Intelligent Information Technology for Inventory and Utilization of Construction and Demolition Waste From Damaged Infrastructure Facilities

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Abstract

This article examines the potential for enhancing the efficiency of inventory management and utilization of construction and demolition waste to create and apply secondary resources during the reconstruction of damaged infrastructure, including objects destroyed by war. This is achieved through the development of an intelligent information technology (IIT). The urgency of addressing this issue is underscored by the fact that large-scale reconstruction of damaged infrastructure demands significant expenditures of domestic and investment-based primary resources. Given the inevitable scarcity of these resources, the development of a secondary raw material market and the ability to extract valuable materials from waste streams for effective reuse become critically important. An analysis of European colleagues' experiences in effectively implementing a circular economy business model to address the limitations of primary resource utilization highlights the necessity of developing IIT for construction and demolition (C&D) waste inventory and utilization. Prior developer experience indicates that IIT can be implemented as a geoinformation system (GIS), enabling the identification of infrastructure objects through a knowledge base. The developed GIS knowledge base contains spatial and attribute data that align with the requirements of the circular economy business model, forming the foundation for a conceptual object inventory system. The intelligent component of the IIT is based on the use of large language models to analyze images of waste generation sites (Sources). This analysis involves interpreting visual cues, classifying types of construction materials, and providing an approximate volume assessment. The article also presents solutions for the preliminary classification of waste reception centers (Sinks) based on attribute and geospatial data, along with the development of an interactive "Sinks-Sources" map and the determination of efficient routes for transporting C&D waste to facilitate the creation of secondary resources.

Keywords

Construction and demolition waste, LLMs, intelligent information technology, geoinformation system, artificial intelligence, reconstruction

1. Introduction

In the current geopolitical situation in Ukraine, large-scale reconstruction of damaged infrastructure facilities, including those destroyed by the war, is of vital importance. This undoubtedly requires high expenditures of domestic and investment primary resources. Given their inevitable scarcity and the trend of increasing prices for their consumption, the development of the secondary raw materials market, as well as the possibility of extracting valuable materials from the waste stream for effective reuse, becomes highly significant.

Under the influence of these factors, the development of an intelligent information technology (IIT) for the inventory and utilization of construction and demolition (C&D) waste is crucial to enhance the efficiency of reconstructing damaged infrastructure facilities based on the use of secondary resources. In developing this technology, the experience of colleagues from European countries regarding the development of a circular economy in addressing the problems of limiting the

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use of primary resources has been considered [1]. This includes reducing investment and transportation costs for processing primary resources and producing building materials, increasing local employment (including green jobs), and potentially reducing CO_2 emissions during the reconstruction process, among other benefits.

For the effective implementation of a circular economy business model using secondary resources, the creation of a geoinformation system (GIS) for infrastructure facilities is proposed, identifying those requiring reconstruction, including those destroyed by the war. The GIS will contain spatial attribute data that aligns with the requirements of the circular economy business model and forms the basis for a conceptual object inventory system. The intelligent component of the technology is based on the use of large language models (LLMs) for analyzing images of waste generation sites and subsequently classifying C&D waste and their reception centers.

2. Literature overview

The paper [2] discusses the general opportunities and challenges of using LLMs (like GPT models) in the construction industry. While not specifically on waste analysis, it sets the stage for how these models can be applied, including for material selection and optimization, which is relevant to waste reuse. The article [3] provides a broader overview of Generative artificial intelligence (AI), including LLMs, in construction. It highlights their potential for diverse tasks, some of which could be adapted for waste management.

The following articles delve into critical aspects of image analysis for damage assessment and waste classification. In [4] evaluate Generative AI models (which can include underlying LLM principles for image tokenization) for classifying structural damage from post-earthquake images. They discuss the use of AI for identifying damage levels and material types. The study [5] specifically focuses on using neural networks (like YOLO and ResNet) for classifying C&D waste from images. While not explicitly using LLMs in the same way as text-based LLMs, it addresses the image analysis aspect for waste classification, which is a crucial part of proposed technology.

Several sources represent the way, how AI is being used for C&D waste management and circular economy. A highly relevant project [6] specifically addressing Ukraine's reconstruction. It demonstrates how AI analyzes drone footage of bombed-out buildings to identify reusable materials. The source [7] discusses various ways AI can contribute to waste reduction and recycling in construction, including AI-assisted deconstruction planning to identify salvageable materials. The paper [8] provides broader insights into how AI, machine learning, and natural language processing (NLP) can optimize waste processes, predict waste generation patterns, and identify opportunities for material reuse and recycling within the context of a circular economy.

Recent advancements highlight how NLP can be used in construction (for textual data, which could complement image analysis). In [9] authors utilize LLMs for analyzing textual data (e.g., accident reports) in construction safety. While not directly about waste, it shows the power of LLMs in processing unstructured text, which could potentially be used for analyzing reports, specifications, or other textual data related to building materials and waste. The review [10] provides a comprehensive overview of NLP applications in construction, highlighting the potential for processing and analyzing text data to achieve “construction intelligence”.

The subsequent research papers focus on the advancements in smart technologies and data-driven approaches for C&D waste management. Research by [11] introduces a strategic framework designed to facilitate the efficacious integration of smart technologies within the realm of C&D waste management. In a separate investigation, [12] meticulously examined the classification of C&D waste, positing it as a pivotal instrument for fostering its efficient reintegration into the material cycle. The researchers thoroughly explored the technological viability of recycling processes and offered prescriptive guidance for implementing pioneering utilization methodologies. The study [13] is a critical review of various machine learning methods used for estimating, classifying, and predicting construction and demolition waste to promote more sustainable waste management. It analyzes the effectiveness and limitations of these methods in addressing waste disposal challenges.

The deployment of GIS presents a compelling prospect for enhanced urban waste specifically, in the study by [14] illustrated the utility of Building information modeling (BIM-models) in digitally simulating the physical attributes of construction projects for planning and management purposes. When synergistically combined with GIS, this approach furnishes robust tools for superior spatial and environmental analysis. The systematic literature review [15] examines the applications of geospatial technologies and remote sensing in construction and demolition waste management. The authors analyze existing research to identify key application scenarios – including waste identification, site selection, quantification, and decision support – and pinpoint research gaps to guide future studies. Moreover, the authors of [16] engineered an automated system capable of precisely identifying the geographical location of demolition waste and optimizing the deployment of resources required for demolition operations and subsequent waste transportation.

Recent research reveals that digital technologies, such as satellite picture evaluation and photogrammetry, can substantially contribute to the accuracy of accounting of C&D waste, in particular in the territories suffering from consistent destruction. These methods allow identifying not only the volumes of waste, but also the geospatial location, which significantly alleviates planning of logistics for secondary resource management [17]. Moreover, when integrating blockchain technologies in data management, a more transparent and reliable material tracing can be achieved, as one of the preconditions for the implementation of an efficient circular economy [18].

Simultaneously, the topic of robotization and automatic sorting of C&D waste becomes more and more current. A range of research emphasizes that the combination of computer vision with robotic manipulations substantially contributes to time efficiency within the material separation process, at the same time decreasing the risk for human negative impact, when working with hazardous materials or in hazardous locations [19]. Alongside the above-mentioned, machine learning algorithms are applied to forecast the generation of C&D waste volumes in specific projects, based on the historical data and construction process-specific parameters [20].

In the context of the European Union's sustainable development policy, a significant role is devoted to synergies of BIM and digital twin technologies with GIS solutions. They allow real-time monitoring not only of the construction process itself, but also of the waste generation and management dynamics [21]. This type of integration allows for modelling of various scenarios for resource reuse and their impact on the decrease in CO_2 emissions [22]. In addition, the social dimension of circular economy business models is being researched more commonly – assessment of involvement of local communities and development of green jobs, which all lead to societal support for various reuse initiatives and societal awareness creation of sustainability issues in a broader scope [23, 24].

3. Research aim statement

The aim of this research is to enhance the efficiency of C&D waste inventory and utilization for the generation and application of secondary resources during the reconstruction of damaged infrastructure facilities, including those destroyed by war, through the development of an intelligent information technology. To achieve this, the following tasks are addressed:

- Developing an automated method for C&D waste inventory based on a comparative analysis of object images before and after destruction. This method will leverage a LLM for interpreting visual features, classifying construction material types, and providing an approximate volume estimation.
- Designing a conceptual scheme for an intelligent information technology system for inventorying and utilizing C&D waste, aimed at facilitating the creation and use of secondary resources.
- Implementing a GIS version for inventorying damaged objects. This GIS will utilize a database of geospatial and attribute data concerning C&D waste reception and utilization centers (Sinks), as well as damaged infrastructure facilities (Sources), and their interconnections. This

will be presented as an interactive map to guide waste movement for subsequent secondary resource recovery.

4. An automated method for construction and demolition waste inventory based on a comparative analysis of object images before and after destruction

The proposed method for automated inventory of C&D waste, based on a comparative analysis of infrastructure object images before and after destruction, consists of the following stages.

Stage 1. Obtaining images of the infrastructure object before and after damage/destruction. Images from drones, satellites, archival, and private sources, as well as BIM-models results (providing a digital 3D representation of the building), are used as sources. For further analysis, the use of visual pairs (before/after) is recommended, as this allows for the localization of damaged areas and the identification of new objects (waste) in the scene. An example of such images for a "School" object in .jpg format, before and after destruction, is shown in Figure 1.

Stage 2. Image analysis for waste classification (concrete, brick, glass, etc.). Specialized machine vision tools or their integration are used to perform image segmentation (i.e., identifying and outlining specific objects or areas in an image, such as ruins, intact parts of a building, different types of debris). The main substages include *image preprocessing, image segmentation (clustering) into objects/fragments, and classification of the segmented objects.* Preprocessing allows for alignment and normalization of brightness/contrast, and the definition of Regions of interest (ROIs) – fragments with waste where building debris (ruins, rubble) is visible, areas containing materials (concrete, brick, metal, etc.), and zones with contrasting changes after destruction (missing walls, roof shifts, etc.). It's worth noting that ROIs are areas that have changed in the "after" images compared to the "before" image (parts of the facade are gone, smoke or debris has appeared) (Figure 2).

Figure 1: Images of the "School" object before and after destruction

```
{
  "roi_1": {
    "location": [150, 300, 450, 600],
    "material": "brick",
    "confidence": 0.87
  },
```

```
  "roi_2": {
    "location": [500, 700, 900, 1100],
    "material": "concrete",
    "confidence": 0.92
  }
}
```


Figure 2: Example of an ROI in JSON format based on "School" object images

Performing object/fragment segmentation requires the use of semantic segmentation models (e.g., U-Net, DeepLabv3+, Mask R-CNN) to extract individual pieces of building materials from the images. This may involve training on a custom dataset of real destruction photographs. When classifying segmented objects, each fragment is assigned a class, for example, concrete, brick, glass, metal, wood, or mixed waste. Models like ResNet, EfficientNet, or visual encoders with CLIP/BLIP2 can be used for multimodal approaches in the case of mixed waste. Existing open-source annotated datasets like TrashNet, TACO, or custom segmented and labeled destruction images are used as annotated datasets.

Stage 3. Waste volume estimation. This is a key stage for practical application. After classifying materials in each ROI of the image, considering its scale, pixel areas are converted into real-world areas. For example, if 1 pixel of the image represents 10 cm, then the area of the ROI segment $S_{roi} = X \times Y \times (0.1 \times 0.1)$ m^2. For two-dimensional ROI images, assumptions are made regarding the thickness of the debris layer; for instance, the thickness of concrete slabs might be around 0.2–0.3 m, and then S_{roi} is recalculated considering the thickness. To obtain more accurate estimates of waste volume, 3D reconstructions are created from multiple images, geometric methods are used for precise calculation of debris cubature, and volumes of the object before and after destruction are compared. An example of an approximate estimation of the volumes of different types of C&D waste based on images of the "School" object before and after destruction is shown in Table 1.*Stage 4. Application of LLM as a multi-instrument for explanation generation.* It is important to note that the scenarios for performing this innovative stage will depend on the initial initialization of the LLM. That is, specifying the LLM's usage mode – standalone or in conjunction with a CV model, and which LLM is used – text-based (GPT-3.5, Gemini) or multimodal (GPT-4o, Gemini Pro Vision). The advantage of using a multimodal LLM is the ability to simultaneously analyze images and text, which is useful when solving the task of automated inventory of C&D waste from images.

The successful execution of the stages for automated C&D waste inventory based on comparative analysis of infrastructure object images before and after destruction depends on the effective generation of prompts for the LLM. The generated prompt must have clear instructions, a description of input and output data, units of measurement for the data, an indication of the level of detail for the result, and the LLM's persona (role). Below is an example of a refined prompt for Gemini (Multimodal) (indicated in quotation marks "").

Table 1
A fragment of the approximate estimation of volumes of various types of C&D waste based on images of the "School" object

Material type	Area, m²	Layer thickness, m	Volume, m³	Approximate weight, t
Concrete	35	0.25	8.75	~20
Brick	22	0.3	6.6	~10
Glass	8	0.02	0.16	~0.4

"Prompt purpose: automated inventory of C&D waste based on images, material classification, volume estimation, and potential for reuse.

Prompt:
Below are four images:

- The first (Image 1) shows an infrastructure object before destruction.
- The next three (Image 2, Image 3, Image 4) show it from different angles after destruction.

Analyze these images together and perform the following.

Identify damaged areas by visual comparison between the “before” image and the three “after” images. Describe the localization and nature of the damages (e.g., facade collapse, roof destruction, etc.).

Identify the types of materials that likely became C&D waste (e.g., concrete, brick, glass, wood, metal). Indicate in which zones they are observed.

Estimate the volume of waste for each material – in cubic meters or approximate percentages of the total volume (if precise measurement is not possible).

Assess the potential for secondary use of each type of waste:

- Suitable for recycling/reuse.
- Partially suitable.
- Unsuitable.

Formulate a structured inventory report in table or JSON format with the following fields:

- Zone: description or coordinates of the damaged area.
- Material_type: type of material.
- Estimated_volume: volume in m³ or %.
- Reuse_potential: brief conclusion regarding secondary use.
- Confidence: confidence level (high / medium / low).”

A fragment of the LLM Gemini's response result in JSON format is shown in Figure 3. The full JSON file is available via link [25].

C&D waste inventory report: the total estimated volume of C&D waste for such a four-story building is approximately 3700–4300 m^3. A detailed report in table format is available via link [25] due to its extensive nature.


```
[
  {
    "zone": "Central Facade and Entrance Group (from foundation to roof)",
    "description_of_damage": "Complete collapse of the upper floors above the entra
    "material_type": "Concrete/Reinforced Concrete",
    "estimated_volume": "60-70% of total volume (approx. 2400-2800 m³)",
    "reuse_potential": "Suitable for recycling (secondary crushed stone, aggregate
    "confidence": "High"
  },
  {
    "zone": "Central Facade and Entrance Group (from foundation to roof)",
    "description_of_damage": "Complete collapse of the upper floors above the entra
    "material_type": "Brick/Stone/Plaster",
    "estimated_volume": "15-20% of total volume (approx. 600-800 m³)",
    "reuse_potential": "Partially suitable (crushing for backfill, limited reuse of
    "confidence": "High"
  },
```


Figure 3: Fragment of LLM response result in JSON format based on “School” object images

5. Conceptual scheme for intelligent IT inventory and utilization of construction and demolition waste

So, can be highlighted the following tasks that can be solved by intelligent IT for inventory and utilization of C&D waste:

- Initial classification of waste reception centers based on attribute data, along with obtaining their geospatial data and creating a corresponding knowledge base for waste reception centers (Sinks).
- Automated inventory of C&D waste based on a comparative analysis of infrastructure object images before and after destruction, including classification of building material types and approximate volume estimation.
- Creation of a corresponding knowledge base for damaged infrastructure objects (Sources) based on attribute and geospatial data.
- Development of an interactive Sinks-Sources map and determination of an efficient route for C&D waste movement with the aim of creating secondary resources.

The general conceptual scheme of intelligent IT for analysis and management of C&D waste is shown in Figure 4.

The imperative for gathering information regarding waste streams for subsequent categorization and processing becomes evident. Two primary methodologies for data acquisition present themselves: the conventional approach employing structured forms for comprehensive waste type enumeration, contextualized by the specific reconstruction project; and the innovative application of AI to ascertain waste types and volumes, contingent upon the characteristics of the reconstruction object.

Comparative analysis of data collection approaches. Each approach possesses distinct advantages and inherent limitations. The form-based user survey offers high fidelity in data capture but is often constrained by the time-intensive nature of manual data entry. Conversely, the AI paradigm facilitates accelerated data acquisition, though its accuracy is intrinsically linked to the robustness of the model's training regimen, typically yielding precision levels that, at present, do not surpass those achieved through meticulous form completion.

This study primarily adopted the form-centric methodology, where users manually input waste quantities via a survey interface. While the AI-driven approach demonstrates considerable promise within the problem domain, warranting extensive further investigation and refinement, its current limitations preclude its standalone application for highly precise inventory.

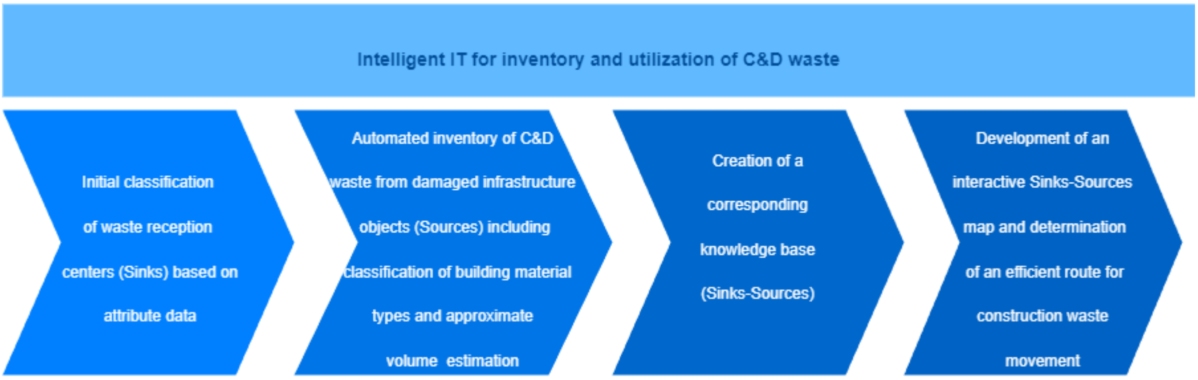


Figure 4: Conceptual scheme of intelligent IT for analysis and management of C&D waste

Challenges in neural network-based waste quantification. The utilization of neural networks for quantifying C&D waste, derived from construction, reconstruction, or demolition sites, through facility-specific data, represents a compelling avenue for estimating waste volumes across various material classifications. Nevertheless, this direction is subject to several significant constraints. Firstly, a more granular specification of criteria for waste generation facilities is requisite. These criteria, while demanding minimal user input, would critically contribute to the accuracy of waste volume predictions. Secondly, a substantial data deficiency poses a considerable hurdle. Neural networks necessitate expansive datasets for training, the acquisition and preparation of which demand substantial preparatory research. Thirdly, the current predictive accuracy of neural network models in this context remains comparatively modest, potentially rendering this method insufficient for robust, actionable recommendations. In sum, while this approach presents inherent disadvantages, its synergistic integration with the aforementioned waste classification techniques has the potential to streamline and enhance analytical outcomes.

Geospatial data and route optimization. The intelligent IT system's output is comprised of geospatial data pertaining to waste reception centers (Sinks), presented as an interactive map. Recommendations are generated concerning the appropriate handling protocols for all waste classes identified by the user via the web form, specifying the optimal nearby waste collection center for each waste type. Future iterations of this IT solution will incorporate capabilities for proposing transportation logistics and determining optimal routes for waste conveyance to collection centers, leveraging GIS.

The task of identifying the optimal transportation route within this problem framework is non-trivial. Firstly, the multiplicity of routes may exceed a single path, attributable to the substantial volume of waste requiring transport and the diverse array of waste types necessitating delivery to distinct collection centers. Secondly, as previously noted, the challenge of calculating the workload for each transport vehicle must be addressed. Additional optimization parameters could include scenarios where the route's origin point is not the construction, reconstruction, or demolition site itself, but rather the initial staging locations of the transport vehicles.

6. Implementation of the Sinks-Sources GIS version for inventorying damaged infrastructure objects

A GIS version for the comprehensive analysis and inventorying of construction and demolition waste has been conceived and developed (Figure 5). This system comprises four primary modules: three were meticulously crafted by our team, specifically the frontend, server, and database, while the fourth module integrates queries to OpenStreetMap to facilitate map visualization on the user's web interface.

System architecture and technologies. The server-side component was engineered using the Java programming language on Java Development Kit 21.0.8, leveraging the robust Spring Framework, including Spring Boot 3.3.0 and Spring Data JPA. For the database management system, PostgreSQL 17.0 was selected, strategically incorporating PostGIS for enhanced geospatial capabilities in future developments. The frontend interface was constructed with Thymeleaf 3.1.3, augmented by standard web technologies such as HTML5, CSS3, and JavaScript ES14.

The server facilitates communication with the user's web application via the HTTP protocol, where incoming requests are processed by controllers and subsequently managed by services. Interaction between the server and the database is orchestrated through Hibernate, a sophisticated library designed for Java-database connectivity.

The BuildingController class is instrumental in data persistence for objects and in analyzing collected data to generate actionable recommendations. Concurrently, the CenterService class is tasked with identifying all waste collection centers that align with the user-specified criteria [26].

User support and waste management features. In its current iteration, this applied IIT aims to assist users in managing C&D waste by compiling a curated list of relevant waste collection centers. These centers, categorized by type, are identified based on their proximity to the construction site and their capacity to accept at least one of the waste types indicated by the user in the input form. Upon initial engagement with the system, users are prompted to specify the geographical location of their construction site on an interactive map (Figure 6).

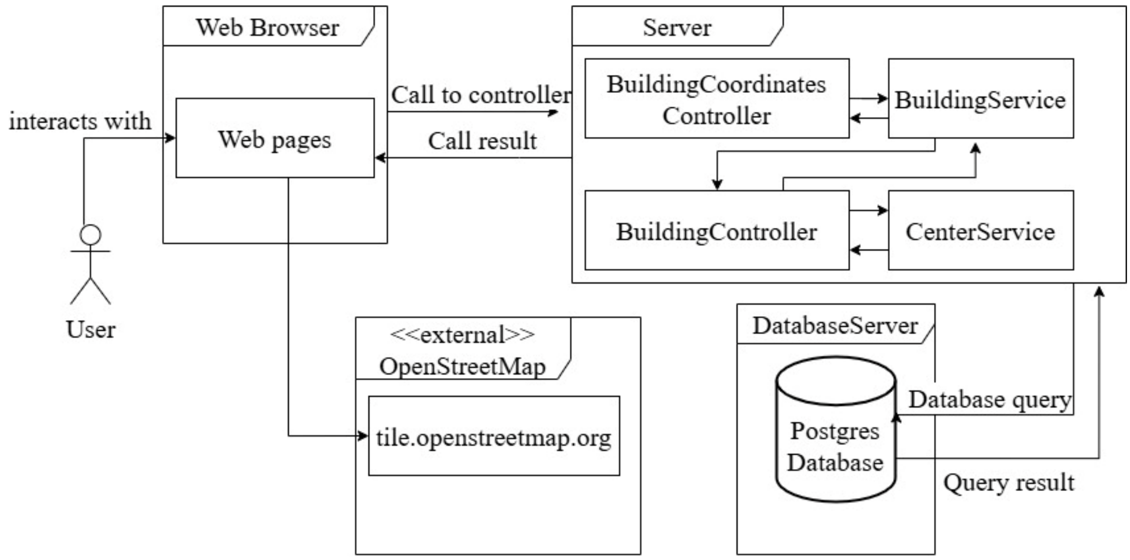


Figure 5: The logic scheme of the C&D waste inventory GIS [26]

Upon completion of the initial step, the user proceeds to the subsequent interface by activating the "Next" button, situated at the bottom of the display. The second page necessitates the input of detailed information pertaining to the construction site. The user's first task is to specify the type of site where the construction activities are taking place (Figure 7). This is followed by a selection identifying the nature of the work that will result in waste generation. Both the site type and the work type are chosen from drop-down menus, allowing the user to select one appropriate alternative from a predefined list. For the classification of construction, reconstruction, or demolition projects, users are prompted to select from predefined categories, including apartments, private houses, industrial buildings, and infrastructure objects. Similarly, for the nature of work leading to waste generation, options provided encompass construction, demolition, repair, or "other" for miscellaneous activities. Both queries mandate a single selection from their respective dropdown lists, ensuring standardized input.

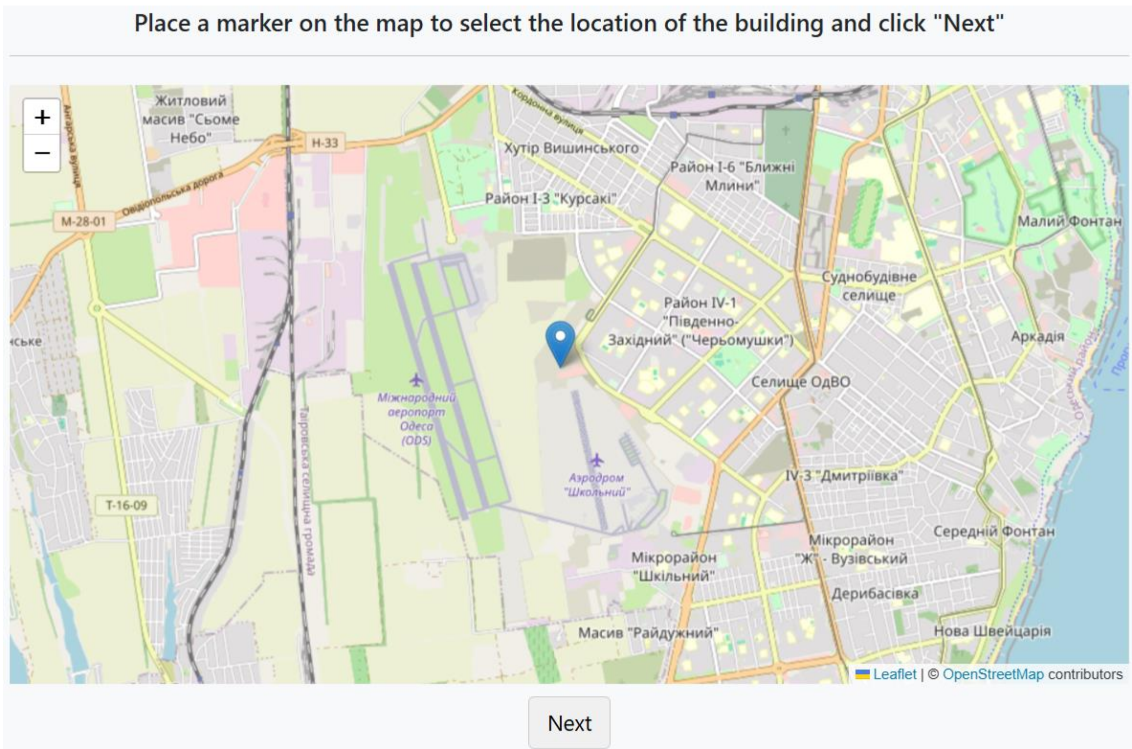


Figure 6: The screen form for selecting a construction, reconstruction or demolition site [26]

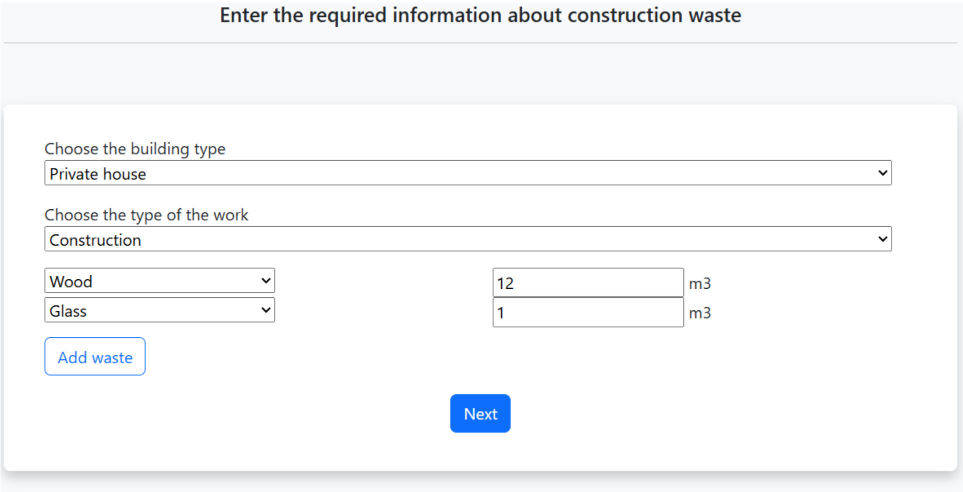


Figure 7: The screen form for entering the data about the waste generation site and the data about the generated C&D waste [26]

Subsequently, users are required to specify waste types and their corresponding volumes in cubic meters. Waste type selection is facilitated through a single-choice dropdown list, promoting data uniformity. Conversely, waste volume is a mandatory numerical input field. For instances involving multiple waste streams, the system provides an "Add waste" button, which dynamically generates additional input rows. Each newly added row necessitates independent specification of waste type and volume, ensuring comprehensive documentation of all generated waste [26].

The predefined waste categories available for selection include:

- Concrete and masonry.
- Wood.
- Metal.
- Drywall.
- Asphalt and roofing materials.
- Glass.
- Plastics.
- Doors, windows and plumbing fixtures.
- Hazardous materials.
- Other.

Upon completion of waste data entry, users advance to the third page by clicking the "Next" button. This page presents a tabular overview of the nearest C&D waste collection centers (Figure 8). The table dynamically indicates which waste types each center accepts, based on the user's previously entered waste data, by marking the relevant cells.

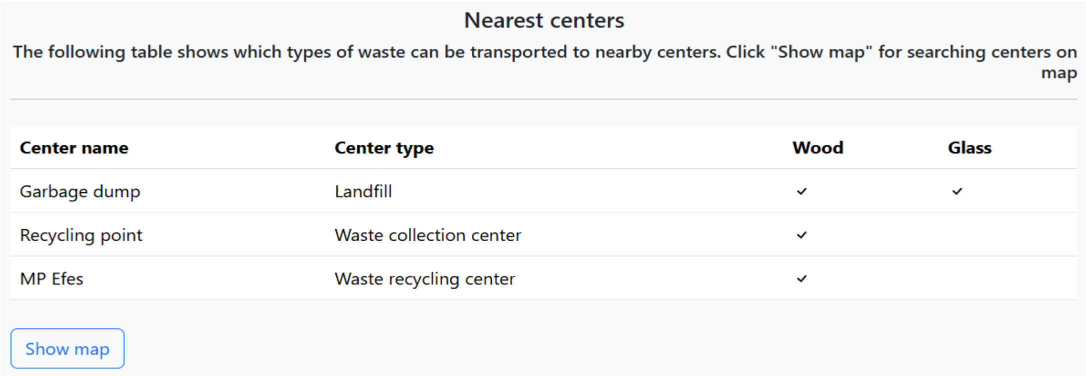
To optimize waste utilization logistics, the system applies maximum allowable distance thresholds for different types of waste collection facilities relative to the construction site:

- Waste collection centers: included if within a 5 km radius.
- Recycling centers: included if within a 10 km radius.
- Landfills: included if within a 20 km radius.

The Chebyshev distance metric d within waste sources A_i and waste collection facilities B_j with the corresponding coordinates (x_i, y_i):

$$d(A,B) = max|x_i - y_i| \quad (1)$$

was employed for distance calculations to enhance computational efficiency, as the precision offered by alternative metrics was deemed unnecessary for this specific task.


Nearest centers

The following table shows which types of waste can be transported to nearby centers. Click "Show map" for searching centers on map

Center name	Center type	Wood	Glass
Garbage dump	Landfill	✓	✓
Recycling point	Waste collection center	✓	
MP Efes	Waste recycling center	✓	

Show map

Figure 8: The screen form for a table of waste collection points closest to the waste generation site [26]

After reviewing the tabular data, users can elect to “Show map”, which transitions them to a subsequent page displaying an interactive map featuring color-coded markers for various waste collection facilities (Figure 9). The marker symbology is as follows:

- Green marker: denotes the location of a construction, reconstruction, or demolition site.
- Blue marker: represents a waste processing (recycling) center.
- Red marker: indicates a landfill designated for waste utilization.
- Orange marker: signifies a general waste collection center.

A comprehensive legend explaining these color codes is accessible at the bottom of the screen. For enhanced usability, hovering over a waste collection center marker triggers a tooltip that displays pertinent facility details, including the facility's name, address, contact number, and a list of accepted waste materials. Crucially, the system filters the displayed centers, ensuring that only those capable of accepting at least one of the waste types specified by the user are rendered on the map, even if other centers are geographically proximate. Users retain the option to return to the tabular view by clicking the “Return to the table” button. It should be noted that the waste collection center data presented in Figure 8 and 9 serves as illustrative test data [26].

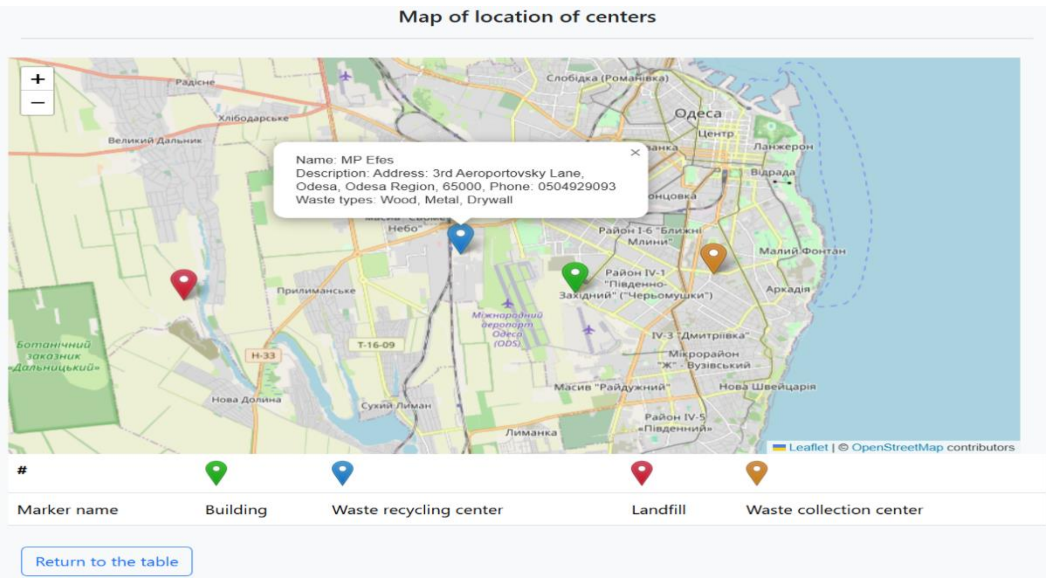


Figure 9: The screen form for the geospatial data about waste collection points closest to the waste generation site [26]

7. Conclusions

The study aims to enhance the efficiency of inventory management and utilization of C&D waste for the creation and application of secondary resources during the reconstruction of damaged infrastructure, including objects destroyed by war, through the development of a suitable IIT.

The necessity of creating an IIT based on the circular economy model is underscored by the fact that large-scale reconstruction of damaged infrastructure demands significant expenditures of domestic and investment-based primary resources. Consequently, the ability to identify and extract valuable materials from C&D waste streams for effective reuse becomes critically important.

The intelligent component of the IIT is founded on the development of an automated method for C&D waste inventory, based on a comparative analysis of object images before and after destruction. After acquiring images of an infrastructure object from drones, satellites, archival sources, private images, and BIM results, these are segmented into ROIs. This involves identifying and delineating ruins, intact building sections, various waste types, and so forth, utilizing specialized machine vision tools. Following the classification of materials within each image ROI, and considering scale, pixel areas are converted into real-world areas. A pre-trained LLM is then employed as a multi-tool to generate explanations regarding the automated inventory of C&D waste.

A GIS version for inventorying damaged objects has been implemented as a web application, allowing users to define waste generation sources and estimate approximate waste volumes. This GIS leverages a database of geospatial and attribute data concerning C&D waste reception and utilization centers, as well as damaged infrastructure objects and their interrelationships. The results are presented as an interactive map for navigating waste movement, aiming to facilitate the recovery of secondary resources. Waste routing considers the type of C&D waste and the type of waste reception center (displayed on the map as markers of different colors), providing suggested waste delivery routes. Among the advantages of this research is the utilization of advanced technologies that enable a preliminary, albeit approximate, assessment of the types and volumes of waste from a destroyed infrastructure object. It also provides potential waste management options and reception centers, integrated with an interactive map. The proposed method, which is based on a comparative analysis of “before” and “after” images using LLMs for visual interpretation, demonstrates significant potential for the rapid and effective classification of materials and estimation of waste volumes. To strengthen the developed conclusions, it would be beneficial to identify and highlight the practical implications of the study, both on the regional and international levels. The developed IIT system not only contributes to more effective application of BDA in the post-war restoration of Ukraine but has real potential of becoming a universal tool for overcoming crises of a similar nature or originating from various natural disasters in different parts of the world. This approach should facilitate a decrease in dependency on primary resources, promote circular economy principles and reduce CO_2 emissions, which would otherwise be generated from the development of new building materials.

With this, this research provides a substantial contribution to the development of sustainable construction and restoration practices and climate change mitigation. It is also important to emphasize the replicability of the developed methodology. The system is based on technologies that are available to a wide range of users – satellite and drone images, open-source computer vision models, LLM and GIS tools. This means that with relatively minor adaptations, this solution can be applied to different geographical areas and construction contexts. Furthermore, replicability provides the opportunity to accumulate comparable data over the long term, which is essential for developing international standards for the accounting and reuse of BDA. Such a perspective significantly expands the practical application of the study and strengthens its relevance in scientific and policy planning discourse.

However, the limitations of this study include its preliminary nature, representing a first approximation of IIT implementation. It does not account for the full diversity and complexity of C&D waste classification or all possible utilization scenarios. Furthermore, the analysis of damaged objects using LLMs provides an approximate estimate with a certain degree of error. The current work also does not incorporate transportation costs to relevant centers, which could render certain waste utilization types economically unfeasible.

Although a full validation using large-scale real-world data (ground truth) was not conducted within the scope of the current study, approximate calculations obtained using the method showed an 87 % correspondence when compared to generalized expert assessments provided by the Odesa State Academy of Civil Engineering and Architecture. This result confirms that the developed technology can serve as a reliable tool for preliminary inventory, logistics optimization, and promoting the transition to a circular economy.

Future research directions involve a more detailed investigation of C&D waste with relevant experts from the construction industry and environmental specialists to refine the developed IIT and improve its quality. Also, there will be focus on expanding the database for both LLM training and for supplementing data on existing and new collection points for C&D waste. Additionally, it is crucial to achieve a full-module assembly of the IIT according to the conceptual scheme, encompassing all tasks the IIT is designed to solve.

Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-4o, Gemini Pro Vision in order to: implement method for automated inventory of C&D waste as described in Section 4 of the article (figures 2 and 3, table 1 and JSON-file and table in [17]). Further, the author(s) used Gemini 2.5 Flash in order to: improve text translation. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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