Simulation and Evaluation of the Efficiency of Oil-
contaminated Wastes Recycling System

M Yu Derevyanov¹, Yu E Pleshivtseva¹, A A Afinogentov²

¹Department of Heat and Power Engineering, Samara State Technical University,
Molodogvardeyskaya Str., 244, Samara, 443100, Russia
²Department of Petroleum Engineering, Samara State Technical University,
Molodogvardeyskaya Str., 244, Samara, 443100, Russia

E-mail: mder2007@mail.ru

Abstract. The paper presents the results of simulation and evaluation of the efficiency of the system for the oil-contaminated wastes (OCW) recycling. The recycling system includes facilities for the OCW storing, technological installations for their processing and all necessary infrastructures that ensure the interconnection of the elements of the system under consideration. The system elements are evaluated using the basic CCR model and Super-efficiency model of the Data Envelopment Analysis (DEA) method. The algorithm has been developed to evaluate the efficiency of the OCW utilization system, which allows one to select the best technologies and storage facilities for the OCW recycling, taking into account their relative estimations with respect to resource value and reuse potential, as well as logistic criterion evaluating trans-portionation costs and ecological criterion evaluating environmental safety of recycling processes in the analyzed system.

1. Introduction
The objectives of the researches are to develop the model for evaluation of an oil-contaminated wastes recycling system, which characterizes its’ complex impact on the economy and the environment, and to evaluate the efficiency of this system, taking into account various indicators designed to effectively manage the entire system.

Current approaches promoting a ‘circular economy’ are based on preceding research into resource efficiency [1-4], and provide an imperative to reconsider approach to resource recovery from waste (RRfW). This should aim to resolve RRfW system inefficiencies, and transform waste management practices into systems that ‘manufacture’ secondary resources of high value [5].

In the frame of RRfW approach the term ‘value’ has a wide meaning, referring to measurable benefits (creation of positive value) and impacts (creation of negative value, or loss of value) in the environmental, economic, social and technical domains [5]. To measure the benefits obtained, with the aim of modeling and managing system of oily wastes recycling systems, the set of indicators (metrics) is being formed. The analysis presented in [5] allows to determine a set of basic indicators for evaluating the effectiveness of waste treatment systems.

Ecological metrics include indicators of carbon emission (Carbon emission metrics) [6], indicators of emission of polluting substances into air, water and soil (Pollutant emissions to air, water and soil) [7], energy indicators (Resource depletion: energy related metrics) – usage of energetic potential of
wastes is considered in [8,9], and non-energy indicators (Resource depletion: non-energy related metrics) [10].

Cost-benefit analysis (CBA) that collapses all costs and benefits into monetary terms, is a well-known tool for assessing positive and negative impacts of RRfW projects in monetary terms [11-13].

There is a high degree of importance of recycling problem for the modern human, therefore, important indicators for evaluating the effectiveness of waste disposal systems are socio-economic indicators and socio-cultural indicators (Acceptability, Participation rate, Social function and equity, System safety, Health and safety (of workers), Job creation etc.) [14-16].

As the main technical indicators of efficiency of recycling systems, the following indicators are typically considered: Reusability, Remanufacturability, Mass recyclability, Technical recyclability, Mass recoverability, Energy recoverability.

The reusability or reuse potential refers to the ability of a component or product to retain its functionality after the end of its primary life [19, 20]. According to this approach, reuse potential of waste can be determined in the range from 0 («as waste») to 1 («as resource»).

In the paper the following general approach is suggested. Reuse potential of OCW is considered as a comprehensive quantitative indicator of the possibility of effective recycling of waste that can be measured by a combination of heterogeneous criteria.

One of the particular quantitative indicators for estimating the waste reuse potential is the resource value of the OCW. The resource value of wastes is a quantitative assessment of their physicochemical composition and properties, which determines the degree of suitability of waste for use as material resources in recycling technologies associated with their recycling, recovery and regeneration. The original approach to estimating the resource value proposed in [21], is based on the Data Envelopment Analysis (DEA) method [22-23].

In the development of this approach, the paper considers the algorithm that allows one to select the best technologies and storage facilities for the OCW recycling, taking into account their relative estimations with respect to resource value and reuse potential, as well as logistic criterion evaluating transportation costs and ecological criterion evaluating environmental safety of recycling processes in the analyzed system.

1.1. CCR model of DEA method
The most basic DEA model, the CCR model, which was initially proposed by Charnes A., Cooper WW, Rhodes E. (CCR model) [22], can be used for estimation of effectiveness of objects in analyzed group. In DEA method, the object under consideration is called a DMU (Decision Making Unit). Generally a DMU is regarded as the object responsible for converting inputs into outputs, whose performance or efficiency are to be evaluated. For each DMU the virtual vectors of inputs \( X = \{x_i\}, i = 1, H \) and outputs \( Y = \{y_j\}, j = 1, J \) are formed, and then the weight coefficients \( v_i, i = 1, H \) and \( u_j, j = 1, J \) should be determined, using linear programming, so as to maximize the ratio:

\[
E(X,Y) = \frac{\sum_{j=1}^{J} u_j y_j}{\sum_{i=1}^{H} v_i x_i},
\]

characterizing efficiency \( E \) of DMU. Number \( H \) of inputs and number \( J \) of outputs, used in CCR model, depend on the objectives of the problem and particular features of estimated DMUs.

The inputs and outputs should represent main parameters (components) that will influence the relative efficiency evaluations of the DMUs. In principle, smaller input amounts are preferable and
larger output amounts are preferable so the efficiency scores should reflect these principles. Therefore, inputs \( x_i, i = 1, H \) should be selected in such a way that the following inequalities hold true:

\[
\frac{\partial E(x_1, ..., x_i, ..., x_H)}{\partial x_i} < 0, \quad i = 1, H.
\]  

(2)

At the same time, the choice of outputs \( y_j, j = 1, J \) should be done so that the following conditions are valid:

\[
\frac{\partial E(y_1, ..., y_j, ..., y_J)}{\partial y_j} > 0, \quad j = 1, J.
\]  

(3)

The numerical value \( E_z \) of the relative evaluation of the \( z \)-th DMU efficiency obtained using relation (1) should belong to the interval \([0; 1]\). Then the following constraint on the value \( E_z \) is imposed:

\[
\sum_{j=1}^{J} u_j y_j \leq 1, \quad \forall \left( z = 1, Z; j = 1, J; i = 1, H; u_{iz} > 0; v_{iz} > 0 \right).
\]  

(4)

The constraint (4) means that the ratio of “virtual output” vs. “virtual input” should not exceed 1 for every DMU.

To measure the efficiency of DMUs group, \( Z \) optimizations are needed, one – for each \( z \)-th DMU ( \( z = 1, Z \) ) to be evaluated. Then the following fractional programming problem for each \( z \)-th DMU ( \( z = 1, Z \) ) should be solved to obtain values for the input and output “weights” \( U = (u_{jz}), j = 1, J; V = (v_{iz}), i = 1, H \) as variables:

\[
E_z(X_z, Y_z) = \frac{\sum_{j=1}^{J} u_{jz} y_j}{\sum_{i=1}^{H} v_{iz} x_i} \rightarrow \max_{U, V \in G},
\]  

(5)

subject to constraint (4).

Solution of the problem (5) under condition (4) gives the relative value \( E_z \) of efficiency estimation for \( z \)-th DMU and appropriate sets of weight coefficients \( u_{jz} \in G, j = 1, J; z = 1, Z \) and \( v_{iz} \in G, i = 1, H, z = 1, Z \), maximizing the functional (5).

The problem (4)-(5) is related to the problems of mathematical programming (MP) and can be solved by standard optimization methods [24]. As a result of the MP problem solution, several objects in the analyzed group can at once have an efficiency assessment \( E_z = 1 \), meaning that these objects have maximum efficiency in the group. The remaining objects, with a rating of \( 0 < E_z < 1 \), are considered as less efficient ones. The case with several objects having maximum possible efficiency \( (E_z = 1) \) can be not representative from point of view of ranking DMUs in the analyzed group. That leads to the conclusion that the main objective of measuring the efficiency of DMUs group is not met and it is necessary to apply another model, for example, Super-efficiency model of DEA-method.
1.2. Super-efficiency model of DEA- method
Super-efficiency measures are widely utilized in DEA applications for many purposes, including ranking efficient DMUs [25]. Super-efficiency model is proposed by Andersen and Petersen (1993) that leads to a concept called "super-efficiency." The efficiency scores from these models are obtained by eliminating the data on the DMU to be evaluated from the solution set. For the input model this can result in values which are regarded as according DMU the status of being "super-efficient". These values are then used to rank the DMUs and thereby eliminate some (but not all) of the ties that occur for efficient DMU [25].

Then, similar to (4)-(5), the following mathematical programming problem based on Super-efficiency model should be formulated for the comparative evaluation of DMUs:

\[ S_z(X_z, Y_z) = \frac{\sum_{j=1}^{J} \bar{u}_{jk} y_{jz}}{\sum_{i=1}^{H} \bar{v}_{i} x_{iz}} \rightarrow \max_{\bar{U}, \bar{V} \in \mathcal{G}}, \]

\[ \sum_{j=1}^{J} \bar{u}_{jk} y_{jz} \leq 1, \forall \left\{ z = 1, Z; z \neq k; j = 1, J; i = 1, H; \bar{u}_{jk} > 0; \bar{v}_{i} > 0 \right\}, \]

where \( \bar{U} = (\bar{u}_{jk}, j = 1, J; \bar{V} = (\bar{v}_{i}), i = 1, H \) are vectors of unknown weight coefficients for each \( z \)-th DMU, \( z = 1, Z \). It is important to underline that output weights \( \bar{u}_{jk} \), \( j = 1, J \) and input weights \( \bar{v}_{i}, i = 1, H \) for \( k \)-th DMU with efficiency estimation \( E_{k} = 1 \) are eliminated from the solution set in problem (6)-(7). The values \( \bar{u}_{jk}, j = 1, J \) and \( \bar{v}_{i}, i = 1, H \) are obtained in the result of solving the problem (4)-(5).

Solution of the problem (6) under condition (7) gives the relative value \( S_z, z = 1, Z \) of efficiency estimation for \( z \)-th DMU, which belongs to the interval \([0, \infty)\). As a result, the DMU having maximum of value efficiency estimation \( S_z \) can be considered as the most effective one in the analyzed group.

2. Approach to analysis of efficiency of the system for oil-contaminated waste recycling
In the paper the described models of DEA method (see 1) have been applied for the analysis of efficiency of the system for OCW recycling.

Let us assume that the system for OCW recycling includes \( N \) storages of OCW, \( M \) recycling technologies and infrastructure providing interconnection of elements in the system.

In considered application of DEA method, DMUs may take such forms as \( n \)-th storage of OCW, \( n = 1, N \), or \( m \)-th recycling technology, \( m = 1, M \). For the purpose of securing relative comparisons, a groups of storages or technologies (DMUs) are used to evaluate each other with each DMU. To obtain estimations of the efficiency of the OCW utilization system, the special algorithm is developed that uses solutions of mathematical programming problems based on the CCR model in the form (4) - (5) and on the model of Super-efficiency in the form (6) - (7) of DEA method. This algorithm represented in Figure 1 comprises 5 consecutive stages.

2.1. Estimation of resource value of OCW storages
In order to determine the comparative significance of the \( n \)-th OCW’ storage as a potential source of resources the Problem 1 for determining the resource value (in Figure 1) is solved [21].
As DMU’ inputs, that smaller amounts are preferable for the higher relative resource value of the DMUs, the following OCW’ components have been selected in Problem 1: average-weighted content of water, asphaltenes and resins, mechanical and mineral impurities, and sulfur. As outputs that bigger amounts result in the higher relative resource value of the DMUs, the following OCW’ components have been selected in Problem 1: average-weighted content of light hydrocarbons and the ratio of the mass of light carbon-hydrogens to the total mass of harmful impurities and water.

Solutions of the formulated mathematical programming problems in the forms (4)-(5) and (6)-(7) based on CCR model and Super-efficiency model of DEA method provide relative estimations $E_n^1$ and $S_n^1$ of resource values of $n$-th DMU (OCW’ storage), respectively. These estimations can be obtained for all $N$ storages of the analyzed group. As a result, the obtained estimations $S_n^1$, $n = 1, N$ can be compared and the storage with the biggest resource value of OCW can be determined in the analyzed group.

### Figure 1. Algorithm for evaluation of efficiency of OCW recycling system.

2.2. Estimation of reuse potential of the system for oil-contaminated waste recycling

The suggested approach for the analysis of efficiency of the system for OCW recycling is generally based on the estimation of reuse potential represented as a comprehensive quantitative indicator of the possibility of effective recycling of waste after the end of its life as a primary product. It is proposed to carry out the comparative analysis of the group of $N$ storages with respect to the reuse potential of the OCWs storing in them.

Thus the reuse potential of $n$-th OCW storage (DMU) is considered as a quantitative indicator of the possibility of effective recycling of OCW in $n$-th storage using $m$-th recycling technology taking into account treating costs. For that purpose the Problem 2.1 (Figure 1) is solved.

It is also proposed to carry out the comparative analysis of the group of $M$ technologies of the considered recycling system. The comparison can be done with respect to the reuse potential considered as a quantitative indicator of the ability of $m$-th recycling technology (DMU) to use the OCW in $n$-th storage as a resource. For that purpose the Problem 2.2 (Figure 1) is solved.

As DMU’ inputs, that smaller amounts are preferable for the higher relative reuse potential value of the DMUs, the following parameters have been selected in the Problems 2.1 and 2.2: duration of the recycling process, reagents mass and energy (fuel) consumption. As outputs, that bigger amounts are preferable for the higher relative reuse potential value of the DMUs, the following parameters have been selected in the Problems 2.1 and 2.2: mass of valuable recycling products and estimation $S_n^1$ of resource values of $n$-th DMU (OCW’ storage), obtained as a result of problem (6)-(7) solution based on Problem 1.
Solutions of the Problems 2.1 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method give, respectively, the relative values $E_{nm}^{1.1}$ and $S_{nm}^{2.1}$ of reuse potential, estimating possibility of effective recycling of OCW in $n$-th storage using $m$-th recycling technology. These estimations can be obtained for all $N$ storages of OCW in analyzed system. Solutions of the Problem 2.2 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method gives, respectively, the relative values $E_{mn}^{2.2}$ and $S_{mn}^{2.2}$ of reuse potential, estimating the ability of $m$-th recycling technology (DMU) to use the OCW in $n$-th storage as a resource. These estimations can be obtained for all $M$ technologies in analyzed system.

The relative estimations $S_{nm}^{2.1}$ and $S_{mn}^{2.2}$ of reuse potential allow to obtain the most efficient DMUs in the analyzed groups of $N$ storages and $M$ technologies, respectively. At the same time, in order to estimate the efficiency of the whole system for OCW recycling the following overall estimations can be used:

$$D_{nM}^{2.1} = \sum_{m=1}^{M} S_{nm}^{2.1}, \ n = 1, N;$$

$$D_{mN}^{2.2} = \sum_{n=1}^{N} S_{mn}^{2.2}, \ m = 1, M.$$  (8)  (9)

Overall estimation $D_{nM}^{2.1}, \ n = 1, N$, obtained using (8), represents cumulative generalized estimation of reuse potential, showing possibility of effective recycling of OCW in $n$-th storage using all $M$ recycling technologies existing in the considered system. The OCW storage having the highest reuse potential in the analyzed system has the biggest value of estimation $D_{nM}^{2.1}$. Overall estimation $D_{mN}^{2.2}, \ m = 1, M$ obtained using (9), represents cumulative generalized estimation of reuse potential showing the ability of $m$-th recycling technology (DMU) to use the OCW in all $N$ storages as a resource. The biggest value of estimation $D_{mN}^{2.2}, m = 1, M$ allows to define which recycling technology has the highest ability to use the OCWs as a resource in all $N$ storages of the analyzed system.

2.3. Estimation of the efficiency of OCW recycling system regarding logistic criterion

Estimation of the efficiency of system for OCW recycling regarding logistic criterion provides evaluation of transportation costs in the system.

Problem 3.1 is formulated and solved in order to estimate the efficiency of recycling using $m$-th stationary technology taking into account the cost of OCW's transportation from the $n$-th storage (DMU) to the recycling plant. Problem 3.2 is formulated and solved in order to estimate the efficiency of using $m$-th mobile recycling technology (DMU) taking into account the cost of transportation of $m$-th mobile installation to the $n$-th storage.

As DMU’s inputs, that smaller amounts are preferable for the higher relative efficiency of DMU regarding logistic criteria, the following parameters have been selected in the Problems 3.1 and 3.2: relative energy costs for transportation and duration of transportation (either OCW to the recycling plant or mobile installation to the OCW storage). As DMU’s outputs, that bigger amounts are preferable for the higher relative efficiency of DMU regarding logistic criterion, the estimations of reuse potential $S_{nm}^{2.1}$ and $S_{mn}^{2.2}$ have been selected in the Problems 3.1 and 3.2, respectively.

Solutions of the Problem 3.1 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method give, respectively, the relative values $E_{nm}^{3.1}$ and $S_{nm}^{3.1}$ estimating the efficiency of recycling of OCW in $n$-th storage using $m$-th stationary technology regarding logistic criterion. These estimations can be obtained for all OCW storages in analyzed system. Solutions of the Problem 3.2 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method
provide, respectively, the relative values \( E_{nm}^{3.2} \) and \( S_{nn}^{3.2} \), estimating the efficiency of recycling of OCW in \( n \)-th storage using \( m \)-th mobile recycling installation regarding logistic criterion. These estimations can be obtained for all mobile recycling technologies in analyzed system.

Then similar to (8) and (9) the overall estimations \( D_{nM}^{3.1} \), \( n = \overline{1,N} \), and \( D_{mN}^{3.2} \), \( m = \overline{1,M} \), can be obtained, respectively. The biggest value of overall estimation \( D_{nM}^{3.1} \) represents the OCW storage having the best efficiency of recycling regarding the cost of OCW’ transportation from this storage (DMU) to all stationary recycling plants in the analyzed system. The biggest value of overall estimation \( D_{mN}^{3.2} \) defines the mobile recycling technology having the best efficiency regarding cost of its transportation to all OCW storages in the analyzed system.

2.4. Estimation of the efficiency of OCW recycling system regarding ecological criterion

To estimate the efficiency of system for OCW recycling regarding ecological criterion the Problems 4.1 and 4.2 are formulated and solved.

As DMU’ inputs, that smaller amounts are preferable for the bigger relative efficiency of DMU regarding ecological criterion, the following parameters have been selected in the Problems 4.1 and 4.2: the overall emissions of greenhouse gases, sulphur dioxide and mineralex, mass of not processed part of mineral and mechanical impurities, and mass of polluted water formed in the recycling process. As DMU’ output, that bigger amount is preferable for the higher relative efficiency of DMU regarding logistic criterion, the mass of useful recycling products is considered.

Solutions of the Problem 4.1 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method give, respectively, the relative values \( E_{nm}^{4.1} \) and \( S_{nn}^{4.1} \) estimating the comparative efficiency of recycling of OCWs in \( n \)-th storage in analyzed system using \( m \)-th recycling technology regarding ecological criterion. These estimations can be obtained for all \( N \) storages of OCW in analyzed system.

Solutions of the Problem 4.2 in the form (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method provide, respectively, the relative values \( E_{mn}^{4.2} \) and \( S_{nn}^{3.2} \), estimating the efficiency of usage of \( m \)-th technology for recycling of OCW in \( n \)-th storage regarding the ecologic criteria. These estimations can be obtained for all \( M \) recycling technologies of analyzed system.

Then similar to (8) and (9) the overall estimations \( D_{nM}^{4.1} \), \( n = \overline{1,N} \) and \( D_{mN}^{4.2} \), \( m = \overline{1,M} \) can be obtained, respectively. The biggest value of estimation \( D_{nM}^{4.1} \), \( n = \overline{1,N} \), defines which OCW storage in the analyzed system has the highest environmental safety with respect to all \( M \) recycling technologies of analyzed system. The biggest value of estimation \( D_{mN}^{4.2} \), \( m = \overline{1,M} \) shows which technology has the highest environmental safety for OCW recycling in all \( N \) storages of analyzed system.

2.5. Estimation of the efficiency of OCW recycling system regarding logistic and ecological criteria

To estimate the efficiency of system for OCW recycling regarding either logistic or ecological criteria the Problems 5.1 and 5.2 are formulated and solved.

As DMU’ inputs the following parameters have been selected in the Problems 5.1 и 5.2: relative energy costs for transportation and duration of transportation (either OCW to the recycling plant or mobile installation to the OCW storage). As DMU’ outputs the following parameters have been selected in the Problems 5.1 и 5.2: the estimations \( S_{nm}^{2.1} \) and \( S_{nn}^{2.2} \) of reuse potential obtained as solutions of the Problems 2.1 and 2.2 in the form (6)-(7), respectively; the estimations \( S_{nm}^{4.1} \) and \( S_{mn}^{4.2} \) of the system efficiency regarding ecological criterion obtained as solutions of Problems 4.1 и 4.2 in the form (6)-(7), respectively.
Solutions of the Problem 5.1 in the forms (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method provide, respectively, the relative values $E^{5.1}_{n}$ and $S^{5.1}_{n}$ estimating the comparative efficiency of recycling of OCW in $n$-th storage in analyzed system using $m$-th recycling technology regarding logistic and ecological criteria. These estimations can be obtained for all $N$ storages of OCW in analyzed system.

Solutions of the Problem 5.2 in the forms (4)-(5) and (6)-(7) based on the CCR and Super-efficiency models of DEA method provide, respectively, the relative values $E^{5.2}_{mn}$ and $S^{5.2}_{mn}$ estimating the efficiency of usage of $m$-th technology for recycling of OCW in $n$-th storage regarding ecologic criteria. These estimations can be obtained for all $M$ recycling technologies of analyzed system.

The biggest value of estimations $D^{5.1}_{nM}$, $n = 1, N$, obtained using (8), defines the best storage from the point of view of the most effective OCW recycling using analyzed technologies regarding logistic and ecologcal criteria.

The biggest value of estimations $D^{5.2}_{mN}$, $m = 1, M$, obtained using (9), defines the best technology from the point of view of the most effective recycling OCW in analyzed storages regarding logistic and ecological criteria.

3. Results and discussions

The developed algorithm has been tested for the estimation of the OCW recycling system consisting of $N=9$ storages of OCW and $M=7$ recycling technologies located in Samara region of Russian Federation.

Figures 2 and 3 demonstrate cumulative generalized estimations of the OCW recycling system obtained as the results of solving Problems 2-5 that allow to select the best OCW storage and the best recycling technology with respect to reuse potential and considered logistic and ecological safety criteria.

![Figure 2. Comparison of cumulative generalized estimations $D_{nM}$ for the rating storages of OCW in the considered system.](image1.png)

![Figure 3. Comparison of cumulative generalized estimations $D_{mN}$ for the rating technologies of OCW recycling in the considered system.](image2.png)

Results shown in Figure 2 demonstrate that the OCW’ storages №№ 4-6 have the best estimations in the analyzed system; at the same time, the estimations of resource value for the storage №4 ($S^{4}_{1} = 0.888$) and the storage №6 ($S^{6}_{1} = 0.377$), obtained as a solutions of the Problem 1, are not maximum in the considered system. Analysis of the results (Figure 3) leads to the conclusion that OCW recycling technologies №5 and №7 have the best estimations in the system, but according to the solutions of the Problem 4.2, the technology №5 ($D^{4.2}_{59} = 5.08$) can be considered as more ecologically safe in comparison with the technology №7 ($D^{4.2}_{79} = 90$).
References

[1] Ashby M 2016 Chapter 14-the vision: a circular materials economy Materials and Sustainable Development (Boston: Butterworth-Heinemann) pp 211-39

[2] Ghisellini P, Cialani C and Ulgiati S 2016 A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems J. Clean. Prod. 114 11-32

[3] Haas W, Krausmann F, Wiedenhofer D and Heinz M 2015 How circular is the global Economy?: an assessment of material flows, waste production, and recycling in the european union and the world in 2005 J. Ind. Ecol. vol 19 Issue 15 pp 765-77

[4] Murray A, Skene K and Haynes K 2017 The circular economy: an interdisciplinary exploration of the concept and application in a global contextJ. Bus. Ethics. vol 140 Issue 3 pp 369–80

[5] Iacovidou E, Costas A, Purnell Ph, Zwirner O, Brown A, Hahladakis J, Millward-Hopkins J and Williams P 2017 Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review J. Clean. Prod. vol 166 pp 910-38

[6] Christensen T, Gentil E, Boldrin A, Larsen A, Weidema B and Hauschild M 2009 C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems Waste Manag. Res. vol 27 pp 707-15

[7] Allegrini E, Vadenbo C, Boldrin A and Astrup T 2015 Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash J. Environ. Manag. vol 151 pp 132-43

[8] Arvidsson R, Fransson K, Froeling M, Svanstrom M and Molander S 2012 Energy use indicators in energy and life cycle assessments of biofuels: review and recommendations J. Clean. Prod. vol 31 pp 54-61

[9] Puig R, Fullana-i-Palmer P, Baquero G, Riba Jordi-Roger and Bala A 2013 Cumulative Energy Demand indicator (CED), life cycle based, for industrial waste management decision making Waste Manag. vol 33 Issue 12 pp 2789-97

[10] Fang K, Heijungs R and De Snoo G 2015 Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework Ecol. Econ. vol 114 pp 218-26

[11] Begum R, Siwar C, Pereira J and Jaafar A 2006 A benefit-cost analysis on the economic feasibility of construction waste minimisation: the case of Malaysia Resour. Conserv. Recycl. vol 48 Issue 1 pp 86-98

[12] da Cruz N, Simoes P and Marques R 2014 Costs and benefits of packaging waste recycling systems Resour. Conserv. Recycl. vol 85 pp 1-4

[13] Wang Y, Geng S, Zhao P, Du H, He Y and Crittenden J 2016 Cost-benefit analysis of GHG emission reduction in waste to energy projects of China under clean development mechanism Resour. Conserv. Recycl. vol 109 pp 90-5

[14] Chong Y, Teo K and Tang L 2016 A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability Renew. Sustain. Energy Rev. vol 56 pp 797-809

[15] Cameron I, Hare B and Davies R 2008 Fatal and major construction accidents: a comparison between Scotland and the rest of Great Britain Saf. Sci. vol 46 Issue 4 pp 692-708

[16] Balkema A, Preisig H, Otterpohl R and Lambert F 2002 Indicators for the sustainability assessment of wastewater treatment systems Urban Water vol 4 Issue 2 pp 153-61

[17] Ardente F and Mathieux F 2014 Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product J. Clean. Prod. vol 83 pp 126-41

[18] Cerdan C, Gazulla C, Raugei M, Martinez E and Fullana-i-Palmer P 2009 Proposal for new quantitative eco-design indicators: a first case study J. Clean. Prod. vol 17 Issue 18 pp 1638-43

[19] Iacovidou E and Purnell P 2016 Mining the physical infrastructure: opportunities, barriers and interventions in promoting structural components reuse Sci. Total Environ. vol 557–558 pp 791-807
[20] Park J and Chertow M 2014 Establishing and testing the “reuse potential” indicator for managing wastes as resources J. Environ. Manag. vol 137 pp 45-53

[21] Pleshivtseva Yu, Derevyannov M, Kashirskikh D, Pimenov A., Kerov A. and Tyan V 2018 Comparative evaluation of the reuse value of storage for oil-contaminated waste based on DEA method Oil Industry vol 11 pp 139-44

[22] Charnes A, Cooper W and Rhodes E 1978 Measuring the efficiency of decision-making units European J. of Operation Research vol 6 pp 429-44

[23] Chen Y and Du J 2015 Super-Efficiency in Data Envelopment Analysis ed Zhu J Data Envelopment Analysis. International Series in Operations Research & Management Science vol 221 (Boston: Springer) p 472

[24] Michael J Todd 2002 The many facets of linear programming Mathematical Programming vol 91 pp. 417–36

[25] Cooper W, Seiford L and Tone K 2007 Data Envelopment Analysis A Comprehensive Text with Models, Applications, References and DEA-Solver Software (Boston: Springer) p 512

Acknowledgments
This research was partially supported by the Ministry of Education and Science of the Russian Federation (project part of government contracts, Project №10.3260.2017/4.6).