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RESOURCE-EFFICIENT METHODS OF MANAGING WASTE FROM THE DESTRUCTION OF TRANSPORT INFRASTRUCTURE UNDER SUSTAINABLE DEVELOPMENT CONDITIONS

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The article examines resource-efficient methods of handling waste generated by the destruction and dismantling of transport infrastructure facilities, including highways, bridges, overpasses, railway tracks and related structures. The relevance of the work is due to the significant volumes of destruction of the transport infrastructure in Ukraine and the need to combine the restoration of transport connections with the rational use of material resources and the reduction of the ecological burden. The purpose of the study is to substantiate a methodical approach to the preliminary comparative assessment of the resource efficiency of alternative scenarios for the management of waste from the destruction of transport infrastructure.

The work systematizes the main material flows, in particular concrete and reinforced concrete, asphalt concrete, metals, soils and railway ballast, as well as identifies factors limiting their reuse and processing. The regulatory principles of such waste management in Ukraine and the European Union are summarized. The methodological basis is the analysis of scientific publications and regulatory documents, the systematization of material flows and the comparative evaluation of scenarios under a single functional unit and agreed boundaries of the system. A system of resource, transport, environmental and economic indicators is proposed for evaluation: the share of waste recovery, the share of high-quality use, substitution of primary raw materials, transport distance and operation, net greenhouse gas emissions in CO_2 equivalent, the share of residues requiring removal and estimated costs.

The application of the approach is demonstrated on a parametric example of processing 1,000 tons of concrete scrap in two ways: by a mobile complex near the place of formation and at a stationary enterprise. Under accepted conditions, the mobile scenario is characterized by less transport operation (8000 vs. 45.000 t·km) and lower net estimated greenhouse gas emissions (−1740 vs. −1320 kg CO_2-eq). At the same time, the stationary scenario provides a higher yield of suitable secondary product (880 vs. 820 t), a higher volume of substitution of primary aggregate (792 vs. 738 t) and lower estimated costs (48.000 vs. UAH 65.500). Consequently, the results do not confirm the universal advantage of one method, but demonstrate the need for a comprehensive comparison of material, logistical, environmental and economic parameters.

The practical significance lies in the possibility of using the proposed approach by local self-government bodies, customers of restoration works and operators of processing facilities for preliminary justification of decisions. The calculations are of a scenario nature and are based on conditional initial data, therefore, for practical application, they must be clarified based on the results of material tests, equipment characteristics, actual transportation routes and budgetary indicators. *Key words:* waste destruction; transport infrastructure; resource efficiency; recycling; secondary aggregate; transport work; greenhouse gas emissions.

Ресурсоефективні методи поводження з відходами руйнації транспортної інфраструктури в умовах сталого розвитку. Сорочинська О.Л.

У статті досліджено ресурсоефективні методи поводження з відходами, що утворюються внаслідок руйнування та демонтажу об'єктів транспортної інфраструктури, зокрема автомобільних доріг, мостів, шляхопроводів, залізничних колій і супутніх споруд. Актуальність роботи зумовлена значними обсягами руйнувань транспортної інфраструктури в Україні та потребою поєднати відновлення транспортних сполучень із раціональним використанням матеріальних ресурсів і зменшенням екологічного навантаження. Метою дослідження є обґрунтування методичного підходу до попереднього порівняльного оцінювання ресурсоефективності альтернативних сценаріїв поводження з відходами руйнації транспортної інфраструктури.

У роботі систематизовано основні матеріальні потоки, зокрема бетон і залізобетон, асфальтобетон, метали, грунти та залізничний баласт, а також визначено чинники, що обмежують їх повторне використання та перероблення. Узагальнено нормативні засади управління такими відходами в Україні та Європейському Союзі. Методологічну основу становлять аналіз наукових публікацій і нормативних документів, систематизація матеріальних потоків та порівняльне оцінювання сценаріїв за єдиної функціональної одиниці й узгоджених меж системи. Для оцінювання запропоновано систему ресурсних, транспортних, екологічних та економічних показників: частку відновлення відходів, частку високоякісного використання, заміщення первинної сировини, транспортну відстань і роботу, чисті викиди парникових газів у CO_2-еквіваленті, частку залишків, що потребують видалення, та розрахункові витрати.

Застосування підходу продемонстровано на параметричному прикладі перероблення 1000 т бетонного лому двома способами: мобільним комплексом поблизу місця утворення та на стаціонарному підприємстві. За прийнятих умов мобільний сценарій характеризується меншою транспортною роботою (8000 проти 45 000 т·км) і нижчими чистими розрахунковими викидами парникових газів (−1740 проти −1320 кг CO_2-екв.). Водночас стаціонарний сценарій забезпечує більший вихід придатного вторинного продукту (880 проти 820 т), більший обсяг заміщення первинного заповнювача (792 проти 738 т) і нижчі розрахункові витрати (48 000 проти 65 500 грн). Отже, результати не підтверджують універсальної переваги одного способу, а демонструють необхідність комплексного зіставлення матеріальних, логістичних, екологічних та економічних параметрів.

Практичне значення полягає в можливості використання запропонованого підходу органами місцевого самоврядування, замовниками відновлювальних робіт і операторами переробних потужностей для попереднього обґрунтування рішень. Розрахунки мають сценарний характер і ґрунтуються на умовних вихідних даних, тому для практичного застосування їх необхідно уточнювати за результатами випробувань матеріалів, характеристиками обладнання, фактичними маршрутами перевезення та кошторисними показниками. *Ключові слова:* відходи руйнації; транспортна інфраструктура; ресурсоефективність; рециклінг; вторинний заповнювач; транспортна робота; викиди парникових газів.

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Statement of the problem. Armed aggression against Ukraine caused large-scale destruction of transport infrastructure. According to RDNA5, as of December 31, 2025, Ukraine's direct losses exceeded $195 billion. USA, and recovery needs for the next decade amount to about 588 billion dollars, of which more than 96 billion dollars. falls on the transport sector [1].

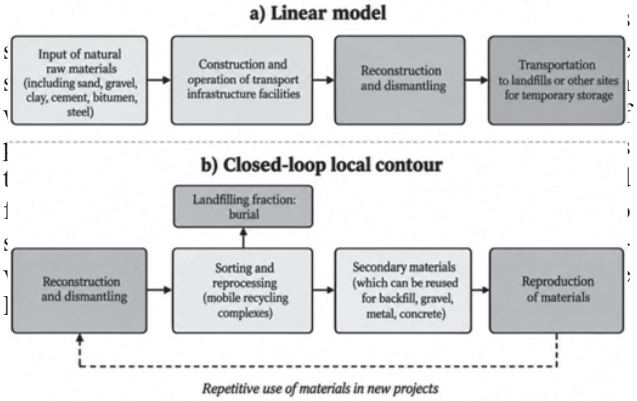

Fig. 1. Linear model and closed local contour of waste management of the destruction of transport infrastructure

Relevance of the study. It is important that resource efficiency is not identical to the very fact of recycling. Processing waste into low-quality material (for example, using high-quality concrete scrap only for backfilling), transporting heavy material over long distances or energy-intensive technological operations can neutralize the ecological and economic effect. Therefore, the methods of handling destruction waste should be evaluated according to quantitative indicators: the share of substitution of primary raw materials, preservation of the functional value of the material, energy intensity, transport component and greenhouse gas emissions.

The connection of the work with important scientific and practical tasks. The study meets the objectives of the UN Sustainable Development Goals № 9 (sustainable infrastructure), № 11 (sustainable cities and communities) and № 12 (responsible consumption and production) [2], as well as the requirements of the Law of Ukraine «On Waste Management» [3], the Procedure for Waste Management from Destruction [4] and strategic documents in the field of waste management [5, 6]. The results of the work can be used by local self-government bodies, customers of road, bridge and railway restoration works and operators of processing facilities.

Analysis of recent research and publications. Research on the management of destruction waste covers the issues of selective dismantling, reuse of materials, assessment of environmental and economic impacts and selection of optimal scenarios. Villoria Sáez and Osmani found differences between EU countries in terms of recycling rates and limited data for comparison [7]. Zhang and co-authors noted the predominance of low-quality mineral waste use over high-quality recycling [8]. The European guidelines specify requirements for pre-dismantling and selective disassembly waste audits [9] and Atstāja and co-authors propose the use of mobile recycling complexes near reconstruction facilities in Ukraine [10].

The possibilities of reusing transport infrastructure materials are addressed in the works of Silva [11], Tam [12], Kisku [13] and Xiao [14]. Researchers note that secondary crushed stone made of concrete scrap has a lower density and higher water absorption than natural, but is suitable for road bases and low-grade concrete. Its application in road construction is also confirmed by the works of Poon and Chan [15], Arulrajah and co-authors [16]. FHWA summarized the practice of using asphalt concrete granulate (RAP) [17], and Zaumanis and co-authors investigated the production of mixtures with its content up to 100 % [18, 19]. The reuse of steel structures is hampered by a lack of information on the properties of the elements, certification and regulatory certainty [20]. Materials recovery approaches in the context of the circular economy are systematized by Ginga and co-authors [21].

Environmental-economic assessment of recycling is based, in particular, on the methodology of life cycle assessment (LCA). Blengini established the dependence of its results on the type of material to be replaced and the distance of carriage [22] and Aurangzeb with co-authors showed that increasing the proportion of RAPs can reduce the environmental impact of asphalt mixtures [23]. Zhang and co-authors developed an approach to evaluating the eco-efficiency of concrete recycling [24]. Dias with co-authors found that secondary aggregates may have a lower environmental impact, but a higher cost compared to natural ones, in particular due to transport costs [25].

To select waste management scenarios, Yi and co-authors combined LCA and life cycle cost estimation with AHP and TOPSIS methods. The best results were obtained by recycling for concrete production and road construction, the worst – landfills [26].

Highlighting previously unresolved parts of the general problem, to which this article is devoted. Despite the availability of research on the processing of construction and demolition waste, assessment of the life cycle of secondary materials and reduction of transport costs, resource, technological, transport and environmental criteria must be agreed upon when choosing a method of managing waste from the destruction of transport infrastructure. For such facilities, material composition heterogeneity, possible pollution and restricted access to waste generation sites are also important. Separate indicators – share of recovery, substitution of primary raw materials, distance of transportation, greenhouse gas emissions – were used in the above works [7, 22–26], but much less attention was paid to waste destruction of the transport infrastructure, in particular in conditions of war destruction, in the considered publications. This justifies the feasibility of comparative evaluation of alter-

native scenarios under uniform starting conditions. This particular gap is partially filled by this article.

The novelty. The scientific novelty consists in clarifying the methodical approach to the comparative assessment of scenarios for the management of waste from the destruction of transport infrastructure by taking into account resource, transport, environmental and economic indicators within a single functional unit. A feature of the approach is the consistent linking of the yield of a suitable secondary product to its functional equivalence to the primary material, the estimated volume of substitution of primary raw materials, transport work, net greenhouse gas emissions and costs. This makes it possible to compare mobile and stationary processing taking into account not only technological characteristics, but also logistical conditions and economic consequences. The proposed approach is intended to justify decisions in advance; it does not imply a predetermined advantage of a particular mode of recycling, since the outcome depends on the parameters of the particular object and the accepted limits of the system.

Research methodology. The purpose of the article – is to substantiate the methodical approach to the preliminary assessment of the resource efficiency of scenarios for the management of waste from the destruction of transport infrastructure based on a comparison of resource, transport, environmental and economic indicators and to demonstrate its application on the parametric example of mobile and stationary processing of concrete scrap.

To achieve the goal, the systematization of material flows and restrictions on the reuse of waste, the determination of comparison indicators, the establishment of a single functional unit and system boundaries, the development of a scenario selection sequence and the determination of the limitations of the approach are provided.

The methodology is based on the analysis of scientific publications, legal acts and official reports, a systematic approach and comparative analysis in accordance with the waste management hierarchy. The assessment covers four groups of indicators: resource – yield of suitable secondary product, substitution of primary raw materials and volume of residues; transport – distance of transportation and transport work; environmental – net greenhouse gas emissions in CO_2 equivalent; economic – costs for processing, transportation, removal of residues and replacement of primary aggregate. Indicators are defined under a single functional unit and consistent system boundaries, which makes it possible to compare scenarios without determining the universally best option. The output parameters of materials, technologies and costs are specified based on the results of tests, equipment characteristics, transportation routes and estimates of a specific object.

Presentation of the main material.

Composition and features of waste destruction of transport infrastructure. Composition and features of waste destruction of transport infrastructure. The composition of destruction waste is determined by the type of transport facility, its design, age and nature of damage. The main material flows and specific associated risks are given in the table. 1.

In terms of mass, waste from the destruction of transport infrastructure is dominated by mineral materials: concrete, asphalt concrete, crushed stone and soil. Metals make up a smaller share, but are characterized by high cost and suitability for reuse and recycling.

War destruction complicates waste management due to the mixing of materials, possible contamination with oil products and combustion products, the presence of dangerous components, in particular asbestos-containing materials, as well as explosive objects. Additional factors are the heterogeneity of debris sizes and the territorial dispersion of waste generation sites, which increases sorting and transportation costs.

Consequently, resource-efficient management of such waste involves preliminary surveying of the area and its demining by authorized services, safe extraction of hazardous components and selective sorting of materials before recycling.

Regulatory and legal regulation of destruction waste management. The normative basis of destruction

Table 1

Main material flows and associated risks of waste from the destruction of transport infrastructure facilities

Object	Main material flows	Specific associated risks
Motor roads	Asphalt concrete; cement concrete; crushed stone and sand of bases and sub-bases; earthwork soil; curbs, elements of fences	Petroleum products after damage; possible resin-containing binders in ancient layers; soil contamination
Bridges, overpasses, overpasses	Reinforced concrete and concrete; structural steel and reinforcement; support elements, deformation joints, support parts	Paint coatings with heavy metals in old steel structures; mixing with soil and water
Railway route	Crushed stone ballast; reinforced concrete and wooden sleepers; rails; fasteners; catenary elements	Antiseptic-impregnated wooden sleepers (hazardous waste); ballast contamination with lubricants
Tunnels, stations, station and warehouse facilities	Reinforced concrete, brick, steel, glass, roofing materials	Asbestos-containing materials in old buildings; fire pollution
Airfield surfaces, port berths	Cement concrete slabs, asphalt concrete, reinforced concrete structures	Pollution by fuel and lubricants

Source: Summarized by the author on [7, 11, 17] and material classification of transport infrastructure facilities.

waste management in Ukraine is the Law of Ukraine «On Waste Management» [3], which establishes the hierarchy of waste management and prioritizes the prevention of its formation, preparation for reuse, recycling and other recovery operations compared to disposal. Special features of the management of waste generated by damage or destruction of facilities are regulated by the relevant procedure approved by the Cabinet of Ministers Resolution № 1073 [4]. The strategic directions of public policy are determined by the National Waste Management Strategy until 2030 and the National Waste Management Plan until 2033 [5; 6].

The European regulatory framework is Directive 2008/98/EC on waste, as amended by Directive (EU) 2018/851 [29; 30]. It establishes a hierarchy of waste management and orients states to increase the level of preparation for reuse, recycling and other material recovery of construction and demolition waste. Practical recommendations for sorting, quality control and improving the reusability of materials are contained in the European Commission's protocol on construction and demolition waste [31] and pre-disassembly audit recommendations [9].

The technical basis for evaluating the reusability of recycled materials is the requirements of the relevant standards for concrete aggregates, road construction materials and asphalt concrete mixtures [33–35]. In practical application, the validity of the relevant national harmonized standards and the requirements for the specific field of use of secondary raw materials must be taken into account.

Resource-efficient methods of handling destruction waste. Resource-efficient management of waste from the destruction of transport infrastructure involves the maximum preservation of the material value of the components, provided that the requirements of environmental safety and the quality of secondary raw materials are met. The choice of technology depends on the type and technical condition of the material, the level of its contamination, the possibility of selective dismantling, the distance to the place of processing and the requirements for the final product.

To systematize possible solutions, the work used a five-level analytical classification of methods of handling destruction waste (Fig. 2). It makes it possible to consistently assess the possibilities of preservation of materials, their reuse and processing, as well as to determine the expediency of other ways of handling unsuitable or dangerous components.

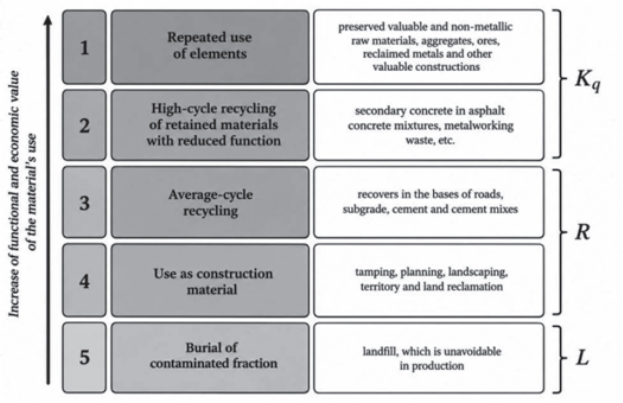

Fig. 2. A five-level analytical classification of the quality of use of waste destruction and related levels for resource efficiency indicators

Source: compiled by the author.

Practical application of these approaches involves preliminary site inspection, separate extraction of materials, sorting and verification of their suitability for further use. In the presence of dangerous components, they are removed and transferred to appropriate handling separately from the main mineral flows.

The main areas of resource-efficient management of destruction waste are the reuse of suitable elements, the processing of mineral materials, the return of metals to the production cycle, and the use of suitable soils and ballast after checking their properties. Concrete and reinforced concrete, after removal of foreign inclusions, are crushed and separated by fractions to obtain a secondary aggregate. Asphalt concrete can be used as a regenerated asphalt concrete material using the appropriate technol-

Table 2

Comparison of methods of processing waste destruction of transport infrastructure

Method	Input stream	Secondary products	Main limitations
Reuse of elements	Preserved prefabricated products, fences, rails	Elements in the output function	Surveys, documentation, compliance with regulations are required
Crushing of concrete and screening	Concrete, reinforced concrete	Secondary crushed stone, mixtures for bases	Higher water absorption; particle limitation in structural concrete
RAP recycling (hot, cold)	Asphalt concrete	Granulate, asphalt concrete mixtures	Homogeneity, aging of the binder, tar is possible
Melting of scrap metal	Fittings, rolled products, rails	New steel	Pollution by coatings, the need for sorting
Restoration of ballast and soils	Ballast, earthwork soil	Ballast, bulk materials	Pollution, humidity, fraction of fines
Burial	Residual fraction	-	The lowest priority in the hierarchy; loss of resource

Source: Compiled by author at [3, 7, 11–20, 23, 24].

ogy. Metal components are sorted by species and transferred for reuse or recycling.

Soils, crushed stone and railway ballast can return to use after assessing their composition, contamination and compliance with technical requirements. Materials containing hazardous substances or not meeting the established requirements should not be directed to recyclable streams without proper processing. The choice of a specific technology is determined not only by the potential yield of secondary material, but also by energy consumption, the need for transportation, the quality of the final product and the impact on the environment.

Resource efficiency indicators and method selection algorithm. For the comparison of methods of handling destruction waste, a system of resource, transport and environmental indicators is proposed, formed taking into account the principles of life cycle assessment ISO 14040 and ISO 14044 [37; 38]. The system includes the share of recovery (*R*), the share of high-quality use (K_q), substitution of primary raw materials (*S*), transport distance (T_d), net global warming potential (GWP_{net}) and the share of residue requiring removal (*L*). Indicators are determined for the same functional unit, system boundaries and accounting period.

1. Share of recovery R – ratio of the mass of waste actually directed to the specified recovery operations to the total mass of waste of the estimated flow for the set accounting period. Recovery operations include preparation for reuse, recycling and other material recovery (in particular, backfilling if the waste replaces other materials); burial before recovery is not included:

$$R = \frac{M_{\text{rec}}}{M_{\text{gen}}} \tag{1}$$

where M_{rec} – mass of waste actually directed to specified recovery operations (reuse, recycling, other recovery);
M_{gen} – total mass of waste within the estimated flow.

2. The share of high-quality use K_q – ratio of the mass of waste directed at the level of 1–2 of the five-level classification (reuse of elements and recycling with preservation of the function of the material), the quality of which is confirmed according to the established criteria, to the total mass of wastев:

$$K_q = \frac{M_q}{M_{\text{gen}}} \tag{2}$$

where M_q – mass of waste that has been reused or recycled while preserving the function of the material and meets quality criteria;
M_{gen} – the same as in formula (1). The quality of the secondary material is confirmed by tests and compliance with the technical requirements for the products for the declared purpose. The indicator makes it possible to take into account downcycling, which is not reflected in the total share of recovery [8].

3. Substitution of primary raw materials *S*. To assess the resource effect, not only the mass of the obtained secondary material is taken into account, but also the volume of primary raw materials, which it actually replaces, taking into account the purpose and properties:

$$S = \frac{M_{\text{virgin,avoided}}}{M_{\text{virgin,baseline}}} \tag{3}$$

where $M_{\text{virgin,avoided}}$ – mass of primary raw material substituted in the selected scenario;
$M_{\text{virgin,baseline}}$ – the mass of primary raw materials required in the base scenario for an equivalent result. The indicator is used only on the condition that the basic scenario and functional equivalence are determined. If additional materials are required to achieve the same function (for example, more cement when using secondary aggregate), their mass is taken into account when determining $M_{\text{virgin,avoided}}$ with a minus sign.

4. Transport component T_d – weighted average by weight of the material transport distance within the estimated flow:

$$T_d = \frac{\sum_i m_i d_i}{M_{\text{gen}}} \tag{4}$$

where m_i – mass of a batch of material i;
d_i – the distance of its transportation;
M_{gen} – total mass of the estimated flow.

Unit of measurement T_d – km. A value is used to evaluate transport work $W = \sum m_i d_i$, which is measured in ton·km; to estimate emissions from transportation, the type of vehicle, loading, mileage without cargo and the emission factor are additionally taken into account.

5. Net global warming potential GWP_{net} – the difference in greenhouse gas emissions within the selected scenario (dismantling, sorting, processing, transportation) and emissions avoided by substitution of primary production:

$$GWP_{net} = M_0\left(e_{poc} + e_{tr}T_d - k_{eq}\eta e_{prim}\right) \tag{5}$$

where M_0 – mass of original concrete scrap, tones;
e_{proc} – specific emissions from recycling, kg CO_2-eq./ton of input raw materials;
e_{tr} – specific emissions of transportation, kg CO_2-eq./(ton·km);
T_d – weighted average transport distance, km;
k_{eq} – coefficient of functional equivalence;
η – yield fraction of suitable secondary product;
e_{prim} – specific emissions of primary aggregate production, kg CO_2-eq./ton.

Correct calculation is possible only under specified functional unit, system limits and emission factors [37, 38]; the unit of measurement is fixed, for example, in kg CO_2-eq. per 1 ton of waste treated or per other clearly defined functional unit. The Blengini results show that the environmental benefit of recycling depends on the nature of the material to be replaced and on the transport distances [22], so the T_d and GWP_{net} indicators should be considered together.

6. Proportion of residue requiring final removal *L*. The denominator shall be the total mass of waste of the stream under assessment and the residue shall include

only those streams which, after the operations envisaged, are not intended to be reused or recovered:

$$L = \frac{M_{\text{res}}}{M_{\text{gen}}} \cdot 100\% \quad (6)$$

where M_{res} – the mass of residue requiring final removal.

M_{res} includes only materials that, after the intended handling operations, require final removal; temporary storage does not in itself mean burial.

For the reproducibility of calculations, data on the mass and directions of waste management, the quality of the secondary product, transport distances and characteristics of transportation, emission factors, costs and conditions for replacing primary raw materials are required. Sources of coefficients and scenario assumptions are noted separately.

Comparison of indicators and scenario selection. Scenarios are compared for the same functional unit and system boundaries. The integral index is not applied in this work: indicators are evaluated separately because they have different units of measurement. Ceteris paribus, scenarios with higher values (R), (K_q) and (S) and lower values (T_d), (GWP_{net}) and (L) are preferred. Only options that meet safety requirements and technical requirements for secondary products are allowed for comparison. If the results according to the criteria are contradictory, the compromises are justified separately, without determining the advantage according to only one indicator.

Based on these indicators, the following method selection algorithm is proposed for each waste stream (Fig. 3):

1. Carry out demining, surveying and initial assessment of the flow; remove hazardous components.
2. Separate the flow according to materials and degree of pollution (concrete, asphalt concrete, metal, soil, mixed flow).
3. Determine elements suitable for reuse based on the results of the examination.
4. For the remaining flows, determine the highest technically achievable level of quality by hierarchy (from 2 to 4) according to product requirements.
5. Estimate the distances to the nearest consumer of secondary products or the location of mobile processing; compare T_d і GWP_{net} for alternative options.
6. Confirm the quality of the secondary material by tests (mechanical and chemical indicators, leaching) [36].
7. Record the values of indicators R, K_q, S, T_d, GWP_{net}, L for reporting and compare scenarios according to the selection rule.

The choice of method is determined not only by technological possibility, but also by resource, environmental and economic consequences, since the advantages of processing can be offset by excessive energy consumption or transportation.

An estimated example of a comparison of concrete scrap handling scenarios. To test the methodology, two scenarios for handling a concrete scrap were compared: recycling by a mobile complex near the place of waste generation (Scenario A) and transportation to a stationary enterprise (Scenario B). The same mass of starting material is adopted for both scenarios; transport work, yield of suitable secondary product, substitution of primary aggregate, residue formation, environmental consequences and costs are taken into account.

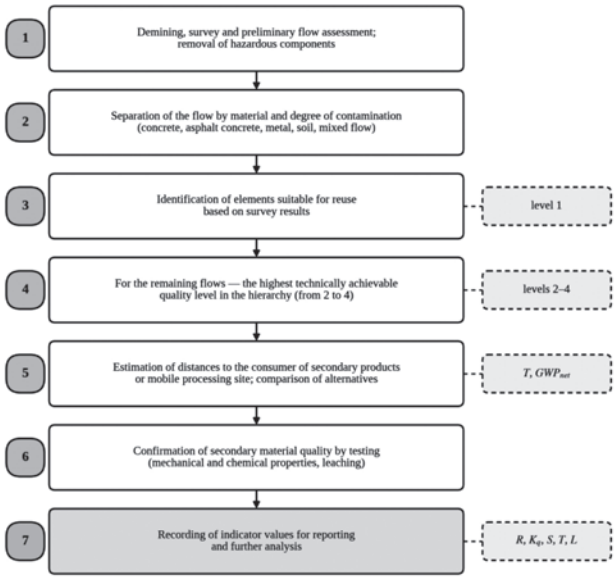

Fig. 3. Algorithm for choosing a resource-efficient method for handling the flow of destruction waste

Source: compiled by the author.

In Scenario A, the concrete scrap is sorted, tested for suitability and recycled by a mobile complex near the site of formation. In Scenario B, the material is transported to a stationary facility for sorting and processing. In both cases, the secondary product is used subject to compliance with technical requirements.

Imprint and assumptions for scenario comparison. The functional unit is the processing of 1.000 tons of concrete scrap of the same composition with the production of secondary crushed stone for the layers of the base of road clothing. The same coefficient of functional equivalence of secondary and primary aggregates is adopted for both scenarios. The values of transport distances, the yield of a suitable product, specific emissions and costs are notional calculation assumptions intended to demonstrate the technique and not to be directly transferred to real objects.

For the comparison of the economic component of the scenarios, the net estimated costs are determined, taking into account the costs of processing the raw material, transportation, removal of the balance and avoided costs for the purchase of primary aggregate, which is replaced by a secondary product:

$$C = M_0 c_{proc} + c_{tr} W + c_{disp} M_{res} - c_{prim} k_{eq} M_q \quad (8)$$

where W – transport work, ton·km;

c_{proc} – specific costs for processing, UAH/ton of input material;

c_{tr} – transportation costs, UAH /(ton·km);
c_{disp} – costs for removal of the balance, UAH/ton;
c_{prim} – the cost of the primary aggregate, UAH/ton.

The boundaries of the system cover the loading of concrete scrap, its transportation and processing, the use of the secondary product, as well as taking into account the production and delivery of the primary aggregate that it replaces. The calculation scheme for comparing scenarios is given in the table. 3.

The numerical values of the circuit parameters are substituted based on the data of a specific object or on scenario assumptions substantiated by sources; in the absence of real data, all assumptions are noted separately and used the same for both scenarios. A comparison based on the results of the calculation should show by what indicators one scenario is better, by what indicators it is worse, and what conditions can change the result, and not repeat the numbers of the table. Yes, provided $T_{d,A} < T_{d,B}$ Scenario A has less transport operation, but this does not guarantee a lower GWP_{net} : according to the scheme (Table. 3) $GWP_{net,A} < GWP_{net,B}$, if the condition is met:

$$e_{proc,A} - e_{proc,B} < e_{tr}\left(T_{d,B} - T_{d,A}\right) + k_{eq} e_{prim}\left(\eta_A - \eta_B\right).$$

Consequently, higher specific emissions of mobile equipment or lower yields of a suitable product may offset the benefit of distance reduction. Similarly, in terms of *S* and *L* indicators, a scenario with a higher yield of a suitable product has an advantage, and in terms of costs, a scenario in which savings on transportation are not covered by a higher cost of processing. If economic and environmental criteria give conflicting results, the values are given separately according to the criteria, and the choice is justified according to the rule given above.

The calculation parameters are conditional and are intended to demonstrate the methodology. For practical application, they are specified according to the characteristics of the equipment, the results of material tests, actual transportation routes and estimated data.

Scenario comparison results. Under the accepted conditions, Scenario A is characterized by lower transport operation – 8.000 ton·km versus 45.000 ton·km in Scenario B, which provides lower net emissions: −1740 versus −1320 kg CO_2-eq. At the same time, Scenario B provides a higher yield of suitable secondary product (880 vs. 820 tons) and, accordingly, more substitution of primary aggregate (792 vs. 738 tons). Its estimated costs are also lower – UAH 48.000 against UAH 65.500 in Scenario A.

Therefore, under the given parameters, Scenario A has an advantage in terms of net emissions, and Scenario B – in terms of secondary product yield and economic indicators. This confirms the need for a comprehensive comparison of resource, environmental and economic criteria. The results obtained are demonstrative: the final choice of method for a specific facility requires refinement of the original data, equipment characteristics, transport routes and costs.

Sensitivity of results to output parameters. The results of the comparison of the scenarios depend on the distance of carriage, the yield of the suitable secondary product, the specific emissions and processing costs, and the functional equivalence factor. Increasing the transport distance, other things being equal, increases transport work, emissions and costs, while reducing the

Table 3

Calculation scheme for comparing scenarios A and B

Indicator	Method of determination	Scenario A	Scenario B
Mass of the original concrete scrap M_0, tons	The same for both scenarios (functional unit)	M_0	M_0
Transport distance T_d, km	$T_d = \sum m_i d_i / M_0$; is m_i – batch mass of original concrete scrap, tons; d_i – the distance of its transportation from the place of formation to the place of processing, km; M_0 – total mass of the original scrap, tons. The delivery of the secondary product to the consumer and the carriage of the residues to the place of removal are not taken into account in this indicator.	T_{dA}	T_{dB}
Yield of suitable secondary product M_q, tons	$M_q = \eta M_0$; output factor η – based on the results of tests or a reasonable assumption	$\eta_A M_0$	$\eta_B M_0$
Substitution of primary material S, %	$S = k_{eq}\eta M_0 / M_0 \cdot 100$ %; k_{eq} – coefficient of functional equivalence	$k_{eq}\eta_A \cdot 100$ %	$k_{eq}\eta_B \cdot 100$ %
Transport work W, ton·km	$W = \sum m_i d_i = M_0 T_d$	$M_0 T_{d,A}$	$M_0 T_{d,B}$
Emissions GWP_{net}, kg CO_2-eq.	$GWP_{net} = M_0(e_{proc} + e_{tr}T_d - k_{eq}\eta e_{prim})$; e_{proc}, e_{tr}, e_{prim} – specific emissions of processing (kg CO_2-eq./ton), haulage (kg CO_2-eq./(ton·km)) and production of primary aggregate (kg CO_2-eq./ton)	$M_0(e_{proc,A} + e_{tr}T_{d,A} - k_{eq}\eta_A e_{prim}$	$M_0(e_{proc,B} + e_{tr}T_{d,B} - k_{eq}\eta_B e_{prim}$
Remainder requiring removal M_{res}, tons	$M_{res} = M_0 - M_{rec}$; $L = M_{res} / M_0 \cdot 100$ %	$M_0 - M_{rec,A}$	$M_0 - M_{rec,B}$
Expenses *C*, hryvnias	$C = M_0 c_{proc} + c_{tr}W + c_{disp}M_{res} - c_{prim}k_{eq}M_q$; specific costs – by estimate or scenario assumption	C_A	C_B

Source: compiled by the author.

Table 4

Output data and results of parametric comparison of scenarios A and B

Indicator	Scenario A mobile recycling	Scenario B stationary processing
Mass of original concrete scrap, tons	1000	1000
Weighted average transport distance, km	8	45
Yield of suitable secondary product, %	82	88
Mass of secondary product, tons	820	880
Functional equivalence coefficient	0.90	0.90
Equivalent substitution primary aggregate, tons	738	792
Transport work, ton·km	8.000	45.000
Specific emissions of processing, kg CO_2-eq./ton of input raw materials	5	3
Specific emissions of transportation, kg CO_2-eq./(ton·km)	0.08	0.08
Specific emissions of primary aggregate production, kg CO_2-eq./ton	10	10
Net emissions, kg CO_2-eq. per functional unit	−1740	−1320
Remainder requiring removal, tonnes *	180	120
Net estimated costs taking into account the replacement of the primary aggregate, UAN *	65.500	48.000

Note: * in the calculation example, it is conventionally accepted that a material that has not become a suitable secondary product needs to be removed. Costs are determined according to scenario assumptions: processing – 180 UAH/ton for Scenario A and 120 UAH/ton for Scenario B; transportation – 2 UAH/(ton·km); removal of the balance – 300 UAH/ton; primary aggregate – 250 UAH/ton. For practical application, the actual distribution of balances and real costs must be taken into account.

yield of a suitable product reduces the volume of substitution of the primary aggregate. Therefore, the practical application of the methodology requires verification of the results for different sets of confirmed initial data. Determining the limit values at which the advantage of scenarios changes requires a separate quantitative sensitivity analysis.

Conditions and barriers of implementation in Ukraine. The main obstacles to resource-efficient management of waste from the destruction of transport infrastructure are not so much the lack of processing technologies, but regulatory, economic and organizational restrictions.

Normative and technical conditions. Order № 1073 regulates the management of waste from destruction and the use of its components [4; 27]. For the use of secondary materials in road construction, confirmation of their quality, compliance with technical requirements and defined conditions of use are important. European experience involves the application of standards for building materials and criteria for terminating waste status [29; 33–35].

Economic conditions. The competitiveness of secondary materials depends on the cost of processing, transportation, product quality and the price of primary raw materials. Mobile complexes located near places where significant volumes of waste are generated can reduce logistics costs. Environmental criteria for public procurement can be an additional tool for stimulating demand [32].

Infrastructure and organization. Uneven territorial placement of waste leads to the need for selective dismantling, preliminary sorting and planning of processing capacities. It is appropriate to reflect in local waste management plans the main material flows, their places of generation and available recycling facilities [3; 28].

Data and monitoring. For the comparability of the results, a single method of accounting for the formation, processing, replacement of primary raw materials, transport emissions and residues that need to be removed is required. The use of the indicator system proposed in this work will make it possible to assess not only the total amount of recovery, but also the quality of the secondary product and the environmental consequences of the scenarios [7].

Main conclusions. The results of the study make it possible to formulate the following conclusions.

1. Waste from the destruction of transport infrastructure contains significant volumes of concrete, asphalt concrete, soil, crushed stone and metal, some of which may be involved in reuse or recycling. The main prerequisites for this are preliminary inspection of the facilities, separate extraction of dangerous components, selective dismantling and sorting of materials.

2. The proposed methodical approach provides a comparison of waste management scenarios by resource, transport, environmental and economic indicators. The use of a single functional unit and harmonized system boundaries makes it possible to estimate the yield of a suitable secondary product, substitution of primary raw materials, transport work, net greenhouse gas emissions and estimated costs.

3. The parametric example demonstrated that under accepted conditions mobile recycling has an advantage in transport operation and net estimated emissions, while stationary – in secondary product output and estimated costs. These results do not universally determine the best scenario, but confirm the need for a comprehensive assessment taking into account the characteristics of the material, logistics and cost of operations.

Research limitations. The methodical approach is demonstrated on a parametric example with conditional

Table 5

Major barriers and possible measures

Barrier	Possible event
Mixity and pollution of waste	Site survey, selective dismantling, primary sorting
Insufficient certainty of requirements for secondary products	Clarification of technical requirements and testing of materials according to their purpose
High processing cost compared to primary raw materials	Optimization of transport routes, mobile processing, environmental procurement criteria
Lack of comparable data on waste management results	The only method of accounting and use of resource efficiency indicators
Presence of dangerous components	Identification, separate removal and handling as required by law

Source: Compiled by author at [4, 7, 27–29, 32].

initial data that are not the results of field measurements. The calculation does not take into account the delivery of the secondary product to the final consumer, the transportation of the residues to the place of removal and the logistics of supplying the primary aggregate. No full quantitative sensitivity analysis was performed either. The numerical results are therefore illustrative in nature and require verification on the actual data of specific objects, specifying system boundaries, secondary product characteristics and transport and economic parameters.

Practical significance and prospects of research. The proposed approach could be used by local governments in planning for waste management from destruction [3; 28], by contracting authorities – to justify the requirements for secondary materials in road works procurement [32], and by operators – to compare pre-processing and siting options for mobile complexes. Further research should be directed to the approbation of the methodology on real objects, confirmation of the quality of secondary products, clarification of logistics and economic data and quantitative analysis of the sensitivity of the results.

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