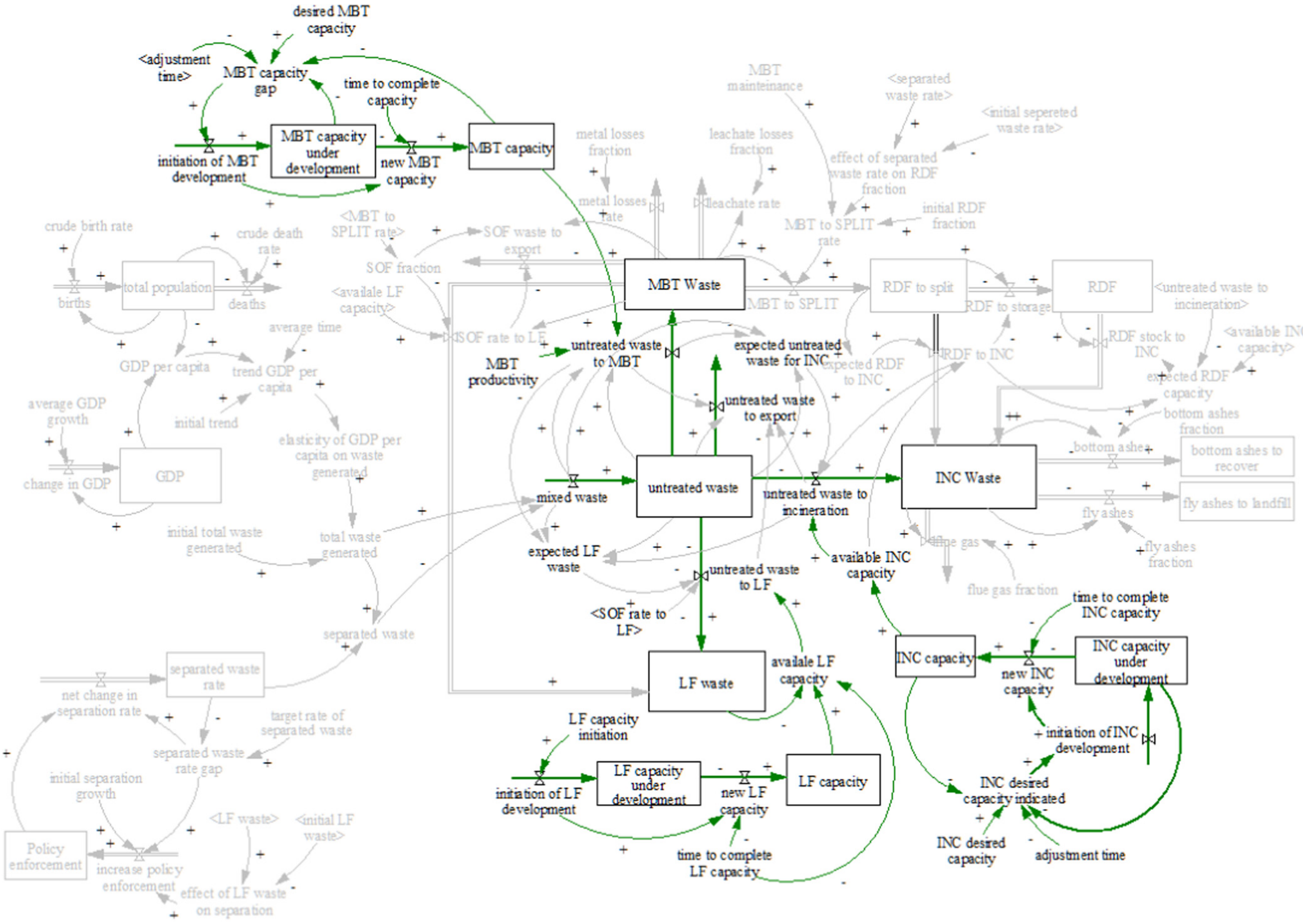


Fig. 4. Adding management of mixed waste to waste generation and separation sector.

4.4. Data

The population data used to parameterise and validate the model was sourced from the Italian Institute of Statistics (ISTAT, 2015). Data on waste generation and separate collection came from the national Institute of Environmental Protection and Research (ISPRA, 2000–2015). In addition, data on infrastructure capacity and waste treatment flows were sourced from ISPRA. Landfill capacity data came from the latest regional report (Regione Campania, 2016). Finally, data on SOF waste were obtained from ISPRA and Impregilo[4] (2001–2004), as prepared by D'Alisa and Armiero (2013).

Limited data availability prevented us from extending the calibration period further back in time. However, a time horizon of 15 years, from 2000 to 2015, is considered sufficient to estimate whether the model is able to replicate the system performance. Table 1 provides the assumptions on model parameters and initial values.

5. Model validation

Two validation tests, structure and behaviour, were conducted to demonstrate the fitness of the model and its suitability for use to conduct informed policy analysis.[5] The behaviour test shows simulated behaviour compared to available time series observed data of selected key variables of interest, as shown in Figs. 6–13 below. In addition, a Theil statistic analysis (Theil, 1966; Sterman, 1984) is presented in Table 2.[6]

The R^2 as shown in Table 2 suggests that the model reproduces the key variables with high accuracy ranging from 0.62 to 0.997. This suggests a strong correlation between the model output and observed data. With regard to the behaviour validity, apart from RDF and separated waste, all the variables have an RMSE of below 20 percent. This strongly indicates that the model endogenously tracks major variables quite well. Moreover, all the key variables, apart from GDP per capita, GDP and RDF, indicate that the major part of the error is with the covariation component (U^C) as compared to bias (U^M) and unequal variance (U^S). This suggests that the simulated variables track the underlying trend well, but diverge when comparing point-by-point, which indicates that the majority of the errors are unsystematic with respect to the purpose of the model.

Figs. 6–13 compare the simulation results to the data available. The graphs confirm that the behaviour of the variables is well reproduced by the model. The amount of waste generated increases from 2.5 in 2000 to almost 2.8 million tons per year in 2006 and then reduces to almost 2.6 million tons per year in 2015, which is consistent with the ISPRA data. The evolution of mixed waste is also well reproduced by the model. The variable

---

[4] Impregilo is the company that has managed the waste management system in Campania since 2000.

[5] For the structure test validation, the model was presented to individuals with experience in waste management to verify its structure and assumptions regarding causal relationships. Thus, the model is firmly grounded in current evidence on waste management.

[6] The Theil Inequality Statistics break down the (Root) Mean Square Error (RMSE) into three components: bias (U^M), unequal variation (U^S), and unequal covariation (U^C) Note that $U^M + U^S + U^C = 1$, as the sum of the three represents the total RMSE.

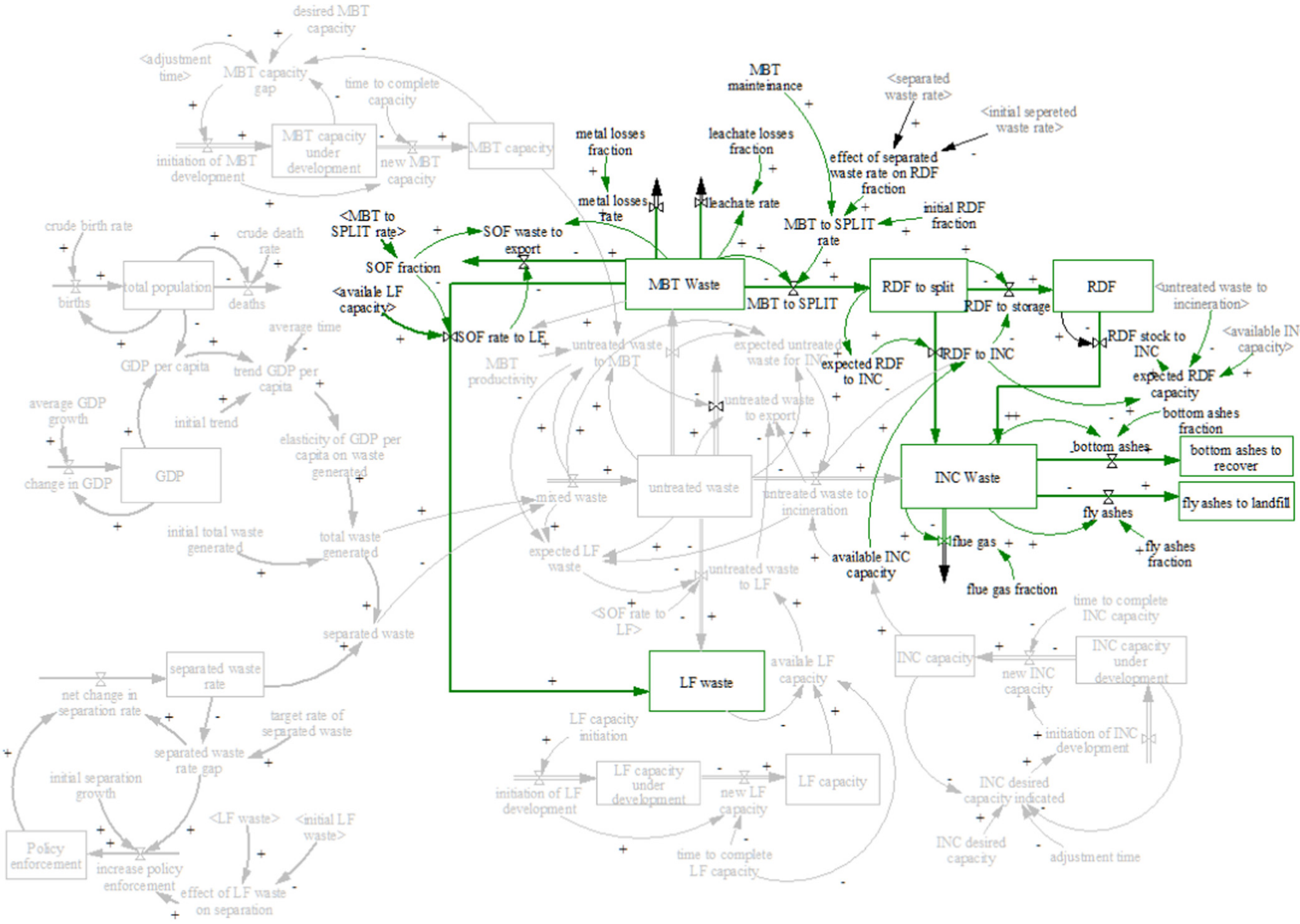


Fig. 5. Adding waste treatment by-product to the waste generation and separation sector and management of mixed waste sector.

Table 1
Model parameters and initial values.

Variable	Value	Unit
Population	5,7e + 006	people
GDP	8.20616e + 010	euro/year
Initial total waste generated	2.59856e + 006	ton/year
Generation per capita	0.46	ton/year/people
Initial growth separation	0.04	dmnl/year
target rate of separated waste	0.6	dmnl
initial separated waste rate	0.02	dmnl
Separated waste	46,044	ton/year
Untreated waste	50,000	ton
LF waste	2.59821e + 006	ton
LF capacity	5.8e + 006	ton
MBT waste	0	ton
RDF to split rate	0.5	1/year
Fraction of split to initial RDF	0.95	1/year
Fraction	0.55	1/year
SOF fraction	0.45	1/year
SOF to landfill waste rate	0.9	1/year
Fly ash rate	0.05	1/year
Bottom ash rate	0.15	1/year

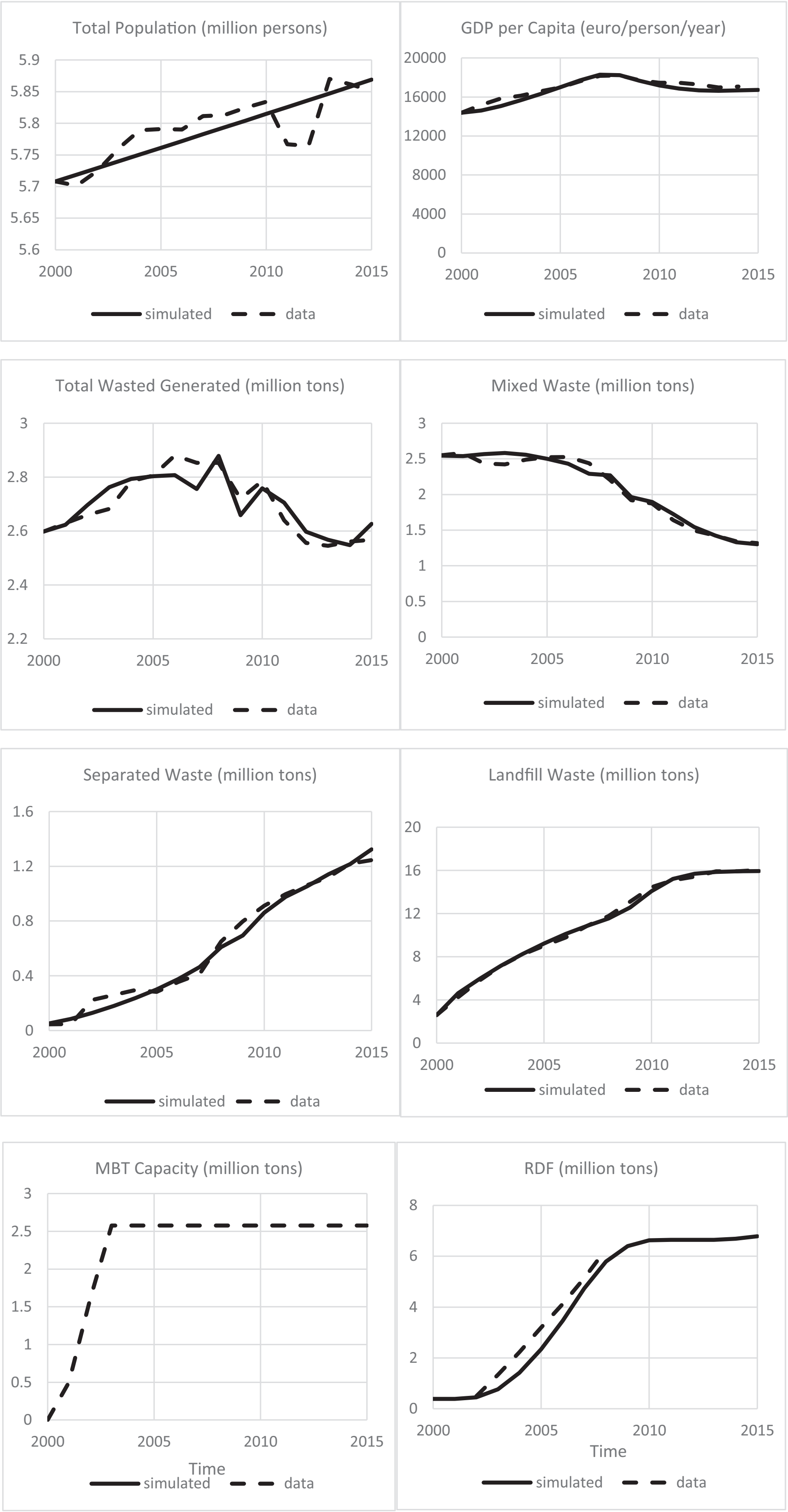
has decreased from 2.5 million tons to about 1.3 million tons, due to the improvement of separate collection from 2008 on. The MBT capacity reproduced is consistent with the historical data and the simulated evolution of RDF stock confirms that almost 6 million tons of RDF had accumulated over the region by 2016.

The evolution of LF waste, resulting from the SOF and untreated waste to LF, also reproduces the historical behaviour well. From 2000 to 2015, about 16 million tons of waste were disposed of into landfill. As a consequence, the model makes it possible to show the evolution of the flow of total waste to be exported, which represents the total untreated waste to be exported (i.e. the amount of waste that was not treated in the regional infrastructures available), and the SOF waste to be exported (i.e. the SOF that was not disposed of in regional landfills because they were full). Fig. 14 shows the evolution of this variable and, according to the simulation results, from 2000 to 2015 about 5.7 million tons of waste were not treated in regional infrastructures but exported to other regions or countries. By contrast, the total amount of waste exported, as shown in the latest regional plan for the period 2003–2015 is around 3.5 million tons. The difference is consistent with D'Alisa and Armiero (2013), who estimate a "hidden flow of waste" of almost 2 million tons from 2000 to in 2007.

The model validation allows us to be confident that the main factors and parameters determining the behaviour of the system are included in the model, which is, therefore, considered capable of providing an analytical framework to explore alternative policies to address the waste management crisis.

6. Policy scenario results

Four different scenarios were selected to explore the likely impact on the main outcomes of interest. Firstly, the evolution of the total waste to be exported is projected under each scenario and the effects on the RDF stock are discussed. Then, the implications on the amount of LF capacity needed to achieve the goal of self-sufficiency are evaluated. The scenarios are based on the poli-



Figs. 6–13. Simulated behaviour versus data.

Table 2
Theil Inequality Statistics results.

Variable	Inequality statistics				
	RMSE	U^M	U^S	U^C	R^2
Total population	0.005	0.022	0.009	0.969	0.629
GDP per capita	0.024	0.482	0.108	0.410	0.949
GDP	0.023	0.597	0.080	0.323	0.969
Total waste generated	0.017	0.000	0.101	0.899	0.820
Mixed waste	0.035	0.062	0.003	0.935	0.969
Separated waste	0.266	0.153	0.000	0.847	0.986
LF waste	0.029	0.015	0.077	0.908	0.997
MBT capacity	0.050	0.024	0.013	0.963	0.973
RDF	0.248	0.822	0.003	0.175	0.983

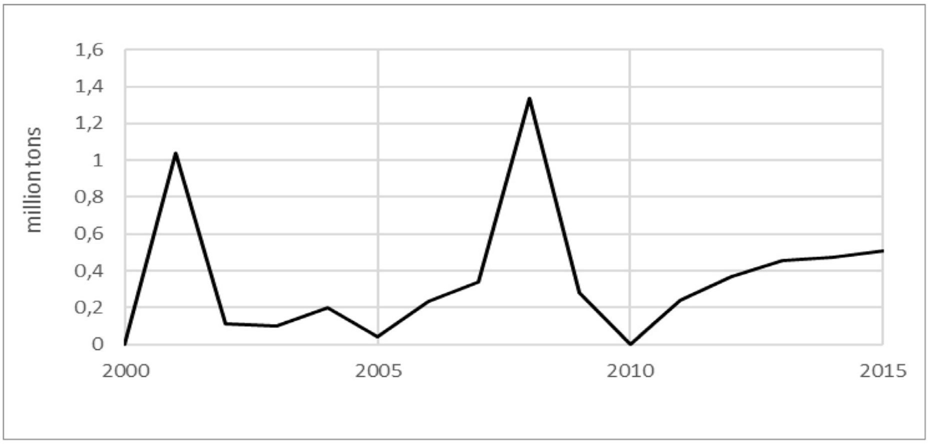


Fig. 14. Simulation of the total waste to be exported under the critical time horizon.

cies proposed by those authorities involved in the waste management process at different institutional levels (regional, EU).[7]

The business as usual (BAU) scenario assumes that all the initial model parameters remain unchanged over the simulation time. Though these parameters are expected to change over time, this simulation serves as a reference point for comparing the other three scenarios considered. In short, the SC target assumed for this scenario is 60% in 2030, MBT is able to treat all the mixed waste produced, and INC waste is 700,000 tons per year.

Policy scenario 1 (EU scenario) is based on the 2012 waste plan cited by the EU Court of Justice in its sentencing.[8] More specifically, under this scenario the SC target is 60%, while the mixed waste is sent directly for incineration, thus avoiding the use of MBT plants to treat it. Then, the incineration capacity is increased to 1,390,000 million tons per year, which is modelled by means of a gradual increase in the flow of untreated waste to INC and a corresponding decrease in untreated waste to MBT. Under this scenario, the additional incineration capacity is expected to be used to also burn stored RDF. Finally, we match these policy inputs with an increase in LF capacity of 560,000 tons based on ISPRA data. It is important to emphasise that this increase only happens in 2018.

Policy scenario 2 (Circular Economy Directive) is an intermediate scenario based on the latest Circular Economy Package proposal, which includes measures to help stimulate Europe's transition towards a circular economy. The SC target considered in this scenario is 65% in 2030. It is matched with an increase in LF capacity by 560,000 tons as in policy scenario 1. MBT plants are assumed to treat the mixed waste produced and an increase in the efficiency of existing INC capacity up to 750,000 tons per year is set with no need to build additional plants.

Lastly, policy scenario 3 (Regional Scenario) is based on the latest waste plan updated in 2016 by the regional government. It simulates a further increase in the SC target, which is set at 70% in 2030,[9] and an increase in LF capacity by 560,000 tons, as in the other policy scenarios. Moreover, it sets an improvement in MBT efficiency as well as an increase in the efficiency of existing INC capacity at 750,000 tons per year.

Once the policy scenarios have been defined, the model developed is used to simulate the evolution of the main variables from 2018 to 2030. Sensitivity analysis is performed on the BAU scenario to observe how a change in the most important parameters affects the outcomes of interest. The target separation rate, GDP growth rate and MBT productivity were identified to be the most important parameters. Using two-way sensitivity analysis approach, each parameter was varied ±25%. The model was then run 1000 times. Next, the average, lower and upper bounds at 95% confidence level were used to show the credible interval of our projection.

Under the BAU scenario, total waste generated is projected to increase from 2.598 million tons in 2000 to 2.732 (with a 95 percent confidence interval of 2.730–2.734) million tons in 2010 and decrease to 2.675 (2.674–2.677) million tons of waste by 2030. Of this, separated waste is projected to increase from 0.859 (0.848–

---

[7] For simplicity's sake we have called these scenarios regional, EU and circular economy, because they are based on targets contained respectively in regional, European and CE plans. However, they also contain our own assumptions and cannot be interpreted as being totally based on institutional plans.

[8] As previously discussed, the EU Court of Justice fined Italy for not implementing the 2012 waste plan.

[9] The SC set in the regional plan is increased to 65% by 2019. For this reason we simulate an increase up to 70% by 2030, assuming this to be a possible progression of the plan, also considering that proposals have been made to increase this target up to 70%.

0.870) million tons in 2010 to 1.601(1.586–1.615) million tons of waste by 2030. Under the BAU scenario, total waste to be exported, which includes untreated waste to export and SOF to export, is projected to increase from 0.028 (0.025–0.032) million tons in 2010 to 0.398 (0.388–0.409) million tons by 2030.

Fig. 15 illustrates the simulation of the policy scenarios considered, showing a common pattern for the first years of the simulation, with the exception of the BAU. The increase in LF capacity leads to a decrease in the total waste to be exported, although at different levels. More specifically, under policy scenario 3, this flow of waste would temporarily fall to zero, due to the significant improvement in separate collection.

However, as LF capacity saturates, if no further capacity is built, the flow of waste to be exported starts increasing until 2024. From 2025 onwards, it decreases slightly under policy scenarios 2 and 3, due to a gradual improvement in SC that allows an upstream reduction in the amount of mixed waste that needs to be treated. Then, under policy scenario 3, this is also associated to a reduction in SOF waste to LF, which further reduces the total amount of waste to be exported. By contrast, under policy scenario 1, the total waste to be exported shows a significant decrease, as new incineration capacity is available in the last five years of the simulation period.

The results suggest that in none of the scenarios explored, the total waste to be exported would reach zero, i.e. the region would not reach self-sufficiency in terms of waste management as imposed by the waste authorities. Under policy scenario 1, this amount would be minimised at the end of the simulation. However, it would be higher than in the other scenarios during the transitional period, due to a lower SC target and delays in the construction process.

Fig. 16 illustrates the evolution of the RDF stock under the scenarios considered. The graph shows no significant reduction in RDF stock over the simulation period under policy scenario 1. This means that the increase in incineration capacity would not resolve the problem of RDF stored throughout the region at least up until 2030. The RDF produced during the transitional period would be the same as in the BAU scenario until the incineration units have been built and would slightly decrease as the additional capacity

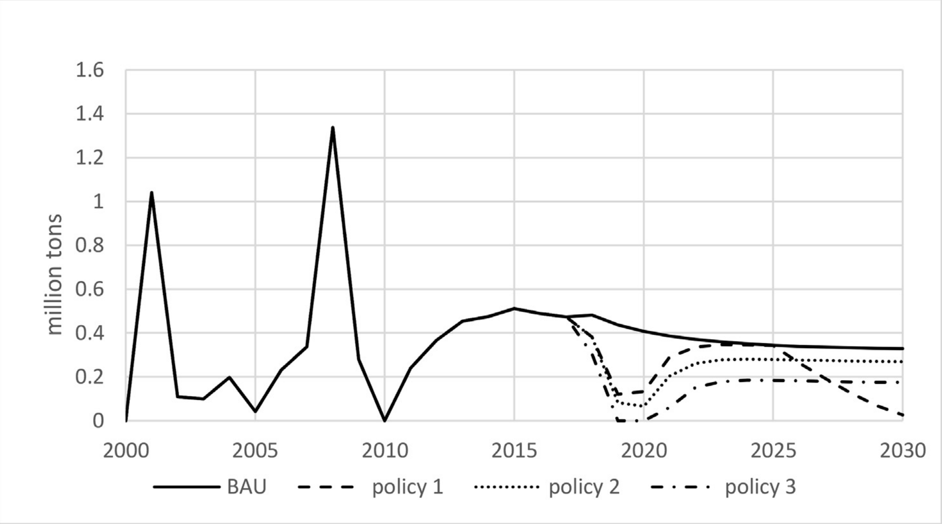


Fig. 15. Simulation of total waste to be exported under different policy scenarios.

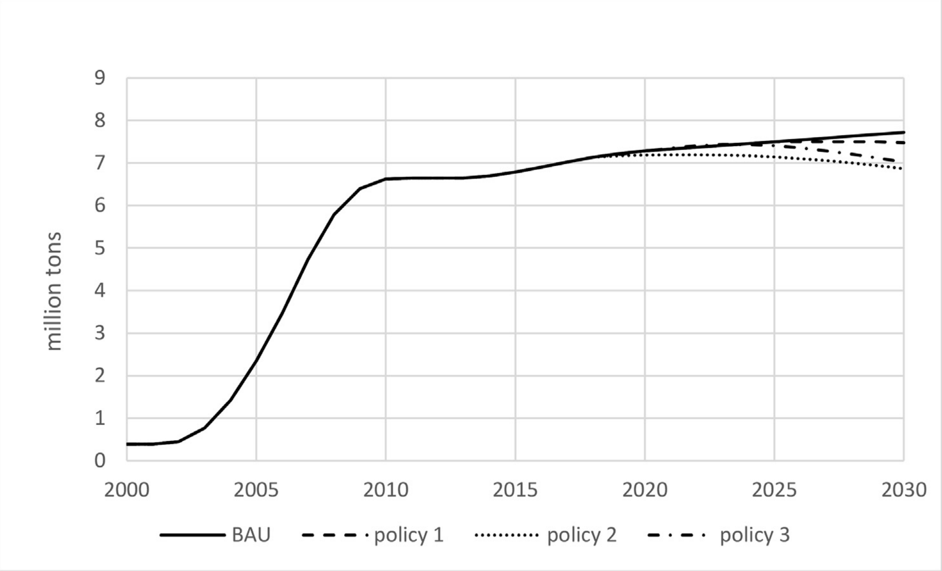


Fig. 16. Simulation of RDF stock under different policy scenarios.

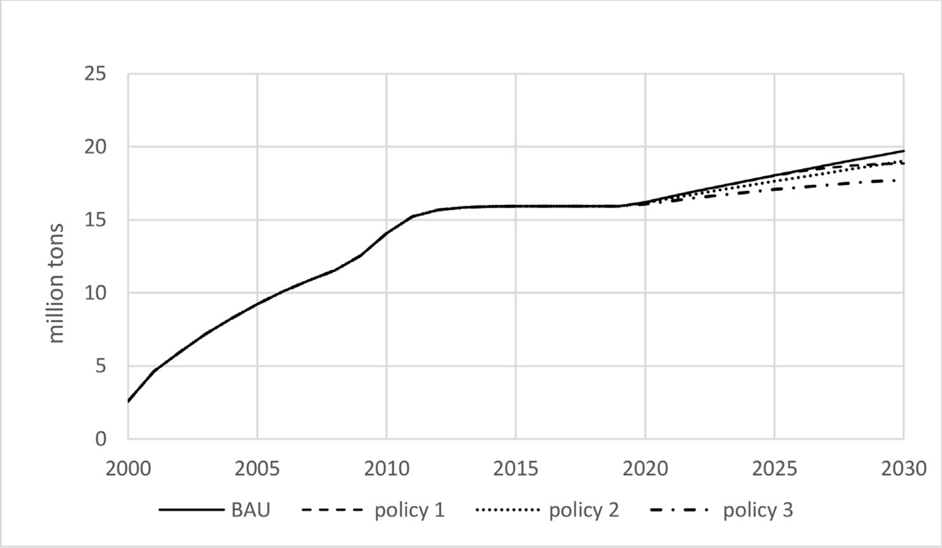


Fig. 17. Simulation of LF waste under different policy scenarios.

Table 3
Landfill rates evolution under different policy scenarios.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BAU	15%	14%	14%	13%	13%	13%	13%	13%	12%	12%	12%
policy 1	13%	11%	11%	11%	11%	10%	10%	10%	10%	10%	10%
policy 2	15%	14%	14%	13%	13%	13%	10%	7%	5%	3%	1%
policy 3	8%	8%	8%	7%	7%	6%	6%	5%	5%	4%	1%

is available. However, an improvement in the SC target would reduce the burden of RDF stock, although this reduction would be slow as can be seen under policy scenarios 2 and 3.

Therefore, as the increase in LF capacity that we assumed was prudently based on the available capacity according to 2016 data, we calculated how much LF capacity would be needed, under each scenario, to avoid waste to be exported and achieve the goal of self-sufficiency over the time horizon considered.

Fig. 17 shows that scenario 3 makes it possible to minimise the landfill capacity increase needed to achieve self-sufficiency. More specifically, an increase in LF capacity of 1.8 million tons would avoid the need to export waste from 2020 over the time period considered. By contrast, the capacity increase needed to achieve self-sufficiency would be around 4 million tons under BAU and about 3 million tons for the rest of policy scenarios.

Finally, Table 3 shows a comparison between the ratios of landfill waste compared to the waste generated under the policy scenarios considered, in order to assess whether the policy scenarios considered meet the target for reducing landfill to a maximum of 10% of municipal waste by 2030, as set in the latest EC proposal.

Under the BAU policy scenario, it can be seen that this target is not met, standing at 12% in 2030, while under policy scenario 1, it is met from 2026 on, gradually reaching 1% by the end of the simulation. Under policy scenario 1, the target is just met in 2025. Finally, under policy scenario 3, the target is reached in 2020 and continues at a lower ratio than required and with a more sustainable pattern over the time horizon considered.

To summarise, the results suggest that the solution proposed under the EU policy scenario is the least desirable, because on the one hand it makes it possible to minimise the total export of waste at the end of the simulation period, but on the other hand the landfill capacity needed to meet the self-sufficiency goal would be higher over the transitional period until the incinerators start to operate. This means that this option would be linked to a major increase in those infrastructures (i.e. landfill and incinerators), the construction of which has been a cause of social conflict over the critical period. By contrast policies that prioritise boosting the separate collection target up would make it possible to minimise the increase in landfill capacity needed to achieve self-sufficiency, and eventually avoid building additional incinerators. As a consequence, this would reduce the risk of social conflict linked to the construction of major infrastructures. Finally, the results confirm that the increase in incineration capacity would not resolve the problem of RDF stock in the short term. Therefore, alternative policies should be identified and assessed to ensure an effective and rapid solution to the problem.

7. Conclusions

The waste crisis in Campania has inspired many works that have described the complex nature of the problem. However, despite the huge body of literature developed, the quantitative analysis in this regard is still limited and most of it provides useful insights into single aspects of the problem without offering a comprehensive dynamic representation of it. In this work, a system dynamic model was developed to provide a framework for a broader analysis of waste management policies.

The model was used to explore the likely impact of alternative waste management policies proposed at different institutional levels to achieve an effective solution to the waste management problem in Campania. The results suggest that waste management policies that focus on boosting waste separation, with an improvement in MBT and INC efficiency, are likely to be more sustainable and eventually achieve the target of self-sufficiency by minimising the increase in infrastructure capacity. By contrast, an increase in incineration capacity would not resolve the problem in the short term and would be associated to an increase in landfill capacity in the transitional period, thereby increasing the risk of social conflict.

The system dynamics modelling approach was useful in providing policy-making with an overview of the waste management dynamics and the policy leverages available to them for sustainable waste management. In light of this insight, policy-makers and waste managers should be aware of the potential of incentivising the population to separate waste generated to reduce the burden of waste requiring final disposal.

The model presented is therefore proposed as a tool to develop a policy laboratory to test different future waste policies, to inform policy makers about the major effects of each alternative and improve the decisional process.

Future developments of the base structure could be related to the inclusion of the separate collection sector dynamics and evaluation of policies aimed at improving the local management of separated waste, especially the organic waste fraction, which is currently mainly treated outside the region. Even though the self-sufficiency goal is not binding for this sector, it would be interesting to assess alternatives for pursuing more sustainable waste management. It is also important to stress that this analysis was conducted at a regional level. However, as differences emerge at a provincial level, a more accurate analysis that takes into account spatial disaggregation would also enhance the study. Possible solutions to the problem of RDF should also be assessed, particularly those related to the conversion of unused MBT capacity.

Finally, even though the model focused on a specific case study, it could be applied in the future to other waste management contexts. To this end, its core structure could be easily changed and adapted to explain the dynamics of a different waste problem.

Acknowledgements

The authors are indebted to Silvio Martinez Vicente for his kind availability and methodological support. They are also grateful to Giacomo D'Alisa for his helpful insights and comments and to Alberto Grosso from ISPRA Campania for his support in providing information and data. Finally, the authors thank the anonymous reviewers for their useful comments.

Funding

This work was supported by a Department of Education Grant IT-799-13 from the Basque Government. Marta Escapa would also like to thank the Spanish Ministry of Economy and Competitiveness, (Project ECO2015-68023-C2-1-R) for partially supporting this work.

Appendix

	Equation and parameter values	Unit
1	Adjustment time = 1	Year
2	Available LF capacity = MAX (0, LF capacity-LF waste)/time to complete LF capacity	Ton/year
3	Average GDP growth ([(2000, −0.05) (2013,0.05)], (2000,0.01), (2001, 0.027), (2002, 0.039), (2003, 0.043), (2006, 0.043), (2007, 0.023), (2008, −0.0288), (2009, −0.03), (2013, 0.0042))	Dmnl/year
4	Average time = 1	Year
5	Births = crude birth rate * total population	Person/year
6	Bottom ashes = bottom ashes fraction * INC waste	Ton/year
7	Bottom ashes fraction = 0.15	Dmnl/year
8	Bottom ashes to recover = INTEG (bottom ashes, 0)	Ton
9	Change in GDP = average GDP growth (Time) * GDP	Euro/year/year
10	Crude birth rate = 0.012	Dmnl/year
11	Crude death rate = 0.010	Dmnl/year
12	Deaths = crude death rate * total population	Person/year
13	Effect of LF waste on separation = WITH LOOKUP (LF waste/initial LF waste, ([(1,0)–(5,5)],(1,0.2),(2,0.2),(3,0.3),(3.6,0.5),(4,1.5),(4.5,2),(5,2))	Dmnl
14	Effect of separation on RDF fraction = WITH LOOKUP (separated waste rate/initial separated waste rate,([(1,0.9)(30,10)], (1,1), (20,1.1), (25,1.15), (26,1.2),(27,1.25),(30,1.3)))	Dmnl/year
15	Elasticity of GDP per capita on waste generated = WITH LOOKUP (trend GDP per capita, ([(−0.04,0)–(0.05, 2)], (−0.033, 1.019), (−0.025, 1.07), (−0.014, 1), (−0.0004, 0.98), (0.0068, 1.11), (0.01, 1), (0.02, 1.0195), (0.03, 1.05), (0.048, 1.1)))	Dmnl
16	Expected RDF capacity = (available INC capacity/time to INC)-SPLIT to INC-untreated waste to INC	Ton/year
17	Expected SPLIT to INC = SPLIT/time to INC	Ton/year
18	Expected untreated waste to INC = MAX (0, untreated waste/time to move waste + mixed waste-untreated waste to MBT)	Ton/year
19	Expected untreated waste to LF = MAX (0, (untreated waste/time to move waste + mixed waste)–untreated waste to MBT – untreated waste to INC)	Ton/year
20	Flue gas = flue gas fraction * INC waste	Ton/year
21	Flue gas fraction= 0.79	Dmnl/year
22	Fly ashes = fly ashes fraction * INC waste	Ton/year
23	Fly ashes fraction = 0.05	Dmnl/year
24	Fly ashes to LF = INTEG (fly ashes, 0)	Ton
25	Fraction of untreated waste to LF = 1	Dmnl/year
26	GDP = INTEG (change in GDP, 8.20616e+010)	Euro/year
27	GDP per capita = GDP/total population	Euro/person/year

(*continued on next page*)

Appendix (*continued*)

	Equation and parameter values	Unit
28	INC capacity = INTEG (new INC capacity, 0)	Ton
29	INC capacity under development = INTEG (initiation of INC development-new INC capacity, 0)	Ton
30	INC desired capacity = 700000	Ton
31	INC desired capacity indicated = (INC desired capacity- (INC capacity + INC capacity under development))/ adjustment time	Ton/year
32	INC Waste = INTEG (RDF to INC+SPLIT to INC + untreated waste to INC-bottom ashes-fly ashes-flue gas, 0)	Ton
33	INC Waste = INTEG (RDF to INC+SPLIT to INC + untreated waste to INC-bottom ashes-fly ashes-flue gas, 0)	Ton
34	Increase policy enforcement = effect of LF waste on separation * initial growth separation * separate waste rate gap	1/year
35	Initial growth separation = 0.04	Dmnl/year
36	Initial LF waste = 2.59821e+006	Ton
37	Initial maintenance = 1	Dmnl
38	Initial RDF fraction = 0.55	Dmnl
39	Initial separated waste rate = 0.02	Dmnl
40	Initial total waste generated = 2.59856e+006	Ton/year
41	Initial trend = 0.01	Dmnl/year
42	Initiation of INC development = INC desired capacity indicated	Ton/year
43	Initiation of LF development = LF capacity initiation(Time)	Ton/year
44	Initiation of MBT development = MBT desired capacity indicated	Ton/year
45	Leachate losses = MBT waste*leachate losses fraction	Ton/year
46	LF capacity = INTEG (new LF capacity, 5.8e+006)	Ton
47	LF capacity initiation = ([(2000, 0)–(2016, 3e+006)], (2000.17, 1.8e+006), (2001.05, 1e+006), (2001.86, 1e+006), (2003.02, 900000), (2004.07, 900000), (2005, 600000), (2006, 600000), (2007.03, 1e+006), (2008.13, 2.7e+006), (2009.06, 300000), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2016, 0), (2018, 0), (2019, 0), (2020, 0))	Ton/year
48	LF capacity under development = INTEG (initiation of LF development-new LF capacity, 1e+006)	Ton
49	LF waste = INTEG (SOF rate to LF + untreated waste to LF, initial LF waste)	Ton
50	MBT capacity under development = INTEG (initiation of MBT development-new MBT capacity, 0)	Ton
51	MBT desired capacity = 2.579e+006	Ton
52	MBT desired capacity indicated = (MBT desired capacity–(MBT capacity + MBT capacity under development))/ adjustment time	Ton/year
53	MBT maintenance = 1	Dmnl
54	MBT productivity ([(2000, 0) – (2018, 2)], (2000, 0), (2001, 1.2), (2002, 0.86), (2003, 0.89), (2004, 0.89), (2005, 0.98), (2006, 0.94), (2007, 0.93), (2008, 0.37), (2009, 0.29), (2010, 0.35), (2011, 0.43), (2012, 0.51), (2013, 0.53), (2014, 0.51), (2018, 0.405))	Dmnl/year
55	MBT to SPLIT = RDF fraction*MBT waste	Ton/year
56	MBT waste = INTEG (untreated waste to MBT-MBT to SPLIT-metal losses-leachate losses-SOF rate to LF – SOF waste to other uses, 0)	Ton
57	Metal losses = metal losses fraction(Time)	Ton/year
58	Metal losses fraction ([(2003, 0) – (2010, 20000)], (2003, 8308), (2004, 9571), (2005, 13577), (2006, 11265), (2007, 9437), (2008, 4559), (2009, 4446), (2010, 5010))	Ton/year
59	Mixed waste = total waste generated-separated waste	Ton/year
60	Net change in separation rate = (Policy enforcement * separate waste rate gap)/adjustment time	1/year
61	New INC capacity = delay material (initiation of INC development, time to complete INC capacity, 0, 0)	Ton/year
62	New LF capacity = delay material (initiation of LF development, time to complete LF capacity, 0, 0)	Ton/year
63	New MBT capacity = delay material (initiation of MBT development, time to complete MBT capacity, 0, 0)	Ton/year
64	Policy enforcement = INTEG (increase policy enforcement, 0.02)	Dmnl
65	Rate LF waste = total LF rate/total waste generated	Dmnl
66	RDF = INTEG (SPLIT to RDF-RDF to INC, 392593)	Ton
67	RDF fraction = initial RDF fraction * effect of separation on RDF fraction * MBT maintenance	Dmnl/year
68	RDF to INC = MIN (expected RDF capacity, RDF/time to INC)	Ton/year
69	Separate waste rate gap = MAX (0, target rate of separated waste-separated waste rate)	Dmnl
70	Separated waste = total waste generated * separated waste rate	Ton/year
71	Separated waste rate = INTEG (net change in separation rate, initial separated waste rate)	Dmnl
72	SOF fraction = 1-RDF fraction	Dmnl/year
73	SOF rate to LF=MAX (0, MIN (MBT waste * SOF fraction, available LF capacity))	Ton/year
74	SOF waste to other uses = MBT waste * SOF fraction-SOF rate to LF	Ton/year
75	SPLIT = INTEG (MBT to SPLIT-SPLIT to INC-SPLIT to RDF, 0)	Ton
76	SPLIT to INC = MIN (available INC capacity/time to INC, expected SPLIT to INC)	Ton/year
77	SPLIT to RDF = (SPLIT/adjustment time)-SPLIT to INC	Ton/year
78	Target rate of separated waste = 0.6	Dmnl
79	Time to complete INC capacity = 7	Year

Appendix (*continued*)

	Equation and parameter values	Unit
80	Time to complete LF capacity = 1	Year
81	Time to complete MBT capacity = 0.8	Year
82	Time to INC = 1	Year
83	TIME TO MOVE WASTE = 1	Year
84	Total export = SOF waste to other uses + untreated waste to export	Ton/year
85	Total LF rate = SOF rate to LF + untreated waste to LF	Ton/year
86	Total population = INTEG (births-deaths, 5.70814e+006)	person
87	Total waste generated = INITIAL TOTAL WASTE GENERATED * elasticity of GDP per capita on waste generated	Ton/year
88	Trend GDP per capita = trend (GDP per capita, average time, initial trend)	Dmnl/year
89	Untreated waste = INTEG (mixed waste-untreated waste to export-untreated waste to INC-untreated waste to LF - untreated waste to MBT, 500000)	Ton
90	Untreated waste to export = MAX (0, (untreated waste/time to move waste + mixed waste)-untreated waste to MBT - untreated waste to INC-untreated waste to LF)	Ton/year
91	Untreated waste to INC = MIN (available INC capacity/time to INC-SPLIT to INC, expected untreated waste to INC)	Ton/year
92	Untreated waste to LF = MAX (0, MIN (available LF capacity-SOF rate to LF, expected untreated waste to LF))	Ton/year
93	Untreated waste to MBT = MIN (untreated waste/time to move waste + mixed waste, MAX (0, MBT productivity (Time) * MBT capacity))	Ton/year

References

Ardi, R., Leisten, R., 2016. Assessing the role of informal sector in WEEE management systems: A System Dynamics approach. Waste Manage. (Oxford) 57 (3–16), 2. https://doi.org/10.1016/j.wasman.2015.11.038.

ARPAC, 2008. Rifiuti, Produzione e gestion in Campania, 2002–2007.

Chaerul, M., Tanaka, M., Shekdar, A.V., 2008. A system dynamics approach for hospital waste management. Waste Manage. (Oxford) 28 (2), 442–449. https://doi.org/10.1016/j.wasman.2007.01.007.

Chung, I.J., 1992. Government regulation of market information as a public policy tool: the dynamics of waste recycling market development. Department of Public Administration and Policy. Albany, Nelson A. Rockefeller College of Public Affairs and Policy.

Chifari, R., Renner, A., Lo Piano, S., Ripa, M., Bukkens, S.G., Giampietro, M., 2017. Development of a municipal solid waste management decision support tool for Naples, Italy. J. Cleaner Prod. 161, 1032–1043. https://doi.org/10.1016/j.jclepro.2017.06.074.

Dace, E., Bazbauers, G., Berzina, A., Davidsen, P., 2014. System dynamics model for analyzing effects of eco-design policy on packaging waste management system. Resour. Conserv. Recycl. 87, 175–190. https://doi.org/10.1016/j.resconrec.2014.04.004.

D'Alisa, G., Burgalassi, D., Healy, H., Walter, M., 2010. Conflict in Campania: Waste emergency or crisis of democracy. Ecol. Econ. 70, 239–249. https://doi.org/10.1016/j.ecolecon.2010.06.021.

D'Alisa, G., Di Nola, M.F., Giampietro, M., 2012. A multi-scale analysis of urban waste metabolism: density of waste disposed in Campania. J. Cleaner Prod. 35, 59–70. https://doi.org/10.1016/j.jclepro.2012.05.017.

D'Alisa, G., Armiero, M., 2013. What happened to the trash? Political miracles and real statistics in an emergency regime. Capitalism, Nat. Socialism 24, 29–45. https://doi.org/10.1080/10455752.2013.849747.

D'Alisa, G., Di Nola, M.F., 2013. Separate collection target: why 65% in 2012? Waste Management in Spatial Environments. Edited by Alessio D'Amato, Massimiliano Mazzanti, Anna Montini. http://dx.doi.org/10.4324/9780203383223.

Dyson, B., Chang, N., 2005. Forecasting municipal solid waste generation in a fast growing urban region with system dynamics modelling. Waste Manage. (Oxford) 25 (7), 669–679. https://doi.org/10.1016/j.wasman.2004.10.005.

EU, 2013. Press release "Italy referred back to Court over waste management in Campania, Commission asks for fines". http://europa.eu/rapid/press-release_IP-13-575_en.htm.

Forrester, J.W., 1961. Industrial Dynamics. MIT, Cambridge.

Forrester, J.W., 1971a. World Dynamics. Wright-Allen Press, Cambridge, MA.

Forrester, J.W., 1971b. Counterintuitive behaviour of social systems. Technol. Rev. 73 (3), 52–68.

Ghisolfi, V., de Lorena, G., Chaves, D., Ribeiro Siman, R., Helena Xavier, L., 2017. System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: A perspective for social inclusion of waste pickers. Waste Manage. 60, 14–31. https://doi.org/10.1016/j.wasman.2016.12.018.

Greyl, L., Vegni, S., Natalicchio, L., Cure, F., Ferretti, J., 2010. The waste crisis in Campania. http://www.ceecec.net/case-studies/waste-crisis-in-campania-italy/.

Hornsby, C., Ripa, M., Vassilo, C., Ulgiati, S., 2017. A roadmap towards integrated assessment and participatory strategies in support of decision-making processes. The case of urban waste management. J. Cleaner Prod. 142, 157–172. https://doi.org/10.1016/j.jclepro.2016.06.189.

Karavezyris, V., Timpe, K.V., Marzi, R., 2002. Application of system dynamics and fuzzy logic to forecasting of municipal solid waste. Math. Comput. Simul 60 (3–5), 149–158. https://doi.org/10.1016/S0378-4754(02)00010-1.

Kum, V., Sharp, A., Harnpornchai, N., 2005. Improving the solid waste management in Phnom Penh city: a strategic approach. Waste Manage. (Oxford) 25 (1), 101–109. https://doi.org/10.1016/j.wasman.2004.09.004.

Inghels, D., Dullaert, W., 2011. An analysis of household waste management policy using systems dynamics modeling. Waste Manage. Res. 29 (4).

ISPRA, 2000–2015. Istituto Superiore per la Protezione e la Ricerca Ambientale, Rapporto Rifiuti [Waste Report]. http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/.

ISTAT, 2001–2015. Statistiche Demografiche [Demo Statistics], http://demo.istat.it/.

Mass, N., 1980. Stock and flow variables and the dynamics of supply and demand. In: Randers, J. (Ed.), Elements of the System Dynamics Method. Pegasus Communications, Waltham, MA.

Mashayekhi, A.N., 1993. Transition in the New York State solid waste system: a dynamic analysis. Syst. Dyn. Rev. 9 (1), 23–47. https://doi.org/10.1002/sdr.4260090103.

Mastellone, M.L., Brunner, P.H., Arena, U., 2009. Scenarios of waste management for a waste emergency area: a substance flow analysis. J. Ind. Ecol. 13 (5), 735–757. https://doi.org/10.1111/j.1530-9290.2009.00155.x.

Meadows, D.H., Meadows, D.I., Randers, J., Behrens III, W.W., 1972. The Limits to Growth. Universe Books, New York.

Meadows, D.H., Randers, J., Meadows, D.I., 2004. The Limits to Growth: The 30-Year Update. Chelsea Green Publishing Company, White River Junction.

Rabitti, P., 2008. Ecoballe. Tutte le verità su discariche, inceneritori, smaltimento abusivo deirifiuti. Edizioni Aliberti, Italy.

Randers, J., Meadows, D.L., 1973. The dynamics of solid waste generation. Wright-Allen Press, Inc., Cambridge, MA, pp. 141–211.

Regione Campania, 2016. Piano Regionale di Gestione dei Rifiuti Urbani [Regional Municipal Waste Plan]. http://www.regione.campania.it/regione/it/tematiche/rifiuti/piano-regionale-di-gestione-dei-rifiuti-urbani-2016?page=1.

Ripa, M., Fiorentino, G., Vacca, V., Ulgiati, S., 2017. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). J. Cleaner Prod. 142, 445–460. https://doi.org/10.1016/j.jclepro.2016.09.149.

Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw Hill.

Sudhir, V., Srinivasan, G., Muraleedharan, V.R., 1997. Planning for sustainable solid waste in Urban India. Syst. Dyn. Rev. 13 (3), 223–246. https://doi.org/10.1002/(SICI)1099-1727(199723)13:3<223::AID-SDR127>3.0.CO;2-Q.

Sufian, M.A., Bala, B.K., 2007. Modeling of urban solid waste management system: the case of Dhaka city. Waste Manage. (Oxford) 27 (7), 858–868. https://doi.org/10.1016/j.wasman.2006.04.011.

Ulli-Beer, S., Andersen, D.F., Richardson, G.P., 2007. Financing a competitive recycling initiative in Switzerland. Ecol. Econ. 62 (3–4), 727–739. https://doi.org/10.1016/j.ecolecon.2006.09.017.