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REALITY DATA CHARACTERIZATION OF RECOVERED CONSTRUCTION MATERIALS FOR GENERATIVE DESIGN

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Abstract: This paper explores potential AI-supported design and construction pipelines for irregular shape buildings after characterizing 3D object features of salvaged building materials. The purpose is to support researchers to achieve goals of generative design, fit-to-a-BIM design, and procurement optimization through well-identified building elements. Steps in redesigning pipelines include data capture, semantic segmentation, and object classification for 3D point clouds and 2D images of recovered materials. Potential to extend these methods to point clouds and images of parts of existing buildings is considered in future work as well. Specifically, object characterization by means of computer vision is discussed in terms of the derivation of critical dimensions, geometric properties, and element conditions. Based on the information generated from these processes, generative design approaches for primarily geometrically constrained design problems are explored first. Next, Rules-based BIM design tools are considered for the potential size fitting method. Finally, a conception for optimizing the procurement process for reused components is proposed. The application of these processing pipelines is practically demonstrated for a simple case of dividing wall material selection and generative design utilizing salvaged bricks in the platform of Visual programming design platform (Grasshopper). It is anticipated that these approaches would be extended in the future to more classes of materials and to more critical design and procurement problems, such as structural design as well as value estimation.

Keywords: Data characterization; Generative design; Construction materials reuse; Scan-to-BIM; Computer vision; Procurement optimization

1. INTRODUCTION

The core of sustainable human and environmental development is indeed the development of energy. With the progress of society and the development of the economy, energy occupies a higher and higher position in the global economy. Therefore, the energy problem has become a difficult problem that urgently needs to be solved by all countries. In terms of energy expenditure, buildings consume 40% of the world's raw materials, 72% of electricity, and 39% of the world's total energy (Benachio et al. 2020). From the perspective of the construction sector, the wastes which are generated during the life cycle processing of building materials cause a lot of energy waste. As a result, the quality of design and construction not only has a direct impact on the lives and work of building occupants but also has a profound impact on the global resources required to create and maintain these buildings. Therefore, it is imperative to promote energy-saving technologies in the construction industry. From the perspective of environmental protection, the reuse and recycling of civil and construction engineering waste and garbage can improve the emission of greenhouse gases such as carbon dioxide and some harmful gases and solids. This has important implications for environmental protection.

This paper focuses on elementary deconstruction theory and preliminary design practice of real data characterization for scanned 3D point clouds and 2D images. It is made up of five parts. Section One introduces the background of reused building components in the Architectural, Engineering, and Construction (AEC) industry under the global situation of energy concerns. Section Two summarizes the development of point cloud recognition and segmentation algorithms to suggest the possibility and importance of introducing state-of-the-art AI techniques to the scenario of scan-to-BIM. Section Three illustrates the methodology from initial-depth to deep-depth deconstruction, design, and reassembly after the extraction of building components by means of data characterization methods. Section Four shows a case study of dividing wall design using the proposed framework for the simple example of recycled bricks. Section Five outlines the process for the reuse of building materials proposed in this article and proposes other aspects to consider for future regenerative building designs.

2. LITERATURE REVIEW

With the advent of deep learning techniques, huge improvements have been achieved in the field of point cloud semantic segmentation. In recent years, researchers have proposed a large number of deep learning- based segmentation models to process point clouds and Figure 1 shows one example. Compared to traditional algorithms, such models perform better and achieve higher benchmarks. According to the processing method of 3D point cloud data, there are two main categories of 3D point cloud semantic segmentation approaches based on deep learning, namely indirect semantic segmentation approaches and direct semantic segmentation approaches. The indirect semantic segmentation method is to convert the original point cloud data into a conventional 3D voxel grid or multi-view, and indirectly extract features from the 3D point cloud data through data transformation, so as to achieve the purpose of object characterization. Therefore, indirect semantic segmentation approaches are further divided into 2D-multi- view-based approaches and 3D-voxelization-based approaches. Its representatives are MVCNN (Su et al. 2015) and SqueezeNet (Iandola et al. 2016), respectively. The direct semantic segmentation approaches directly extract feature information from point cloud data. Without conversion to voxels and multi-views, the architecture preserves the inherent information within the native point to predict point-level semantics. Its representatives are mainly PointNet (Qi et al. 2017a), PointNet++ (Qi et al. 2017b), and etc. Therefore, there exists a strong technical basis for object recognition and characteristic extraction for point cloud models rather than only 2D images, that is, relying on these object characterization techniques for point cloud models which are based on deep learning is feasible today.

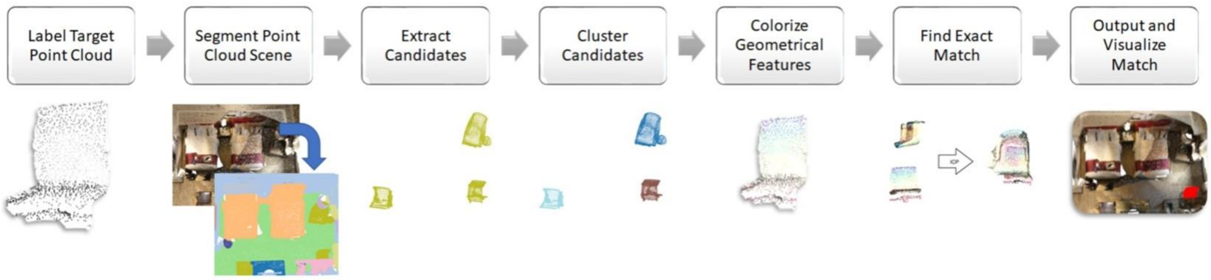

Figure 1: Semantic segmentation of scenes from 3D point cloud files (Morales 2020)

3. METHODOLOGY

3.1 Data Characterization

3.1.1 Data Characterization Algorithm

A bounding volume is a simple geometric space that contains objects of complex shapes. The purpose of adding bounding volumes to objects is to quickly perform collision detection or to filter before accurate collision detection (that is, when bounding volumes collide, accurate collision detection and processing are performed). Bounding volume types include sphere, axis-aligned bounding box (AABB), directed bounding box (OBB), 8-DOP, and convex hull (Karamizadeh et al. 2020). Oriented Bounding Box (OBB) is a well- selected method that determines the size and orientation of the box according to the geometry of the object itself to solve the Data Characterization for building elements problem. The box does not need to be perpendicular to the coordinate axis. This makes it possible to choose the most suitable and compact containment box. The generation of OBB boxes is more complicated than that of AABB boxes. Generally, the distribution of all vertices of the object in space is considered, and the best direction (that is, several axes of the OBB box) is found through a certain algorithm. Besides, the principal component analysis (PCA), a technique for simplifying a dataset, is introduced for finding the best direction. Typically, it transforms the data into a new coordinate system such that the first-largest variance of any data projection is in the first coordinate (called the first principal component), and the second-largest variance is in the second coordinate (the second principal component) Element (Iandola et al. 2016).

3.1.2 Object Measurement Practice

Therefore, the regular building components, which are generally utilized in the construction and often recycled after the demolition (including bricks, doors, windows, beams, columns, and others), can achieve measurement of the geometric dimensions of objects through this designed data characterization algorithm. Firstly, the scanned point cloud model file (.obj format) needs to be opened in the software and prepared for filtering noise and clearing edges. After that, convert the cleaned point cloud file into the .pcd format file and save it in order to recognize the scale and measure the dimension. Next, open the written C++ program in the Visual Studio platform. In the code, change the input point cloud file path and save the update program. Lastly, run this program and the output has two kinds of parameters as the Figure 2 shows. The first one is the data output, which includes the point cloud number, length (x value), width (y value), and height (z value) of the point cloud building component model. The second one is visual output, which shows the point cloud model and its bounding box which could perfectly match the minimal outer boundary of the building component. Additionally, the dimensional measurements may be accurate down to the micron level when the scanned point cloud model is accurate and completely noise-free ideally.

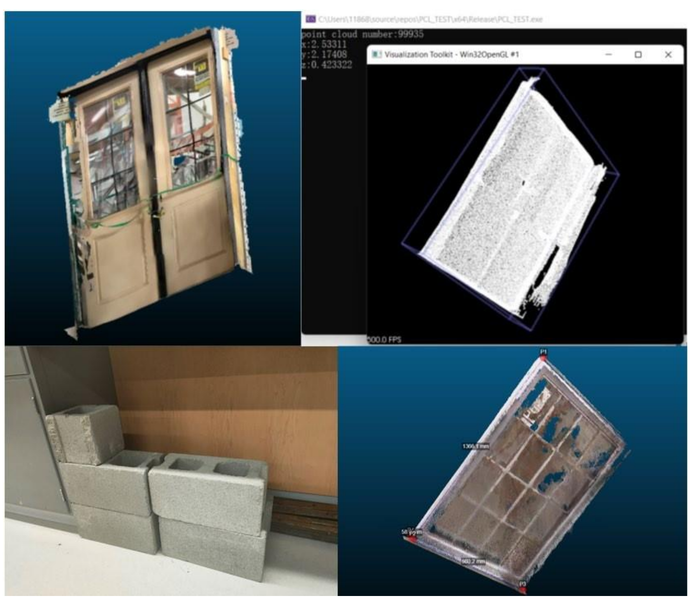

Figure 2: Automatic measurement of door dimensions and feasibility for other building components (such as bricks and windows)

3.2 Generative design

3.2.1 Traditional Generative Design

The generative design is the first and foremost concept that allows intelligent AI running in CAD software to exercise some kind of parametric control throughout the design process. It requires that computers have enough computational power, that is, they can complete numerous calculations and develop considerable possibilities at the same time. Generally, this supports an approach where the design problem can be abstracted into a class of mathematical problems and combined with human choices and environmental influences. Some architectural design modeling software such as Autodesk Revit or Rhinoceros 3D is plugged with generative design tools. Thus, the user can enter multiple constraints for the design, and then the generative algorithm can make a variety of choices. For example, in the preliminary design of a building, the generative design algorithm can consider various factors such as manufacturing process, construction cost, material cost, material weight, structural design, road patency, part clearance, and so on. Architects and Engineers can thereby substantially explore more different solutions and design options than previously possible.

The generative design allows architects and engineers to browse a large number of different building options, select their favorite, and then start designing more refined structures on top of the model. Editable CAD geometry is generated, so it is easier to rely on algorithms to work with architects rather than just architects. Then, thousands of design alternatives can be developed based on the constraints entered by the designer. Generative technology is a creative process. For example, Figure 3 below shows one kind of outcome of generative design. This creative process has been used in art and design for quite some time, but they are mainly concerned with abstract creative methods to avoid prejudging and copying novel works. The use of analytical engineering software and computer programming enables custom design approaches that go beyond industry standard 3D BIM software to resolve practical conflicts and constraints often faced in buildings by employing a unique and creative design process.

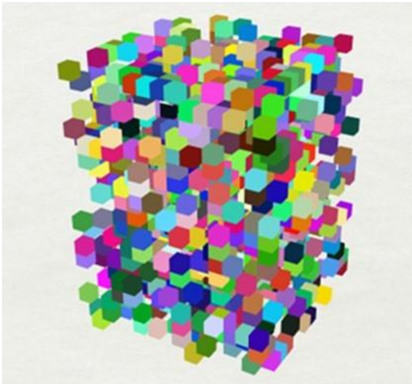

Figure 3: Generative design for the building layout using cellular automata algorithm

3.2.2 AI-supported Generative Design

The Architectural generative design based on learning algorithms learns the existing architectural design works with the help of learning algorithms so that the algorithm can grasp the statistical laws within the sample and realize the direction of architectural generative design. In the process of architectural design, most architects believe that their creations are full of contingency, and their designs are often driven by "inspiration" and consider many elements related to architecture. Therefore, taking classical programming as an example, trying to use various rules and commands to control the generation of buildings requires more and more factors to be considered, and the program will become more and more complex, but it is difficult to achieve the same level of design as humans. Therefore, some researchers try to use artificial intelligence technology to let computers copy existing architectural works, learn the statistical laws in them, and finally reach the level of an architectural design similar to that of humans. For example, some architectural generative design methods are based on deep learning algorithms. The reason why deep learning is so intelligent lies in its accurate capture of the internal statistical laws of data samples. In recent years, there has been more and more research on architectural design methods with the help of deep learning. Table 1 briefly summarizes relevant literature.

Table 1: Notable Advances in Deep Learning for Design

Year	Researchers	Tech	Summary
2018	Newton, D.	3DCNNs	Researchers utilized 3D CNNs to explore generative design methods for architectural concepts
2018	Zheng, H.	Pix2PixHD	The authors used Pix2PixHD to explore the generative design of apartment floor plans
2018	Zheng, H.	CGAN	The researchers used CGAN to demonstrate the experiment of generating building plans and satellite maps from boundary and color patch maps, exploring the possibility of generating building plans using deep learning
2019	Chaillou, S.	Pix2Pix	The researchers utilized the Pix2Pix model to explore the automatic generation of building floor plans
2019	Newton, D.	DCGAN	Using DCGAN to learn 100 international-style building plans; research showed that small data samples can also achieve good results
2021	Nauata, N.	House-GAN++	Researchers proposed a new graph-constrained GAN and use three metrics to measure the quality of the generated house layouts

3.3 Fit-to-a-BIM design

BIM technology can perform component size optimization, component splitting, component reinforcement, and collision inspection, which greatly shortens the work time for drawing disclosure and drawing review, and enables some designers' omissions or unreasonable designs to be corrected in time.

3.3.1 Standardized Design

In the development of architecture, the modulus is not only a unit of size but also a value-added unit of scale coordination. As the basis for the production and size coordination of building components, the modulus can well unify the dimensional relationship of various components, so it is conducive to industrialized production, to achieve coordination and communication between building parts. While reducing construction costs, efficient and fast production can be achieved. For example, as Figure 4 illustrates, the value of a basic modulus can be 100mm, which is represented by the symbol M, that is, 1M=100mm, and the size of some components of the module unit is a multiple of the basic modulus. Through the use of modules, the internal dimensions of the reused building parts’ modular units can be greatly standardized, thereby forming a relationship proportional to the basic module. In the prefabricated assembly design of the element unit, how to install it accurately requires careful checking of the dimensions of the building components. Modular components can be divided into load-bearing components, enclosure components, and modular furniture components according to their different functions in the building. The use of modular components not only enriches the form of design but also improves the size fit level of building materials reuse.

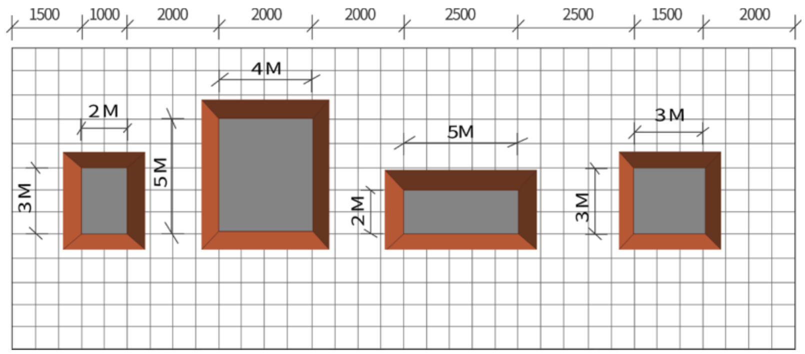

Figure 4: Modulus design of modular components

3.3.2 Size Fit Unit

The idea of modularization of architectural elements is not limited to dividing the reused building materials into unit modules, but it can also divide the building into basic components. Different components can be universal through standardized processing, and modular components can independently constitute architectural design elements, and can also exist as an important part of the building. Therefore, the standardized design of the salvaged building components is also an important embodiment of the modular idea in the prefabricated building.

After that, utilizing BIM technology, the modular control of the components can be realized by setting the logical relationship of the size of the components in advance. Establish the corresponding component family in advance, and then set the basic information of the component as the condition of component parameterization control, such as the length, width, material information, and so on of the component. After the component is loaded into the project, the parameterized control can be realized by adjusting the component information.

3.4 Procurement Optimization

3.4.1 Disassembling Components

Building assembly refers to the disassembling of building components, focusing on the reuse of building components. Building disassembling will have a great impact on the reuse of construction waste. The basis of disassembly is to disassemble different building materials and components through different disassembling processes and methods. In this process, for some components with relatively intact functions, the damage during the disassembling process should be avoided as much as possible, so as to facilitate the recovery and reuse of building components.

For the disassembly of the building, the feasibility of the disassembly of building should be analyzed first. On the basis of confirming that the disassembly is feasible, further investigation and analysis should be carried out, and the list of disassembly should be listed. In general, the disassembly process is as follows: interior decoration materials - doors and windows, heating, pipelines - roof waterproofing, insulation layer - roof structure - partition walls and load-bearing, walls or columns - floor slabs, layer by layer down to the foundation.

The disassembly method is mainly manual disassembly or mechanical disassembly. Firstly, manual disassembly can achieve excellent results in the recycling and reuse of waste building materials, because the manual disassembling process can maximize the protection of most building components. In this way, the workers are required to disassemble the buildings in the reverse order of the construction of the building during the disassembling process. To ensure the protection of building components, in the process of disassembling, due to the certain danger, it is necessary to provide necessary protection to workers to ensure the safety of workers. Secondly, when using machinery for building disassembly, mechanical operators should avoid damage to some building components in the process of mechanical disassembly. Pure mechanical disassembling is widely used when demolishing buildings, but it also means a lot of construction waste production. The optimized method shown in Figure 5 is to combine manual disassembly and mechanical disassembly. Purely manual disassembly will not only consume a lot of manpower and labor time but also cause low disassembly efficiency and harm the personal safety of the disassembly workers. Simply using mechanical disassembly cannot effectively protect building components. The combination of man and machine has the dual advantages of manual disassembling and mechanical disassembling process, which can effectively reduce the use of manpower and improve the disassembly efficiency. However, in the disassembling process, it is necessary to avoid the injury of the machinery to the workers.

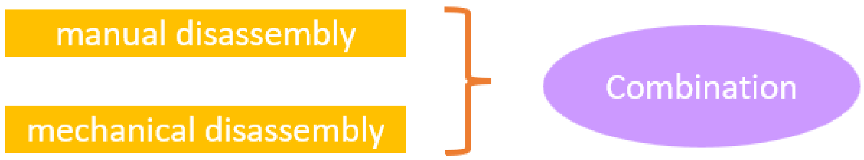

Figure 5: Optimizing method of disassembly

3.4.2 Transporting Components

After the building is disassembled, the first thing to consider is the storage of building components. If extensive stacking is also adopted, it will inevitably cause damage to the disassembled building components and is not conducive to the reuse of building components. Therefore, we must have a sound storage management method. When saving, it should be stored and managed according to the classification of building components and construction waste for reuse. Storage can also be on-site and off- site. In the process of building disassembling, storage on site should be classified according to classification, and some building components and materials that are prone to damage and corrosion, such as wooden components and reinforced materials, should be well protected. For off-site storage, the classification and protection of materials and components should also be done well, but transportation management should also be done well.

In the process of transportation of building components, it is also easier to be damaged. For example, some glass components, etc., are easily broken during transportation if they are not properly protected. Other materials, if not protected during transportation, may also cause irreparable damage such as cracking, deformation, etc. If the damage is serious, it will no longer have the value of recycling. Therefore, good transportation protection is also an important part of the waste recycling process.

3.4.3 Reassembling components

In 1975, Professor Eastman, the "father of BIM (Building Information Modeling)", proposed "a computer-based description of a building" in his research topic named "Building Description System", in order to realize the visualization as well as quantitative analysis of construction projects and improve the efficiency of engineering construction (Volk et al. 2014). The building information model is used to simulate the real information of the building through digital information simulation. It has five characteristics of visualization, coordination, simulation, optimization, and drawing. As the pipeline in Figure 6 and 7 below demonstrate, using BIM to manage the whole process of building dismantling can not only effectively strengthen the storage management and transportation management of building components but also effectively promote the reuse of construction waste.

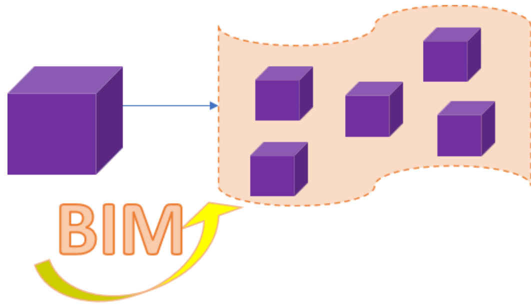

Figure 6: BIM assisted building dismantling process

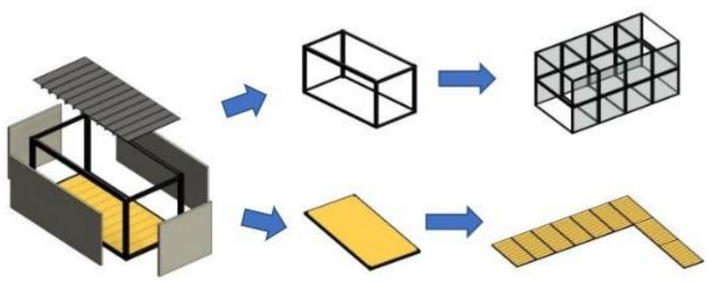

Figure 7: Process of disassembly and reassembly

When a building is reassembled, it will have a great impact on the use of building waste components and waste building materials. This will have a greater impact on the transformation of the old city. For example, in the process of renovation of the old city, if the design concept is to make full use of the dismantled waste building materials. In the process of building dismantling, more attention will be paid to the protection of components, which will have a very favorable impact on the reuse of building components. Some structurally functional components can be reused in the process of renovation. Taking masonry as an example, if attention is paid to protection during the dismantling process, and the original appearance and architectural style of the old city are to be maintained during the renovation process, these dismantled materials will be the best materials. At the same time, in the design of some structures, landscape sketches, landscape sculptures, etc., these bricks and stones can be fully utilized because they are in harmony with the local natural environment.

4. CASE STUDY

After data characterization of the brick building elements, the dimension of bricks can be gotten. Then, the design and construction of the partition wall are carried out using a limited number of those waste bricks in an idle site space as Figure 8 shows. Specifically, the original intention of its design is to be different from the common rigid brick walls. The original brick wall is first dismantled by a combination of manual dismantling and machine dismantling, the total bricks remaining available is 300 Bricks. Afterward, automatically measuring the brick size is L x W x H = 75 x 25 x 15 mm as input values separately. Therefore, its modulus is 5mm. In fit-in-BIM design, the size unit can be standardized as 1M=5mm for size adaptation between bricks. However, due to the monotonicity of bricks, a parameterization that is different from traditional brick walls is adopted. The masonry form gives the traditional materials new flexibility, allowing them to radiate a new breath and vitality that is different from the traditional. Because the construction site of the brick wall is mostly made of local materials, it is often surrounded by mountains. Therefore, it is hoped that the wall will create the effect of a mountain. In terms of brick wall composition, the design information is used to generate the existing space composition and brick wall scheme by means of parametric design using the Rhino + Grasshopper visual programming software platform. The brick wall of generative design rotates the bricks at different angles, forming different staggers on the horizontal overlap, creating different angles, different shadows, and different rhythms under the sunlight. The change has resulted in an exceptionally rich space.

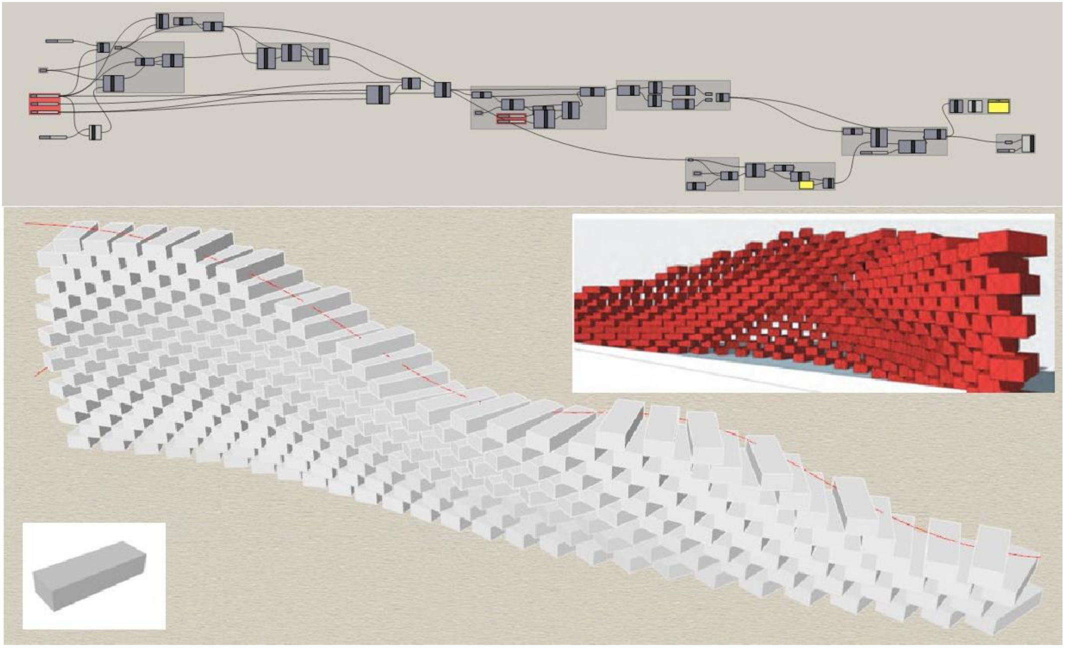

Figure 8: Redesigned dividing wall scheme with recovered bricks of the same size

5. CONCLUSION AND FUTURE WORK

The production of building materials and components usually means a lot of carbon consumption and huge emissions of air waste. Therefore, recovery, reuse, and recycling are increasingly valued in the construction field as an alternative option. With the acceleration of global urbanization in recent years, a large number of waste building materials generated in urban development are difficult to recycle, resulting in land occupation, environmental pollution, resource waste, and other hazards. Therefore, how to reasonably and effectively recycle and reuse waste materials and then better meet the corresponding architectural design requirements has become a problem that designers have to consider. This article starts with point cloud semantic segmentation and analyzes the generative design process of construction waste deconstruction and reuse. Besides, it also studies the application method and development direction of old building elements in modern architecture.

In the field of future development, an artificial intelligence-supported redesign platform for recovered and reused building components will be launched one day. Starting from the components of residential design drawings, a fully automatic intelligent drawing review process will be formed. It can not only realize the automatic import of component models and site area division, and can perform automatic component recognition and export design scheme. This development lays the foundation for the automatic modeling of building information, and finally integrates all the information in the whole life cycle of the building such as planning, design, construction, operation, and maintenance management, and eventually realizes real-time data update and intelligent management.

It has become the consensus of the international community to develop a green and low-carbon economy to cope with climate change. As the main area of energy consumption, buildings should shoulder the main role of building a circular economy. Building regeneration is to extend the life cycle of buildings through various means such as space renovation and reuse, and the use of new materials. It not only preserves the historical and cultural memory of the city but also helps reduce construction waste pollution and economic waste caused by the demolition of a large number of old buildings. Therefore, in the subsequent research, the reuse of building components in abandoned residential houses and idle industrial plants not only needs to involve architectural design methods and architectural techniques but also needs to consider the expression of regionality and diversity of architecture as a cultural platform.

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