Integrating Building Information Modeling, Deep Learning, and Web Map Service for Sustainable Post-Disaster Building Recovery Planning

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Abstract

Building recovery is always a major issue after disasters due to the urgent need for efficient assessment of damaged buildings and effective management of required resources. At the same time, it is necessary that building recovery planning considers the impact of used materials on the environment as well as the proper allocation of budgets. In this paper, we propose a novel integrated post-disaster building recovery planning system that utilizes Building Information Modeling (BIM), Deep Learning (DL), and Web Map Service (WMS). BIM provides 3D models and detailed information for buildings; DL enhances the accuracy and efficiency of building assessment; WMS generates reliable data on locations and for route planning. The BIM-DL-WMS integration would contribute significantly to building recovery planning by automating building element assessment, cost estimation, and carbon emission analysis for repair/retrofit materials and material delivery. This developed system would make post-disaster building recovery planning more efficient, effective, and sustainable. The framework of the BIM-DL-WMS system is elaborated on in detail in this paper. The implementation of the system could be applied to not only single-building recovery planning but also the recovery planning of a district or even a town or city.

Keywords –

Building Information Modeling; Deep Learning; Web Map Service; Post-Disaster Building Recovery

1 Introduction and Background

The report published by the UN Office for Disaster Risk Reduction in 2020 [1] showed an increasing number of disasters in the past two decades, which led to more attention and efforts in pre- and post-disaster research. Building recovery is a post-disaster phase that requires attention and is as important as other post-disaster phases like mitigation and emergency response. In the building recovery phase, various problems related to building assessment and building rehabilitation arise due to unintegrated data and poor management. These problems sometimes lead to delays in handling building damages and cause some of them to be abandoned in the end, for the government or building owners are unable to make timely decisions with adequate data. Therefore, it is necessary to develop an integrated post-disaster building recovery planning system to tackle these problems and help stakeholders resolve the problems.

At the same time, decarbonization has become a major concern nowadays in construction, due to an increasing awareness for sustainability. According to UNEP [2], the building and construction sector was responsible for over 34% of global energy consumption and 37% of global energy- and process-related CO_2 emissions in 2021, with building materials contributing to around 9% of overall energy-related CO_2 emissions. To meet the sustainability goal, minimization of carbon emission should be considered in the selection of rehabilitation methods, whether repair or retrofit, in post-disaster building recovery planning. The selection of materials, energy consumption of construction activities, and transportation means for material delivery should all be considered.

Building Information Modeling (BIM) could provide 3D models and relevant building elements data, and these data could be easily integrated with other data or software via an Application Programming Interface (API). Deep Learning (DL) has been proven to be an effective artificial intelligence tool, and has been used to classify building damages and recognize building element damages. The Geographic Information System (GIS)-based Web Map Service (WMS) could provide fairly reliable information on locations, distance calculation and transportation route planning, and the WMS API enables WMS to interoperate with other applications. In view of these advantages, this study integrates BIM, DL and WMS to propose a sustainability-oriented post-disaster building recovery planning system. The framework of the proposed system and an example are presented in this paper. The application of the system could be a single damaged building, a damaged block, a district, or even a city.

2 Literature Review

The literature review in this paper covers four areas: (1) Post-disaster building recovery; (2) Decarbonization for sustainability in post-disaster building recovery; (3) Integration of Building Information Modeling (BIM) and Deep Learning (DL) in building assessment; and (4) Potential of BIM and Web Map Service (WMS) applications for decarbonization in building recovery. They are elaborated on in detail below.

2.1 Post-Disaster Building Recovery

In the post-disaster stage, building recovery is an important phase to be carried out as a continuation after the emergency response phase [3]. Building recovery has some functions, including identifying a disaster's physical impact and proposing a rehabilitation design [4]. Building assessment and rehabilitation design are essential activities of building recovery to support the decision-making for recovery execution strategies.

Some researchers divided damage assessment for buildings into three levels [5, 6]. The first level is a rapid assessment that evaluates the impact of damage based on the visual appearance of the exterior of a building and the condition of its surroundings. The second level is a detailed assessment that evaluates the damaged elements of the building from the exterior and interior of the building based on visual inspection parameters. At this level, moderate and light damages will be repaired. For severe damages or the third level, in-depth analysis is required and structural analysis will be conducted based on some tests of the existing strength of the building.

Building rehabilitation design focuses on repair and retrofit methods. The determination of repair and retrofit methods considers the damage conditions and building performance requirements based on design codes. The selection of materials for repair and retrofit, quantity take-off, and cost estimation are carried out under building rehabilitation design.

Several studies have developed several frameworks regarding the use of technology in post-disaster recovery. For example, Baarimah et al. [7] propose a comprehensive framework for integrating BIM adoption for post-disaster recovery projects by connecting the components with stakeholders. Meanwhile, several other studies have developed a BIM-based framework related to the virtual construction permitting process [8] and blockchain technology [9] in post-disaster recovery. However, there needs to be a gap in developing a framework that integrates BIM with Web Map Service and uses deep learning in post-disaster building recovery.

2.2 Decarbonization for Sustainability in Post-Disaster Building Recovery

Sustainability during building construction refers to all construction activities and processes that have the least harmful environmental and social impacts [10]. Decarbonization is one way to achieve the sustainability goal, which represents an alternative way of working that reduces carbon emissions. In the building sector, decarbonization can be achieved through the production of more efficient building materials, the use of more environmentally friendly materials, and reduced energy consumption [11].

In the case of construction activities in buildings, the approach to analyzing the impact of carbon emissions uses the calculation of carbon emissions in materials, energy consumption, and transportation [12-14]. Calculation of carbon emissions in materials is done by calculating embodied carbon materials as a representation of material production. For activities on the construction site, the calculation of carbon emissions takes account of the use of tools in cleaning activities, installation of supporting equipment, repair and retrofit activities. Also, transportation carbon impact analysis is used as an approach to calculating carbon emissions produced for the delivery of materials and equipment by suppliers.

The above could be implemented in post-disaster building recovery planning. Building recovery planning should consider selecting lower-carbon repair and retrofit materials, using equipment that produces less energy, using supporting tools to strengthen structural elements more efficiently, and transporting materials using more environmentally friendly modes of transportation over shorter distances. Lu and Xu [15] asserted that post-disaster reconstruction could provide a unique opportunity to migrate to a low-carbon mode and move forward with sustainable development.

2.3 Integration of BIM and DL in Building Assessment

Deep Learning (DL) applications have become an interesting topic in the construction sector during the last few years. DL comes with the capability to automate tasks for object recognition, data processing and process monitoring [16]. This predictive capability also supports more accurate object detection, detection of possible impacts and decision-making. These DL capabilities have also been applied to building assessments to date.

In building assessment, DL can be applied for many purposes, e.g. to classify collapsed buildings, classify the level of damage to buildings, classify the type of damage, identify building elements, and recognize areas of damage through images. Aerial images [17, 18] and street view images [19] are used as input to the deep learning process to detect collapsed buildings. Also, the use of more detailed images of building elements and certain areas of the building focuses on assessing elements and damage [20]. Some studies integrate DL with BIM due to the capability of BIM to provide detailed building data in 3D models and share information with other platforms.

In addition to 3D reconstruction using BIM 3D models, integration of BIM and DL is widely applied through the use of BIM data for inspection purposes [21], analysis of element conditions [22], automation data integration [23], and semantic analysis of building regulation [24]. In terms of using data integration, BIM can supply information about detailed elements used in analysis or recognition using DL processing. For example, the use of BIM data and DL networks can support infrastructure lifecycle management that monitors and assesses component condition [25].

2.4 The Potential of BIM and WMS Applications for Decarbonization in Building Recovery

Web Map Service (WMS) is an industry-standard protocol for delivering georeferenced map images generated by a map server from data provided by a GIS database via a web interface [26], such as Google Maps, OpenStreetMap, and Apple Maps. WMS provides the best service benefits in finding location points and planning routes in a free and interactive way. Route planning by WMS is considered comfortable to use on various platforms and very accurate since it is supported by actual maps provided by the GIS server system. In its application, the use of WMS can be integrated with other services and software through the API for transferring information.

Several studies have explored the use of WMS in the construction sector. Chen and Nguyen [27] integrated BIM and WMS as decision support tools for the source selection of sustainable construction materials. Chen and Nguyen [28] also developed a framework for location and transportation analysis in green building certifications using BIM-WMS integration. Li [29] integrated WMS and Dynamo BIM for assessment tools around possible construction sites. Farzad Jalaei [30] proposed an integrated methodology for a green building certification system at the initial design stage of a project based on BIM and WMS. Furthermore, Wen et al. [31] and Deng et al. [32] stated that the integration of BIM and GIS-based map services is very applicable to building design assessment and building recovery. In relation to research on the integration of BIM and GIS, such integration has decreased considerably in the last decade compared to the previous one [31]. This condition encourages the need to further develop BIM-WMS integration research, especially in the post-disaster and sustainability fields, to support good management in the construction project cycle to respond to disasters.

3 The Approach of BIM-DL-WMS Integration for Post-Disaster Building Recovery

The application of technology for an integrated system in post-disaster building recovery remains a challenge. The latest developments in the application of technology in any sector, including construction, require truly interoperable data integration. Environmental differences in implementing these technologies require a bridge to transfer data and unify information in a platform. The maturity of each technology is the key in integrating these technologies.

Integration between BIM, DL, and WMS has the potential to provide significant added value in post-disaster building recovery. Consideration of sustainability through decarbonization efforts requires such integration in the same system. Thus, the idea of a sustainable integrated post-disaster building recovery system is to provide a building recovery system that considers sustainability in the rehabilitation of damaged elements with the support of DL for damage assessment, WMS to calculate sustainability parameters, and BIM as the data backbone at the element level. A BIM Level of Development (LOD) of 300 provides access to information for specific element types [33]. The use of information at the element level is suitable for post-disaster building recovery since both damage and rehabilitation also occur at the building element level.

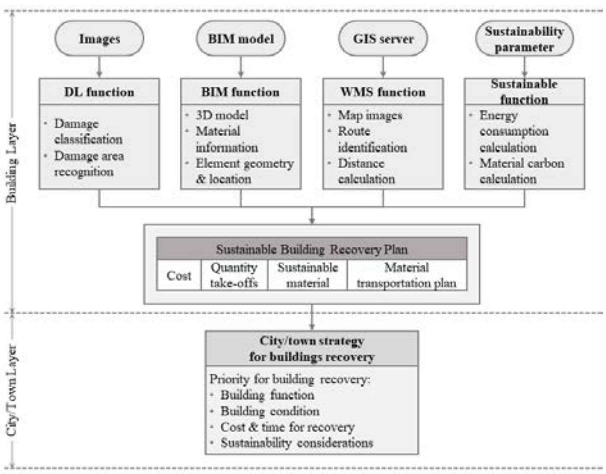

Figure 1. An Approach to Sustainable Integrated Post-Disaster Building Recovery

The approach to sustainable integrated post-disaster building recovery (Figure 1) comes from four main components: (1) DL for damage classification and damage area recognition; (2) BIM with 3D models, materials and element parameters; (3) WMS for map images, route identification, and distance calculation; and (4) sustainability-oriented carbon emission calculation for building elements and materials. The output of this system is a building recovery plan with information on design rehabilitation, quantity take-off, cost, carbon emission impact, and material transportation plan. Furthermore, at the city/town layer, recovery plans for buildings can assist the government or building owners in making building recovery priority decisions. Further benefits of this building recovery system can be applied for material efficiency, recovery execution optimization, and smart cities data support.

4 Sustainable Integrated Post-Disaster Building Recovery Plan

4.1 Framework

A developed flowchart for the proposed sustainable post-disaster building recovery planning system integrating BIM, DL, and WMS (Figure 2) shows how the concepts in Section 3 could be implemented. The flowchart depicts four main stages: (1) Building damage assessment; (2) Building damage analysis; (3) Recovery plan preparation; and (4) Sustainable material evaluation. The flowchart outlines the recovery planning process for a single building using low-carbon materials. The proposed framework is developed from an existing building recovery system by an authorized organization and has been verified by some professional engineers in earthquake and structural engineering.

Building damage assessment elaborates the BIM-data-based inspection process and damage assessment using the DL method. The framework requires the BIM model LOD 300, which facilitates object-level coordination. In addition, the BIM data supports the digital inspection form. Meanwhile, a building without a BIM model will make the framework application take longer to prepare the BIM model and can only do the inspection by manual form.

In the rapid assessment inspection, DL can assist in classifying collapsed and intact buildings. Meanwhile, in a detailed assessment, DL classifies the level of damage, type of damage, and damaged area of the elements. The building recovery system in this study focuses on buildings with elemental damages rather than collapsed buildings. The BIM-based inspection digital form allows the visual inspection results to connect to BIM data. Building damage analysis is a way to confirm the damage after a building damage assessment. Damage classification at the severe level requires confirmation from engineers because of the potential global impact on the building structure. Building structural analysis helps calculate building strength performance through manual simulation by engineers. The proposed building damage analysis could facilitate engineers in conducting analyses through the support of 3D BIM models.

Recovery planning starts with preparing repair or retrofit methods, all the way to producing a building recovery plan. This stage automatically calculates quantity take-off and recovery costs, comprising components of materials, labor, equipment and other relevant items. The quantity calculation uses data from the BIM model and results of semantic segmentation from DL.

The sustainable material evaluation considers carbon emissions from three sources, namely, embodied material carbon, energy consumption in recovery activities, and carbon emissions in material delivery. The WMS module provides a map image for determining the site location and supplier location so that transportation planning and resulting carbon emission could be calculated automatically. The total carbon emission of a material can then be considered in the selection of materials. This system generates a sustainable building recovery plan with information on damaged elements, volume, recovery cost, carbon emission, and delivery transportation plan.

For the recovery planning of a district or a city, the system could provide information about the inspected building location, material repair needed volume, recovery cost, and transportation plan. The district recovery planning system opens the way to optimize the cost and decarbonized recovery plan by optimizing retrofit method selection, recovery execution schedule and material transportation plan. Moreover, the building recovery plan is essential to support the local government's decision-making in budget allocation and recovery priority strategies.

4.2 Demonstration

An example of the stages described in the flowchart in Figure 2 is given in Figure 3. The example shows the functions of BIM, DL, and WMS in a designed building recovery system. The example uses a real-case scenario from a building in Indonesia. The results show that the BIM-DL-WMS integration can support the output of a sustainable building recovery plan in the form of an alternative recovery planning scenario with technical, cost and environmental impact information.

Figure 3(A) shows the application of DL to the classification of images of damaged building elements and to semantic segmentation for identifying the damaged area in damaged building element images. The pixel amount for the damage and element is a basis for calculating the material repair needed volume. In this example, EfficientNet is used as the image classification architecture, and UNet is selected as the semantic segmentation architecture. For image classification, the results show an accuracy of 89.23% with 800 images. For semantic segmentation, the intersection over union (IoU) result is 49.8%, with 120 training images. This prediction still requires development, especially in the number of sample images and training efficiency, but the results obtained show that this method is capable of achieving the goal.

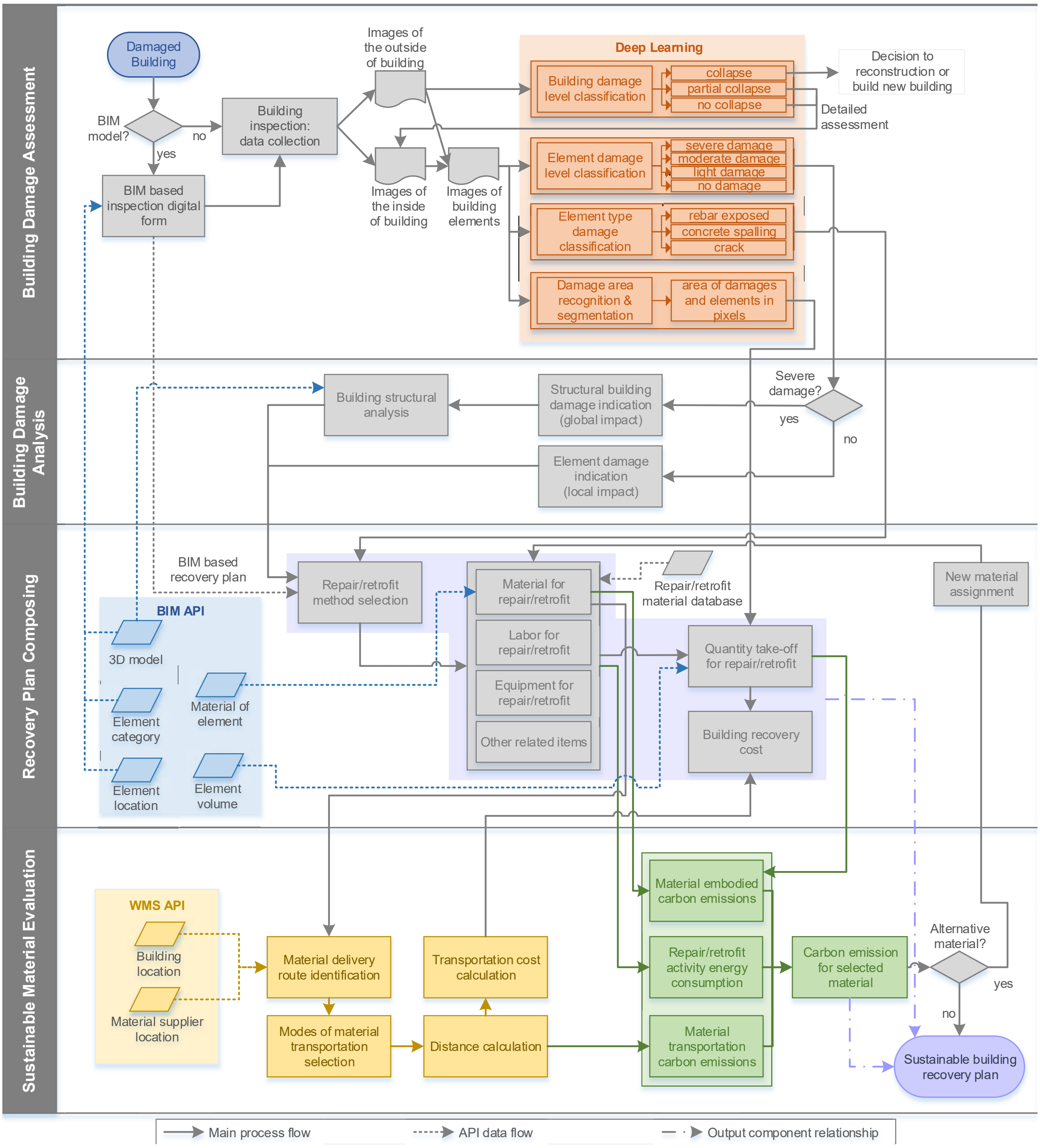

Figure 2. Flowchart of BIM-DL-WMS Integration for Sustainable Post-Disaster Building Recovery Planning

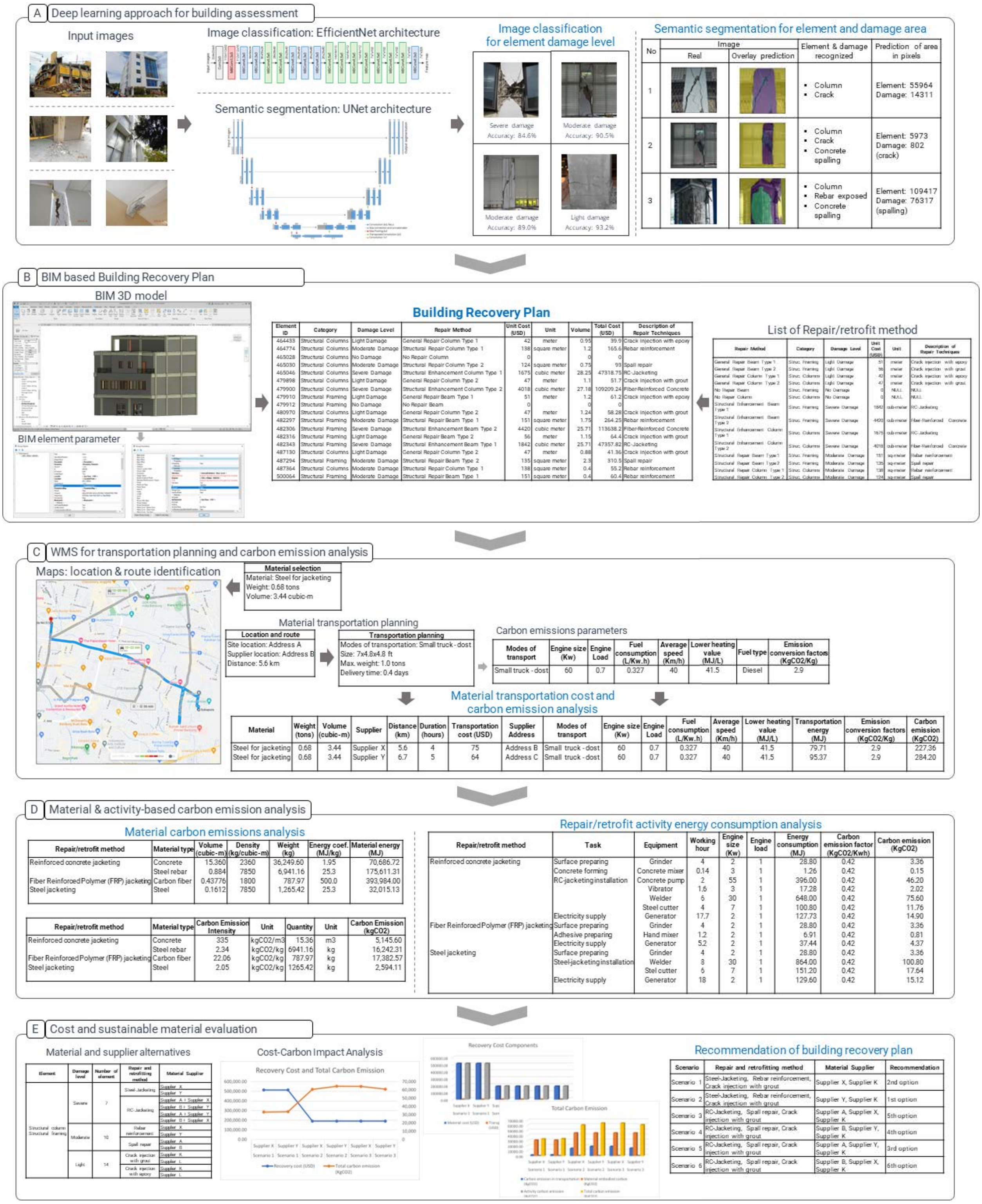

Figure 3. Implementation Example of Sustainable Post-Disaster Building Recovery Planning

Figure 3(B) shows the preparation of a building recovery plan through BIM data and a list of repair/retrofit methods. The first step is to create a 3D BIM model and access the parameter elements, followed by compiling a list of element rehabilitation methods (repair and retrofit) by engineers in the database. Afterwards, a building recovery plan is developed with data from the database and parameters from BIM, damage inputs from processed DL results, and a list of rehabilitation methods. API provides a way to access data in the BIM model, which is connected to WMS and the other parameter in a Windows Forms/Graphical User Interface (GUI) for a building recovery plan.

Material transportation planning and calculation of carbon emissions from transportation are presented in Figure 3(C). WMS provides map images and locations of sites and suppliers. The distance between the site and the supplier's location is used for transportation planning by determining the mode of transportation. The transportation plan and carbon emission parameters are inputs to material transportation cost and carbon emission analysis.

Figure 3(D) shows the calculation of the embodied carbon emissions for the materials selected for rehabilitation and the energy consumption calculation for the planned building recovery activities. Determination of new materials can be an alternative in order to obtain alternative costs and carbon emissions.

Figure 3(E) shows the results of a sustainable building recovery plan. The results obtained are alternative materials for repair/retrofit with technical information on rehabilitation, volume, cost, and carbon emissions. This building recovery plan provides BIM-based damaged element condition data with comprehensive recovery information to support decision-making. Furthermore, sustainable building recovery planning is able to provide an integrated system supported by BIM, DL, and WMS as a tool for decision-makers to set recovery priorities and allocate budgets with consideration of material impacts on the environment.

5 Conclusions and Recommendations

Post-disaster building recovery planning faces challenges in assessing building damages and producing rehabilitation plans in a timely manner, with unintegrated data, poor management, and unaware environmental impacts. Sustainability-oriented post-disaster building recovery planning aims to address these challenges by providing a decarbonized post-disaster building recovery planning system through the integration of the Building Information Model (BIM), Deep Learning (DL), and Web Map Service (WMS). The proposed BIM-DL-WMS-integrated system could achieve the goal of decarbonization through the selection of low-carbon emission materials. The flowchart of the BIM-DL-WMS system was proposed, and an example is presented to demonstrate the implementation of the system. The proposed system offers an efficient and effective way for post-disaster building recovery planning that could be implemented either at a single building level or at a city/town/district level.

However, this study has several limitations related to limited datasets on the damaged element and detail of framework implementation on district recovery planning. Another issue is the availability of the BIM model before a disaster. In the future, it is hoped that more and more data and the real case would accommodate upgrading the system, while the BIM model also would be applied to all buildings.

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