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"Gheorghe Asachi" Technical University of Iasi, Romania

ECO-EFFICIENT DECISION SUPPORT MODEL OF SOLID WASTE RECYCLING

Stanislav Avsec[1]*, Branko Kaučič[2]

[1]University of Ljubljana, Faculty of Education, Kardeljeva ploščad 16, SI-1000 Ljubljana, Slovenia
[2]Initut, Institute of Information Technology, Ulica Eve Lovše 18, SI-2000 Maribor, Slovenia

Abstract

This paper describes an eco-efficiency decision support model for of end-of-life solid waste recycling. A holistic approach in balancing environmental pollution concern and waste recycling is required. A system dynamic model is based on mathematical model of the supply chain, and decision-making analysis is supported with the online spreadsheets. A criterion function-based modelling is used as a core model for simulation that uses net present value-based metrics of the supply chain activities. The economic and recovery effects of processing are determined. The system model combines technology process model, operational model, and macro and micro economic model, to locate all production-related technical requirements, effects, risks, and associated costs. The supply chain assessment based on criterion function assures a better technological foresight of environmental impact and preserved quality. The eco-efficiency indicators were developed. These indicators are used to evaluate the performance of the whole recycling system. The combination of technology and economic parameters dynamic modelling offers several advantages over existing modelling methodologies: they consider multiple products/process matrixes driven by the available inputs, and can respond to rapidly changing conditions in technology and economics. Theoretical framework on these aspects is provided in this paper, followed by a description of the dynamic modelling framework. An example case involving online simulation tool is presented to demonstrate the type of analyses possible using of the model developed in this study.

Key words: decision-making online tool, eco-efficiency, net present value based metrics, process-based cost modelling, solid waste recycling

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1. Introduction

Over the last decades, a traditional research topic in the waste management field has been focused on developing tools and methods to help decision-makers with tactical decisions over waste management systems.

With the increase of waste generation, reduction of available land, emerging technology of waste recycling and recovery, and the rising concern of environmental and health impacts, solid waste (SW) management systems are becoming more and more sophisticated. Many system parameters and their interrelationships appear uncertain.

Uncertainties can be presented in various stages of the policy cycle ranging from the initial detection of a problem to policy formulation and, eventually, monitoring and adjustment to existing policies (Wardekker et al., 2008). These uncertainties can be further amplified by the complex features of the system components and by their associations with economic implications and environmental concerns being examined (Li and Huang, 2006). Therefore, in response to such uncertainties, it is desirable to develop effective SW management methods by which efficient management strategies with satisfactory economic and environmental efficiencies could be generated. The prediction of SW generation

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[*] Author to whom all correspondence should be addressed: e-mail: stanislav.avsec@pef.uni-lj.si; Phone: +386-1-589-2224; Fax: +386-1-534-7997

plays an important role in SW management where stress to be done on recycling.

As recycling systems for SW become more widespread, understanding the economic and environmental performance of such systems becomes critical, both to enable improvement of existing systems and to design and implement new systems. Unfortunately, the variety of system architectural and contextual possibilities makes empirical inference of causality challenging. To address this issue, this paper presents a modelling framework to project the economic and environmental performance of both existing and prospective recycling systems.

Decision-makers within waste processing are faced daily with questions about the choice of recycling or disposal. Complexity of products dictates demanufacturing options, where environmental impacts and product end-of-life value have to be considered. Material streams after demanufacturing can be re-used as inputs in a chain value or/and in end-use markets. Very frequently, economically optimized decisions exclude environmentally consequences due to deficit of company operational supported capabilities.

To bridge the environmental effects exclusion at decision-making of waste processing, a precise and updated metrical model of an operational performance and mapping mechanism are needed. By this, a clear influence of processing decisions can be shown and explained with size and direction of impacts. This paper introduces a modelling framework that accomplishes aforementioned goals. Modelling is based on criterion function on which a net present value-based model of chain value activities is developed. Model incorporates both technical/technological aspects and environmental impacts of the recycling process. Processing costs are determined with the incoming material stream composition. Net present value, a recycling rate and labor costs are calculated and optimized with the operational metrics model. Net present value is a stable metric because it relies on real basis collected data and foresights environmental impacts and retained quality (Gregory et al., 2006).

The model also has the advantage that simulations can be run over different periods of time and provides the facility to conduct partial simulations to focus on specific sectors/areas of a model. The model developed here presents systems dynamic method developed to help in assessment of waste management options that are often done by planners and decision-makers. The usability of the model is demonstrated by single case modifications of technological and economic parameters, and by running a forecast simulation for the chosen period. By this approach, an eco-efficient decision-making process is developed. Several waste processing predictors include waste generation, recycling rate, landfilling efficacy, labor cost, and other economic cost and benefits.

This paper begins with backgrounds considering other demanufacturing modelling efforts, and metrics based on different value-based approaches for waste recycling. The materials and methods with dynamic eco-efficacy model development are followed. Afterward, a demonstration of dynamic eco-efficacy modelling is introduced. An online simulation tool is presented as effective tool for demanufacturers. In conclusive part, a justification and eligibility of the research is stressed. A feasible decision-making tool is delivered to advance SW recycling system.

2. Background

The growing requirements for sustainable development and low carbon society influenced the introduction of different waste management models to reduce impact on the environment and to gain benefit for the society. Recently, several methods and methodologies were used to optimize economic and environmental impacts in decision-making process for waste recycling. Different approaches were introduced which include the following decision-support frameworks: (a) The life-cycle assessment (LCA); (b) The cost-benefit analysis (CBA); and (c) The multi-criteria decision-making (MCDM).

All these approaches have several weak issues which have to be considered. LCA model include the following weaknesses (Karmperis et al., 2013): (a) modelling of LCA is a time-consuming process; (b) the assumptions (boundary conditions, input data, weights) in a LCA model might be subjective; (c) LCA does not specifically quantify impacts on eco-system; and (d) limitations in model cause low reliable results. CBA models may have deficit at (Karmperis et al., 2013): (a) valuing non-market goods can be complicated; (b) CBA does not allow precise measurement of complex eco-systems; (c) values of variables used in CBA could vary in a wide range; and (d) CBA is time-consuming. At MCDM modelling are the following weaknesses (Karmperis et al., 2013): (a) MCDM models do not provide data for waste minimization and waste prevention; (b) opportunity cost of alternatives trade-off are included just at few models; and (c) different criteria weight values cause the subjective selection.

Some differentiators were derived from aforementioned models: (a) determination/measure of environmental impact; (b) scope of the system evaluated; and (c) reliability of results varies. To bridge the difficulty of incorporating so much economic, technology, and environmental data for complex products, Gregory et al. (2006) suggest use of intelligent software tools to handle these tasks efficiently. A systems analysis has to be applied on disassembly and recycling in the separate models (Gregory et al., 2006).

Extensive research efforts have been undertaken in addressing uncertainties in SW management problems through stochastic, fuzzy, and interval programming approaches (Azam et al., 2009; Song and Li, 2009; Sun and Huang, 2010; Yeomans, 2008). Stochastic programming can deal with decision problems whose coefficients are not certainly known but can be represented as chances or probabilities. The main advantage of the stochastic programming methods is that they do not simply reduce the complexity of the programming problems; instead, they allow decision-makers to have a complete view of the effects of uncertainties and the relationships between uncertain inputs and resulting solutions. However, the stochastic programming methods require probabilistic specifications for uncertain parameters whereas, in SW management problems, it is often associated with difficulties in acquiring probability distribution for a random event when data are not enough (Li and Huang, 2011). Fuzzy logic, based on fuzzy set theory, can be applied at the analysis of systems with uncertainties. It suits the situations in which the uncertainties cannot be expressed as probability distributions, such that adoption of fuzzy membership functions becomes an attractive alternative (Xu et al., 2009). A large number of samples are generally required to identify the probability density function for the occurrence of a phenomenon, whereas subjective description of the fuzzy membership function is usually applied to the determination of fuzziness (Chang and Davila, 2006).

Interval programming is another alternative for handling uncertainties in the model's left- and right-hand sides and also those that cannot be quantified as membership or distribution functions, because interval (or grey) numbers with known lower and upper limits are acceptable as its uncertain inputs. Therefore, interval programming may become effective for many real-world problems in which only a very few samples exist and uncertain parameters cannot be described with probability distributions (Li and Huang, 2011). However, interval programming models may become infeasible when some left- or right-hand side parameters have large intervals. This occurs when some system conditions are very uncertain, making it difficult to quantify these possible ranges as reasonably small intervals (Li and Huang, 2011).

To tackle a combination of multiple uncertainties, a number of integrated methods were proposed. A grey fuzzy dynamic model for the prediction of SW generation was developed (Chen and Chang, 2000), in which the technique of fuzzy goal regression was employed to minimize the discrepancy between the predicted and observed values. An inexact two-stage programming model for planning SW management under uncertainty was explored (Maqsood and Huang, 2003), in which interval parameters were incorporated within a two-stage stochastic optimization framework. A grey minimax regret integer programming approach to outline an optimal regional coordination of SW routing and possible landfill or incinerator construction under an uncertain environment was proposed (Chang and Davila, 2006). A stochastic integrated waste management model on the basis of a life-cycle inventory approach was proposed (El Hanandeh and El Zein, 2010a), which allowed a systematic consideration of uncertainty. An inexact scenario-based probabilistic programming approach for identifying optimal waste-flow allocation and facility-capacity expansion strategies was proposed (Li and Huang, 2011); the proposed method can handle uncertainties described as intervals and probabilities and also support assessing the risk of violating constraints; however, it encountered challenge when constraints were associated with fuzzy and random features owing to the fact that decision makers expressed different subjective judgments upon the same problem. Nowadays, game-theoretic approaches in decision support models for SW are very often. The most critical issues, which are included in decision-support models developed within these frameworks, are (Karmperis et al., 2013): (a) In LCA, most critical issues are the assumptions used by analysts. (b) In CBA models, crucial are the selection of the discount rate and the level of analysis. (c) Most critical issues in MCDM framework models are the selection of evaluation criteria and further the selection of the criteria weight values.

To overcome these issues, El Hanandeh and El Zein (2010b) suggest a modified version of MCDM to cope with uncertainty in criteria weightings and threshold values. Decision-making process is time-depended and can occur during waste processing. A strategic decision-making can be supported from the aforementioned research findings. During the in-place demanufacturing systems different hurdles may limit the use of knowledge gained from this research. Dynamics of waste processing claims from demanufacturer in-time data and capability to variable control. A demanufacturer must considers the following dynamics: (a) values of material stream vary; (b) some key parameters are very sensitive, because of narrow range of data set; (c) processing costs, including extra start-up may vary; (d) in demanufacturing operations, data gained from regular basis are reliable enough; and (e) modifications of some parameters can altered not linearly, out from the modelling pathways. To support strategic decision, very detailed analysis has to be done on real data. All possible variable impacts must be investigated in-place with modification the operations of waste processing where economic and environmental predictors have to be considered.

Since all frameworks have shortcomings, it is suggested that future models should be developed combining suitably of the LCA, CBA and MCDM frameworks to maximize their strengths or/and minimize their weaknesses. Therefore, as the extension of previous efforts, systems dynamic modelling approach will be advanced in response to the aforementioned deficiencies. Systems dynamic modelling approach will incorporate micro and macro economics measures, environmental measures, labor and product life-cycle value, and technology and technological progress. It will facilitate dynamic analyses for long-term decisions of facility-capacity expansion and waste-flow allocation plans and should be socially and environmentally acceptable to fulfil sustainability needs (Dyson and Chang, 2005; Morissey and Browne, 2004; Petts, 2000; Weng and Fujiwara, 2011). The results will be used for generating a range of decision alternatives under various system conditions and thus helping decision-makers to identify desired waste management policies under uncertainty.

In the following section, a system model development, based on systems dynamic modelling approach, will be described.

3. Material and methods

The system model developed in this study concentrates on SW recycling system main functions, namely collection, processing, and system management (Dahmus et al., 2008). The model developed in this study Waste should be the subject of separated collection and should be stored in appropriate containers (Gentil et al., 2009). In most cases municipal services are authorized to handle the collected waste. Waste shall be either recycled or disposed of to landfills. Disposal of waste should be a subject of concern since there are significant differences in disposing waste of to landfills or make it a part of the recycling and re-use process. The whole process is a matter of costs. Another component, which has to be considered, is the environmental hazard.

Waste in the recycling process can have a huge impact on the environment. The concern of either to dispose the waste of to a landfill or to recycle it is one issue. Another issue is the impact on the environment with the production of new products, which are not made of secondary resources, but of primary natural resources. Use of natural resources means an additional environmental burden.

Therefore, it is for each product necessary to estimate the costs of disposing it off to landfills, including external costs (p_7 for the disposal industry and p_6 for the end-user). Solving environmental issues demands a systematic approach. Fig. 1 shows the environmental management. Such an approach is enabled in terms of the systematic theory. Optimal leadership of logistic systems (including feedback) involves the goal to achieve the optimal value added of the entire chain. Since it is a matter of a large horizon programme, it is appropriate to include the so-called criteria function of the net present value (Kollikkathara and Yu, 2010). Logistics of waste recycling can be interpreted as an extended responsibility of the producer in the same chain (Del-Moral-Avila et al., 2016).

Responsibility is to be reflected: (a) in the form of purchasing waste products with the price p_6 (if the waste has certain value, the price is positive; if the inducer has huge costs with the waste disposal, the price is negative); (b) as the total amount of costs because of disposing the waste at landfill sites, including any ecological payments p_7 (continuous negative parameter) for each unit of the waste at the landfill site.

Fig. 2 shows a basic scheme of recycling process. A systematic approach claims a broad range of inputs, while for the specific scenarios modelling a smaller set of model inputs may be used. It is proved that actual data can replace some modelled values (Dahmus et al., 2008). Recycling inputs include the following factors of production: (a) streams of end-of-life products $P_{4,5}$, measured with the size of waste P_6 generated in time T_6, (b) capital and labor (symbol L for both). Output is the stream measured by a share of waste P_6 generated in time T_6, demonstrated as $P_2' = \alpha\, P'_{4,5}$. Size of the output contingent is determined in the form: $P_2 = \alpha\, P_6$.

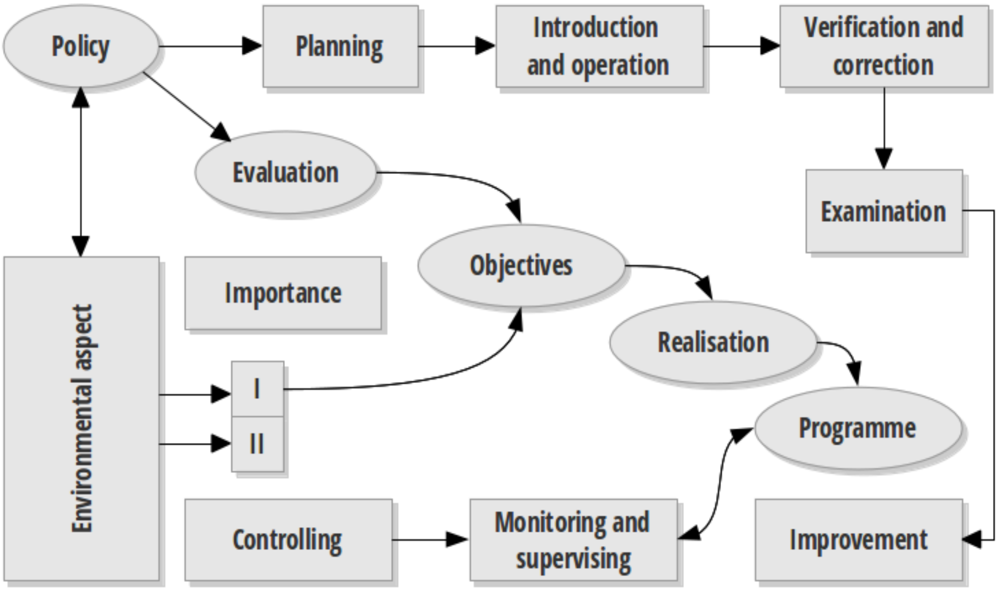


Fig. 1. An environmental management model

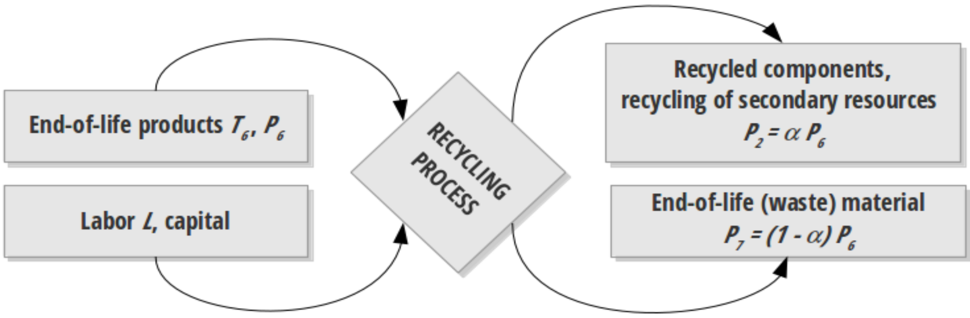


Fig. 2. Recycling process, including end-of-life products and labor

At model development, the following parameters are considered, as indicated in Table 1. The question arises if recycling of spent products is profitable and if so, when does it become optimal, considering the net present value of all recycling activities. Those can be determined as seen in Table 2.

Table 1. System model development parameters

T_6	Amount of time, necessary to start the production, including P_6
P_6	Size of the waste, generated in T_6
P_7	$(1-\alpha)$ P_6 Amount of waste to be dispose of to landfills
α/α^*	Rate of the recycled waste
L/L^*	Amount of input (labor and other factors of production) for each waste series/optimal amount of labor and labor-related factors of production
c_L	Price of labor and labor-related capital (input raw materials not included)
c_lL	Cost of labor and other labor-related factors of production in recycling of one stream
A, δ, γ	Parameters related to technology and product quality (at the end-of-life period)
ρ	Interest rate
K_6	Fixed costs for each start-up in T_6
$P'_{4,5}$	Source waste stream as input for recycling; $T_6 = P_6/P'_{4,5}$
p_2	Price of the semi-manufactured product (positive parameter)
p_7	Price of waste, sent to landfills (negative parameter, which includes costs for transport and environmental taxes)
p_6	Acquisition price of a spent product (often negative)
NPV	Net present value

Net present value NPV could be defined as (Eq. 1):

$$NPV_{rec} = [(p_2\alpha + p_7(1-\alpha))P_6/(1-e^{-\rho T_6})] - \\ - p_6P_6/(\rho T_6) - c_L L/(1-e^{-\rho T_6}) - K_6/(1-e^{-\rho T_6}) \quad (1)$$

The Cobb-Douglas production function (Barnett, 2007) applies to for each production cycle, namely $\alpha P_6 = AL^{\gamma}P_6^{\delta}$, which is followed by the recycling rate (Eq. 2):

$$\alpha = A\,L^{\gamma}\,P_6^{\delta-1} \quad (2)$$

Table 2. Recycling activities determination

$p_2\ \alpha\ P_6/(1-e^{-\rho T6})$	Discounted amount of all recycled waste income
$p_7\ (1-\alpha)\ P_6/(1-e^{-\rho T6})$	Discounted value of all costs, related to landfilling
$p_6\ P'_{4,5}/\rho$	Discounted value of all purchased spent products in the input stream
$c_L\ L/(1-e^{-\rho T6})$	Discounted value of all labor and other labor-related factors of production in the recycling process
$K_6/(1-e^{-\rho T6})$	Discounted value of all costs related to the recycling start-up

The parameters A, δ and γ depend on the used technology, any technological progress and the end-of-life product quality. Such values of P_6^* and $L^{*\prime}$ have to be found, so that the optimal net present value of all activities considering the reverse logistics is NPV^* ($NPV = NPV^*$). Considering α is never equal to 1, an optimal value may be expressed by Eqs. (3-5):

$$NPV_{rec} = ((p_2 - p_7)AL^{\gamma}P_6^{\delta} + p_7P_6 - \\ - c_L L - K_6)/(1-e^{-\rho T_6}) - p_6 P'_{4,5}/\rho \quad (3)$$

$$\frac{\partial NPV_{rec}}{\partial P_6} = \\ = \frac{(\delta(p_2 - p_7)AL^{\gamma}P_6^{\delta-1} + p_7)(1-e^{-\rho P_6/P'_{4,5}})}{(1-e^{-\rho P_6/P'_{4,5}})^2} - \\ - \frac{(\rho/P_{4,5})e^{-\rho P_6/P'_{4,5}}((p_2 - p_7)AL^{\gamma}P_6^{\delta}}{(1-e^{-\rho P_6/P'_{4,5}})^2} + \\ + \frac{p_7P_6 - c_L L - K_6)}{(1-e^{-\rho P_6/P'_{4,5}})^2} = 0 \quad (4)$$

$$\frac{\partial NPV_{rec}}{\partial L} = \frac{(\gamma(p_2 - p_7)AL^{\gamma-1}P_6^{\delta} - c_L}{1-e^{-\rho P_6/P_{4,5}}} = 0 \quad (5)$$

By choosing a Cobb-Douglas type production function, it is assumed implicitly not only that virgin and recycled materials are essential inputs to production, but more specific that inputs are perfectly substitutable, i.e. the substitution elasticity is equal to unity. The Cobb-Douglas function can be seen as a limit case of a more general technology (Pittel et al., 2005). The choice of this particular functional form thereby points out that the production of intermediates could also be interpreted as part of a larger integrated production process, namely the production of final output.

The value of recycling rate is considered in the range from 0–1 and the technological parameters are in the range $0 < \delta, \gamma < 0$ and $0 < \delta + \gamma < 1$ (Grubbsröm et al., 2007) under the following conditions (Eq. 6):

$$
\begin{aligned}
& e^{-\rho P_6 / P_{4,5}} \neq 1 \\
& -\rho P_6 / P'_{4,5} \neq 0 \\
& \rho \neq 0 \,, \rho > 0 \\
& 0 < \rho P_6 / P'_{4,5} << 1 \,; \\
& \delta\,(p_2 - p_7)\, A L^{\gamma}\, {P_6}^{\delta-1} + p_7 \neq 0 \qquad (6)
\end{aligned}
$$

From Eq. (5), an optimum point of $(L^*, {P_6}^*)$ may be expressed as (Eq. 7):

$$(p_2 - p_7)\, A L^{\gamma} {P_6}^{\delta} = c_L L / \gamma \qquad (7)$$

The latter from Eq. (4) may be expressed as (Eq. 8):

$$(\delta\ c_L L\ /\ P_6 \gamma\ +\ p_7)\ (1\ -\ e^{-\rho P_6 / P'_{4,5}})-\ (\rho\ /\ P'_{4,5})\cdot \\ \cdot\, e^{-\rho P_6 / P'_{4,5}}\ (c_L L(1- \gamma)/ \gamma + p_7 P_6 - K_6) = 0 \qquad (8)$$

With the development of the series
$e^{\rho P_6 / P'_{4,5}} = 1 + \rho P_6 / P'_{4,5} + \ldots$,
and the linear approximation, it may be expressed as (Eq. 9):

$$(1 - e^{-\rho P_6 / P'_{4,5}}) = (e^{\rho P_6 / P'_{4,5}} - 1)/\ e^{\rho P_6 / P'_{4,5}} \approx (\rho P_6 / P'_{4,5})/(1 + \rho P_6 / P'_{4,5}) \qquad (9)$$

Eqs. (8-9) lead to the conclusion that for the optimum point $(L^*, {P_6}^*)$:

$$
\begin{aligned}
& ((\delta\, c_L L / P_6 \gamma + p_7)\, \rho P_6 / P'_{4,5}) / (1 + \rho P_6 / P'_{4,5}) - (\rho\, P_6 / P'_{4,5})\, (c_L L (1- \gamma)/ P_6\, \gamma + p_7 - K_6/P_6) / (1 + \rho\, P_6 / / P'_{4,5}) \approx 0 \\
& (\delta\, c_L L / P_6 \gamma + p_7) - (c_L L (1- \gamma)/P_6\, \gamma + p_7 - K_6/P_6) \approx 0 \\
& (1 - \delta - \gamma) c_L L / P_6 \gamma \approx K_6 / P_6
\end{aligned}
$$

Therefore (Eq. 10):

$$L^* \approx \gamma\, K_6 / c_L\, (1- \gamma - \delta) \qquad (10)$$

From Eq. (7) and under consideration of Eq. (10), the parameter of ${P_6}^*$ may be expressed as (Eq. 11):

$${P_6}^* \approx (\, {c_L}^{\gamma}\, (K_6 / (1- \gamma - \delta))^{1-\gamma} / (A \gamma^{\gamma}\, (p_2 - p_7)))^{1/\delta} \qquad (11)$$

Therefore, the optimal recycling rate α^* is expressed as (Eq. 12):

$$\alpha^* = A\ (\gamma\ K_6\ /\ c_L\ (1- \gamma - \delta))^{\gamma}\ ((\ {c_L}^{\gamma}\ (\gamma\ K_6 / (1- \gamma - \delta))^{1-\gamma} / \gamma (p_2 - p_7)\ A)^{1/\delta})^{\delta-1} \qquad (12)$$

A dynamic system model is designed and built on technological/technical details and thus an investigation/study of main operating and technology parameters modifications is enabled to optimizing cost. Modelling parameters of developed system model can be used as: (a) to foresee and to judge manufacturing/processing cost; (b) to cover a broad range of processing conditions, including environmental impacts; (c) to construct re-balance due to changes in design and in demanufacturing process; and (d) to provide wide range of the cost-based processing scenarios/operational regimes due to technical and market/economic malfunctions.

An impact of the parameters on the optimal solution is demonstrated in next section.

4. Modelling of solid waste recycling

An example of modelling of SW recycling is presented here to demonstrate some of the model's capabilities. The model analysis is limited to the scope of technological parameters of A (technological progress), γ (recycling technology changes) and δ (quality of end-of-life product), and economic parameters (price impact) p_7 (environmental taxes changes), p_6 (end-of-life product price), ρ (interest rate), and c_L (price of labor force). Two scenarios are analyzed, assuming modification of the technological parameter A, and the economic parameter p_7 (ecological taxes).

4.1. Impact of technology/technological changes

Using reverse logistics, a significant reduction of waste amounts could be achieved, which are disposed of to landfills. The ratio between landfilling and recycling has to be determined in an optimal manner, applying to all activities in the supply chain.

Waste management is like any other economic activity under the influence of economical laws. Economic concerns might be considered key issues for decision-making and selection of technologies in SW management systems (Ghinea and Gavrilescu, 2016). Based on experience, waste management is economical only at certain rates. The minimum thresholds of technological efficiency in the waste management process vary according to the used technology. Technology is knowledge and processing of input materials (in this case waste), with the involvement of the required factors of production. Moreover, technology impacts might be crucial at the solid waste modelling and analysis (Inglezakis et al., 2016).

Table 3. Modification of parameter *A*

p_2	p_7	A	L	γ	L^{γ}	$L^{*\gamma}$	P_6	δ	P_6^{δ}
2	-0.50	**0.60**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**0.70**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**0.75**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**0.80**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**0.90**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**0.95**	0.05	0.30	0.41	4.90	40	0.20	2.09
2	-0.50	**1.07**	0.05	0.30	0.41	4.90	40	0.20	2.09
c_L	K_6	p_6	$P'_{4,5}$	ρ	$e^{-\rho P_6 / P'_{4,5}}$	$e^{-\rho P^*_6 / P'_{4,5}}$	$1/\gamma$-1	$1/\delta$	δ-1
0.03	10	-1	50	0.008	0.994	0.97644	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.98903	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.99222	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.99436	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.99687	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.99761	-1.43	5	-0.80
0.03	10	-1	50	0.008	0.994	0.99868	-1.43	5	-0.80

Different values of parameter *A* (impact of the technological progress on recycling) are a result of new technologies and the manner of production organization. Modification of technological parameter *A* is shown in Table 3. Other model parameters remain constant. As parameter *A* changes, the *NPV* also changes (because of the modification of the variables $L = L^*$ and $P_6 = P_6^*$ the variable α^* takes new values (as shown in Table 4).

Table 4. Results of parameter *A* modification

NPV^*	NPV	α	L^*	P^*_6	α^*
3257	1747	0.01	200	149	0.05
3472	1781	0.01	200	69	0.12
3627	1797	0.02	200	49	0.16
3825	1814	0.02	200	35	0.23
4396	1848	0.02	200	20	0.41
4793	1864	0.02	200	15	0.53
6152	1904	0.02	200	8	0.97

The recycling rate α also increases, the amount of labor is constant (since technology has no impact on labor). In such cases, technological progress is of significant importance, since it has a huge influence on environmental recovery. The conditions for an optimal solution and the maximum value added are given in Table 5. As the value of parameter *A* increases (and other parameters remain constant), the optimal rate of waste for recycling and re-use also increases. Parameter *A* impact on *NPV* and NPV^* is shown in Fig. 3.

The proposed model also allows modification of other technological parameters. Fig. 4 shows main characteristics and functions of the online tool. The same methodology is used for modelling of parameters γ and δ. Any demanufacturer can use decision-making tool for modification of these parameters to find optimal solutions for key recycling technological and economic parameters. Eco-efficiency-informed decision-making tool is developed and available for further exploitation at http://www.initut.com/research/solid-waste.

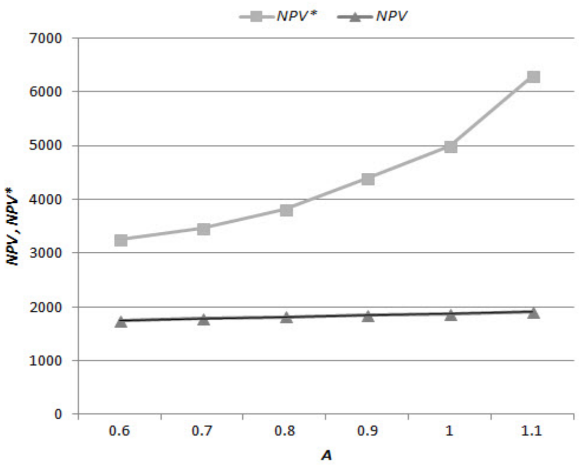
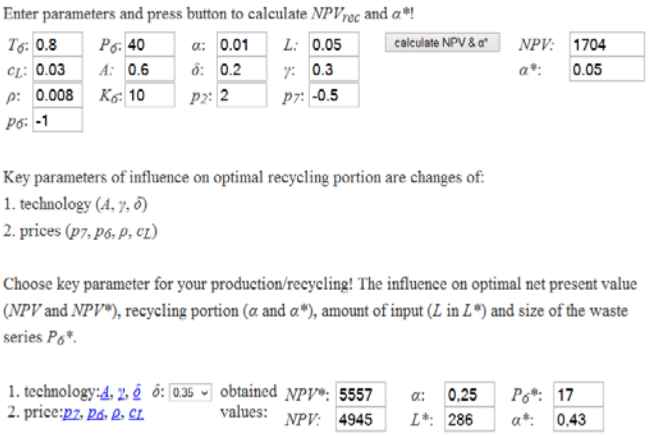


Fig. 3. Impact of modifications of parameter *A*

Modifications of parameter γ implicate adaptation of technology in the process (e.g., change/increase of facilities). Thus, the recycling rates increase and also the amount of the labor as input in the process. Fig. 5 illustrates the impact of parameter γ on *NPV* and NPV^*.


Enter parameters and press button to calculate NPV_{rec} and α*!

T_6: 0.8
P_6: 40
α: 0.01
L: 0.05
c_L: 0.03
A: 0.6
δ: 0.2
γ: 0.3
ρ: 0.008
K_6: 10
p_2: 2
p_7: -0.5
p_6: -1

NPV: 1704
α*: 0.05

Key parameters of influence on optimal recycling portion are changes of:

1. technology (A, γ, δ)
2. prices (p_7, p_6, ρ, c_L)

Choose key parameter for your production/recycling! The influence on optimal net present value (NPV and NPV*), recycling portion (α and α*), amount of input (L in L*) and size of the waste series P_6*.

1. technology: A, γ, δ δ: 0.35
2. price: p_7, p_6, ρ, c_L

obtained values:
NPV*: 5557
NPV: 4945
α: 0,25
L*: 286
P_6*: 17
α*: 0,43

Fig. 4. An online tool for modelling the optimal recycling rate

Improved technology reduces the time between each start-up process, leaving the start-up costs unchanged. Therefore, a need for as much startups as possible occurs with the same amount of start-up costs.

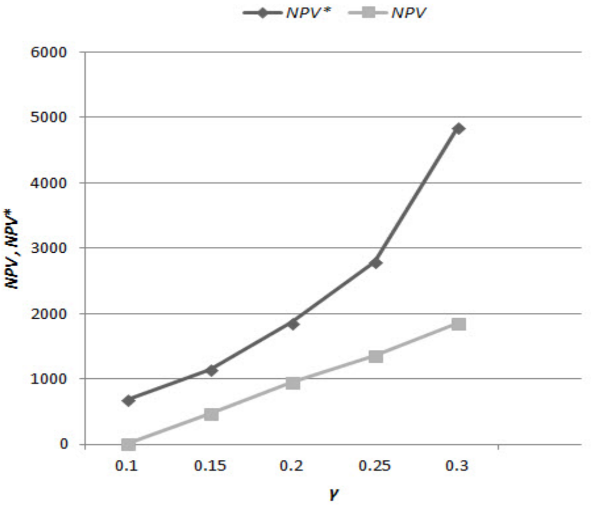


Fig. 5. Impact of modifications of parameter *γ*

Results show that it is important to put lots of effort in technology development, since it has an important impact on the parameter *γ* value and on the environmental recovery.

When a product is at the end-of-life cycle, its quality and quantity have a certain impact on parameter *δ*. If the parameter value increases (thus, if the quality at the end-of-life cycle increases) the rate of recycling also rises. This means that products are of better quality, so there is less material sent to landfills and more material is part of the recycling and the re-using process. With the recycling rate growing, a need for more labor occurs, which leads to increased amounts of waste in one series. Amount of time implicated at *NPV*, and necessary to start each operation, increases as it is shown in Fig. 6.

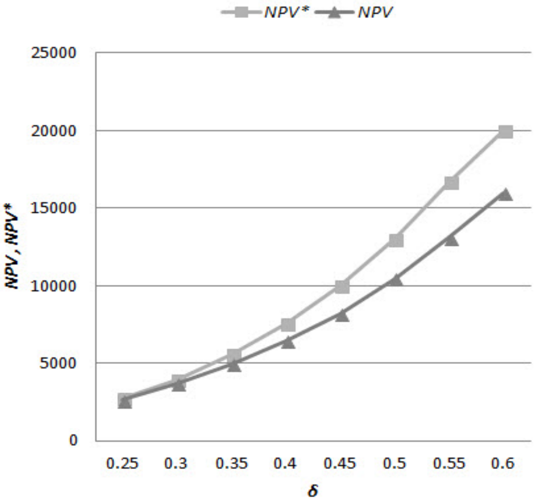


Fig. 6. Impact of modifications of parameter *δ*

Previous examples show the impact of parameters on the optimal net present value, recycling rate and the labor input. Parameters are different in each region or country. Different locations have various advantages and disadvantages. They represent a so-called counter balance to the transport costs in the cells of global logistics chain activities (Grubbsröm et al., 2007). Moreover, waste quantity in urbanized area is correlated with infrastructure development and employment in industry (Talalaj, 2017).

Table 5. Conditions for optimal solution

$e^{-\rho P^*_6 / P'_{4,5}} \neq 1$	$-\rho P^*_6 / P'_{4,5} \neq 0$	$0 < \rho P^*_6 / P'_{4,5} << 1$	$\delta(p_2-p_7)AL^{*\gamma}P^{*\delta-1}_6+p_7 \neq 0$	$\rho \neq 0; \rho > 0$
0.97644	-0.02384	0.02384	-0.70834	0.00650
0.98903	-0.01103	0.01103	-0.79969	0.00650
0.99222	-0.00781	0.00781	-0.83706	0.00650
0.99436	-0.00566	0.00566	-0.86712	0.00650
0.99687	-0.00314	0.00314	-0.89891	0.00650
0.99761	-0.00240	0.00240	-0.89689	0.00650
0.99868	-0.00132	0.00132	-0.82684	0.00650

Table 6. Modification of environmental taxes, p_7

p_2	p_7	A	L	γ	L^γ	$L^{*\gamma}$	P_6	δ	P_6^δ
3	**-0.60**	0.60	50	0.50	7.07	9.13	40	0.20	2.09
3	**-0.70**	0.60	50	0.50	7.07	9.13	40	0.20	2.09
3	**-0.80**	0.60	50	0.50	7.07	9.13	40	0.20	2.09
3	**-0.90**	0.60	50	0.50	7.07	9.13	40	0.20	2.09
3	**-0.97**	0.60	50	0.50	7.07	9.13	40	0.20	2.09
c_L	K_6	p_6	$P'_{4,5}$	ρ	$e^{-\rho P_6 / P'_{4,5}}$	$e^{-\rho P^*_6 / P'_{4,5}}$	$1/\gamma-1$	$1/\delta$	$\delta-1$
0.20	10	-1	50	0.007	0.99481	0.99821	-2	5	-0.80
0.20	10	-1	50	0.007	0.99481	0.99844	-2	5	-0.80
0.20	10	-1	50	0.007	0.99481	0.99863	-2	5	-0.80
0.20	10	-1	50	0.007	0.99481	0.99880	-2	5	-0.80
0.20	10	-1	50	0.007	0.99481	0.99890	-2	5	-0.80

4.2. Economic aspects - pricing

As mentioned above, price is a huge and decisive factor in taking waste management decisions. Price is the basis for deciding whether an activity is economically or environmentally reasonable. Companies, which main activity is not waste management or reverse logistics, don't have such issues. This is more a concern of companies and performers in environmental recovery. An example of ecological taxes parameter p_7 modification is presented. Table 6 shows modifications of landfilling costs, including operational costs and environmental taxes. All other model parameters remain constant. Changes of environmental taxes have impact on the recycling rate and the $NPV = NPV^*$.

A change of *NPV* of optimal decisive parameter is shown in Table 7 with change of optimal NPV^*. If a region has none (which is almost never the case) or low environmental taxes, there is no need (or no motivation) for separate waste collection and recycling. The conditions for an optimal solution and the maximum value added are given, Table 8. Environmental taxes are one of the most important financial sources for proper and effective waste management. Taxes are an important mechanism to achieve environmental goals, such as reducing amounts of waste at the origin, reducing landfilling, decreasing the amount of biological degradable waste, increasing the ratio of separate waste collection (various waste streams) and an increasing rate of recycling and waste utilization (Kollikkathara and Yu, 2010).

Separate waste collection might have positive impact on production costs (Bartolacci et al., 2017). Especially, environmental taxes can be considered carefully at the incineration of the residual waste (household hazardous waste) where energy recovery should be calculated accordingly (Popita et al., 2017). If environmental taxes are high, the value of the *NPV* decreases, what is shown in Fig. 7, but the waste logistics and recycling gain significant importance (Grubbsröm et al., 2007).

Very important part of pricing is modification of interest rate ρ. Modification of ρ can be observed in details using online tool. The modification of interest rates has impact on the net present value of all values added in all cycles, what is shown in Fig. 8. Method used for modification of parameter p_6 is the same, and the use of online tool is advised. When the parameter p_6 increases, values of *NPV* and *NPV** also increase. Recycling rate and input labor are constant. The time between each start-up remains constant. A producer is responsible for his products after their life-cycle is expired. This responsibility results in the price of the waste.

The value of waste depends on quality, type and the current price situation on the global market. Some waste has no value and means only costs. In such a case, the parameter p_6 has a negative range. More often, the waste has some value since it can be recycled. If the costs of landfilling in the demanufacturing industry do not change, there is no impact on the value of the variables. As the purchase price p_6 for waste is increasing, the values of *NPV* and NPV^* are decreasing recycling rate and labor input are unchanged.

Parameter p_6 could be either positive or negative. If the values of parameter's variations are the same, sending waste to landfills is equally to processing it in recycling. The consumer's decision is in such a case irrelevant (it doesn't matter if he sends the waste to a landfill or to a recycling site). Labor cost sometimes present decisive factor to choose a right rate of recycling, especially when environmental impact is considered.

Modification of labor costs c_L can be explored in details using online tool. If the parameter is increasing, the values of *NPV* and *NPV** are decreasing as it is shown in Fig. 9. Therefore, the recycling rate and labor input amounts are reduced. Time periods between each start-up are growing. These results provide a necessary element required to enable data-driven decision-making regarding the preferred processing pathway for the products.

Table 7. Results of parameter p_7 modification

NPV^*	NPV	α	L^*	P^*_6	α^*
6791	5367	0.22	83	14	0.67
6567	4767	0.22	83	12	0.75
6405	4167	0.22	83	11	0.83
6311	3567	0.22	83	9	0.92
6288	3147	0.22	83	8	0.99

Table 8. Optimal solution considering operational cost and environmental taxes

$e^{-\rho P^*_6 / P'_{4,5}} \neq 1$	$-\rho P^*_6 / P'_{4,5} \neq 0$	$0 < \rho P^*_6 / P'_{4,5} << 1$	$\delta(p_2-p_7)AL^{*\gamma}P^{*\delta-1}_6+p_7 \neq 0$	$\rho \neq 0; \rho > 0$
0.99821	-0.00179	0.00179	-1.88329	0.00650
0.99844	-0.00157	0.00157	-2.28344	0.00650
0.99863	-0.00137	0.00137	-2.69740	0.00650
0.99880	-0.00120	0.00120	-3.12450	0.00650
0.99890	-0.00110	0.00110	-3.43091	0.00650

With the presented system dynamic model of costs, a new knowledge and insights are gained that not only these external factors, but also other factors (such as net present value of the waste, landfilling costs and labor) have certain impact on the issue whether to recycle or send waste to landfills.

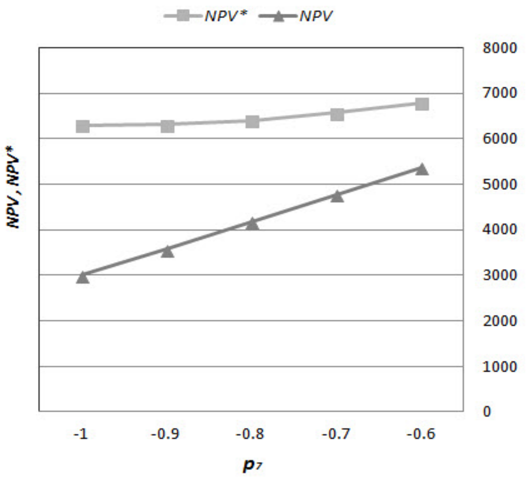


Fig. 7. Impact of modifications of parameter p_7

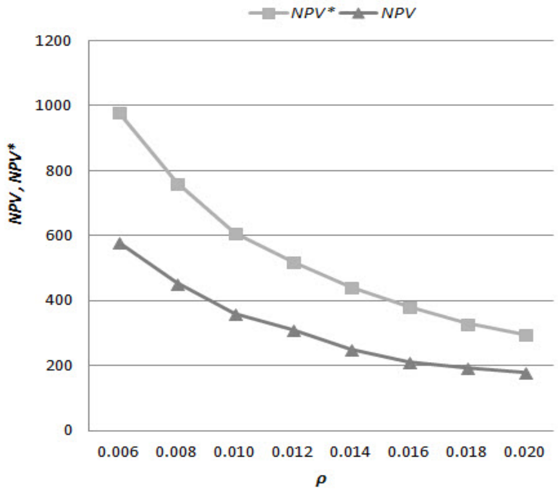


Fig. 8. Impact of modifications of parameter ρ

The higher are the landfilling costs, the option of recycling gets on power. With combination of producer responsibility and the cost of landfilling, a system of production can be established, where the producer will manufacture products, which can be recycled or re-used. Secondary/recycled products have a certain value and can be re-used as secondary raw materials; this is another motivation for proper separate waste collection and waste management. By comparison of each of the parameters and by consideration of the entire model, a decision-making for waste recycling or/and landfilling can be done.

An optimal solution has to be determined, afterward a balance between the requirements of the producer (taking responsibility for their product at the end-of -life cycle), and the nature is established. These results provide a necessary element required to enable data-driven decision-making regarding the preferred processing pathway for these products.

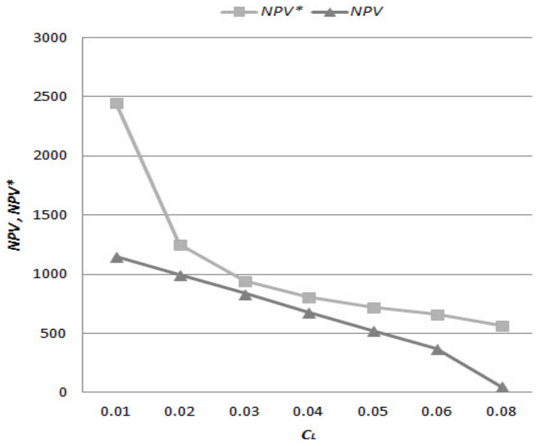


Fig. 9. Impact of modifications of parameter C_L

Technological progress of the supply chain has a huge role in the environmental recovery organization. The quality of a product at the end-of-life cycle, input and output material prices, labor input (along with the related capital), and landfilling are another important factors in the process.

External factors (technology and product quality) have positive impact on the modifications in the supply chain. Growth of the value of those factors means an increased net present value and a higher recycling rate. Labor input also grows; the time between each start-up is shorter (start-up costs remain the same). In such cases it is reasonable to invest in new technologies and new products to generate/produce them from usable recycling materials. All this leads to less environmental burden.

5. Conclusions

A system dynamic model based on technological changes predictors and net present value metrics of solid waste recycling has been developed. Eco-efficient processing decisions of demanufacturers are enabled. Multiple waste stream processing is advanced and the online simulation tool developed provides modifications and sharp control over technology changes and economic factors impact. The input data are collected on the regular basis, thus the developed model can provides effective decision-making about the optimal values of labor costs, net present value, and recycling rate.

Most detailed environmental impacts may be analyzed through online simulation intelligent tool, where cost optimization and technological performance are built on sensitive metrics.

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