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Construction waste recycling in the circular economy model

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Abstract. The disposal of construction waste, the amount of which is constantly growing due to hostilities in Ukraine and outdated housing stock that has lost its consumer properties is an acute problem. The study proposes adopting the circular economy and the principles of improving the security and environmental situation in Ukraine to restore the country's potential. The article analyzes the main stages and processes of construction waste disposal, taking into account their fractional recycling and reuse in the reconstruction of settlements, which is based on the rational use of resources and innovations and will reduce the cost of restoring destroyed settlement areas. Efficient construction is possible only if environmental and economic indicators are improved, the level of safety and manufacturability are improved. A methodology for assessing the effectiveness of future construction has been developed and recommendations for its improvement have been given.

1. Introduction

During the military conflict and after it ends, numerous damaged buildings remain in the territory of Ukraine, negatively affecting the environmental condition of the area, resulting in irrational nature management and requiring an urgent solution. The majority of these buildings are dangerous and can cause collapses, injuries to citizens, fires, and other undesirable events that can be neutralized by disposing of destroyed buildings, restoring the ecological environment, and building new, eco-friendly, energy-efficient houses and facilities.

Taking into account the experience of leading countries in waste sorting and recycling, one should initially consider each building from the perspective of its maximum utility function, i.e. to create a classification of buildings and building materials according to the possibility of their repeated use or recycling. One of the goals of this research is to find the best possible solution for the most efficient use of available technology and capacity of the region to restore rapidly the destroyed territories given innovative technologies, digitalization of the economy and information systems.

The purpose of this study is to develop a construction waste recycling model that will be implemented in Ukraine in the post-war period, resolve administrative and environmental problems in these territories, create the classification of recycling facilities and their structural components in the context of restoration of Ukrainian populated areas, European integration and principles of circular economy.

However, to solve the above-mentioned tasks and reconstruct Ukrainian territories after the war, we primarily need an efficient organizational and economic system based on the principles of transparency, inclusiveness, openness, environmental friendliness, maximum contribution of each program executor, absence of shady schemes and democracy in order to build a common, successful future in Ukraine and increase the economic potential of the country.

Besides, sorting and fractional recycling of construction waste can substantially decrease expenses for new premises, resulting in resource saving and reducing the financial burden on the Ukrainian economy, which is experiencing tough times because of military operations, the loss of territories, resources, less budget revenues and high defense expenditures. For recycling of construction waste, the authors offer to construct contemporary mobile waste recycling complexes near the destroyed populated areas with preliminary waste sorting and deep cleaning. Although the cost of recycling will be increased due to transportation expenses for delivery to the recycling facility, the environmental effect and impact on the quality of public life will be more positive and, in money equivalent, will be more appropriate than waste burial or recycling at the site of destruction.

2. Related works

One of the problems arising during sorting of the remains of buildings after destruction as a result of military operations in Ukraine is the presence of elements destroyed by fire, hazardous chemicals and biological waste in case of deaths in the building. However, in such crisis situations as war, there are likely to be risks of facing environmental degradation and exacerbation of problems associated with the accumulation of unprocessed waste [1]. There are some particularities of the recycling of construction materials primarily caused by the nature of materials and their physical and chemical properties, which contributes to the development of new recycling methods for each fraction of waste and improvement of the efficiency of existing recycling systems [2]. The key direction is the sorting of construction waste for rational processing and better recycling, as well as the increase in alternative waste management options [3].

It is noted that the shredding and processing of concrete structures into a powdered state can be further used as a natural aggregate for new building structures or elements in other industries, which will not only contribute to resource saving but also to energy efficiency due to the high thermal insulating properties of the material [4]. One of the factors contributing to the secondary use of construction residues is a relatively long period of waste decomposition, the environmental impact on public health, the availability of limited land areas in Ukraine for landfills and alternative ways of using land resources. Ecological problems should take precedence over commercial ones, and the impact of waste on the ecosystem is substantial and spreads between countries, while recycling contributes to the emergence of new disposal methods and the development of science [5].

The experience of previous generations makes us reconsider waste flows and their economic viability due to the creation of new trends and technologies based on the principles of circular economy and able to resolve problems caused by excessive consumption of products, wars and poor economic state, which results in a new market based on the secondary use of products [6].

The analysis of information sources shows the relevance of the problem and the interest of numerous scientists in this issue. However, the world still has no single concept of construction waste management, which makes this research appropriate and relevant, while the military conflict in Ukraine poses new challenges to society and science and requires the urgent solution, making this work unique and having the practical application in the future in Ukraine and abroad.

3. Results

Reconsideration of the role of waste in developed countries began in the early 20th century when one started adopting the first analogues of production focused on the secondary use of goods and resources, improvement of ecology, which gave an impetus to the development of the so-called circular economy based on the concept of maximum waste recycling, resource saving and energy efficiency.

The complexity of extracting resources, their limited availability, the high cost of technological primary products and the creation of dangerous landfills resulted in the change in traditional forms of waste management and turned this area into a business that could not only improve the environmental condition but also generate profits and increase the public utility of produced goods.

The strategic importance of resources for Ukraine facing the war is substantial due to resource saving, funds for the reconstruction of the country, the establishment of the European standards and principles. Therefore, secondary waste recycling based on the principles of the green economic system and recirculation is the priority of development. According to Ukrainian sources of information, 3.5 million Ukrainians have damaged or destroyed homes as of June 1. It is referred to 116 thousand facilities with a total area of 14 million square meters. They include 12.3 thousand multi-storey buildings (12 million sq.m.) and 104.1 thousand individual estates (1.7 million sq.m.) [7].

If taking into account, as of June 2022, the occupied territories (about 10% of the Ukrainian territory) where the total populated areas or most buildings are destroyed (over 70%), the number of buildings grows to 320 thousand and constantly increases with every day of military operations.

Besides, taking into account the obsolete housing stock in Ukraine, the operation period of which has either expired or is close to the end, the number of emergency buildings and structures unfit for use, it is viable to conduct the nationwide upgrade of the infrastructure of populated areas according to global contemporary environmental standards, principles of energy efficiency and safety, which will also improve the quality of public life and reduce the risks of living activities.

To improve the results of monitoring and efficiency of the reconstruction of Ukrainian populated areas, one suggests involving local authorities and local administrations, public organizations and activists at the regional level, which will allow improving the quality and transparency of the project controlled at the state level. The economic exhaustion caused by the war will attract local investments and international aid, which is expected to be implemented in each region with the involvement of developed countries and the delegation of responsibility to each participant in the process.

Creating a balance between state, international, public and business structures in the establishment of the waste disposal sector and the reconstruction of Ukraine plays a fundamental role in choosing methods of project implementation and monitoring. The experience of developed countries shows positive trends when increasing the role of businesses and entrepreneurship in waste recycling processes, adoption of innovations and eco-friendliness, which could increase the country's economic growth, provide new jobs and restore national ecological and economic indicators.

When implementing the project of infrastructure renovation and building reconstruction complying with maximum eco-friendliness and principles of circular economy, one should apply several general stages:

- Preliminary dismantling of the filling of the building with waste sorting.
- Separation and dismantling of the most valuable parts of the building.
- Disassembly and sorting by fractions of complex structures.
- Dismantling of concrete products.
- Basement dismantling with fractional sorting.
- Monitoring of physical and chemical properties of pre-sorted trash, selection of elements that can be used in the future without recycling.
- Selection of a recycling method for this waste fraction for the secondary use.
- Introduction of corrections to the existing reconstruction projects given available resources.
- Construction waste recycling and its turning into goods (resources).
- Secondary use of fractionally recycled waste.

When dismantling residential buildings, it is viable to use the technology of diamond cutting and element-by-element demolition of the building to better remove different fractions of trash, which will significantly reduce the cost of future construction.

Secondary recycling technologies will depend on the condition of waste, its further application and expediency of recycling, taking into account other influencing factors.

Disposal stage	
Dismantling of the structure, separation of waste into fractions	Roofing material
	Furniture, equipment, other fillings
	Marble, tile products, undamaged coating
	Exploitable insulation materials, infrastructure elements of the building
	Exploitable window and door systems
	Blocks
	Exploitable metal structures
	Wood, beam
	Brick, etc.

Fig. 1. Scheme for separating the main fractions of waste that can be used as a resource without pre-recycling from buildings not suitable for use as a result of military operations.

The next stage after waste sorting and transportation to the recycling facility will be its recycling, technologically different for each component. Key elements to be recycled are presented in Fig. 2.

Fraction to be recycled	Technology	Resulting resource
Concrete scrap	Removal of contaminants, shredding, sieving	Concrete aggregate (RCA)
Metal waste	Fractional separation, removal of contaminants, cutting, remelting	Raw materials for rolled metal products
Glass waste	Sorting, washing, magnetic separation of crushing	Recycled glass scrap, plastic filler
Wires, rubber products (wiring after separation by fractions)	Cleaning, shredding, pyrolysis, regeneration, thermal pressing	Synthetic oil, thermolysis gas, carbon black, regenerate, rubber
Plastic waste	Sorting, shredding, cleaning, drying, pressing, granulation	Flex, film, polystyrene
Wood, chipboard, middle density fiberboard, etc.	Purification, grinding, pyrolysis,	Secondary crushed stone
Roofing and bitumen waste	Purification, grinding	Thermal insulation materials, arbolite, chipboard
Crushed stone, asphalt and concrete waste	Dry cleaning, grinding, chemical dissolution	Bitumen powder, bitumen-polymer raw material, ecowool
Linoleum, polyvinylchloride waste		Thermal insulation materials, polymer raw materials

Fig. 2. Key components of construction waste, which require recycling after pre-sorting for their secondary use

In addition to the environmental friendliness of recycling, these technologies can have a positive impact on the resource potential for the reconstruction of Ukraine's populated areas, reduce the energy burden, increase the commodity production turnover, create new jobs, give an impetus to the adoption of eco-efficient technologies and innovations, as well as attract investors and international companies to reconstruct the country.

With every house built after the war being equipped with a bomb shelter with anti-radiation properties, the construction will be based on hydro and thermal insulation materials that can be obtained from secondary raw materials generated by the disassembly and recycling of construction waste.

It is also viable to cover the windows of future buildings with a transparent film preventing injuries caused by chipping and destruction of glass products, which can be obtained by waste recycling.

It is preferable to use eco-friendly and lightweight materials for construction to ensure less injury in case of destruction. For example, it can be peat blocks that can be mixed for different parts of construction with ceramic blocks, foam concrete, gypsum, sandwich panels, which are also reasonable to obtain using recycled raw materials. Besides, one can apply 3D printers to create buildings using recycled construction waste as raw materials, which will substantially reduce the cost and time of creating structures, and the technologies have already been described and tested by international companies [8].

According to this construction method, the optimality criterion can be a function of utility for society (Q), meeting the criteria of environmental friendliness (y1), efficiency (y2), safety (y3) and technological capacity (y4), which can be shown using the matrix of scores from 1 to 10 where the highest indicator reflects the best performance of a particular analyzed parameter:

$$Q(y1, y2, y3, y4) \rightarrow max \quad (1)$$

Table 1 show that the maximum score of the facility is possible only in case of using eco-friendly and innovative materials, which, firstly, should be environmentally safe and, secondly, should be built according to the standards in a short period and using principles of circular economy. Besides, it will positively affect the majority of building parameters.

In addition, the parameters of the presence of waste with and without burial are disclosed, which also brings a tangible negative impact on the ecosystem, resulting in the deterioration of the environment. The foregoing is primarily due to the irrational use of natural resources, as a result of which there is a negative impact on health and an increase in morbidity, the risk of dangerous situations. In this regard, the desire for a minimum impact on the environment is associated with the harmonious existence of man and the natural system based on energy efficiency, the use of innovative solutions, and the automation of production processes and operations. The presence of the outdated housing stock or the use of non-ecological materials for construction should also be considered a risk factor that can lead to deterioration of public health and additional costs of its recovery or public expenditures in case of the loss of human capability to work.

In case of several construction implementation strategies, it would be better to prefer projects with higher indicators of safety and eco-friendliness according to the principle of maximizing the utility function [9-11].

In case of a risk factor, most of its impact is distributed according to the principle of a circle with the action radius R and areas of influence of different power (N). The number of individuals (n) who can feel the given risk in the given radius is measured in the average population density in the given time period in the given area.

The expert assessment of the risk occurrence in the particular territory is calculated by the formula:

$$r = \frac{t}{T} * \sum_{i=1}^{M} (n * w) \quad (2)$$

where t is the number of risk events in the given location (time of influence), T is the total number of events (examined time interval).

Table 1. Matrix of construction performance indicators (CPI)

CPI	Environmental friendliness	Efficiency	Safety	Innovativeness
0-1	Presence of waste without disposal, tangible negative impact on the ecosystem, constant degradation of the environment, irrational use of natural resources, lack of environmental control.	High cost of construction (more than 10 thousand USD per sq.m.), too low rate of construction (more than 5 years for a building of 1000 sq.m., 5 floors high).	Unstable system, tangible negative impact on citizens (deterioration of health, increased morbidit), risk of dangerous situations, unpredictability, insecurity, lack of response to changes and possible risks.	Use of outdated and inefficient technologies, irrational use of resources, lack of individual approach to construction, lack of automation.
2	Waste disposal by burial, negative cumulative impact on the ecosystem, environmental degradation, irrational use of natural resources, lack of efficient environmental control.	High cost of construction (8-10 thousand USD), low rate of construction (4-5 years for a building of 1000 sq.m., 5 floors high).	Unstable system, negative impact on citizens (deterioration of health, increased morbidity and mortality), risk of dangerous situations, unpredictability, insecurity, low speed of response to changes.	Use of outdated and relatively inefficient technologies, irrational use of resources, lack of individual approach to construction, minimum level of automation.
3	Waste disposal by burial with pre-sorting of valuable fractions, negative cumulative impact on the ecosystem, partial environmental degradation, irrational use of resources, poor environmental control at the state.	Relatively high cost of construction (7-8 thousand USD), low rate of construction (about 4 years for a building of 1000 sq.m., 5 floors high).	Instability, large number of risks, low level of responsibility, relative insecurity, low planning horizon (1-2 years), below average speed of response to changes.	Use of outdated and relatively inefficient technologies, relatively irrational use of resources, regional approach to construction, minimum level of automation.
4	Waste disposal by burial with pre-sorting of valuable fractions, negative cumulative impact on the ecosystem, environmental degradation, irrational use of natural resources, poor environmental control at the state level.	Relatively high cost of construction (6-7 thousand USD), low rate of construction (3-4 years for a building of 1000 sq.m., 5 floors high).	Low level of healthcare, large number of risks, large number of contractors and doubtfully responsible individuals, below average culture and education of the population, moderate sustainability of systems, average planning horizon (2-3 years), below average speed of response to changes.	Use of technologies (until 1990), relatively irrational use of resources, regional approach to construction, insufficient level of automation.
5	Waste disposal by burial with pre-sorting of valuable fractions and gas extraction plant, negative cumulative impact on the ecosystem, tangible environmental degradation, irrational use of natural resources, average environmental control at the state and community level.	Moderate cost of construction (5-6 thousand USD), moderate rate of construction (about 3 years for a building of 1000 sq.m., 5 floors high).	Moderate level of healthcare, large number of risks, large number of contractors and doubtfully responsible individuals, average culture and education of the population, moderate sustainability of systems, average planning horizon (3-4 years), moderate speed of response to changes.	Use of technologies (until 2000), partially irrational use of resources, regional approach to construction, moderate level of automation.

6	Waste disposal by burning or burial with pre-sorting, natural self-recovery, little degradation of the ecosystem, moderate environmental control.	Moderate cost of construction (4-5 thousand USD), moderate rate of construction (2.5-3 years for a building of 1000 sq.m., 5 floors high).	Average level of healthcare, relative safety, average culture and education of the population, relative sustainability of systems, average planning horizon (4-5 years), average speed of response to changes.	Use of technologies (until 2008), use of technologies and equipment purchased in developed countries as obsolete or inefficient, regional approach to construction, average level of automation.
7	Waste disposal by burning or burial with pre-sorting, availability of treatment facilities, natural self-recovery, little degradation of the ecosystem, moderate environmental control (business, government, society).	Reasonable cost of construction (about 3-4 thousand USD), average rate of construction (about 2 years for a building of 1000 sq.m., 5 floors high).	Above average level of healthcare, relative safety, sufficient culture and education, relative sustainability of systems, average planning horizon (about 5 years), average speed of response to changes.	Use of innovations and tested technologies (no older than 30 years), high efficiency of technologies, automation at the level of 50-75%, partial optimization of systems and processes.
8	Low negative impact on the ecosystem, 20-30% of waste remains unrecycled, self-recovery of the environment, human and natural system existence with little impact and modifications of the natural environment, relative energy efficiency.	Competitive cost of construction (2-3 thousand USD), high rate of construction (about 1 year for a building of 1000 sq.m., 5 floors high).	Above average level of healthcare, relative safety, sufficient culture and education, sustainability, high planning horizon (more than 5 years), sufficient speed of response to changes.	Use of cutting-edge solutions, implementation and testing of startups, 75-90% automation of production processes and system operations, rationality, optimization.
9	Low negative impact on the ecosystem, 0-20% of waste remains unrecycled, self-recovery of the environment, harmonious human and natural system existence with little impact and modifications of the natural environment, energy efficiency.	Competitive cost of construction (300 USD – 2 thousand USD), high rate of construction (0.5-1 year for a building of 1000 sq.m., 5 floors high).	High level of healthcare and good health of residents, safety, high culture and education, sustainability, high planning horizon, quite rapid speed of response to changes.	Use of innovative solutions (no more than 10 years from the date of patenting), 90% automation of production processes and system operations, rationality, high optimization.
10	No negative impact on the ecosystem, 0% of waste, recovery of the environment, harmonious human and natural system existence, energy efficiency.	Low cost per square meter of construction (no more than 300 USD), high rate of construction (up to 6 months).	Improved health of residents, safety, high culture and education, sustainability and stability, rapid response to changes	Use of innovative solutions (no more than 5 years from the date of patenting), automation of production processes and operations, maximum optimization.

Fig. 3 shows that in case of two risk factors (e.g., the first one – the missile hitting the building, leading to diseases that can be treated using financial expenditures, the second one – the permanent negative impact on public health because of the construction made of non-ecological raw materials), which can be estimated in money equivalent (w – costs of human health recovery or neutralization of risk causes), there is the increase in the intersection of areas of influence (orange).

When assessing their power (N) and the number of people suffering from the negative impact (n), one should calculate the integral indicator of the strength of risk factors for the given location.

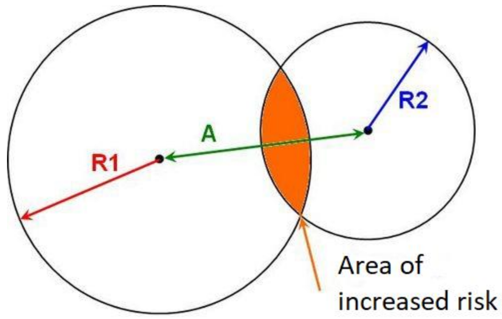

Fig. 3. Areas of influence from two negative factors on the given territory.

It allows us to assess the safety of territories and technologies that will be used to build new facilities when military operations in Ukraine end.

When analyzing risk factors in the construction of territories after the war in Ukraine, one should draw up a table of potential risks to the population in order to reduce the negative impact in certain regions of Ukraine, promptly prevent risks and ensure public awareness of the real picture of life activities in this territory, specifying the possible risk factors, their power and radius of influence.

To illustrate and promptly correct the data, one suggests developing an interactive map of risk factors with a possibility of creating layers and their analysis, forecasting of further growth and elimination of negative impacts, taking into account the ecological state of territories [12-14].

The interactive map can be designed using such software products as QGIS, Google Earth, gvSIG, OpenStreetMap and other geographic information software that can combine spatial placement of given objects and their properties, interactivity, layer analysis and free access. Moreover, the developed product can be used in mobile apps.

Monitoring of the environmental situation when developing further steps after the war should be based not only on the assumption of self-recovery of natural resources with no pollutants but also on the thorough analysis of all ecosystem components that can affect the life of human beings and other creatures. Therefore, the first task for society will be to clear territories of waste, neutralize risk factors and establish the infrastructure [15-17]. The first stages of country’s reconstruction should already be pre-planned and created given the principles of circular economy and the introduction of innovations, involvement of leading international companies, foundations and institutions based on environmental guidelines and the development of a safe environment for human life. Thus, construction waste recycling, including maximum processing, will be the foundation for further scenario approaches to making managerial decisions and creating restored Ukraine that will be a place of state-of-the-art technologies characterized by the high quality of life and the ecological and economic growth.

4. Conclusions

Currently, the world is facing the critical problem of accumulated construction waste accompanied by the increasing amount of garbage and fractions that have a long decomposition period. Ukraine is characterized by the large number of destroyed facilities and infrastructure objects as a result of military operations, which creates an additional environmental load and increases risks to public life. At the same time, most post-Soviet countries still have the obsolete housing stock with the expired operation period, the reconstruction of which makes no sense because of the physical deterioration and high cost of the process.

The study offers to adopt the principles of circular economy with construction waste recycling, which will substantially reduce financial and resource expenses for new facilities and will be an extra impetus to attract investments in Ukraine's restoration and involve international partners.

Construction waste recycling should be based on trash pre-sorting and stage-by-stage fractional processing at the new waste disposal plant located outside the populated area in case of its transportation to reduce the environmental load on territories of human residence. To build the infrastructure and restore the populated areas, the authors suggest using available secondary raw materials and neutralizing negative impacts of materials.

The presented system of construction performance assessment is aimed at combining ecological and economic factors, safety and innovativeness factors, positively affecting the resulting indicators and improving the quality of public life. To increase the awareness, promptly respond to risk factors and prevent negative impacts, one suggests developing the interactive map of risks to the population of the given territory. The map should include layers with information about risk factors, their elimination or neutralization, as well as the ecological and economic assessment.

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